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Hot Dogs – Advancing the Epidemiology and Clinical Definition of Heat-Related Illness in UK Dogs

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“Global warming is not a conqueror to kneel before - but a challenge to rise to. A challenge we must rise to.” Joe Lieberman.

Abstract

Heat-related illness (HRI) is a progressive, potentially fatal disorder that occurs when body temperature overwhelms thermoregulation leading to biochemical derangements, organ damage and ultimately irreversible damage to the neurological system. Traditionally termed heatstroke, the British public have typically associated severe HRI with dogs dying in hot cars. However, dogs can develop HRI following exposure to heat in any environment not just in hot cars - and following exercise. As global warming increases the severity and frequency of extreme heat events, understanding the triggers of canine HRI and which dogs are most at risk is vital to protect canine welfare. This thesis aimed to explore the epidemiology of HRI in dogs in the UK and review the clinical presentation and diagnosis of canine HRI to identify future strategies to protect the health and welfare of dogs amidst rising global temperatures. This thesis included investigating tympanic membrane temperature as a method for monitoring body temperature in exercising dogs. Male dogs, increasing ambient temperature, and high speed were factors associated with exercise induced hyperthermia. VetCompass, a database of primary-care veterinary practice patient records, was used to identify dogs presented for treatment of HRI. Analysis of these HRI events identified canine risk factors for HRI including breed, skull shape, age, bodyweight and being overweight, and identified that exercise was the predominant trigger of HRI in UK dogs. Relative risk analysis of clinical signs reported for dogs with HRI was used to develop the novel VetCompass Clinical Grading Tool to support the diagnosis and management of HRI in dogs. These results triggered a national educational campaign “Dogs Die on Hot Walks” aiming to improve public awareness of the leading cause of canine HRI and suggest improving veterinary and public recognition of mild HRI is a key strategy to reduce canine mortality from HRI.

Acknowledgements

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Dr Anne Carter kick-started this project, and I will be forever grateful to her for pouncing on me and asking if I had any ideas on how to monitor body temperature in dogs that drag their humans around muddy (and often freezing) fields at dawn in the British countryside. What started as a cup of coffee debating the merits of rectal versus alternative methods of temperature monitoring (in dogs, mostly) ultimately inspired this thesis. Anne's constant support included guidance, mentorship, coffee, introductions, dogs, bacon, cake, early morning walks to rage against the world, and so much more. Anne is much more than Director of Studies for this thesis, she is the other half of "Hot Dogs", and I wouldn't be where I am without her. Thank you for everything.

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Each of the published Chapters presented in this thesis underwent peer review, a process that was instrumental in the creation of the final published works. Without the reviewers and editors at each journal there would be no publications to include in this thesis, so I thank you all for your constructive feedback and likely unpaid service to the scientific community. Thank you also to my examiners, who were both instrumental in shaping the final version of this thesis, pushing me to advance my understanding and be more critical of my methods.

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Finally, thank you Mum and Dad for insisting I go to vet school rather than become a riding instructor, but mainly for supporting me in everything I've done and filling my world with animals, the art of medicine and nursing, and a quest for knowledge.

Murphy (left) and Monty (right) Carter, the original canine members of Hot Dogs (Photo by Dr Anne Carter).

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List of publications included in this thesis

Chapter Two:

Hall, E. J., & Carter, A. J. (2017). Comparison of rectal and tympanic membrane temperature in healthy exercising dogs. *Comparative Exercise Physiology*, 13(1), 37–44. https://doi.org/10.3920/CEP160034

Chapter Three:

Hall, E. J., & Carter, A. J. (2017). Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer. *Veterinary Nursing Journal*, 32(12), 369–373. https://doi.org/10.1080/17415349.2017.1377133

Chapter Four:

Carter, A. J., & **Hall, E. J.** (2018). Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK. *Journal of Thermal Biology*, *72*, 33–38. https://doi.org/10.1016/j.jtherbio.2017.12.006

Chapter Five:

Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016. *Scientific Reports*, *10*(1), 9128. https://doi.org/10.1038/s41598-020-66015-8

Chapter Six:

Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). Dogs Don't Die Just in Hot Cars—Exertional Heat-Related Illness (Heatstroke) Is a Greater Threat to UK Dogs. *Animals*, *10*(8), 1324. https://doi.org/10.3390/ani10081324

Chapter Seven:

Hall, E. J., Carter, A. J., Bradbury, J., Barfield, D., & O'Neill, D. G. (2021). Proposing the VetCompass clinical grading tool for heat-related illness in dogs. *Scientific Reports*, *11*(1), 6828. https://doi.org/10.1038/s41598-021-86235-w

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Abbreviations

BOAS	Brachycephalic obstructive airway syndrome
CI	Confidence interval
EPR	Electronic patient record
GLM	General linear model
HRI	Heat-related illness
IFSS	International Federation of Sleddog Sports
KC	Kennel Club (The)
NCIT	Non-contact infra-red thermometer
OR	Odds ratio
ROC	Receiver operating characteristic
RT	Rectal temperature
SAVSNET	Small animal veterinary surveillance network
SD	Standard deviation
TMT	Tympanic membrane temperature
UK	United Kingdom
UK BWG	United Kingdom Brachycephalic Working Group
US	United States
UTCI	Universal thermal comfort index
VetCompass	Veterinary companion animal surveillance system
WBGT	Wet bulb globe temperature

Word counts

Critical Studies:

Section I – 7,311

Section II – 2,549

Section III –2,461

Section IV – 3,290

Section V –1,694

Section VI – 5,643

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Chapter Three – 2,625

Chapter Four – 7,475

Chapter Five – 9,408

Chapter Six – 8,280

Chapter Seven – 6,871

Published chapters word count – 39746

Overall thesis:

Total word count: 62,694

Section I: Introduction

Introduction to the research studies and thesis structure

This thesis presents the results of six published studies that address four key themes with an overarching aim to advance the understanding of the epidemiology and recognition of heat-related illness in pet dogs. A key concept that has underpinned the recognition and formal diagnosis of heat-related illness is the measurement of canine body temperature, to recognise when that temperature has exceeded “normal” reference limits and initiated thermal damage to body tissues resulting in disease. Indeed, body temperature measurement forms an important part of most veterinary clinical examinations, yet much of the guidance relating to performing and interpreting a canine temperature measurement previously lacked a robust evidence-base. Meanwhile, climate change is causing increasingly frequent heat-wave events and global temperatures are rising; the incidence and severity of canine heat-related illness will increase unless mitigation strategies can be implemented. Yet, previous research exploring the risk factors and causes of heat-related illness in dogs was limited to relatively small case series from referral veterinary hospitals, so did not accurately represent the wider UK dog population. From the start, the goal was to widely disseminate the findings presented in this thesis so that they could be acted upon immediately, by publishing the results as quickly as possible and in open access format where feasible.

Each of the studies included in this thesis aims to further the understanding of the risk factors for, and identification of, heat-related illness in companion dogs. The goal is to identify ways of improving public education to reduce the occurrence of this potentially fatal condition in order to safeguard canine welfare in the face of global warming.

As the thesis is prepared in alternative format, the overall project is presented as six sections comprising a combination of chapters based on *published journal articles* and parts of the over-arching *critical study* of the work and its implications. The *critical study* is presented throughout the thesis, first in this introductory chapter that situates the body of work and identifies the key evidence gaps, then in a critical narrative of the publications within each of the four sections that address those evidence gaps, and finally as the general discussion. Where *published journal articles* are included, they are presented as chapters that are based on the accepted manuscript version of the study, using the original data from the publication but including revised analysis, presentation, and discussion of the results, with the published version included in an appendix.

Section I presents a narrative literature review (***Chapter One – critical study***) that introduces heat-related illness, how the terminology and diagnosis of the condition has developed in human medicine, and how the condition has been researched in veterinary medicine with a focus on canine patients. A brief introduction to canine thermoregulation is presented, with a review of the methods used for temperature measurement in canine medicine and research. The review highlights the evidence-gaps that this thesis addresses in relation to the epidemiology and diagnosis of heat-related illness in dogs and the measurement of canine body temperature.

Section II comprises two published studies that explored an alternative method of body temperature measurement in dogs by comparing ear thermometer results to those from rectal thermometers (***Chapter Two – published study***), then established a statistically derived normal temperature reference range using tympanic membrane (ear) thermometers (***Chapter Three – published study***). These chapters address the evidence gap "What is an abnormal canine body temperature?" and are followed by a critical review of the works since their publication (***critical study***).

Section III reports an investigation of post-race body temperatures of dogs competing in a canine sport to address the evidence gap "What factors influence canine body temperature during exercise?" (***Chapter Four – published study***). This is followed by a critical review of the study and work that has extended this work (***critical study***).

Section IV includes two published studies using veterinary clinical data from the VetCompass research database that investigate the incidence and risk factors for HRI in pet dogs (***Chapter Five – published study***), and then identify the triggers for HRI (***Chapter Six – published study***). These studies address the evidence gap "How often and why do dogs develop heat-related illness?" and are followed by a critical review of the works and their impact (***critical study***).

Section V presents a novel clinical grading tool that assists diagnosis of HRI in dogs, developed through analysis of data on the clinical signs presented by dogs with HRI treated by UK veterinary practices in the VetCompass database (***Chapter Seven – published study***). This study addresses the evidence gap "How can heat-related illness severity be graded?" and is followed by a critical review of the work (***critical study***).

Finally, **Section VI** (***Chapter Eight)*** presents a general discussion aiming to summarise the overall findings of the thesis, the contribution to the wider literature and the wider impact of the research within policy and practice.

An illustration of the thesis structure is provided in Figure I.1.

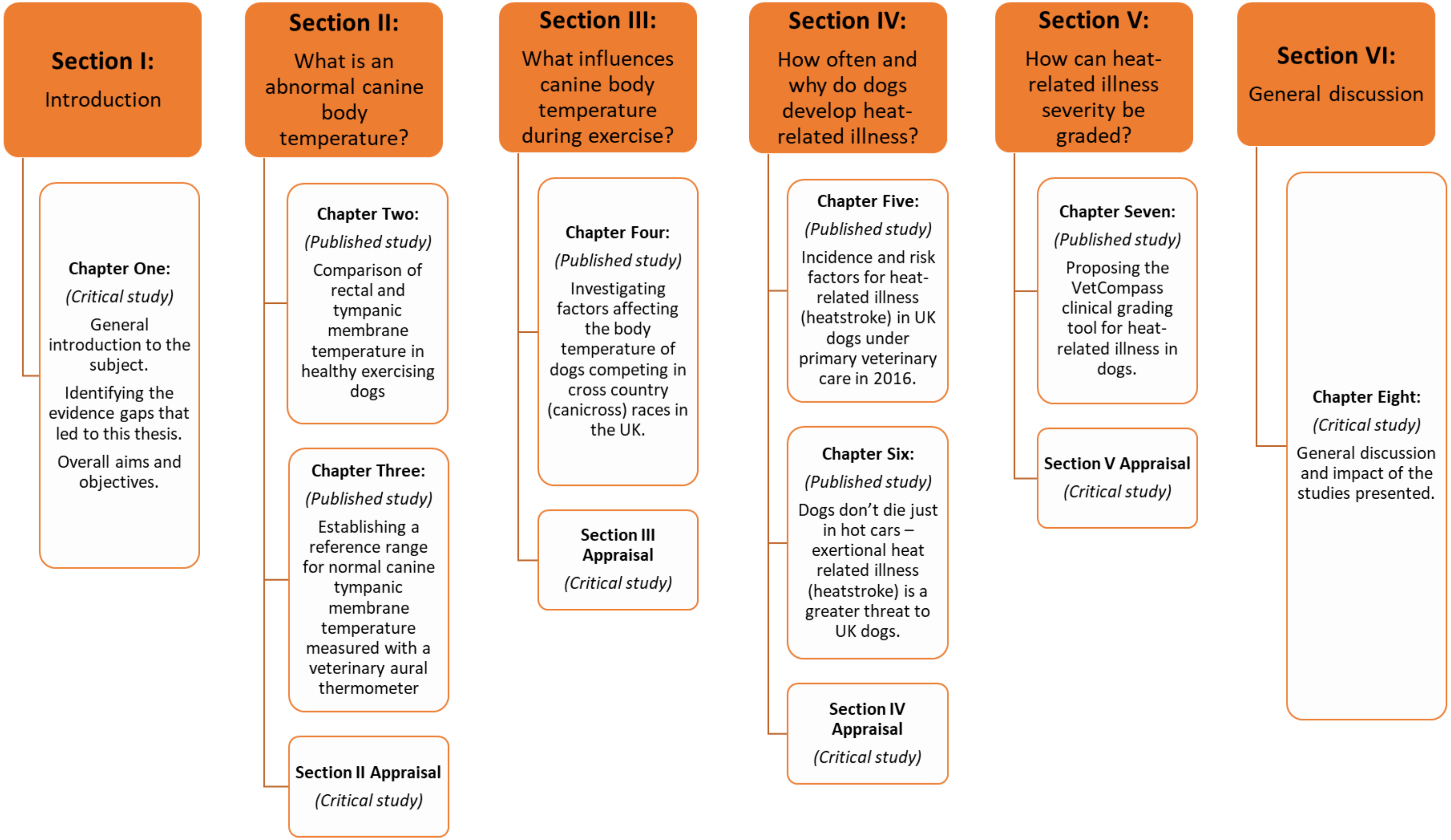


Figure I.1 Structure of the thesis.

Chapter One: Getting hot under the collar: why a better understanding of heat-related illness is essential for canine welfare.

1.1 Introduction

Dogs are the most popular companion animal species in the UK, with approximately one third of all households owning at least one dog, and a current estimated population of 12.5 million dogs (PFMA, 2021). Dogs interweave with almost every aspect of human society, providing companionship, fulfilling service roles such as guiding, searching, combat and medical detection, and competing in canine sports (Cobb et al., 2021; Mcneely & Linquist, 2007; Palmer, 2021; Valentini, 2014). Many of these roles depend on physical activity and the reported benefits of dog ownership are frequently linked to exercising dogs in the great outdoors (Powell et al., 2019; Westgarth et al., 2019). However, rising global temperatures and increasingly frequent extreme heat events triggered by climate change (Mora et al., 2017), have the potential to seriously impact the role dogs play in society, posing a threat to canine health and welfare through heat-related illness (HRI).

The UK dog population is changing, as veterinary professionals in the UK have reported rising levels of canine obesity (PFMA, 2019), with around half of the UK dog population considered to be obese (German et al., 2018; PFMA, 2019). Whilst diet is a major factor in the development of obesity, inadequate exercise also contributes (German et al., 2020). It is therefore concerning that in 2018 over 80% of dog owners reported that heat and humidity in summer resulted in dogs undertaking less vigorous exercise and having overall reduced activity levels (Hall et al., 2021). Obese dogs have reduced thermoregulatory ability due to the insulating effect of excess body fat, and reduced respiratory capacity due to excess fat in the thoracic cavity (Flournoy et al., 2003).

Brachycephalic (flat-faced) dogs have also become increasingly popular, with French Bulldog registrations rising by a factor of ten from 2009 to 2015 (The Kennel Club, 2021b) to become the breed with the most new Kennel Club registrations in 2018 (The Kennel Club, 2018) and remaining the second most commonly registered breed to date (Figure 1.1). Brachycephalic dogs frequently overheat as reported by their owners (Packer et al., 2019); these dogs often struggle to regulate their temperature in response to exercise and stressful situations (Davis et al., 2017; Lilja-Maula et al., 2017). Understanding the risk of HRI to UK dogs, including factors for and triggers of HRI, is therefore an important initial step towards mitigating the impact of climate and canine breed demography change on the human-canine relationship (Hall et al., 2021; Protopopova et al., 2021).

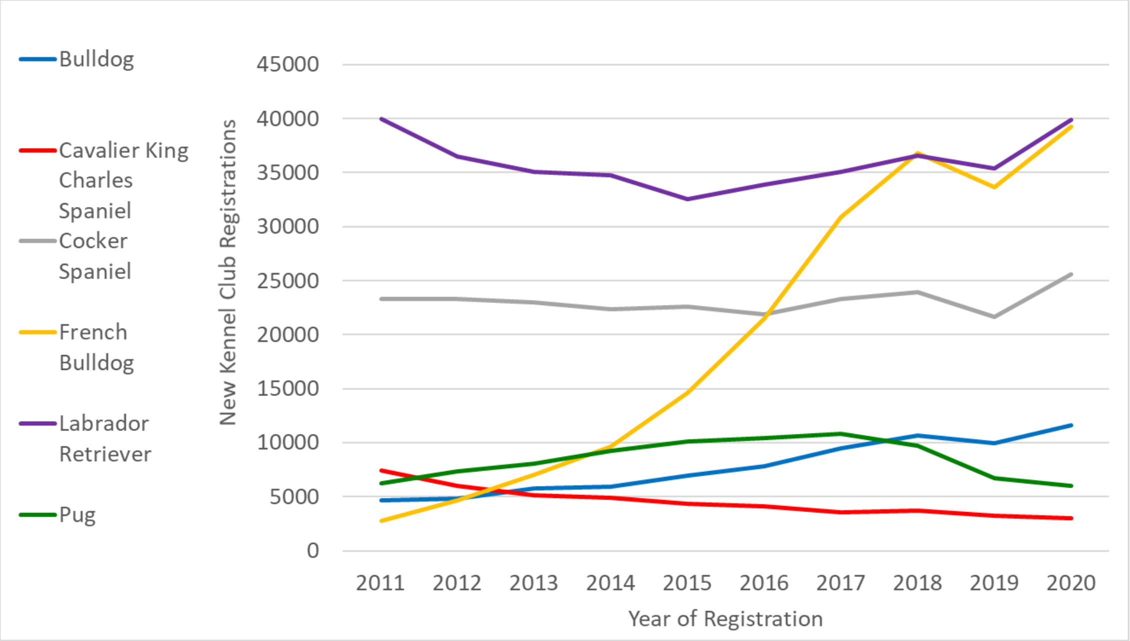


Figure 1.1. Annual breed registrations with the UK Kennel Club from 2011-2020 for a selection of popular breeds (The Kennel Club, 2021a).

This introductory chapter defines heat-related illness, outlines thermoregulation in dogs and how canine conformation and health can impact thermoregulatory capacity and effectiveness, and summarises the literature relating to temperature measurement in dogs. In doing so, the evidence gaps that formed the underpinning rationale for the later research projects presented in Sections II to V of this thesis are revealed.

1.2 Heat-related illness (HRI)

Canine body temperature is tightly regulated by the thermoregulatory control centre located in the preoptic area of the anterior hypothalamus (Ramsey & Tasker, 2017). When body temperature exceeds the normal reference range - currently estimated to be approximately 37.2-39.2°C (Konietschke et al., 2014) - this is termed either pyrexia (fever) or hyperthermia, depending on the underlying cause of the temperature increase (Ramsey & Tasker, 2017). Pyrexia describes an increase in body temperature triggered by the acute phase response to infection, inflammation, or injury, where pyrogens released from the damaged tissue trigger an increase in the thermoregulatory set point in the anterior hypothalamus (Ramsey & Tasker, 2017). This allows the body temperature to rise without initiating cooling mechanisms, resulting in a persistently elevated temperature. Canine body temperature rarely exceeds 41.1°C during pyrexia (Ramsey & Tasker, 2017). In contrast, there is no change to the thermoregulatory set point during hyperthermia, meaning the individual will use both behavioural and physiological responses to try and cool down once the normal temperature set point has been exceeded (Miller, 2015; Ramsey & Tasker, 2017).

Hyperthermia can be caused by:

- increased muscle activity from exercise, seizures, or tremors;
- ingestion of certain medications or toxins;
- metabolic diseases such as hyperthyroidism and hypocalcaemia;
- exposure to increased environmental temperature (Ramsey & Tasker, 2017).

If an individual's thermoregulatory response to hyperthermia is effective (and ambient conditions permit), body temperature will return to normal. However, the thermoregulatory response can be overwhelmed if the animal remains exposed to an elevated ambient temperature, particularly if humidity is high and there is little air movement (e.g., a hot car), or if muscle activity continues, or if the animal's thermoregulatory mechanisms are compromised (see 1.3 Canine thermoregulation) (Ramsey & Tasker, 2017). Prolonged hyperthermia and/or extreme hyperthermia can progress to heat-related illness (HRI) which is characterised by thermal damage to tissues and biochemical derangements that can lead to organ failure and ultimately death (Bouchama & Knochel, 2002).

1.2.1 Evidence Gap: How can heat-related illness severity be graded?

The terms "heat stress", "heat exhaustion" and "heat stroke" were previously used to describe the progressive stages of HRI (sometimes termed heat-induced illness) in human medicine (Bouchama & Knochel, 2002). Bouchama and Knochel's (2002) definitions of heat-induced illnesses for human patients were largely reliant on patient-reported clinical symptoms such as anxiety, headache and delirium, and increased body temperature (see Table 1.2.1). These definitions were adapted for use in dogs, with Bruchim et al. (2006) suggesting that the most severe stage, heat stroke, in dogs be defined by a body temperature >41°C alongside central nervous system dysfunction. Prior to the publication of the studies presented in this thesis (Chapters Four-Six), research exploring heat-induced illness in dogs was limited to either laboratory based experimental procedures (Amsterdam et al., 1986; Bynum et al., 1977, 1978; Magazanik, Epstein, et al., 1980; Magazanik, Shapiro, et al., 1980; Oglesbee et al., 1999; Shapiro et al., 1973; White et al., 1993, 1987), or case series reporting the presentation and outcomes from dogs treated at university veterinary hospitals in the USA (Drobatz & Macintire, 1996), Israel (Bruchim et al., 2006) and Germany (Teichmann et al., 2014) which were limited to the most severe stage of the condition, heat stroke.

Table 1.2.1. Bouchama and Knochel's (2002) heat-induced illness definitions.

Heat-induced illness term	Clinical symptoms and patient history	Body temperature
Heat stress	Patient perception of discomfort, signs of physiological strain (e.g., sweating, fast pulse). History of exposure to a hot environment, especially exercise/labour.	May be normal.
Heat exhaustion	Patient symptoms: intense thirst, weakness, dizziness, discomfort, anxiety, fainting and headache.	Temperature may be normal, below normal, or slightly elevated (>37 to <40°C).
Heat stroke	Patient presents with central nervous system abnormalities including delirium, seizures, or coma. History of exposure to hot environment or strenuous physical work.	Body temperature >40°C.

As HRI is a potentially fatal condition in all species, rapid recognition of the disorder and management of affected patients is essential to limit morbidity and mortality (Bouchama & Knochel, 2002; Glazer, 2005). Yamamoto et al. (2015) noted the difficulty in differentiating between heat exhaustion and heat stroke in human patients, and identified that the decision to hospitalise a patient typically relied upon individual clinician discretion. This subjective approach to patient care is at odds with modern evidence-based medicine principles. The use of inaccurate terminology at hospital admission (heat exhaustion versus heat stroke) impacts epidemiological reporting and risk factor identification (Yamamoto et al., 2015). Yamamoto et al. (2015) proposed that heat stress, heat exhaustion and heat stroke should be considered as stages that lie along a spectrum of HRI; a patient with heat stress could progress to develop heat exhaustion, and a patient with severe heat exhaustion could progress to develop heat stroke. They proposed including all stages of HRI in epidemiological studies, to allow risk factors for mild to moderate HRI (heat stress and heat exhaustion) to be identified, rather than focusing exclusively on the patients presented with the advanced or severe grade of the disorder (heat stroke).

Yamamoto et al. (2015) identified an additional concern relating to use of body temperature as a diagnostic criterion for defining HRI; body temperature can change rapidly following cessation of activity or removal from a hot environment, meaning a temperature recorded at hospital admission is unlikely to be the peak temperature experienced by the patient (Shapiro & Seidman, 1990). Furthermore, the majority of human patients presenting to hospitals for management of HRI have already been actively cooled by the emergency services, therefore body temperature on admission to hospital may have returned to normal, or even dropped below normal (Shapiro & Seidman, 1990), which would preclude a diagnosis of heat stroke if the diagnosis was dependent on body temperature exceeding a critical threshold (Yamamoto et al., 2015). This could lead to a patient being mis-diagnosed with a mild stage of HRI, despite having experienced prolonged hyperthermia prior to being cooled. In turn, this could delay instigation of advanced diagnostic testing and aggressive therapies required to prevent associated long-term organ dysfunction, or even led to death, which can occur following severe heat stroke (Bouchama & Knochel, 2002).

The work of Yamamoto et al. (2015) ultimately led to the development of the Japanese Association for Acute Medicine Committee's classification system for the severity of heat-related illnesses (Hifumi et al., 2018; Yamamoto et al., 2018), which will be discussed further in Section V. This classification system proposes that HRI should be considered as a progressive disorder, with staging of HRI reliant upon clinical signs and not patient body temperature. This novel HRI system has been shown to identify patients with severe HRI more accurately, specifically those at greater risk of death (Yamamoto et al., 2018).

Periods of heat and humidity too severe for human physiological tolerance have doubled in frequency since 1979 (Raymond et al., 2020), with around 30% of the world's population currently exposed to such conditions for at least 20 days per year (Mora et al., 2017). If current greenhouse gas emissions continue, by 2100 this exposure to deadly environmental conditions is predicted to affect ~74% of the global population (Mora et al., 2017). In the UK, climate change is predicted to result in a 257% increase in human heat-related deaths by the 2050s (Hajat et al., 2014), prompting the Government to classify "risks to health, wellbeing and productivity from high temperature" as a priority area for mitigation strategy planning (House of Commons Environmental Audit Committee, 2018). The current (2018) UK heatwave plan includes a heat-health watch alert system, but acknowledges that more work is urgently needed (House of Commons Environmental Audit Committee, 2018). Heat early warning systems and action plans can reduce heat exposure risk effectively, and should be based upon both ambient temperature thresholds and region specific epidemiological evidence of increased HRI hospital admissions (Vaidyanathan et al., 2019). Accurate diagnosis of HRI severity at point of admission is therefore important to ensure epidemiological evidence can support the effectiveness of such early warning systems (Yamamoto et al., 2018).

1.2.2 Evidence Gap: How often and why do dogs develop heat-related illness?

As domestic dogs intertwine with almost every aspect of modern human society, fulfilling roles including companionship, motivation to exercise, military work, medical detection and medical services, it is essential when planning mitigation strategies for global warming that canine health and welfare is also considered (Hall et al., 2021; Protopopova et al., 2021). As previously noted, earlier studies reviewing HRI in dogs tended to focus exclusively on heat stroke in dogs presented to university teaching hospitals, thereby effectively excluding dogs with the less severe forms of HRI (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014). The previous veterinary literature is therefore affected by the same limitations as the human literature, with imprecise diagnostic criteria likely resulting in misclassification of some dogs affected by HRI, and risk factors focused purely on those dogs affected by the most severe grade of the disease.

Reliance upon patient data from university teaching hospitals is an additional challenge in the previous veterinary literature that may be affected by referral bias (Bartlett et al., 2010). Cases referred to university teaching hospitals typically represent the most severe forms of conditions which can impact disease prevalence estimation. Referral populations also typically select highly motivated owners with sufficient financial means to afford advanced diagnostic testing and clinical management (O’Neill et al., 2014). For this reason, VetCompass (the Veterinary Companion Animal Surveillance System) was developed at the Royal Veterinary College in collaboration with the University of Sydney to provide access to de-identified primary-care veterinary practice data (O'Neill et al., 2014). Using primary-care data for epidemiological studies allows more realistic estimations of disease incidence than is possible using referral hospital data only. Using population level data also offers greater precision when exploring disease risk factors. Access to such large datasets is therefore important for the practice of evidence-based veterinary medicine (Holmes & Cockcroft, 2004).

Previous studies reviewing HRI in dogs were therefore unable to accurately estimate the annual HRI incidence, due to low case numbers and a hospital (denominator) population that did not reflect the general canine population (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014). Those previous studies included only “heat stroke” cases, meaning any risk factor identification applied only to the more severe grade of HRI, and was likely skewed by the referral bias. Many previous HRI studies in dogs used an HRI definition based on Bouchama and Knochel’s (2002) classical heat induced illness scale, using body temperature at presentation as part of the diagnostic criteria meaning severe HRI cases that had cooled prior to presentation were potentially excluded. Whilst there is no dedicated paramedic/emergency response service for dogs, dog owners may provide first aid treatment to their pet before seeking veterinary care, so using canine body temperature at presentation as a diagnostic criterion for HRI is as problematic in veterinary medicine as it is in human medicine. The epidemiology of HRI as a progressive condition (including all grades) has therefore not been explored in canine patients; this “evidence gap” forms the rationale for this thesis.

Chapters Five to Seven of this thesis present published research studies that aim to support the practice of evidence-based veterinary medicine when identifying, grading the severity, and monitoring, HRI in dogs. The VetCompass database was used to generate primary-care veterinary data reporting the incidence, risk factors and triggers for HRI in UK dogs in the studies presented in Chapters Five (Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016) and Six (Dogs Don't Die Just in Hot Cars - Exertional Heat-Related Illness (Heatstroke) Is a Greater Threat to UK Dogs). Following the example Yamamoto et al. (2015, 2018) set for human medicine, the studies presented in this thesis included all stages of HRI in dogs, and ultimately adapted by the Japanese Association for Acute Medicine Committee's novel classification system (Hifumi et al., 2018; Yamamoto et al., 2018) for the severity of heat-related illnesses for canine patients in Chapter Seven (Proposing the VetCompass clinical grading tool for heat-related illness in dogs).

1.3 Canine thermoregulation

Body temperature can influence (and limit) biochemical processes that are essential for life. Increased body temperature can alter rates of reaction and induce both reversible and irreversible changes to the structure and function of proteins and enzymes that fuel and regulate the body (Daniel & Danson, 2010). Many mammalian species have evolved complex systems of endothermic homeothermy to tightly regulate their body temperature to within 1-2°C of 38°C (Table 1.3.1), to ensure optimal conditions for biochemical reactions reliant upon enzyme activity(Robinson, 2012; Ruben, 1995).

Table 1.3.1. Recently established normal body temperature ranges in companion animal species (Hall, 2021).

Species	Normal temperature reference range (°C)	Site of temperature measurement (method of measurement)	Reference range statistically derived using veterinary reference interval guidelines (Friedrichs et al., 2012)?	Source
Cat	36.7-38.9	Rectal (digital thermometer)	Yes	(Levy et al., 2015)
Dog	37.2–39.2	Rectal (digital thermometer)	Not reported	(Konietschke et al., 2014)
Dog	36.6-38.8	Ear (Vet-Temp thermometer)	Yes	(Hall & Carter, 2017)
Ferret	37.9-39.9	Rectal (digital thermometer at 2cm depth)	No	(Aguilar et al., 2019)
Horse	36.0-38.0	Rectal (digital thermometer at 5cm depth)	Yes	(Hall, Carter, et al., 2019)
Rabbit	37.4-39.6	Rectal (digital thermometer at 3cm depth)	Yes	(Gallego, 2017)

Severe HRI occurs when thermal damage leads to multi-organ failure, characterised by neurological dysfunction, coagulopathy, metabolic acidosis, and renal and hepatic pathology (Bouchama & Knochel, 2002; Bruchim et al., 2017). When body temperature rises above 41°C, irreversible denaturing of proteins and enzymes begins, with permanent brain damage possible (Lewis & Foster, 1976). At 43°C, coagulopathy occurs with multi-organ haemorrhage and damage evident on both gross and histopathological examination of tissues (Shapiro et al., 1973). When body temperature is sustained at 49-50°C for 5 minutes or more, all cellular structures are destroyed, leading to cellular necrosis (Buckley, 1972 in Johnson et al., 2006). Mammals have therefore evolved several physiological mechanisms to prevent uncontrolled body temperature variation including thermoregulation, acclimatisation, acute phase response and induction of heat shock proteins (Hemmelgarn & Gannon, 2013). Heat dissipation can be achieved through both behavioural changes and physiological mechanisms (Figure 1.3.1). Behavioural changes include seeking cooler locations, reducing or ceasing activity, postural changes to expose hairless regions to cooler surfaces or the air, and immersion in water (Figure 1.3.2).

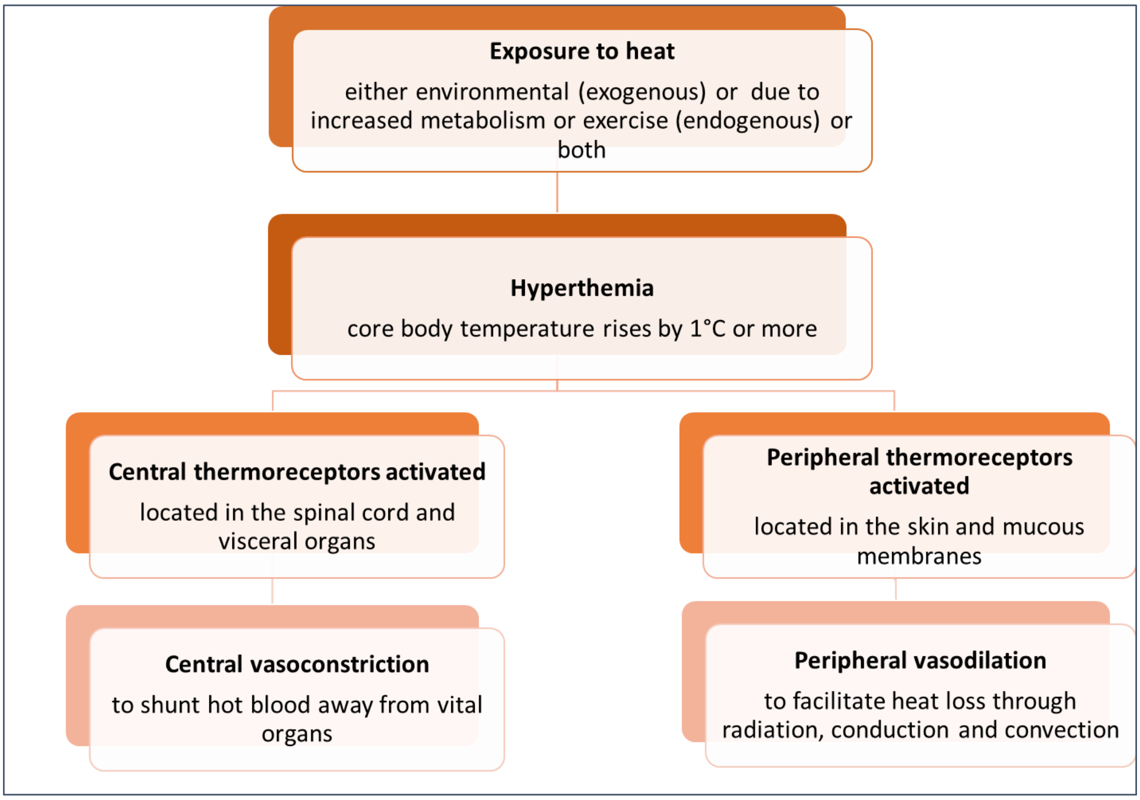
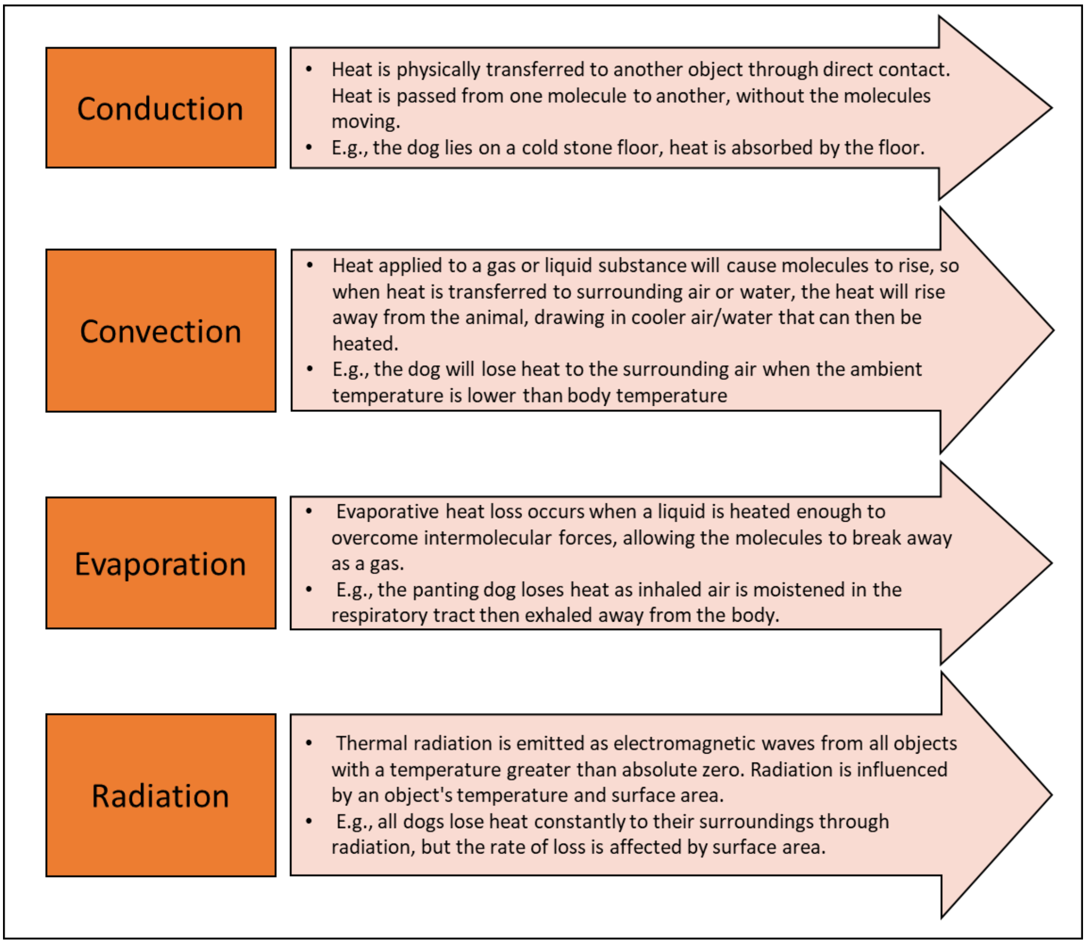


Figure 1.3.1. Early compensatory stages of thermoregulation (adapted from Hemmelgarn and Gannon, 2013).

Figure 1.3.2. Hendricks the German Shorthaired Pointer immerses himself in some muddy water to cool off after a training session in December (ambient temperature approximately 4°C). Photo: Dr Anne Carter.

There are three mechanisms that allow heat transfer between the body and the environment: conduction, convection and radiation (see Figure 1.3.3) (Robinson, 2012). Evaporation, sometimes referred to as the fourth mechanism of heat transfer, is a form of convective heat loss that involves a heated liquid changing state to a gas. Animals can use all four mechanisms to facilitate thermoregulation and heat loss (Robinson, 2012). For example:

- Dogs will lie on cold flooring to cool via conduction.
- The position of hairs can be altered to facilitate air movement which increases convective heat loss, and dogs will actively seek to enter water to facilitate convective heat loss in water.
- Dogs can increase heat loss via radiation by changing their posture: extending limbs away from the body will increase the dog's surface area allowing more radiative heat loss, whereas a dog feeling cold may sit or lie in a tucked posture, reducing surface area to conserve heat. Radiation of heat is also impacted by body composition and conformation. Lean, long-legged breeds (such as Greyhounds) have a greater surface area, so will lose more heat via radiation than squat, short-legged breeds (such as Pugs). Overweight and obese animals have relatively reduced body surface area, which reduces heat radiation, and have increased fat tissue insulating blood from the skin which reduces convection and conduction of heat away from the body.
- Evaporative heat loss can occur either through evaporation of sweat from the skin (in species such as humans and horses), or via the respiratory tract (e.g., panting in dogs).



Conduction

- Heat is physically transferred to another object through direct contact. Heat is passed from one molecule to another, without the molecules moving.
- E.g., the dog lies on a cold stone floor, heat is absorbed by the floor.

Convection

- Heat applied to a gas or liquid substance will cause molecules to rise, so when heat is transferred to surrounding air or water, the heat will rise away from the animal, drawing in cooler air/water that can then be heated.
- E.g., the dog will lose heat to the surrounding air when the ambient temperature is lower than body temperature

Evaporation

- Evaporative heat loss occurs when a liquid is heated enough to overcome intermolecular forces, allowing the molecules to break away as a gas.
- E.g., the panting dog loses heat as inhaled air is moistened in the respiratory tract then exhaled away from the body.

Radiation

- Thermal radiation is emitted as electromagnetic waves from all objects with a temperature greater than absolute zero. Radiation is influenced by an object's temperature and surface area.
- E.g., all dogs lose heat constantly to their surroundings through radiation, but the rate of loss is affected by surface area.

Figure 1.3.3. The three fundamental mechanisms of heat transfer between a body and the environment (Robinson, 2012).

When ambient temperature approaches core body temperature, evaporative heat loss becomes increasingly important for heat dissipation to maintain normothermia (Flournoy et al., 2003). The major difference between canine and human thermoregulation relates to the predominant mechanism used to facilitate evaporative heat loss; humans use sweating whereas dogs use panting. In humans, evaporation is achieved primarily through sweating from secretions of eccrine (merocrine) sweat glands in the skin of the entire body. In contrast, whilst dogs possess apocrine sweat glands in their haired skin all over the body, these glands do not appear to play a primary role in thermoregulation through sweating. Instead they appear to be principally involved in protecting the skin from direct thermal burns through conduction (Aoki & Wada, 1951) and pheromone production (Cotton et al., 1975; Cotton & van Hasselt, 1972). Dogs do however, have eccrine sweat glands on their paw pads (Takahashi, 1964), thought to play a role in improving traction when running by increasing friction between the pad and the ground (Adelman et al., 1975). Cutaneous evaporation from all canine sweat glands has been shown to contribute to around 10-20% of the total water loss through evaporation in dogs exposed to high air temperature (41°C) and dogs exercised at similar temperatures (Taylor et al., 1971). Taylor et al. (1971) assert that this suggests that cutaneous evaporation plays a minor role in heat loss compared to respiratory evaporation.

Rather than sweating, dogs use respiratory evaporation through panting as the primary mechanism for heat dissipation during hyperthermia (Goldberg et al., 1981). A lateral nasal gland produces fluid to facilitate evaporation within the nasal cavities (Blatt et al., 1972) and there is a concurrent increase in saliva production that ensures constant moisture for evaporation from the tongue and mouth (Hammel and Sharp, 1971 in Baker et al., 1983). The pattern of air flow through the respiratory tract can be altered depending on the degree of hyperthermia experienced and the demand for additional respiration (Goldberg et al., 1981). At ambient temperatures below 26°C, or during low intensity exercise, dogs inhale and exhale through the nose (pattern 1). Above 30°C, dogs will start to use two alternative air flow patterns, either inhalation through the nose and exhalation through both the nose and mouth (pattern 2), or inhalation through both the nose and mouth and exhalation through both the nose and mouth (pattern 3) (Goldberg et al., 1981). Patterns 2 and 3 tend to be used interchangeably, however the proportion of time using pattern 3 increases as exercise intensity and ambient temperature increase (Goldberg et al., 1981). Nevertheless, evaporative cooling reduces total body water, so cannot be maintained indefinitely as eventually fluid losses lead to reduced circulating blood volumes, hypoperfusion of tissues, circulatory collapse and, ultimately, death (Flournoy et al., 2003; Robinson, 2012). To conserve blood volume, dogs can vary the water lost through panting depending on their hydration status. For example, dehydrated dogs develop higher body temperatures during exercise than hydrated dogs because they conserve water, namely through significantly reduced saliva production (Baker et al., 1983). Dehydrated dogs also reduce evaporative water loss through panting once exercise has ceased because panting is triggered at higher body temperatures than seen in hydrated dogs (Baker et al., 1983).

The effectiveness of panting is influenced by the surface area available for evaporative heat loss (Oechtering et al., 2016; Schmidt-Nielsen et al., 1970). Both the length of the nasal cavity and the scrolling conchal bones comprising the nasal turbinates determine the surface area available and, therefore, the potential for evaporative heat loss (Oechtering et al., 2016). Figures 1.3.4-1.3.6 illustrate the relative difference in muzzle length between brachycephalic, mesocephalic and dolichocephalic dog breeds. Brachycephalic dog breeds have reduced capacity for evaporative heat loss through lack of nasal turbinate surface area due to reduced nasal cavity length (Oechtering et al., 2016). Brachycephalic dog breeds are often diagnosed with brachycephalic obstructive airway syndrome (BOAS), a syndrome which describes anatomical changes to the respiratory tract characterised by narrowing of the airway and increased resistance to airflow (Harvey, 1989). One anatomical feature contributing to the increased resistance to airflow is the congestion and inflammation of the tissue overlying the nasal turbinates (Schuenemann & Oechtering, 2014). Inflamed turbinates can swell to the degree that they result in mucosal contact points, areas where the nasal turbinates make contact, effectively closing the airway and preventing airflow (Schuenemann & Oechtering, 2014). Faced with increased resistance to airflow, brachycephalic dogs therefore use more muscular force via the thoracic musculature, and often additional force from the abdomen, to facilitate air movement; this additional muscular effort, in turn, produces additional metabolic heat (Davis et al., 2017). Thermoregulation through panting is therefore less effective for brachycephalic dogs and increased respiratory effort can instead contribute further to hyperthermia.

Figure 1.3.4. A Pug skull illustrating a brachycephalic skull shape. Brachycephaly is defined as a skull that is shorter from front to back than it is wide, giving a rounded shape. Photo: Claire Mitchell.

Figure 1.3.5. A Labrador Retriever skull illustrating a mesocephalic skull shape. Mesocephaly is defined as a skull with an equal width to length, giving a square shape. Photo: Claire Mitchell.

Figure 1.3.6. A Greyhound skull illustrating a dolichocephalic skull shape. Dolichocephaly is defined as a skull which is longer front to back than it is wide. Photo: Claire Mitchell.

1.4 Temperature measurement

Body temperature measurement is frequently used as a screening tool for disorders such as infectious diseases (e.g., to detect fever), therefore, an accurate reference range is needed to define when a temperature is considered “abnormal” (Lumsden & Mullen, 1978). Hausmann et al. (2018) recently redefined normal and febrile body temperatures for adult humans as 36.5°C and 37.5°C, respectively, using over 5000 crowdsourced oral temperature measurements from 329 participants. They highlighted that the previous normal (37°C) and febrile (38°C) temperature values were defined by Wunderlich in 1868, in a study that measured axillary temperature using a foot-long thermometer that took up to 20 minutes to equilibrate and had to be read *in situ* (Mackowiak et al., 1992). There is also speculation that the thermometer Wunderlich used was inaccurately calibrated (Haller, 1985). Whilst the medical community should be concerned that the reference limits for one of the most frequently performed clinical examination measurements have been based on a likely inaccurate study that pre-dated modern statistical methods for deriving normal reference ranges, at least they cite the source of those reference limits. It is difficult to determine if a reference range can be applied to a specific individual or scenario unless there is a citation to the origin of a reference range. For example, Wunderlich’s normal temperature values were established measuring temperature at the axilla, so clinicians can expect a temperature monitored at a different anatomical site to differ and interpret the results accordingly (Mackowiak et al., 1992). Many veterinary textbooks state a normal reference range for canine body temperature, but fail to cite the source of the proposed range or the anatomical location where the temperature should be measured when using said range (Fielder, 2016; Goddard & Phillips, 2011; Miller, 2009, 2015; Ramsey & Tasker, 2017). Therefore, the likely accuracy of the range is hard to determine.

Internal temperature is not uniform throughout the body (Nakamura, 2010). Indeed, as the respiratory tract and skin are involved in thermoregulation, it is unsurprising that there is temperature variation by anatomical location. Blood temperature is considered to be the true “core” temperature, where pulmonary artery thermistors are considered the “gold standard” for assessing core body temperature (Gomart et al., 2014; Greer et al., 2007; Lamb & McBrearty, 2013). However, arterial thermistor placement is invasive and impractical for routine temperature monitoring, so alternative proxy measures of core temperature can be taken using oesophageal or urinary bladder thermometer placement (Barnes et al., 2017; Watson et al., 2015). Nevertheless, these measures are only practical for anaesthetised patients. Therefore, rectal thermometry is considered the best estimate of core temperature in conscious animals. For example, in their study of anaesthetised dogs, Greer et al. (2007)

reported that almost 95% of rectal temperature readings were within 0.5°C of pulmonary artery temperature (0.5°C is generally considered to be the clinically acceptable difference between thermometer readings from different thermometer types), although the majority of those rectal temperature readings were higher than the concurrent arterial temperature. Whilst human body temperature is frequently measured by oral thermometry, this is impractical in veterinary medicine, as many species use respiration as a site of thermoregulation (meaning the mouth is often open which will lower the temperature) and few animals would tolerate the insertion of a thermometer without the potential for instrument damage from chewing.

Yet, rectal thermometry is not without risks or limitations. Most canine patients require restraint in order to perform rectal thermometry, while some canine patients will not tolerate the procedure (Gomart et al., 2014; Lamb & McBrearty, 2013; Smith et al., 2015). There is also evidence in other species that the stress associated with handling and placement of the thermometer probe can itself increase body temperature (Ozawa et al., 2017). Gomart et al. (2014) measured behaviours indicative of stress (vocalisation, lip licking, shaking, panting and defensive behaviour) and heart rate elevation following rectal, axillary and ear thermometry. They reported that heart rate elevation was highest for rectal thermometry, and stress behaviour was most frequently displayed following rectal thermometry (Gomart et al., 2014). As rectal thermometry has the potential to cause stress in dogs, repeated canine rectal temperature measurements could exceed the threshold of the requirement for Home Office Licensing under the Animals (Scientific Procedures) Act 1986 in the UK. Indeed, the Home Office Inspectorate narrowly voted to approve the study presented in Chapter Two, that involved a maximum of six rectal temperature readings spread over three different periods of exercise, without the need for a Project License. Rectal thermometry is therefore an unsuitable method of measuring body temperature, when repeated measurements are needed purely for research purposes, unless a Home Office License is granted.

In addition, rectal thermometers can transmit infection, so thorough disinfection is needed which requires the use of glutaraldehyde (a highly irritant disinfectant) with a 10 minute contact time (Rutala et al., 2019) which is impractical in most veterinary settings. Thermometer covers are available to reduce the risk of infection transmission between patients, and have been shown to have no impact on the accuracy of temperature readings (Jolivet et al., 2020), although the covers contribute to single use plastic waste (Koytcheva et al., 2021). Furthermore, accurate rectal thermometry requires training, as failure to contact the rectal wall can result in gas or faeces within the rectum affecting the accuracy of temperature measurement (Naylor et al., 2012), and animals with peri-anal disease or poor anal tone are likely to have increased air present in the rectum which will lower the temperature (Kreissl & Neiger, 2015).

Non-contact infra-red thermometers (NCIT) can be used to measure the surface temperature of various anatomical locations and offer an alternative to oral or rectal thermometry in human patients (Chiappini et al., 2011). However, they have so far proven problematic for veterinary patients. In humans, the hairless skin on the forehead overlying the temporal artery provides the ideal location for temperature measurement (Greenes & Fleisher, 2004) and has been used to screen for fever during both Ebola and Covid-19 (Hussain et al., 2021). In contrast, dogs have limited areas of hairless skin, meaning most veterinary studies have evaluated the eye surface temperature for NCIT use (Figure 1.4.1). Whilst NCIT use on the ocular surface of horses has shown some promise (Carter et al., 2019), results from studies measuring canine ocular surface temperature using NCITs all suggest that ocular temperature does not reflect rectal temperature and is in fact relatively constant during both hypo- and hyperthermia (Hall, Fleming, et al., 2019; Kreissl & Neiger, 2015; Zanghi, 2016). Surface temperature from other anatomical locations in dogs has been explored, but to date no site has been identified that provides a suitably accurate alternative compared to rectal temperature (Cugmas et al., 2020; Rizzo et al., 2017).

Figure 1.4.1. Ocular surface temperature measurement using a non-contact infra-red thermometer on the very compliant Tilly the Labrador retriever. (Image from Hall et al., 2019).

Infra-red thermometry can also be used to measure tympanic membrane temperature, by inserting an anatomically tailored device into the ear canal. The anatomy of the ear canal is different between human and veterinary patients; therefore, a veterinary-specific ear thermometer is required to measure true tympanic membrane temperature rather than the surface temperature of the ear canal (Figure 1.4.2). Studies comparing canine tympanic membrane temperature (measured with human ear thermometers) to rectal temperature have yielded mixed results, with differences ranging from -0.115°C to 1.27°C (Huang & Shih, 1998; Konietschke et al., 2014; Piccione et al., 2011; Southward et al., 2006; Yanmaz et al., 2015). Studies using the veterinary-specific devices tend to report better agreement between rectal and ear temperature (Gomart et al., 2014; Gonzalez et al., 2002; Greer et al., 2007; Lamb & McBrearty, 2013; Piccione et al., 2011; Rexroat et al., 1999; Wiedemann et al., 2006), although most studies report that ear temperature is typically lower than rectal temperature. Nevertheless, studies published prior to 2016 included only veterinary patients who were potentially experiencing stress or excitement which can elevate body temperature (Bragg et al., 2015), or anaesthetised animals that commonly develop hypothermia (Sessler, 2016). For example, Bragg et al., (2015) examined dogs in their home environment and then in a veterinary clinic and reported that 22/30 dogs had higher body temperature in the clinic versus at home, indicating stress or excitement in the clinic. However, the median temperature increase was only 0.2°C (temperature differences ranged from -0.44 to 1.06°C), which would not be considered clinically significant as a difference of 0.3 to 0.5 °C is typically considered clinically acceptable when comparing thermometers (Greer et al., 2007; Konietschke et al., 2014; Makic et al., 2011).

Therefore, those previously published studies did not evaluate ear temperature in healthy, conscious animals at rest, so could be subject to variation due to stress or the effects of anaesthesia. In addition, previous studies did not include animals with non-pathological temperature elevation (e.g. hyperthermia due to exercise, rather than stress or pathology) and Gomart et al., (2014) identified that further research was needed to determine the accuracy of ear thermometers for detecting hyperthermia. This evidence gap was the rationale for the study presented in Chapter Two (Comparison of rectal and tympanic membrane temperature in healthy exercising dogs).

Figure 1.4.2. A human ear thermometer (left) alongside a veterinary ear thermometer designed for use with dogs (image from Hall & Carter, 2017).

1.4.1 Evidence Gap: What is an abnormal canine body temperature?

One of the challenges associated with evaluating thermometer accuracy, and indeed evaluating any temperature measurements from a dog, is the lack of a robust, statistically-derived normal temperature reference range for rectal temperature in dogs (Hall, 2021). Whilst Konietschke et al. (2014) proposed a canine rectal temperature reference range of 37.2–39.2°C, their study included just 62 dogs presented to a veterinary hospital (meaning the dogs were potentially aroused or stressed at the time of measurement, resulting in elevated temperature), and did not report the statistical methods used to derive the reference range, making it impossible to determine reliability (Friedrichs et al., 2012). As previously noted, most veterinary textbooks simply state a normal reference range with no acknowledgement of sources such as how they were derived or what animal populations were used, preventing evaluation of their accuracy. Furthermore, recent studies reviewing the normal rectal temperature ranges for healthy cats (Levy et al., 2015) and horses (Hall, Carter et al., 2019) have reported that previously published values appear to be too high, mirroring the findings of Hausmann et al. (2018) in humans.

With no reliable reference range available for canine body temperature, accurate interpretation of temperature measurements is challenging. As noted previously, temperature varies by anatomical location, and ear temperature is typically lower than rectal temperature when measured concurrently (Gomart et al., 2014; Greer et al., 2007; Smith et al., 2015; Zanghi, 2016). Sousa (2016) therefore argues that temperature measurements from different body sites should not be interpreted interchangeably with published rectal reference ranges, and instead reference ranges specific to each anatomical site are needed for accurate interpretation of results. This evidence gap was the rationale for the study presented in Chapter Three (Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer).

1.4.2 Evidence Gap: What factors influence canine body temperature during exercise?

Finally, the previous definition of heat stroke in dogs included the elevation of body temperature above 41°C, along with clinical signs such as neurological dysfunction (Bruchim et al., 2006). However, studies measuring the body temperature of dogs participating in sled dog races (Phillips et al., 1981), Greyhound races (McNicholl et al., 2016), and military working trials (O'Brien et al., 2018) have demonstrated that dogs regularly develop temperatures exceeding 41°C during exercise without showing any clinical signs of heat-related illness. All of these studies included dogs that had undergone extensive physical training, which can acclimatise the body to heat by inducing thermo-protective mechanisms such as production of heat shock proteins (Bruchim et al., 2019) and lowering the temperature threshold that triggers heat dissipation mechanisms (Horowitz, 2001). Heat shock proteins have a cytoprotective role, protecting proteins from thermal damage that can trigger cell death and tissue damage (Sharp et al., 1999). Heat acclimatised canine athletes are therefore better able to tolerate elevations in body temperature that could be dangerous to non-heat acclimatised dogs (Bruchim et al., 2019).

Canicross is a sport that involves dogs running in harness with their owner/handler over various distances, and has become increasingly popular amongst pet dog owners looking to increase their own, and their dog's, wellbeing and fitness through outdoor exercise (The Kennel Club, 2017). Many canicross clubs offer races to competitors of all abilities, so whilst some dogs are seasoned canine athletes likely to be acclimatised to heat, there are also novice competitors running with dogs that may lack fitness and heat acclimatisation (Lafuente & Whyle, 2018). Whilst canicross in the UK is typically an autumn to spring sport, climate change has resulted in increasing variability in seasonal weather (Mora et al., 2017), so some race events coincide with unseasonably warm weather. Consequently, concerns were raised within the UK canicross community that dogs were overheating. In addition, there were anecdotal reports of dogs dying from heat stroke following canicross races. As an experienced canicross racer and canine welfare scientist, Dr Carter (Director of Studies for this thesis) was approached by a local club, Canicross Midlands, for advice regarding safe running conditions for dogs. With no UK based, pet dog exercising temperature research available in the existing literature, this provided the evidence gap and rationale for the study presented in Chapter Four (Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK).

1.5 Research aim and objectives

The aim of this thesis was to explore the epidemiology of HRI in UK dogs and improve the clinical recognition of HRI through more accurate grading of the disease. The following objectives were set to address the four evidence gaps identified during the literature review:

1. To statistically derive a normal temperature reference range for healthy dogs using a minimally invasive thermometer suitable for field use.
2. To identify factors that influence canine body temperature during exercise.
3. To estimate the incidence of HRI in UK dogs presenting to primary-care veterinary practices and identify risk factors and triggers for HRI.
4. To develop a clinical grading tool for canine HRI using clinical signs observed in dogs presented to primary-care practice.

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Section II. What is an abnormal canine body temperature?

II.1 Section introduction:

This section presents novel results from the evaluation of veterinary ear thermometers, an alternative to rectal thermometers, as a method of monitoring canine body temperature. Chapter Two presents a comparison of rectal and tympanic membrane temperature (measured with a veterinary ear thermometer) in healthy dogs in a non-veterinary clinic setting. This comparative study includes pre and post exercise temperature monitoring to evaluate the accuracy of the ear thermometer in hyperthermic dogs in order to address whether tympanic membrane temperature is an accurate measurement of canine body temperatures. Chapter Three presents a novel reference range for canine body temperature measured with an ear thermometer, derived from a population of healthy dogs in a non-veterinary clinic setting. This study addresses the evidence gap "*What is an abnormal canine body temperature?*". A critical appraisal of the works follows the two published studies presented in Chapters Two and Three, reviewing the reception of the studies in the wider scientific community and how subsequent publications have built upon the findings presented here.

This section contains reworked analyses and critical appraisal of the following published studies:

Chapter Two:

Hall, E. J., & Carter, A. J. (2017). Comparison of rectal and tympanic membrane temperature in healthy exercising dogs. *Comparative Exercise Physiology*, 13(1), 37–44. https://doi.org/10.3920/CEP160034

Chapter Three:

Hall, E. J., & Carter, A. (2017). Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer. *Veterinary Nursing Journal*, 32(12), 369–373. https://doi.org/10.1080/17415349.2017.1377133

Chapter Two: Comparison of rectal and tympanic membrane temperature in healthy exercising dogs.

This is a revised investigation using the original data from an article published by Wageningen Academic Comparative Exercise Physiology on 06.03.2017 available online: https://doi.org/10.3920/CEP160034

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Conflicts of interest: The authors have no conflicting interests to declare.

Keywords: hyperthermia, canine athlete, aural thermometer, temperature monitoring

2.1 Abstract

The ability to monitor body temperature in athletes at risk of hyperthermia is essential in all species. Currently, the only commonly accepted temperature monitoring site in dogs is the rectum. This is impractical in field situations as it takes time, requires additional handlers to restrain the dog and is not tolerated by all animals. Tympanic membrane temperature (TMT) monitoring may provide a rapid measure of body temperature to facilitate identification of heat stress and heat stroke in canine athletes. In human studies, TMT diverges from rectal temperature (RT) as body temperature increases during exercise induced hyperthermia so is not recommended for monitoring human athletes. If the same divergence occurs in dogs, TMT may not be suitable for use when monitoring the temperature of canine athletes.

The aim of the study was to determine if TMT diverged from RT following exercise in healthy dogs.

Twenty-four healthy dogs were recruited to the study. Body temperature was measured using a veterinary auricular infrared thermometer (VetTemp) to record tympanic membrane temperature and an electric predictive rectal thermometer. Temperatures were recorded pre and post exercise in a non-clinical setting, familiar to the dogs.

The linear mixed model showed that exercise had no effect on the difference between RT and TMT (*β = 0.01, 95%CI =* -0.12 to 0.15). The overall mean difference of RT minus TMT was 0.4˚C (n = 116). A modified Bland Altman analysis identified a bias of 1.01 (lower limit of agreement 0.99, upper limit of agreement 1.03) for the ratio of RT/TMT, and 68.4% of

paired RT/TMT readings fell within the accepted 0.5˚C difference in temperature recording method.

In line with previously reported TMT to RT comparison studies in dogs, this study found that TMT measured consistently lower than RT. The hypothesis that dogs would show greater differences between TMT and RT following exercise was not supported, suggesting that TMT could be used to monitor body temperature in exercising dogs where RT is not possible.

2.2 Introduction

Exertional heat stroke occurs when core temperature exceeds the body's thermoregulatory mechanism, typically after strenuous exercise, when athletes are not appropriately acclimatised to the ambient conditions, or when exercising in high ambient temperatures (Reniker & Mann, 2002). As the popularity of canine sports continues to increase (The Kennel Club, 2017) there is an increased risk of exertional heat stroke occurring (Hall & Carter, 2016). The ability to measure canine athlete temperatures during training and racing events is essential for identifying those at risk of heat injury, as rapid treatment has been shown to reduce mortality (Bruchim et al., 2006).

The ability to estimate body temperature is essential for animal welfare, as core temperature measurements from the trachea, oesophagus or a central vascular space require the use of invasive and potentially painful techniques which are impractical for most field or clinical settings (Miller, 2009). There are a number of non-invasive body temperature monitoring devices, however the literature to support their use is lacking.

Rectal temperature (RT) is the most widely used method of estimating core temperature in veterinary medicine (Greer et al., 2007; Southward et al., 2006), however this method is not tolerated in all dogs (Lamb & McBrearty, 2013) and can prove impractical in non-clinical situations. Where rectal temperature is tolerated, assistance is often required in order to restrain the patient for temperature measurement. Lamb and McBrearty (2013) reported that 45.5% of conscious canine patients required additional restraint for rectal thermometry. For these reasons there has been continued interest in alternative methods of estimating core temperature, such as infrared auricular thermometers, axillary temperature recording and the use of infrared thermography (Lamb & McBrearty, 2013; Yanmaz et al., 2015). Infrared auricular thermometers measure the tympanic membrane temperature (TMT) and provide an attractive alternative to RT measurement, both in terms of speed (Greer et al., 2007) and patient tolerance. Lamb and McBrearty (2013) reported that conscious canine patients were less likely to require additional restraint for TMT measurement than RT measurement.

However, auricular thermometers have been found to vary in accuracy at predicting RT with mean RT minus TMT differences ranging from -0.015˚C to 1.27˚C (Huang & Huang, 1999; Huang & Shih, 1998; Konietschke et al., 2014; Piccione et al., 2011; Sousa et al., 2011, 2013; Southward et al., 2006; Yanmaz et al., 2015). This variation may be due to the use of non-veterinary specific auricular thermometers. The veterinary specific devices appear to be more reliable with mean differences ranging from -0.015 ˚C to 0.77 ˚C (Gomart et al., 2014; Gonzalez et al., 2002; Greer et al., 2007; Lamb & McBrearty, 2013; Piccione et al., 2011; Rexroat et al., 1999; Smith et al., 2015; Wiedemann et al., 2006). The majority of these studies report that TMT measures consistently lower than rectal temperature. Improved accuracy of the veterinary specific thermometer has been reported in hypothermic patients when compared to hyperthermic patients in a clinical setting (Greer et al., 2007). Southward *et al*. (2006) hypothesised that the device would be less accurate in hyperthermic patients, based on results from the human literature. The findings of Greer *et al.* (2007) were in support of this theory; however, they investigated anaesthetised laboratory animals with endotoxin induced pyrexia. To date, the effects of physiological, exercise induced hyperthermia on device accuracy have not been investigated in canine athletes.

Within the human medicine literature, a review of TMT versus RT in exercising, hyperthermic athletes, found that TMT increasingly diverges from RT as athlete temperature increases (Huggins et al., 2012). Due to the potential risk of under reporting hyperthermia, it has been suggested that TMT is not a suitable method of monitoring body temperature in human athletes. If this divergence is also present in canine athletes, the same limitations will apply to the tympanic membrane (TM) thermometer, namely underreporting hyperthermia.

The need to monitor canine temperature is not restricted to veterinary settings. Where activities take place in warmer climates, there is an increased risk of both environmental and exertional heat stroke (Johnson et al., 2006). Non-invasive methods of monitoring temperature should ideally be available to ensure rapid identification of animals suffering from heat stress and heat stroke, as morbidity and mortality both reduce if the animal is presented quickly for veterinary care (Bruchim et al., 2006). Increasingly pet owners are becoming aware of the technology available for monitoring their pets' vital signs, including animal specific health monitoring devices such as the PetPace collar, the Voyce Health

Monitor collar, and animal specific TM thermometers such as the Pet-Temp Instant Ear Thermometers. As participation in canine sporting activities increases, owner interest in canine athletic performance and health monitoring is also likely to increase. Within canine sport, owners are beginning to be encouraged to monitor temperature as a sign of performance (Canine Health Foundation, 2015). Internet forums also show that owners are monitoring their dog's temperature using these devices when deciding whether to seek veterinary advice for a sick animal. It is therefore essential that pet owners and professionals are made aware of any potential limitations of this method of temperature measurement. If aural thermometers are to be used by pet owners in a non-clinical setting, a normal temperature range for TMT is necessary in order to prevent hyperthermia going undetected.

Gomart *et al*. (2014) published a table of correction factors for use with the Pet-Temp, to predict RT from TMT measurement, but do not comment on the statistical impact of applying these factors. However, their study was limited to hospitalised, clinical canine patients and concluded that further investigation was needed to evaluate these techniques in hyperthermic dogs. To date, no other TMT to RT comparison study has used healthy exercising dogs, away from a clinical veterinary setting. As body temperature can increase with anxiety (Levy et al., 2015), this study was conducted in a non-clinical setting to ensure dogs were not stressed by an unfamiliar environment.

The aim of the study was to determine if TMT diverged from RT following routine daily exercise, in a group of healthy dogs in a non-veterinary environment.   The impact of ambient conditions on the difference between the two thermometers was also monitored.

2.3 Material and Methods

The study was approved by the Nottingham Trent University's School of Animal, Rural and Environmental Science's ethics approval group.

Animals

Dogs were recruited from a population of university staff owned pets and members of a local canine sporting club. Owners were required to confirm that their dogs were fit and healthy, not undergoing veterinary treatment and showing no clinical evidence of otitis externa. Sample size was determined by pre study power analysis, at least 22 dogs were needed to achieve a study power of 80%, with an error = 0.05, to detect a 0.6 ˚C (SD 1 ˚C) difference between the two methods. This was based on the mean TMT of the sample reported by Gomart *et al*. (2014). Twenty-four dogs (15 males, 9 females) were recruited, representing eight breed types: cocker spaniel (n=4), Labrador retrievers (n=4), lurchers (n=4), Welsh springer spaniels (n=2), pugs (n=2), collie (n=1), pointer (n=1), springer spaniel (n=1) and cross breeds (n=5). Ages ranged from 6 months to 15 years. All temperature recordings were taken during periods of the dogs' routine exercise, taking place in the East Midlands, UK, throughout a twelve-month period. The purpose of the period of exercise was to elevate body temperature in a non-clinical, physiological manner. In order to limit the impact of the study on the dog's normal routine, the duration, type and intensity of exercise completed was not standardised. The types of exercise included brisk walking on lead, free running off lead and off lead play but was of at least 20 minutes duration.

Temperature measurements

TMT was recorded using one new Vet-Temp VT-150 Instant Ear Thermometer (Advanced Monitors Corporation, California, USA), covered by a single use Vet-Temp DPC-500 probe cover (Advanced Monitors Corporation, California, USA). The Vet-Temp thermometer measures temperatures between 32.2-43.3˚C, with an accuracy of ±0.2˚C. The thermometer was used as per the manufacturer's instructions (see Figure 2.3.1), with no lubrication and a reading being obtained following the audible alarm. If a reading reported an error code, the probe cover was changed, and the process repeated.

Figure 2.3.1. A Vet-Temp auricular thermometer being used: the dog's ear is pulled out and down, with the probe angled towards the opposite jaw (a probe cover is in place but not visible in this picture).

Rectal temperature was recorded using a V966F Vicks Comfortflex Digital Thermometer (KAZ Incorporated, New York, USA), which alarms once a stable peak temperature is reached. The Comfortflex Digital Thermometer measures temperatures between 32-42.9 ˚C with an accuracy of ±0.2˚C at room temperature. Prior to the study, the thermometer was tested in water baths of 35˚C and 40˚C and found to be within 0.1˚C of the reference mercury thermometer. The thermometer was lubricated using K-Y jelly (Johnson & Johnson, France), inserted at least 2cm into the rectum and held against the rectal wall until the alarm sounded.

All readings were collected by one author to remove any operator bias, and both thermometers were familiar to the author through routine use in clinical practice. All dogs were lightly restrained by an assistant for both temperature recordings. Individuals involved in taking temperature and restraint of the dogs were familiar to the dogs. In all cases, TMT was recorded first, to limit any influence stress response to the RT recording could have on the results. Left or right ears were selected depending on the positioning of the patient following restraint, to reflect the likely situation in a clinical practice or home environment.

Both TMT and RT recordings were taken at rest, and immediately following a period of exercise to elevate core temperature. Where geographical location allowed, repeated measures were taken (17/24 dogs) in order to assess temperature variation in individual animals. The ambient temperature, relative humidity and wind speed were recorded for every period of exercise. Over the course of the study, mean value for ambient temperature was 12.5˚C (range 4.9-20.5 ˚C), windspeed was 2.44m/s (range 0.36-6.64m/s) and relative humidity was 68.4% (range 42.5-92.9%). Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK), and RD 506-9650 Anemometer (R.S. Components Ltd., Northamptonshire, UK). In order to evaluate the overall impact of these environmental conditions, the results were used to calculate Universal Thermal Comfort Index (UTCI) values (Jendritzky et al., 2012). UTCI was calculated from ambient temperature (˚C), relative humidity (%) and wind speed (m/s) using the UTCI calculator (http://www.utci.org/) and varied from -2.6˚C to 15.6˚C.

Statistical analysis

Descriptive statistics (mean, standard deviation [SD] and range) were calculated using Microsoft Excel (v16, Redmond, WA, USA). The RT to TMT difference was calculated for each pair or readings and was used to determine the number of paired readings with an RT to TMT difference of ≤0.5˚C. The RT temperature change from pre to post exercise was also calculated for each measurement event to determine the temperature change due to exercise.

Statistical analyses were undertaken using SPSS 29.0 (IMB Inc., Armonk, NY, USA). A linear mixed model was used to test the hypothesis that the independent variables *measurement site*, *exercise*, and *UTCI* would affect the dependent variable (*canine temperature*). The fixed effects included were *UTCI*, measurement *site* (ear (TMT) or rectum (RT)), and *exercise* (pre or post exercise), with *dog* included as a random effect to account for repeated measures The intraclass correlation coefficient for the random effect *dog* was calculated to explore the proportion of the temperature variance explained by the individual dogs. The general form of the model was:

$$\textit{Canine temperature}_{it} = \beta_0 + \beta_1 \textit{UTCI}_{it} + \beta_2 \textit{Measurement site}_{it} + \beta_3 \textit{Exercise}_{it} + \textit{Dog}_i + \textit{Residual}_{it}$$

Where $\textit{Canine temperature}_{it}$ is the outcome (body temperature) for subject *i* at time *t*, β_0 is the fixed intercept, $\textit{UTCI}_{it,}$ $\textit{Measurement site}_{it}$, and $\textit{Exercise}_{it}$ are observations of the covariate/fixed effects for subject *i* at time *t*, $\beta_{1\text{-}3}$ are the regression coefficients for the covariate/fixed effects, $\textit{dog}_i$ is the random effect, and $\textit{Residual}_{it}$ is the error for subject *i* at time *t*.

A linear mixed model was also used to test the hypothesis that the independent variables *exercise* and *UTCI* would affect the dependent variable (RT to TMT difference). The fixed effects were *UTCI* and *exercise* (pre/post), with *dog* included as a random effect. The general form of the model was:

$$\textit{RT to TMT difference}_{it} = \beta_0 + \beta_1 \textit{UTCI}_{it} + \beta_2 \textit{exercise}_{it} + \textit{Dog}_{I} + \textit{Residual}_{it}$$

To assess the agreement between TMT and RT measurements, a nested Bland Altman plot was generated and limits of agreement were calculated to account for the repeated measures from individuals under different environmental conditions (Altman & Bland, 1999; Zou, 2013). This analysis was performed in R studio (https:// www.r-project.org), using the *agree_nest* function from the package *SimplyAgree* (Caldwell, 2022). Using the same package, the *checkmethod* function was used to assess the normality (using Shapiro-Wilk test), heteroscedasticity (using the Bahan-Preusch test) and proportional bias of the data (by testing for linear slope on the residuals plot). Due to the presence of proportional bias, as recommended by Altman & Bland (1999), the data were plotted with the ratio of RT to TMT against the mean of the two temperatures. In line with previous studies, an acceptable limit of difference between the two temperature recording sites was set at

±0.5˚C (Greer et al., 2007; Lamb & McBrearty, 2013). A value of P < 0.05 was considered significant.

2.4 Results

A total of 116 paired temperature measurements were recorded, ranging from 1 to 8 paired measurements per dog (median = 6, mean = 4.6). Pre exercise RT readings ranged from 37.4˚C to 39.1˚C (mean = 38.3˚C, SD = 0.4˚C) and TMT ranged from 36.7˚C to 38.8˚C (mean = 37.9˚C, SD = 0.5˚C). Post exercise RT readings ranged from 38.3˚C to 40.0˚C (mean = 39.0˚C, SD = 0.4˚C) and TMT ranged from 37.4˚C to 39.7˚C (mean= 38.6˚C, SD = 0.5˚C). The range of RT increase recorded following exercise was 0.1 to1.4 ˚C (mean = 0.7˚C, SD = 0.4˚C, n = 58). TMT under reported body temperature when compared to RT in 95 of the pair measurements (82%), 80 pairs of readings (68.4%) fell within the accepted 0.5˚C difference in temperature recording method (Figure 2.4.1).

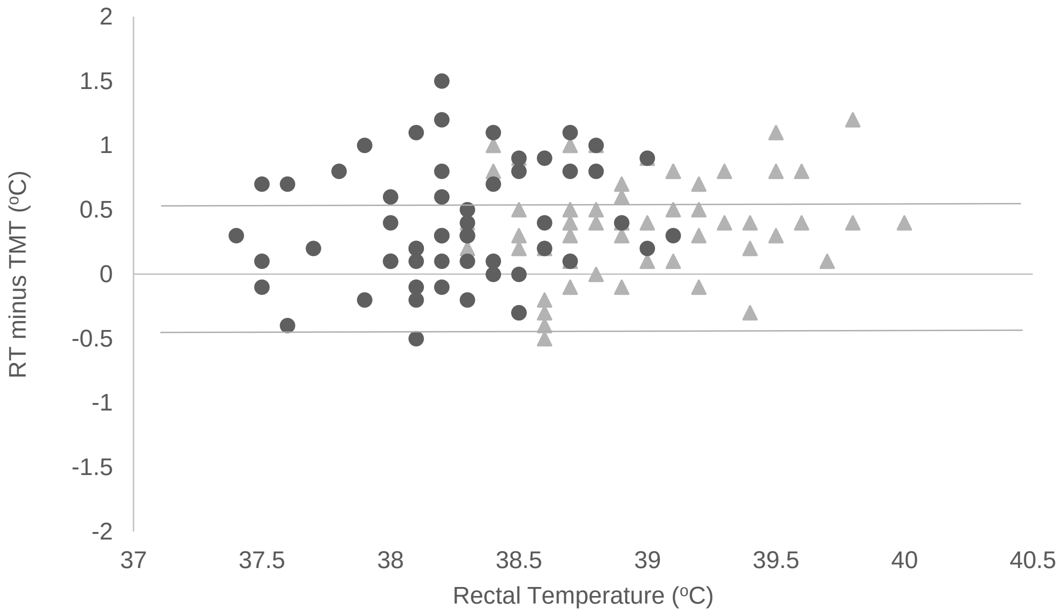

Figure 2.4.1. Rectal temperature (RT) plotted against the rectal temperature minus tympanic membrane temperature (RT minus TMT). Circles represent readings pre-exercise, triangles represent readings post exercise. The solid lines represent the clinically acceptable limits of agreement between two temperature recording devices (±0.5˚C).

The linear mixed model showed a significant effect of measurement site, exercise, and UTCI on canine body temperature (see Table 2.4.1.). The TMT measurement site had a significant negative effect on body temperature, whilst exercise and an increase in UTCI had significant positive effects. The intra-class correlation coefficient for dog in this model was 0.30, indicating relatively high variability of TMT readings from each individual dog.

Table 2.4.1. Linear mixed model results showing the effect of three parameters on canine body temperature.

Model parameter	***β coefficient***	**95% confidence interval**	***p*-value**
Interval	38.1	37.9 to 38.3	<0.001
Measurement site – tympanic membrane (compared to rectal)	-0.4	-0.5 to -0.3	<0.001
Exercise – post (compared to pre)	0.7	0.6 to 0.8	<0.001
UTCI (˚C)	0.02	0.00 to 0.03	0.023

For all data, RT minus TMT ranged from -0.5˚C to 1.5˚C (mean = 0.4˚C, SD = 0.4˚C, n = 116). Pre exercise RT minus TMT ranged from -0.5˚C to 1.5˚C (mean = 0.4˚C, SD = 0.4˚C n=58). Post exercise RT minus TMT ranged from -0.5˚C to 1.2˚C (mean = 0.4˚C, SD = 0.4˚C n=58).

Figure 2.4.2 shows the RT minus TMT for each individual dog that had repeated measures taken, for each repeated sample pair, and demonstrates the variability within each individual. The mean RT minus TMT for each dog ranged from 0.14˚C to 0.87˚C, and there was no consistent difference in RT minus TMT for any animal.

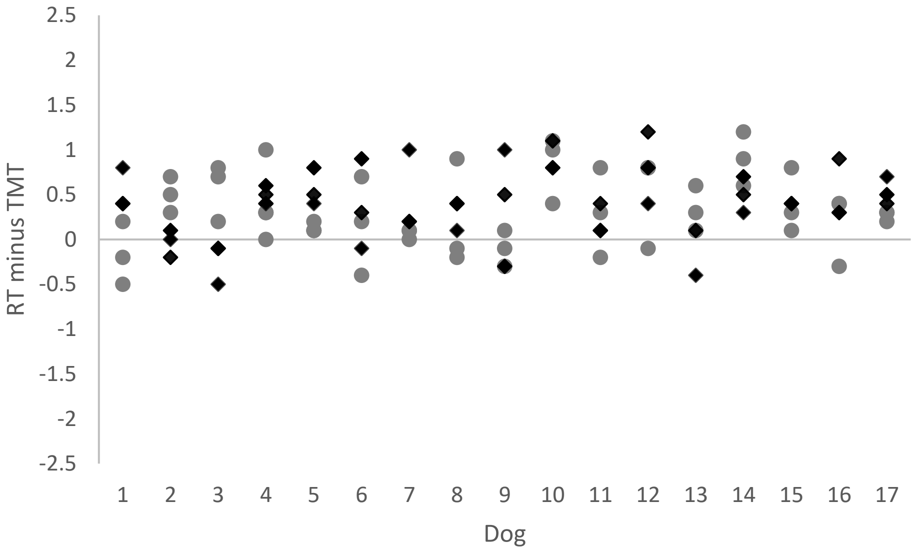

Figure 2.4.2. Rectal temperature minus tympanic membrane temperature (RT minus TMT) values for each individual dog. Circles represent readings pre-exercise, triangles represent readings post exercise.

The linear mixed model showed no significant effect of exercise or UTCI on temperature difference (RT-TMT) (see Table 2.4.2.). The intra-class correlation coefficient for dog in this model was 0.21, indicating relatively high variability of TMT readings from each individual dog.

Table 2.4.2. Linear mixed model results showing the effect of two parameters on temperature difference (rectal temperature minus tympanic membrane temperature).

Model parameter	***β coefficient***	**95% confidence interval**	***p*-value**
Intercept	0.3	0.1 to 0.6	0.002
Exercise – post (compared to pre)	0.01	-0.12 to 0.15	0.842
UTCI (˚C)	0.004	-0.01 to 0.02	0.616

The nested Bland Altman analysis showed a bias of 0.40˚C (95%CI 0.29 to 0.51˚C), with a lower limit of agreement of -0.43˚C (90%CI -0.60 to -0.31˚C), and upper limit of agreement of 1.23˚C (90%CI 1.11 to 1.40˚C) (see Figure 2.4.3.). The data were normally distributed and heteroskedasticity of the data was acceptable (p = 0.086), but proportional bias was detected (p = 0.002), with variance of the residuals decreasing as the mean RT/TMT increases. A revised Bland Altman plot was therefore used, with a ratio of RT to TMT bias of 1.01 (lower limit of agreement 0.99, upper limit of agreement 1.03) (Figure 2.4.4.).

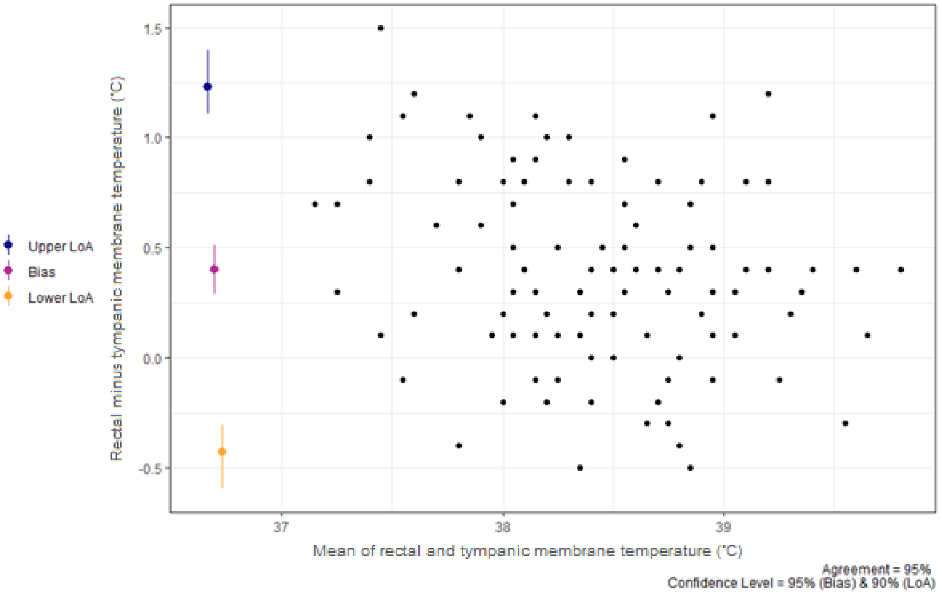

Figure 2.4.3. Nested Bland Altman plot (for repeated measures) of rectal and tympanic membrane temperatures.

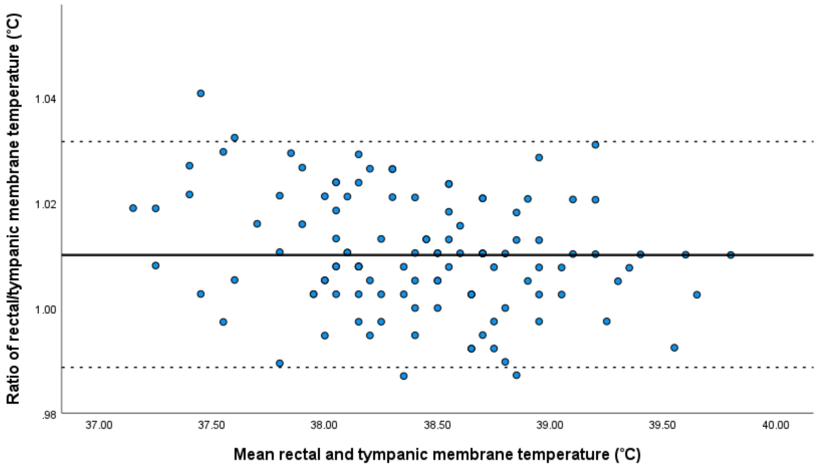

Figure 2.4.4. Modified Bland Altman plot (for data with proportional bias) of the ratio of rectal and tympanic membrane temperatures against the mean of the temperatures. The solid line indicates the bias, the dotted lines indicate the upper and lower limits of agreement.

2.5 Discussion

Human research shows that TMT diverges from RT during exercise induced hyperthermia (Huggins et al., 2012). In contrast, whilst the present study in dogs found no effect of exercise on RT minus TMT, the Bland Altman analysis revealed that the RT to TMT difference decreased as the mean of the two temperatures increased. This suggests that TMT may be suitable as an alternative means of monitoring body temperature in exercising dogs.

The acceptable limit of difference between two temperature monitoring devices is generally reported as ±0.5˚C in both human and animal studies (Greer et al., 2007; Lamb & McBrearty, 2013; Niven et al., 2015; Sousa et al., 2011). In the present study, 31.6% of TMT readings fell outside the accepted 0.5˚C difference, similar to the findings reported by Lamb and McBrearty (2013). Therefore, it could be argued this method of temperature measurement is not clinically acceptable.

Rectal temperature does not represent core blood temperature. Rectal temperature readings can be influenced by the presence of faecal material, rectal inflammation and changes in blood supply to the rectum. Greer *et al*., (2007) demonstrated that canine pulmonary artery temperature differed to simultaneous RT recordings by more than 0.5˚C in 5.72% of readings and found that RT frequently recorded temperatures higher than true core temperature (189/297 readings). In human paediatric patients, rectal temperature has been shown to lag behind temporal artery temperature as cooling occurs (Greenes &

Fleisher, 2004). In exercising adults TMT has been shown to peak earlier than RT, with RT continuing to increase 5-10 minutes after the cessation of exercise (Newsham et al., 2002). To the author's knowledge there are no published studies investigating this potential lag between rectal and blood temperature during post exercise cooling in dogs. Greer *et al*. (2007) suggested that a lag could be responsible for the differences between rectal and pulmonary artery temperature recordings in anaesthetised dogs, however this was not specifically analysed or investigated. Osinchuk *et al*. (2014) used ingestible telemetry devices to compare rectal to core gastrointestinal temperature in exercising dogs. They reported that core temperature increased and decreased faster than rectal temperature, suggesting that rectal temperature lags behind core temperature in strenuously exercising dogs.

As the type and duration of exercise being undertaken by the dogs in this study was not controlled, it is possible that some dogs could have begun cooling prior to temperature measurement. This could potentially explain some of the differences seen between RT and TMT. The tympanic membrane unlike the rectal mucosa, is also in contact with the air so could potentially be influenced by ambient conditions. The temperature readings in this study were taken all year round, in all seasons and types of weather, resulting in a wide range of ambient conditions and no correlation was found between ambient conditions and RT minus TMT.

When evaluating body temperature in any animal, it is standard practice to make a comparison to the normal reference range for that species in order to categorise the patient as normothermic, hypothermic or hyperthermic. Normal reference ranges for canine rectal temperature vary amongst the literature and the data to support these ranges is not always referenced. For example, one text states a normal range of 38.3-38.7˚C (Seymour, 2007), then states a range of 38.3-39.2˚C (Goddard & Phillips, 2011) in the following edition, with no reference to the primary sources of information. The range of RT recorded in resting healthy dogs in this study was 37.4-39.1˚C, possibly a reflection of the low stress, familiar environment in which the temperatures were measured. In the present study, a short period of exercise increased RT by up to 1.4 ˚C. This is comparable to dogs undertaking a short walk to the practice or experiencing a period of stress whilst in the waiting room, therefore temperatures recorded in a clinical setting have the potential to be elevated beyond the dog's normal resting temperature. Konietschke *et al*., (2014) highlighted the lack of consistent reference ranges for dogs, in particular at the lower limit, and reported a similar range of temperatures from healthy dogs, 37.2-39.2˚C, perhaps suggesting the need for a review of the standard canine rectal temperature reference range. A review of normal rectal temperatures in cats, highlighted a similar lack of consistent reference ranges, and suggested a new reference interval of 36.7-38.9˚C following examination of healthy adult cats acclimatised to their environments (Levy et al., 2015).

Of particular importance is the upper limit for normal temperature, most commonly stated as 39.2˚C (Miller, 2009). Heat stroke, is a potentially fatal condition in all species, and in dogs can occur once core body temperature exceeds 41˚C (Romanucci & Della Salda, 2013). Rapid diagnosis, cooling and presentation to a veterinary hospital in under 1.5hrs have been shown to be critical factors in patient survival (Bruchim et al., 2006). The present study has shown that healthy dogs completing short periods of routine exercise in the UK can reach a RT of 40˚C, highlighting the potential risks facing dogs exercising over longer periods during the warmer spring and summer months.

Gomart *et al*., (2014) suggested using correction factors to improve the reliability of the TMT when compared to RT but did not report how significant these improvements were. This required using three different correction factors ranging from +0.2˚C to +0.6˚C determined by sex and coat type. In practice, this would be impractical to recommend to owners. These factors also assume that RT minus TMT is consistent for every dog, which is not supported by the findings of this study. The results of the present study would support using a correction factor of 1.01 multiplied by the TMT value, however the practical application and accuracy of this correction factor requires additional research.

As most studies comparing RT to TMT have found that TMT underreports body temperature, a simpler method of ensuring non-veterinary professionals (e.g., pet owners) are aware of this difference, would be to establish a normal TMT reference range for dogs. The PetTemp instruction manual and company website currently reports a normal ear temperature range of 37.7 to 39.4˚C (Admon, 2016), although no references are provided to indicate the source of this range. Konietschke *et al.* (2014) used 62 dogs to establish a normal rectal temperature range, the reported range of aural temperatures in those animals was 37.1 to 39.1˚C, however they did not use a veterinary specific aural thermometer and the measurements were obtained in a clinical setting. Additional research is required to establish a normal TMT reference range in dogs.

The main reasons pet owners measure their dog's temperature are to identify signs of ill health, or when exercising a dog at risk of developing exertional hyperthermia. In both situations identification of hyperthermia is the trigger for action by the owner. The dog owner either seeks veterinary attention for their animal in the case of illness or stops exercising and begins cooling their animal in the event of exertional hyperthermia. In a clinical setting this over reporting of body temperature could complicate patient care, however rectal thermometry is still gold standard for patient monitoring, so it is unlikely this would actually harm any patients. In a non-clinical setting over reporting body temperature might result in owners seeking veterinary attention or stopping a dog’s exercise needlessly, but neither of these situations would cause any harm to the dog. Conversely, if owners continue to rely on the current “normal” ear temperature range, they may be reassured that their dog’s temperature is normal, when in fact it could be hyperthermic. If they failed to seek veterinary care or continued exercising their dog, this could have dangerous consequences. It could therefore be argued that under-reporting hyperthermia is more dangerous than over-reporting hyperthermia, especially for animals at risk of heatstroke where delaying seeking veterinary treatment increases the risk of (Bruchim et al., 2006).

At present, the main temperature monitoring method available to owners is rectal thermometry, and as previously mentioned, RT is not tolerated in all dogs, and often requires additional restraint by an assistant (Lamb & McBrearty, 2013). RT monitoring may therefore not be possible for many dog owners wishing to monitor their pet’s body temperature at home, or whilst exercising. The Vet-Temp and Pet-Temp auricular thermometers, offer a potential solution to that problem, and are tolerated well in most dogs (211/212 dogs), with only 24% requiring additional restraint in a veterinary setting (Lamb & McBrearty, 2013). For owners of athletic dogs completing strenuous exercise, or competing in hot climates, the aural thermometers offer a method of monitoring their dog for heatstroke, a potentially fatal condition. However, they should be advised to use caution interpreting the results using RT reference ranges, to prevent under reporting of hyperthermia.

Whilst power analysis was used to determine the number of dogs recruited, the sample size was relatively small compared to some of the previous veterinary hospital-based sample populations. The sample size estimate was also based on an estimated mean RT to TMT difference of 0.6˚C, and SD of 1˚C. So, to detect a difference of 0.3˚C with a SD of 0.5˚C would require 44 dogs. The recruitment of dogs (through canine sports participation and veterinary staff) also likely resulted in a sample biased towards active, athletically fit dogs with a normal body condition score. This is not representative of the wider canine population as over 50% of UK dogs are estimated to be overweight or obese (German et al., 2018). As the study recruited a range of dog breeds, ages, sizes and coat types, the effects of these differences could not be evaluated due to the small number of dogs. Ideally, TMT would be compared to blood temperature in healthy dogs with exertional hyperthermia to fully evaluate this temperature recording method, however this would be both impractical and unethical.

Due to the variable types, intensities and duration of exercise undertaken, only 14 dogs reached a temperature considered to be hyperthermic. This limited the evaluation of the aural device for identifying hyperthermia. Recruiting a group of dogs all completing the same type and duration of intense exercise could potentially standardise the elevation in temperature, however individual variation would still impact the overall change in body temperature as reported by Angle and Gillette (2011). Such selective canine recruitment would also potentially limit the application of any results generated, as intensive canine sporting activities often attract specific breeds or ages of dogs, meaning the younger, older or less sporting breeds would not be represented.

2.6 Conclusion

In line with previous research reported in a clinical setting, this study found that TMT measured consistently lower than RT. The hypothesis that dogs, like humans, would show greater differences in RT minus TMT following exercise, has not been supported by the findings of this study. This suggests that auricular devices could offer a less invasive, better tolerated method of monitoring body temperature in exercising animals, where RT is not possible. Perhaps the simplest way to prevent hyperthermia going undetected, would be to establish a normal reference range for canine tympanic membrane temperature, and ensure this reference range is communicated to dog owners using aural thermometers.

2.7 References

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Chapter Three: Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer.

This is a revised investigation using the original data from an article published by Taylor & Francis in the Veterinary Nursing Journal on 16.11.2017 available online: https://doi.org/10.1080/17415349.2017.1377133

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3.1 Abstract

Studies have shown that tympanic membrane temperature (TMT) under reports body temperature when compared to rectal temperature. This could lead to misinterpretation of the TMT, if comparing the result to a rectal temperature range. The aim of this study was to establish a normal canine TMT reference range. Resting TMTs were measured from 157 healthy dogs, in a range of ambient temperatures. The normal reference range for canine TMT was found to be 36.5-38.8°C. This range should be considered by pet owners and veterinary professionals when interpreting TMT measured with a veterinary aural thermometer, to avoid misinterpretation of the results.

3.2 Introduction

In both human and veterinary medicine measuring body temperature remains an important part of any thorough clinical examination. Abnormal body temperature can indicate a range of critical conditions, so it is essential that devices used to measure body temperature are reliable and accurate. Despite considerable scientific advances in digital thermometry and thermography, rectal thermometers remain the gold standard for less-invasive body temperature measurement in veterinary patients, with pulmonary artery, oesophageal and urinary bladder temperatures providing more invasive, but true core temperature measurements. As rectal thermometry can cause stress and require additional restraint in some veterinary patients (Lamb & McBrearty, 2013) there is on-going interest in developing a reliable, less invasive method of accurately measuring body temperature. Aural thermometry remains the most promising alternative method of temperature measurement, but recent studies suggest their readings should be interpreted with caution when compared to rectal temperature reference ranges (Gomart et al., 2014; Hall & Carter, 2017; Zanghi, 2016)

There are numerous studies evaluating the use of aural thermometers in dogs, namely the animal specific PetTemp® and VetTemp® (Advanced Monitors Corporation, California, USA). TMT measurement has been shown to be better tolerated by canine patients in a veterinary setting when compared to rectal thermometry (Gomart et al., 2014; Lamb & McBrearty, 2013), suggesting that for patients where rectal thermometry is impossible due to pathology or patient temperament, TMT can provide a suitable alternative for measuring body temperature (Gomart et al., 2014; Gonzalez et al., 2002; Greer et al., 2007; Hall & Carter, 2017; Lamb & McBrearty, 2013; Rexroat et al., 1999; Southward et al., 2006; Zanghi, 2016). Four of these studies report that TMT underestimates rectal temperature (Gomart et al., 2014; Hall & Carter, 2017; Southward et al., 2006; Zanghi, 2016) mirroring the findings of Yeoh et al. (2017) in primates. This has important implications when using TMT to measure canine body temperature as improper interpretation of the readings could result in misdiagnosis and inappropriate treatment.

The PetTemp® manufacturer guidelines recommend using a normal canine and feline TMT range of 37.7-39.4°C (Admon, 1999). This range is not comparable (specifically at the upper limit) to other published temperature reference ranges (see Table 3.2.1). This lack of consistency defining the normal temperature range is problematic particularly for pet owners trying to interpret their own dog's body temperature. This variation could reflect the populations of animals used to define "normal canine temperature". If the dogs' temperatures were measured in a veterinary setting, rather than a familiar home environment, stress could increase the animal's body temperature, resulting in an artificially elevated temperature being incorporated into the normal range.

Table 3.2.1. Published normal canine rectal reference ranges, their sources and accessibility to pet owners.

Source	Accessibility of source	Lower temperature limit	Upper temperature limit
***Fielder* (2016)**	On-line veterinary manual open access	37.9°C	39.9°C
***Miller* (2009)**	Textbook		39.2°C
***Goddard and Phillips* (2011)**	Textbook	38.2°C	39.2°C
***Konietschke et al.* (2014)**	Open access article	37.2°C	39.2 °C

The aim of this study was to determine the normal canine TMT reference range (when measured with a veterinary aural device) using healthy dogs. To provide a suitable sample size, data were pooled from previous projects measuring TMT in resting, healthy dogs. The effect of ambient temperature on TMT was also investigated.

3.3 Materials and Methods

This study and all previous projects have been approved by Nottingham Trent University's School of Animal, Rural and Environmental Science's ethics approval group.

Animals

The reference population was recruited to try and reflect the general population of pet dogs within the UK including a range of ages (juvenile to geriatric), both entire and neutered animals of both sex, half of the top 20 pedigree dog breeds in the UK (The Kennel Club, 2017) and a number of crossbreeds. All animals recruited to the study were deemed to be fit and healthy by their owner, with no obvious clinical signs or recent history to suggest systemic disease; shivering dogs were not included in the reference population. If otitis externa was present in one ear, the unaffected ear was used for temperature measurement. Although a previous study has shown that there is no significant difference between the TMT measured in dog's ears with and without otitis externa (Gonzalez et al., 2002), the authors of this paper have found that excessive cerumen or aural discharge can obscure the VetTemp® lens and impact the accuracy. Animals with bilateral ear disease were excluded from the study. All TMT measurements were taken at rest, in a non-veterinary environment. Two study populations were used for data collection, the first group includes pet dogs owned largely by members of staff at Nottingham Trent University. These animals were examined indoors, in a familiar environment between June 2015 and June 2017. The second study group were examined outside, prior to competing in a canicross race (dogs harnessed to their owner either running, biking or scootering over approximately 4km cross country courses) between November 2015 and April 2017. All data collection took place within the East and West Midlands, UK.

The pet dog population consisted of 32 dogs including 12 females (9 neutered) and 20 males (11 neutered), aged 6 months to 16 years (mean = 6 years). Ten breed types were represented in this sample: spaniel (n=7), cross breeds (n=6), Labrador retriever (n=5), lurcher (n=3), collie (n=3), whippet (n=2), pug (n=2), terrier (n=2), Chihuahua (n=1) and pointer (n=1). Body weight was not recorded. TMT measurements were taken in a temperature-controlled environment, dogs were acclimatised to the temperature prior to thermometry.

The canicross dog population consisted of 125 dogs including 52 females (22 neutered) and 73 males (31 neutered), aged 1 -10 years old (mean = 4 years). Twenty-five breed types were represented in the sample, the most numerous being: cross breed (n=19), pointer (n=17), collie (n=15), spaniel (n=15), lurcher (n=7), husky (n=6), Hungarian vizsla (n=5), Weimaraner (n=5) other breed types (n=36). Body weight was not recorded. Ambient temperature was measured prior to TMT measurement, dogs were acclimatised to the ambient conditions prior to thermometry.

In total, the study population included 157 dogs, representing 28 breed types. . . An additional 30 dogs were recruited at an outdoor canine event in the West Midlands, UK, held in August 2017 to validate the reference range. The dogs' TMTs were measured at rest using the same selection criteria as the main study population. The validation population included 10 females (4 neutered) and 20 males (10 neutered), aged 5.5 months to 14 years (mean = 5 years) and included 14 breed types.

Ambient conditions

Prior to TMT measurement, ambient temperature was recorded. Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK).

Tympanic membrane temperature measurement

Four new VetTemp® VT-150 Instant Ear Thermometers (Advanced Monitors Corporation, California, USA) were used to measure TMT, as per manufacturer's instructions (see Figure 3.3.1) covered by a single use VetTemp® DPC-500 probe cover (Advanced Monitors Corporation, California, USA). The VetTemp® thermometer measures body temperatures between 32.2-43.3°C, with an accuracy of ±0.2°C, within ambient temperatures of 0-40°C. All thermometers were tested reading the surface temperature of a water bath filled with opaque liquid (in an attempt to mimic the surface of the tympanic membrane), and were found to read within ±0.2°C of 36.0°C, 37.0°C and 38.0°C.

Figure 3.3.1. A VetTemp® aural thermometer in use.

All TMT readings were performed by the same investigator, following a standardised method used to examine animals in veterinary practice. Ears used for measurement were chosen based on presentation and restraint of the dog, to reflect the likely situation in practice. Operator accuracy was not formally assessed as part of this study.

Statistical analysis

Statistical analyses were undertaken using SPSS 29.0 (IMB Inc., Armonk, NY, USA). The two populations of dogs were first analysed separately the TMTs of neither population were normally distributed when tested with the Shapiro-Wilk test for normality. To determine if the two samples could be pooled, Mann-Whitney U tests were used to determine if TMT differed between the indoor and outdoor populations and if TMT differed by sex. Spearman's Rank correlation was used to test for a correlation between ambient temperature and TMT. Significance was indicated at $P<0.05$ for all tests.

The TMTs were then analysed to determine the reference interval, using methods described by Friedrichs et al. (2012). A histogram was plotted to identify potential outliers, and Dixon's range statistic and Tukey's interquartile fences were used to determine if outliers should be eliminated from further analysis. As the reference population exceeded 120 samples, non-parametric methods were used, taking the 2.5th and 97.5th fractiles as the lower and upper reference limits with 90% confidence intervals (CI) calculated nonparametrically (Horn & Pesce, 2003). Reference Value Advisor freeware (Geffré et al., 2011) was used to calculate the reference range and confidence intervals. To determine if the reference population was a sufficient size, Boyd and Harris' recommendation that the CI of the limits not exceed 0.2 times the width of the reference interval was tested (Friedrichs et al., 2012). . A direct validation method was used, comparing the TMT results from an additional 30 healthy individuals to the calculated reference interval (Friedrichs et al., 2012). More than three readings outside this range would be cause for rejection of the reference interval.

3.4 Results

The median indoor temperature was 20.5°C (range 19.0-21.2°C). For outdoor measurements, the median ambient temperature was 9.8°C (range 3.3-16.2°C). During the validation data collection, the median temperature was 19.5°C (range 15.4-24.7°C).

Thirty-two TMT measurements were recorded from the indoor dog population, median TMT = 37.5°C (interquartile range [IQR] 37.2-37.9°C),. 125 TMT measurements were recorded from the outdoor dog population, median TMT = 37.5 (IQR 37.1-38.0°C).. There was no significant difference between indoor versus outdoor TMT measurements (Z = -0.635, p = 0.525), therefore all data were pooled for further analysis. There was no significant effect of sex on TMT (Z = -0.488, p = 0.625) when tested using the Mann-Whitney U test therefore no partitioning by sex was indicated.

The pooled data were then analysed to establish a reference range, no outliers were identified using either Dixon's or Tukey's outlier tests, therefore 157 TMT readings were used for the reference interval calculation. The reference range calculated was 36.5-38.8°C (90%CI = 36.2-36.5°C at the lower end, 90%CI = 38.7-39.1°C at the upper end). Neither CI exceeded 0.2 times the width of the reference range, which suggests no additional reference samples are needed (CSLI, 2008 cited in Friedrichs et al., 2012). There was no significant correlation between ambient temperature and TMT (R_s = -0.007 P = 0.894) (see Figure 3.4.1). .

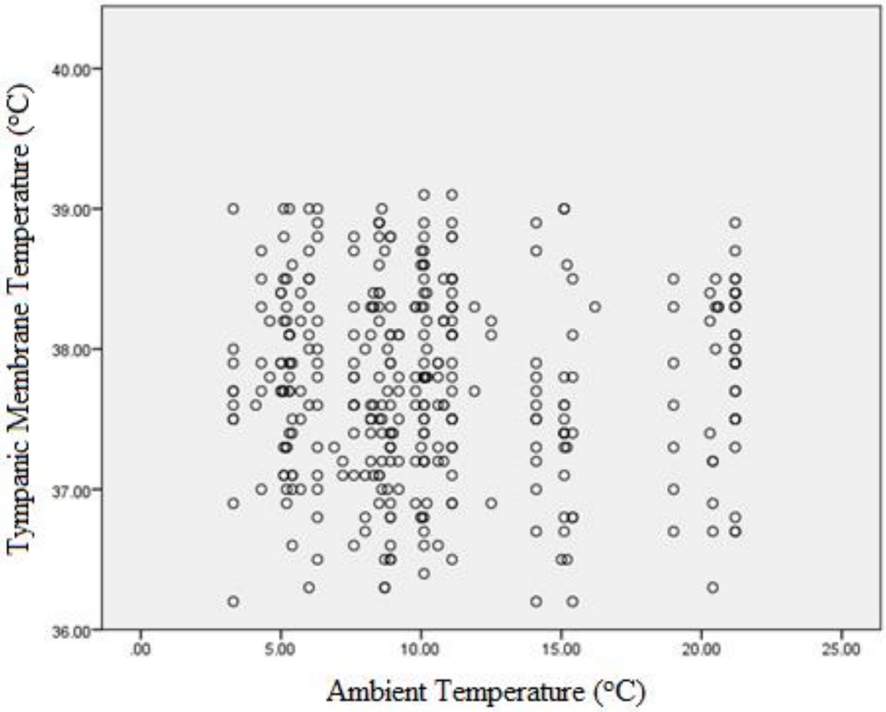

Figure 3.4.1. Scatter plot of the ambient temperature versus tympanic membrane temperature of healthy dogs.

Validation

TMT readings from the 30 dogs in the validation population all fell within this reference interval (36.5 – 38.8°C), with a median TMT of 37.9°C (range 37.0-38.5°C). The reference interval was therefore accepted.

3.5 Discussion

When measured with a veterinary aural thermometer, the normal range of TMT in healthy dogs was found to be 36.5-38.8°C. This is lower than the range of 37.7-39.4°C stated by the thermometer manufacturer (Admon, 2016). Continued use of the manufacturers recommended temperature range, or published canine rectal temperature ranges could result in hypothermia being over diagnosed, hyperthermia being missed and patients being inappropriately treated.

As the PetTemp® is marketed specifically to pet owners as a means of measuring their dog's temperature it is essential that owners understand how to interpret the results for their animal. Global warming is impacting the frequency of unseasonal heat waves (WMO, 2016), increasing the risk of heatstroke in all species, but particularly dogs as their ability to lose heat is quickly impaired as temperature and humidity increase (Hemmelgarn & Gannon, 2013). A dog owner may use their animal's body temperature to reach a decision about seeking veterinary advice for heat related diseases, or how to manage their animals' competition or training. The reference range for canine TMT suggested in this study should reduce the likelihood of hyperthermia being missed, ensuring owners are not falsely reassured by a "normal" temperature measurement potentially putting their animal at risk.

As this study only recorded TMT, with no rectal, or core temperature measurement to compare the results to, there is a possibility some of the animals measured were not normothermic when assessed. Therefore, nothing can be said about the accuracy of the thermometry device from this study alone. Ideally, TMT would have been measured alongside rectal thermometry, however this could have affected the dog's body temperature through stress. Additionally, requiring dogs to have rectal thermometry and aural thermometry performed would have limited the number of dogs recruited to the outdoor study.

Whilst the establishment of a normal canine TMT reference range should improve the interpretation of TMT, it is important to acknowledge the limitations of TMT measurement as a clinical tool. Aural thermometers have been shown to result in more variation than rectal thermometry when operator accuracy has been investigated formally (Greer et al., 2007). This degree of inaccuracy is one of the reasons aural thermometers cannot replace rectal thermometers as the routine method of measuring body temperature in clinical patients. The tympanic membrane does not have a consistent temperature in primates (Yeoh et al., 2017), and variations between the anatomy of different dog breeds could result in a lack of consistency of probe placement. These factors could explain the reported variability of TMT when compared to rectal temperature (Lamb & McBrearty, 2013). It is also essential that the disposable probe covers are used and changed between every patient. This not only prevents potential transmission of infections between patients, but also protects the probe from accumulation of debris which can reduce accuracy of the device (Admon, 2016).

Although the use of human aural thermometers has been investigated in dogs, the shape of the probe is considerably different to that of the veterinary specific devices (see Figure 3.5.1), meaning in many dogs the human thermometer is likely to be reading the skin lining the ear canal, rather than the tympanic membrane (Greer et al., 2007). The reference range established in the present study is therefore unlikely to be accurate when used to interpret results from a human ear thermometer.

Figure 3.5.1. A human aural thermometer alongside a VetTemp® aural thermometer with probe cover in place.

As the present study measured TMT in a non-veterinary setting, additional work establishing a reference range in veterinary patients would be beneficial. The stress of visiting a veterinary practice can elevate body temperature, establishing how this affects the upper end of the reference range could aid veterinary professionals in interpretation of the temperature measurements.

3.6 Conclusion

The findings of this study would support a normal canine TMT reference range of 36.5-38.8°C. This is in line with previous research reporting that TMT reads approximately 0.4°C below rectal temperature (Gomart et al., 2014; Hall & Carter, 2017; Zanghi, 2016), when using a normal rectal temperature range of 37.2-39.2°C (Konietschke et al., 2014). TMT is a useful screening tool to assess body temperature in dogs; however, as TMT is not as reliable as rectal thermometry, when monitoring clinical patients TMT measurement should be followed up by rectal thermometry should hypo- or hyperthermia be detected.

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Section II Appraisal

II.2 Critical appraisal of the study methods – Chapter Two

When evaluating a novel or alternative diagnostic test (such as temperature measurement), there are a number of ways the results of the test can be evaluated and compared to a "gold standard" or existing test option. The original published version of Chapter Two (Hall & Carter, 2017a) used a basic scatterplot to compare rectal temperature to the difference between rectal and ear temperature, this is not in line with many of the wider veterinary diagnostic testing literature that use a Bland-Altman plot (Altman & Bland, 1983) when comparing thermometer devices (Gomart et al., 2014; Greer et al., 2007; Lamb & McBrearty, 2013; Zanghi, 2016). The Bland-Altman plot is recommended for comparing diagnostic testing methods and involves plotting the mean of the readings provided by the two devices against the difference between the two devices. Limits of agreement are then calculated by subtracting 1.96 multiplied by the standard deviation of the differences, from the mean difference between the two devices (Bland & Altman, 1986); 95% of the differences should lie within this limit if the differences are normally distributed. However, the assumptions of the Bland-Altman method are that the two measurement methods have the same precision, the precision is constant and does not depend on the true latent trait (e.g., the true core temperature), and the bias is constant (e.g., the difference between the two measurements is constant) (Bland & Altman, 1986). When these assumptions are not true, use of the Bland-Altman plot is invalid, as it can mask issues such as proportional bias (Hartnack, 2014; Taffé, 2021).

The assumptions required for the use of a Bland Altman plot were not valid for use in the study presented in Chapter Two, evidenced from previous studies that compared rectal temperature to ear temperature (using a veterinary ear thermometer) in canine patients (Gomart et al., 2014; Lamb & McBrearty, 2013). Both of these studies suggested that the rectal to ear temperature difference was not consistent, the difference decreased as the mean of rectal and ear temperature increased (Gomart et al., 2014; Lamb & McBrearty, 2013), suggesting proportional bias between the two devices. Greer et al. (2007) also compared ear temperature to rectal temperature (using a human ear thermometer) and reported a higher variation between duplicate temperature readings from the ear thermometer than the rectal thermometer (Greer et al., 2007). As a result, the original published version of Chapter Two (Hall & Carter, 2017a) incorrectly presented a simple scatter plot of RT to TMT difference versus RT instead of a Bland Altman plot. In addition, the original published version failed to account for the use of repeated measures and attempted to test the correction factor of 0.4°C without collecting additional data to perform this validation. The analysis and results are therefore flawed.

The reworked study presented in Chapter Two attempts to address the errors in the original publication, by using a Bland Altman analysis that accounts for repeated measures over time (Altman & Bland, 1999; Zou, 2013). Further analysis of the data also revealed proportional bias, as reported in earlier studies by Gomart et al. (2014) and Lamb & McBrearty (2013). The use of a single correction factor would therefore be inappropriate, so any attempts to evaluate the use of a correction factor were also removed from the reworked study.

Further limitations to the study presented in Chapter Two relate to the procedure used to collect temperature measurements. As a single operator collected all measurements, with no attempts to blind the operator to results, observer bias may have influenced the acceptance or rejection of measurements based on knowledge of the readings from the two thermometer devices. Should this study be repeated, one way to avoid operator bias, reduce the impact of the study on the dogs, and facilitate additional evaluation of temperature variation due to individual dog, would be to compare TMT to core temperature, using ingestible telemetry devices. This would eliminate the need for RT measurements and would enable blinding of the operator collecting the TMT measurements. Removing the need for RT measurements would enable additional TMT measurements to be undertaken, such as temperature in both familiar and veterinary environments, to evaluate the effect of the veterinary environment on canine body temperature. Due to the presence of proportional bias between the RT and TMT measurements, attempting to validate a correction factor for TMT holds limited value. Instead, further research should aim to evaluate the TMT reference range proposed in Chapter Three, to determine if using the suggested upper limit improves detection of hyperthermia in dogs.

Three months before the publication of Chapter Two, Zanghi (2016) published a study titled "Eye and ear temperature using infrared thermography are related to rectal temperature in dogs at rest or with exercise". Zanghi's study presented an evaluation of ear and eye temperature as alternatives to rectal temperature using 32 healthy, laboratory-housed dogs from two breeds (Beagle and Labrador Retriever). Zanghi reported that ear temperature underestimated rectal temperature by 0.1-0.3°C at rest, and 0.4-0.6°C following exercise, which is similar to the 0.4°C difference reported in Chapter Two (Hall & Carter, 2017a). Zanghi concluded that ear (but not eye) temperature reflects rectal temperature in dogs at rest and following exercise. Although the results presented in the two studies (Hall & Carter, 2017a; Zanghi, 2016) use different populations of animals (laboratory versus pet dogs and different breeds) and were conducted in different locations (US versus UK), the similarities support the reliability of the results presented in Chapter Two.

Finally, Chapter Two compared ear to rectal temperature in just 24 dogs, representing eight breed types. Although a pre-study sample size estimation was calculated (which suggested 22 dogs were needed), this relatively small sample size did not allow evaluation of breed effect on ear to rectal temperature difference. As the study involved temperature measurement before and after periods of exercise, requiring dogs to be tolerant of both rectal and ear thermometer use, recruitment of additional dogs was challenging and ultimately beyond the financial limitations of the study. Despite the small sample size, the results are comparable to the findings of Zanghi (2016) and Gomart et al. (2014).

II.3 Critical appraisal of the study methods – Chapter Three

Chapter Three presents a novel normal temperature reference range for healthy dogs measured with an ear thermometer based on ear temperature readings from 157 dogs (Hall & Carter, 2017b). An additional 30 dogs were recruited for validation of the reference range (Hall & Carter, 2017b), as recommended by the American Society for Veterinary Clinical Pathology (Friedrichs et al., 2012). A sample size of at least 120 individuals is recommended by Friedrichs et al. (2012) to determine novel reference ranges, with consideration of the demographics of the wider animal population. Therefore, the sample size used in Chapter Three is appropriate.

A further recommendation for the selection of reference individuals when establishing a reference range is that health status should be confirmed for all animals included in the reference population (Friedrichs et al., 2012), and one limitation of the study in Chapter Three was the reliance upon owner-reported health status rather than a veterinary examination. However, performing a clinical examination on every dog prior to inclusion in the study could have influenced the dog’s temperature. Bragg et al. (2015) demonstrated that a veterinary hospital visit causes stress to dogs, with associated elevation in rectal temperature. However, the median temperature for the 30 study dogs was only 0.2°C higher in the clinic and therefore location of examination was considered to be of no clinical significance, the most extreme difference in the study population was a temperature 1.06°C higher in the clinic (Bragg et al., 2015).

Whilst an increase of 0.2°C may not be clinically significant when measuring the temperature of a single patient, Bragg et al. (2015) reported that over 60% of the dogs in their study experienced an elevation in body temperature when travelling to the clinic. It is therefore feasible that a reference range derived from a population of dogs presenting to veterinary clinics would have a higher upper limit compared to the reference range established in Chapter Three. Any change to the upper reference limit of a reference range applied to all dogs presenting for veterinary care could have the potential to alter the treatment of many dogs and could therefore be considered clinically significant. Within the literature, differences of 0.3°C (Konietschke et al., 2014) and 0.5°C (Greer et al., 2007) have been proposed as clinically significant temperature differences between thermometer devices, but decisions regarding interpretation of body temperature tend to be made with consideration to reference ranges. In reality, as highlighted in Chapter Three, reference ranges published in veterinary textbooks have upper limits ranging from 39.2-39.9°C. Therefore, the real-world impact of including mildly hyperthermic dogs within a reference population would likely be minimal.

By recruiting a reference population from dogs away from a veterinary clinic setting, and by using a population of dogs predominantly recruited from sporting events, the reference population used in Chapter Three is unlikely to be representative of, and therefore not generalisable to, the general UK dog population. Dogs participating in canine sports are less likely to be obese (Kluess et al., 2021), and are less likely to be geriatric due to restrictions on participation for canine welfare. The effects of age and bodyweight on body temperature were not explored in Chapter Three. However, both variables are known to impact thermoregulation and resting body temperature (Flournoy et al., 2003; Montoya Navarrete et al., 2021) so should be explored to determine the need for partitioning of the reference range into age and body condition categories. Future research should therefore aim to calculate a temperature reference range from a veterinary clinic population, with a reference population more representative of the general dog population (breed, age, body condition and fitness variation) and using rectal temperature to measure body temperature. This would allow the need for partitioning to be evaluated and would provide a reference range specific to the most commonly used anatomical site for temperature measurement in veterinary practice.

One of the goals of this thesis is to improve dog owner awareness of heat-related illness and suggest possible mitigation strategies to protect canine welfare in the face of global warming. Establishing a normal temperature reference range for healthy dogs at rest was therefore an important outcome of this study. Encouraging owners to measure their dog's temperature at home and following exercise is one way to empower them with a better understanding of their dog's heat-related illness risk. In order to perform and interpret at-home temperature measurements, a well-tolerated thermometer is needed (such as an ear thermometer), alongside an anatomically appropriate and accurate normal temperature reference range. Chapters Two and Three provide evidence to support this approach to monitoring canine health and welfare.

II.4 Reception of the published work

Zanghi's (2016) open-access paper comparing ear, eye and rectal temperature has (to date) been cited 56 times (using Google Scholar as the broadest measure of citations), versus 22 citations for the study presented in Chapter Two (Hall & Carter, 2017a). This highlights the importance of open-access publication for visibility of scientific findings.

The methods used in Chapter Two were used to carry out two additional projects that evaluated the use of non-contact infra-red thermometers (NCIT) to measure eye surface temperature as an estimate of core temperature in companion animals. The first study compared eye surface temperature to rectal temperature in cats, and ear temperature in dogs. As ear temperature still requires physical contact with the patient and some dogs resent insertion of the thermometer, it was hoped that non-contact eye thermometry could offer a better tolerated, faster method of measuring body temperature. Reflecting Zanghi's (2016) results once again, eye temperature was found to be inconsistent with ear temperature in dogs, and inconsistent with rectal temperature in cats (Hall, Fleming, et al., 2019). There is still ongoing interest in evaluating the use of NCIT and thermography for estimating body temperature within the wider scientific community, however to date, no studies have found a suitable anatomical location where measuring surface temperature provides an accurate representation of core body temperature (Casas-Alvarado et al., 2022; Cugmas et al., 2020; Kahng & Brundage, 2020; Kreissl & Neiger, 2015; Kwon & Brundage, 2019; Nutt et al., 2016; Rizzo et al., 2017; Zanghi, 2016).

The second study compared rectal temperature to eye surface temperature in healthy horses, finding that in over 80% of readings one of the animal-specific NCIT devices reported a temperature measurement within ± 0.5°C of rectal temperature (Carter et al., 2019). As rectal thermometry poses a risk to both the operator and the patient in equine veterinary practice (risk of kicking or crush injury to the operator, risk of rectal trauma to the horse), finding a safe, accurate, non-contact method of estimating core temperature could offer important advances in patient monitoring. As this equine study included only healthy exercising horses, further research is needed to evaluate the sensitivity and specificity of NCIT use for detecting hypo- and hyperthermia in clinical patients before eye surface temperature can be recommended for routine use.

Recognising the continued importance of rectal thermometry for temperature monitoring in clinical practice, the methods used in Chapter Three were repeated to establish a normal resting rectal temperature reference range for horses. The horses living at the Brackenhurst Equestrian Centre have rectal temperature measurements performed on a regular basis as part of the yard's biosecurity protocols, meaning a large dataset of resting temperatures was available from the centre's records. The previously published reference ranges for normal equine rectal temperature suffered from the same poor reporting highlighted in Section One for dogs. The normal reference range of 36.0 - 38.0°C was statistically derived using over 600 rectal temperature measurements (Hall, Carter, et al., 2019). Again, reflecting our findings Chapter Three, this novel equine temperature reference range has a lower upper reference range than the previously published studies, likely reflecting the low-stress environment and handling techniques used during temperature measurements.

As body temperature measurement forms a crucial part of any clinical examination, an important aim of this thesis was to ensure that veterinary practitioners have access to evidence-based reference ranges and evidence to support or refute the use of alternatives to rectal thermometry to improve clinical practice. This influenced our choice of journal when publishing these studies, aiming to ensure access specifically to veterinary nursing professionals who are primarily responsible for patient monitoring within veterinary practices. I have subsequently published a review of current temperature monitoring research highlighting recent advances in establishing evidence-based normal temperature reference ranges in companion species and critically reviewing alternative temperature monitoring options (Hall, 2021). An updated, statistically derived canine normal rectal temperature reference range is still urgently needed and has been the focus of a student research project I supervised, using VetCompass data. This novel reference range will hopefully be presented at BSAVA Congress and published in 2024.

The two studies presented in this Section II provided a means of measuring canine body temperature in a field situation and interpreting those measurements using the novel normal ear temperature reference range. This was an important step that enabled the progression to field work, monitoring canine temperature at canicross race events to explore the impact of environmental conditions and exercise on canine hyperthermia, which is presented in Section III.

Chapter Two Metrics (May 2024):
Scopus Citations: 16
Google Scholar Citations: 24

Chapter Three Metrics (May 2024):
Scopus Citations not available
Google Scholar Citations: 13

Wider engagement:

Conference presentations:

- Carter, A. J. & Hall, E. J. (2018) "Non-invasive temperature monitoring of canine athletes" Proceedings of the 6th Canine Science Forum, Budapest, Hungary. 5th July 2018
- Carter, A. J. & Hall, E. J. (2019) Non-invasive temperature monitoring in domestic species. Invited speaker at the British Society of Animal Science Annual Conference, Edinburgh, UK. 11th April 2019
- Werth, A. S., Hall, E. J., Bradbury, J., & O'Neill, D. G. (2024). Hot Dogs - Getting to the bottom of " normal " temperatures for dogs presenting to UK veterinary clinics. BSAVA Congress Proceedings 2024 - Clinical Abstracts, Manchester, UK. 21st March 2024. https://www.bsavalibrary.com/content/chapter/10.22233/9781913859411.ch158

Publications expanding this work:

- Hall, E. J., Fleming, A., & Carter, A. J. (2019). Investigating the use of non-contact infrared thermometers in cats and dogs. The Veterinary Nurse, 10(2), 109–115. https://doi.org/10.12968/vetn.2019.10.2.109
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Section III: What influences canine body temperature during exercise?

III.1 Section introduction:

This section presents the findings from a two-year study monitoring the pre- and post-exercise body temperature of pet dogs competing in canicross races in the UK. The study presented in Chapter Four uses the normal tympanic membrane temperature reference range established in Chapter Three to evaluate canine body temperature pre- and post-exercise, then explores the relationship between intrinsic (canine) and extrinsic (environmental) factors on post-exercise body temperature. Whilst previous studies have explored the factors influencing post-exercise body temperature in canine athletes competing in Greyhound racing and sled-dog racing, Chapter Four specifically targets pet dogs of a variety of different breeds to ensure the results are generalisable to the wider UK dog population. Chapter Four addresses the evidence gap "*What factors influence canine body temperature during exercise*?", followed by a critical appraisal of the study, highlighting the work that has subsequently built upon the results presented here and identifying additional work still to be done.

This Section contains an edited version of the following published study:

Chapter Four:

Carter, A. J., & Hall, E. J. (2018). Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK. *Journal of Thermal Biology*, *72*, 33–38. https://doi.org/10.1016/j.jtherbio.2017.12.006

Chapter Four: Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK.

This is a reworked version of the article published by Elsevier, Journal of Thermal Biology on 21.12.2017 available online: https://doi.org/10.1016/j.jtherbio.2017.12.006

Authors: A. J. Carter & E. J. Hall

Conflicts of interest: Neither author has any conflicts of interest, or financial interest in this work.

Keywords: Exercise-induced hyperthermia, canine heatstroke, running with dogs, aural thermometer, canine athlete

Highlights

- Canicross races are typically run over winter to avoid running dogs in hot weather.
- Rising ambient temperature had a significant, positive (albeit small) effect on dog's post-race temperatures and significantly increased the odds of post-race hyperthermia.
- Average race speed had a positive effect on canine post-race temperature and increased the odds of post-race hyperthermia.
- Dogs exceeded the critical temperature threshold of >40.6°C (associated with heatstroke) at all race events despite relatively cool ambient temperatures.

4.1 Abstract

Increasing numbers of people are running with their dogs, particularly in harness through the sport canicross. Whilst canicross races are typically held in the winter months, some human centred events are encouraging running with dogs in summer months, potentially putting dogs at risk of heat related injuries, including heatstroke. The aim of this project was to investigate the effects of ambient conditions and running speed on post-race temperature of canicross dogs in the UK and investigate the potential risk of heatstroke to canicross racing dogs. The effects of canine characteristics (e.g., sex, coat colour and coat length) were explored in order to identify factors that could increase the risk of exercise-induced hyperthermia (defined as body temperature exceeding the upper normal limit of 38.8°C). Overall, 108 dogs were recruited from 10 race days, where ambient conditions ranged from -5 to 11°C measured as universal thermal comfort index (UTCI). A total of 281 post race tympanic membrane temperatures were recorded, ranging from 37.0 - 42.5°C. No variables were identified as significantly affecting pre-race temperature. However, sex (male), and an increase in UTCI and speed significantly increased post-race temperature. Male dogs had 2.4 times the odds of developing post-race hyperthermia (95%CI 1.10 to 5.21) compared to female dogs, and both UTCI and speed increased the odds of post-race hyperthermia. Prolonged elevation of body temperature above 40.6°C is associated with the development of heatstroke; at every race dogs exceeded this critical temperature, with 17.6% (n = 19) of the overall study population exceeding this temperature throughout the study period. The results suggest male dogs, increased ambient temperature (measured as UTCI), and increased speed of running all increase the risk of heatstroke in racing canicross dogs. Further research is required to investigate the impact of environmental conditions on post-race cooling, to better understand safe running conditions for dogs.

4.2 Introduction

The sport canicross involves competitors completing a cross country style race either running, cycling or scootering, whilst harnessed to dogs (see Figure 4.1). The dogs normally run ahead, taking up the slack in the bungee line and providing some assistance to the runner. Canicross is an effective means of exercising both runner and dog over relatively short ‘sprint’ distances of approximately 5km (although longer competitive distances are run). Now formally recognised by The Kennel Club, the sport has been run competitively in the UK since 2000, with increasing numbers of competitors taking part in races around the country (The Kennel Club, 2017). As race results are ultimately linked to both human and dog speed, the sport can promote increased physical activity, encouraging people to exercise with their dog to improve their race times, competitive performance, health and fitness in both species.

Figure 4.1: One dog canicross competitor on the left, one dog bikejor competitor on the right.

There have been several studies exploring ways of encouraging dog owners to spend more time walking and exercising with their dogs (Rhodes et al., 2012; Schneider et al., 2015; Westgarth et al., 2014, 2015), however studies exploring the impact of this advice (both positive and negative) on the dog are lacking. Encouraging owners to increase their activity levels through dog walking or running, could place the dog at risk of conditions such as heatstroke, as unfit dogs show significantly reduced exercise endurance and increased rate of temperature rise (Nazar et al., 1992) compared to healthy dogs. As heatstroke is a potentially fatal condition and has been reported following just six minutes of exercise in hot ambient conditions (Bruchim et al., 2006), advising owners to start exercising with their unfit dog in spring or summer months could prove extremely dangerous for the dog. At present advice regarding safe ambient temperature thresholds for exercising with dogs is lacking.

Heatstroke is defined as a systemic inflammatory response leading to multi organ dysfunction and brain damage, associated with hyperthermia (Bouchama & Knochel, 2002), in dogs heatstroke is typically associated with rectal temperatures exceeding 41°C (Flournoy et al., 2003). One veterinary hospital has reported an increase in the number of dogs presenting with exertional heatstroke (caused by exercise) compared to environmental heatstroke (typically following vehicle confinement), with 73% of recent cases being categorised as exertional heatstroke (Bruchim et al., 2017), compared to 58% of cases previously reported (Aroch et al., 2009). The increase in popularity of amateur canine sports participation in the UK, combined with increasing episodes of warm weather during traditionally colder months in autumn and early spring (WMO, 2017), could potentially increase the risk of canine exertional heatstroke occurring (Hall & Carter, 2016).

Traditionally canicross races are run during the autumn-spring, to avoid warm weather for both the runners' and the dogs' benefit. Dogs are more likely to develop heatstroke following prolonged exercise in warm conditions, as they can only sweat through their paw pads, relying mainly on convection and radiation of heat, then panting to allow evaporative heat loss for thermoregulation (Johnson et al., 2006). As ambient temperature increases, heat loss through convection and radiation is limited (Johnson et al., 2006). When competing at canicross events owners are reminded to monitor their own dogs for signs of over-heating, and many canicross clubs have their own informal rules on safe competition conditions. Guidelines on suitable working temperatures are limited and are reliant on personal experience and anecdote. One such recommendation used by canicross groups and on-line discussion forums is "do not run your dog if ambient temperature (°C) x humidity (%) > 1000", where multiplying the ambient temperature by the relative humidity is used to determine if it is safe to run with your dog (Cani-Sports Edinburgh, n.d.; Highland Canicrossers, n.d.). Studies investigating the validity of this guideline are lacking, and to date, there have been no studies investigating body temperature in pet dogs competing in canicross races. Whilst the effect of exercise on body temperature has been investigated in both long distance sled racing dogs (Phillips et al., 1981), and in greyhounds competing in shorter sprint races under 1km (McNicholl et al., 2016) there has been no research investigating the temperature of pet dogs racing over middle distances such a canicross race (around 3-5km).

To develop more robust guidelines for safe environmental conditions for canine sports, additional investigation into the effect of ambient conditions on canine athlete body temperature is needed. Physical exercise can exceed thermoregulatory mechanisms, potentially impacting animal health and performance (Piccione et al., 2012; Robbins et al., 2017). Monitoring body temperature is therefore important to monitor the health, physiological status and welfare of exercising, competing or working animals (Rizzo et al., 2017). As temperature, humidity and wind speed all influence body temperature, it is important to consider the thermal impact of the combined effect of all three, when investigating environmental impact on body temperature. Universal thermal comfort index (UTCI) incorporates all of these factors to calculate a "feels like" temperature that reflects the ambient conditions as a whole (Jendritzky et al., 2012). This allows individual environmental conditions to be measured in the field, then combined using the UTCI calculation to provide an ambient temperature that reflects the overall impact of the conditions present.

Aural thermometers measuring tympanic membrane temperature (TMT) have been investigated in comparison with rectal thermometers and have been found to be an effective alternative for monitoring temperature in dogs pre- and post-exercise (Hall & Carter, 2017a; Robbins et al., 2017; Zanghi, 2016). As aural thermometers are faster and often better tolerated that rectal thermometers (Gomart et al., 2014; Lamb & McBrearty, 2013) they offer an ideal means of monitoring immediate post-race body temperature in the canine athlete under field conditions. Aural thermometers under-report body temperature when compared to rectal temperature in dogs, by around 0.4°C when measured with an animal specific device (Gomart et al., 2014; Hall & Carter, 2017b; Zanghi, 2016), and by around 1.3°C using a human aural thermometer (Piccione et al., 2011). It is therefore important to use an animal specific thermometer and an appropriate reference range when interpreting ear temperature readings (Hall & Carter, 2017b).

The aims of the study were to investigate the effects of varying ambient conditions on the tympanic membrane temperature (TMT) of privately owned pet dogs competing in middle distance canicross races, and the occurence of post-race temperatures associated with heatstroke. In addition, the effects of race speed, sex and coat colour on post-race temperature were also explored to identify canine characteristics that could increase the risk of exercise-induced hyperthermia.

4.3 Methods

This study was approved by Nottingham Trent University's School of Animal, Rural and Environmental Sciences ethics committee.

4.3.1 The race courses

Canicross runners, scooter and bikejor competitors competed with their dogs over a course 3.8 - 4.5km in length over two consecutive days (the course was identical on both days). All dogs had previously competed in canicross races and were at least one year of age for canicross, and two years for scooter and bikejor races. Data were collected at five race weekends (10 individual races) over the 2015-16 and 2016-17 Canicross Midlands race seasons, run between November and April at four venues in the East and West Midlands, UK.

4.3.2 The animals

Canine participants were recruited opportunistically from those competing at the canicross events; all owners of competing dogs were invited to participate in the study (there were no inclusion criteria related to experience or performance level in the sport) but there were no incentives to participate. The only exclusion criteria were dogs with an aversion to the thermometer or disease of the ear canal. Between 18 and 35 dogs were examined on each race day, providing data for 108 dogs (59 male, 49 female) aged 1-10 years old (mean 4.4 years) over the 10 races. Breed types represented included: crossbreed (n = 18), Border Collie (n = 18), German Short-Haired Pointer (n = 13), Husky (N = 8) and Cocker Spaniel (n = 6) and other (n = 45). Across the multiple race dates, dogs' temperatures were recorded pre- and post-race between one and nine times (mean 2.6 times per dog) to give 281 post-race temperature data points, of which 210 also had pre-race temperature recorded.

4.3.3 Temperature Measurements

TMT was measured pre-race in each dog in the two-hour period prior to competition and post-race, immediately after crossing the finish line of the race. As sampling was opportunistic it was not possible to obtain pre-race TMT readings for all dogs. Left or right ears were selected depending on the positioning of the dog following light restraint. TMT was recorded using a Vet-Temp VT-150 Instant Ear Thermometer (Advanced Monitors Corporation, California, USA), covered by a single use Vet-Temp DPC-500 probe cover. The Vet-Temp thermometer measures temperatures between 32.2 and 43.3°C, with an accuracy of ±0.2°C. The thermometer was used as per the manufacturer's instructions with no lubrication, and a reading being obtained following the audible alarm. If a reading reported an error code, the probe cover was changed, and the process repeated. If an error code occurred a second time, the reading was discounted.

Hyperthermia was defined as TMT greater than the upper normal limit of 38.8°C, using the previously established normal canine TMT range of 36.5-38.8°C (Hall & Carter, 2017b). The number of dogs' temperatures >40.6°C was also noted, as this is equivalent to a rectal temperature of 41.0°C considered to be the critical body temperature over which heatstroke is likely; TMT has been shown to measure approximately 0.4°C lower than rectal temperature following exercise (Hall & Carter, 2017a; Zanghi, 2016).

4.3.4 Ambient conditions

Ambient conditions (temperature, humidity and wind speed) were recorded prior to collecting the pre-race TMT and at approximately 30-minute intervals until the last post-race temperature had been recorded. Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK), and RD 506-9650 Anemometer (R.S. Components Ltd., Northamptonshire, UK). To evaluate the overall impact of these environmental conditions, the results were used to calculate Universal Thermal Comfort Index

(UTCI) values (Jendritzky et al., 2012). UTCI was calculated from ambient temperature (°C), relative humidity (%) and wind speed (m/s) using the UTCI calculator (http://www.utci.org/). The mean UTCI temperature for the duration of the race period was then calculated. Additionally, the mean 'ambient temperature x humidity' was calculated for each race event.

The shade temperature recorded at the nearest Met Office weather station was also recorded for the duration of the race, to allow comparison between this and the non-shade on-site temperature measurement.

4.3.5 Additional information

Time to complete the course was used to calculate average race speed (km/h), age of the dog, breed, coat colour and coat length and were recorded for all participants. As the data were collected in the field it was not possible to weigh the dogs, therefore an estimation of each dog's bodyweight (BW) was used (based on their breed and sex) to categorise each dog into a weight category of <10kg, 10-<20kg, 20-<30kg or 30kg or over.

4.3.6 Statistical analysis

Data were checked for normality using the Kolmogorov-Smirnov test and statistics were undertaken using SPSS 29.0 (IMB Inc., Armonk, NY, USA). The study was a prospective, observational study, with repeated measures from some individuals. To account for the repeated temperature measures, four linear mixed models were used to test the hypothesis that the categorical variables sex, coat colour, coat length, and BW category, alongside continuous variables speed (km/h), and UTCI (°C) would affect the dog's 1. pre- and 2. post-race TMT readings, and the binary outcomes of 3. post-race hyperthermia (TMT > 38.8°C) and 4. post-race TMT > 40.6°C (see Table 4.3.6.1). An alternative model in which "temperature x humidity" replaced UTCI was used to explore the utility of "temperature x humidity" as a predictor of canine post-race TMT. Acknowledging that the factors influencing canine body temperature during exercise extend beyond the variables measured in the present study, the mixed models were not used to attempt to build predictive models. The linear mixed models were used as a purely exploratory method of estimating the effect of the canine, race and ambient weather variables on pre- and post-race TMT. Therefore, no model selection or model evaluation methods were used. Variables with a *p*-value <0.05 were considered to have a significant effect on the dependent variable.

Table 4.3.1. Mixed models used to explore the effects of canine, race and weather variables on canine tympanic membrane temperature (TMT) pre- and post-race, in dogs competing in canicross races in UK.

Dependent variable	**Mixed model type**	**General form of the exploratory model***
Pre-race TMT (°C)	Linear mixed model	$\text{Pre-race } TMT_{it} = \beta_0 + \beta_1 BW\ Category_{it} + \beta_2 Sex_{it} + \beta_3 Coat\ colour_{it} + \beta_4 Coat\ length + \beta_5 UTCI_{it} + Residual_{it}$
Post-race TMT (°C)	Linear mixed model	$\text{Post-race } TMT_{it} = \beta_0 + \beta_1 BW\ Category_{it} + \beta_2 Sex_{it} + \beta_3 Coat\ colour_{it} + \beta_4 Coat\ length + \beta_5 UTCI_{it} + \beta_6 Speed_{it} + Residual_{it}$
Post-race hyperthermia (TMT > 38.8°C)	Generalised linear mixed model (binary logistic regression)	$\text{Post-race hyperthermia}_{it} \sim Bernoulli(\mu_{it})$ $Logit\ (\mu_{it}) = \beta_0 + \beta_1 BW\ Category_{it} + \beta_2 Sex_{it} + \beta_3 Coat\ colour_{it} + \beta_4 Coat\ length + \beta_5 UTCI_{it} + \beta_6 Speed_{it} + dog_i$
Post-race TMT > 40.6°C	Generalised linear mixed model (binary logistic regression)	$\text{Post-race } TMT > 40.6°C_{it} \sim Bernoulli(\mu_{it})$ $Logit\ (\mu_{it}) = \beta_0 + \beta_1 BW\ Category_{it} + \beta_2 Sex_{it} + \beta_3 Coat\ colour_{it} + \beta_4 Coat\ length + \beta_5 UTCI_{it} + \beta_6 Speed_{it} + dog_i$

*Where $dependent\ variable_{it}$ is the observation of the outcome for subject *i* at time *t*, β_0 is the random intercept, $BW\ category_{it}$, Sex_{it}, $Coat\ colour_{it}$, $Coat\ length_{it}$, $UTCI_{it}$, and $Speed_{it}$ are observations of the covariate/fixed effects for subject *i* at time *t*, $\beta_{1\text{-}6}$ are the regression coefficients for the covariate/fixed effects, and $Residual_{it}$ is the error for subject *i* at time *t*. For all models the $Dog_i \sim N(0, \sigma^2_{dog})$, $Residual_{it} \sim N(0, \sigma^2_{residual})$

4.4 Results

4.4.1 Ambient conditions

Across the 10 race days the mean ambient temperature recorded was 8.8°C ± 3.2 (range 3.3 - 15.4°C), the mean shade temperature recorded by the Met Office weather station was 7.6°C ± 3.2 (range 2.5 - 13.5°C) with the Met Office temperature recording a lower temperature on all but one occasion and reading up to 5.5°C lower than the site temperature. Mean site humidity was 77.9% ± 12.3 (range 55.0 - 96.1%), mean site wind speed was 10.7m/s ± 7.4 (range 0 – 26.6m/s). The mean calculated UTCI temperature for all race days was 5.1°C (range -5.0 - 11.7°C).

4.4.2 Effect of canine characteristics, speed and ambient weather on tympanic membrane temperature

The pre-race TMT ranged from 36.2 - 39.1°C across all readings, and was not significantly affected by BW category, sex, coat colour, coat length, or UTCI (Table 4.4.1). The intra-class correlation for dog in this model was 0.18.

Table 4.4.1: Descriptive statistics and linear mixed model results for pre-race tympanic membrane temperature (TMT) in dogs competing in canicross races in the UK. Overall parameter *p*-values are shown in italics.

Model parameter	Variable categories	Mean TMT ± SD (°C)	Estimate	95% Confidence interval	*p*-value
Intercept			37.31	36.46 to 38.15	*<0.001*
BW category	<10kg	37.2 ± 0.7	-0.48	-1.04 to 0.08	0.090
	10-<20kg	37.8 ± 0.7	0.15	-0.23 to 0.52	0.447
	20-<30kg	37.7 ± 0.7	0.23	-0.17 to 0.63	0.252
	≥30kg	37.7 ± 0.7	Comparator		*0.056*
Sex	Male	37.7 ± 0.6	0.04	-0.19 to 0.26	0.754
	Female	37.7 ± 0.7	Comparator		*0.754*
Coat length	Short	37.6 ± 0.7	0.09	-0.64 to 0.82	0.808
	Medium	37.8 ± 0.6	0.34	-0.44 to 1.13	0.389
	Long	37.6 ± 0.5	Comparator		*0.231*
Coat colour	Pale	37.6 ± 0.6	0.04	-0.24 to 0.32	0.767
	Medium	37.7 ± 0.6	0.16	-0.22 to 0.53	0.401
	Dark	37.7 ± 0.6	Comparator		0.690
UTCI			-0.003	-0.02 to 0.02	*0.741*

The post-race TMTs ranged from 37.0 to 42.5°C across all events. The variables sex, an increase in UTCI, and an increase in speed had a significant effect on post-race TMT, with male dogs developing significantly higher post-race TMTs that female dogs, and both UTCI and speed significantly increasing post-race TMT (Table 4.4.3). The intra-class correlation for dog was

0.41. “Temperature x humidity” had no significant effect on post-race TMT (estimate = 0.0002, 95%CI -0.0001 to 0.001, *p* = 0.212) when it replaced UTCI in the model.

Table 4.4.3: Descriptive statistics and linear mixed model results for post-race tympanic membrane temperature (TMT) in dogs competing in canicross races in the UK. Overall parameter *p*-values are shown in italics.

Model parameter	**Variable categories**	**Mean TMT change ± SD (°C)**	**Estimate**	**95% Confidence interval**	***p*-value**
Intercept			38.76	37.89 to 39.63	*<0.001*
BW category	<10kg	39.1 ± 0.8	-0.40	-1.25 to 0.46	0.360
	10-<20kg	39.4 ± 0.9	-0.10	-0.67 to 0.47	0.731
	20-<30kg	39.4 ± 1.1	-0.16	-0.77 to 0.45	0.605
	≥30kg	39.2 ± 1.2	Comparator		*0.808*
Sex	Male	39.6 ± 1.0	0.48	0.18 to 0.79	0.002
	Female	39.1 ± 1.0	Comparator		*0.002*
Coat length	Short	39.3 ± 1.0	-0.59	-1.24 to 0.07	0.077
	Medium	39.5 ± 1.1	-0.46	-1.19 to 0.28	0.221
	Long	39.6 ± 1.0	Comparator		*0.187*
Coat colour	Pale	39.5 ± 1.1	0.06	-0.35 to 0.46	0.788
	Medium	39.0 ± 1.0	-0.29	-0.82 to 0.23	0.273
	Dark	39.4 ± 0.8	Comparator		*0.304*
UTCI			0.04	0.01 to 0.06	*0.003*
Speed			0.05	0.01 to 0.09	*0.007*

4.4.3 Critical temperatures

Overall, 199 of the 281 (70.8%) post-race TMT readings were hyperthermic. Sex, UTCI, and speed were significantly associated with post-race hyperthermia, male dogs had 2.4 times the odds (95%CI 1.1 to 5.21) of developing post-race hyperthermia compared to female dogs (Table 4.4.4). Speed and UTCI both positively affected post-race hyperthermia. “Temperature x humidity” had no significant effect on post-race hyperthermia (odds ratio = 1.00, 95%CI 1.00-1.00, *p* = 0.209) when it replaced UTCI in the model.

Table 4.4.4. The percentage of dogs developing post-race hyperthermia (tympanic membrane temperature (TMT) > 38.8°C) post-race, and generalised linear mixed model (binomial logistic regression) results for post-race hyperthermia. Overall parameter *p*-values are shown in italics.

Model parameter	**Variable categories**	**Percentage of dogs with post-race hyperthermia (TMT > 38.8°C)**	**Odds ratio**	**95% Confidence interval**	***p*-value**
Intercept			0.11	0.01 to 1.16	*0.067*
BW category	<10kg	62.5	1.62	0.23 to 11.72	0.629
	10-<20kg	71.7	0.78	0.12 to 5.08	0.793
	20-<30kg	70.9	0.97	0.18 to 5.27	0.967
	≥30kg	71.9	Comparator		*0.805*
Sex	Male	79.0	2.4	1.1 to 5.21	0.027
	Female	75.0	Comparator		*0.027*
Coat length	Short	67.4	4.85	0.80 to 29.56	0.086
	Medium	73.1	3.44	0.47 to 25.19	0.223
	Long	81.3	Comparator		*0.203*
Coat colour	Pale	70.8	1.42	0.49 to 4.11	0.502
	Medium	56.3	3.1	0.84 to 11.4	0.088
	Dark	80.6	Comparator		*0.210*
UTCI			1.09	1.02 to 1.18	*0.015*
Speed			1.22	1.08 to 1.37	*0.001*

The dogs reaching the critical temperature of greater than 40.6°C, accounted for the top 10.7% of all post-race TMT readings recorded across the 10 race days (n = 30), including 19 (17.6%) of the 108 dogs. None of the variables tested were found to be significantly associated with a post-race TMT exceeding the critical threshold of 40.6°C (Table 4.4.5). “Temperature x humidity” had no significant effect on post-race hyperthermia (odds ratio = 1.00, 95%CI 1.00-1.00, *p* = 0.524) when it replaced UTCI in the model.

Table 4.4.5. The percentage of dogs developing a post-race tympanic membrane temperature (TMT) > 40.6°C post-race, and generalised linear mixed model (binomial logistic regression) results for post-race TMT > 40.6°C. Overall parameter *p*-values are shown in italics.

Model parameter	**Variable categories**	**Percentage (%) of dogs with post-race hyperthermia (TMT > 38.8°C)**	**Odds ratio**	**95% Confidence interval**	***p*-value**
Intercept			0.02	0.00 to 0.48	*0.016*
BW category	<10kg	0.0			0.992
	10-<20kg	9.4	0.39	0.06 to 2.65	0.333
	20-<30kg	12.6	0.54	0.07 to 4.12	0.547
	≥30kg	12.5	Comparator		*0.815*
Sex	Male	15.3	3.24	0.89 to 11.86	0.075
	Female	4.8	Comparator		*0.075*
Coat length	Short	8.1	0.25	0.02 to 3.22	0.289
	Medium	13.1	0.39	0.02 to 6.22	0.500
	Long	12.5	Comparator		*0.518*
Coat colour	Pale	14.3	2.92	0.60 to 14.20	0.183
	Medium	6.3	1.00	0.11 to 9.05	0.999
	Dark	5.6	Comparator		*0.268*
UTCI			1.06	0.95 to 1.18	*0.335*
Speed			1.10	0.96 to 1.26	*0.183*

~ indicates a variable category where the odds ratio cannot be calculated as no dogs developed a TMT > 40.6°C.

4.5 Discussion

This study found a significant positive effect of increasing ambient temperature on post-race TMT, and post-race hyperthermia in dogs exercising in ambient conditions ranging from -5.0 - 11.7°C (UTCI). This is in line with McNicholl et al. (2016) who reported a small effect of ambient temperature on greyhound post-race temperatures, and Phillips et al. (1981) who found a strong effect of ambient temperature on mean post-race rectal temperature in sled dogs. Ambient temperature (UTCI) was not associated with post-race temperature exceeding the critical threshold of 40.6°C, which suggests that there are other factors involved in the development of profound hyperthermia that were not measured as part of the present study.

The body temperature of exercising dogs is known to be influenced by many non-environmental factors. The intra-class correlation for dog was 0.41 in the linear mixed model exploring post-race TMT, highlighting the variation in post-race temperature even within the individual dogs. The results of this study support the findings of McNicholl et al. (2016); male dogs were significantly hotter post-race, experienced greater temperature increase, and were more likely to be hyperthermic post-race, compared to female dogs. Neither coat colour nor coat length significantly affected post-race temperature or post-race hyperthermia. This study also supports the findings of Chapman & Baker (1984), increasing exercise intensity - in this case speed - had a positive effect on post-race temperature and post-race hyperthermia. Body size had no effect on post-exercise temperature in the present study, which conflicts with the findings of McNicholl et al. (2016) and Phillips et al. (1981). However, it must be noted that body weight was estimated in the present study which could explain these conflicting results. Conditioning (Ferasin & Marcora, 2009; Nazar et al., 1992; Ready & Morgan, 1984), hydration (Baker et al., 1983), and diet (Ober et al., 2016) have also been found to influence post exercise body temperature. Although these factors were not investigated as part of this project, they are likely to have influenced the results. It is probable that the pet dogs taking part in this study, would have experienced variations in their feeding, hydration, and conditioning both between different dogs, and between races for individual dogs. Additionally, the different racecourses had different terrains and inclines at different points in the race, also known to influence rate of temperature elevation in exercising dogs (Chapman & Baker, 1984). The combination of these varying factors could have influenced both rate of temperature increase, and post-race temperature and may explain the lack of effect of UTCI temperature and post-race TMT exceeding the critical threshold of 40.6°C.

At every race in this study, at least one dog developed a post-race body temperature that would be considered at risk for developing heatstroke (TMT > 40.6°C). The highest recorded post-race TMT was 42.5°C. This is comparable to the highest TMT (42.4 °C) reported by Robbins et al. (2017), following 30 minutes of intermittent exercise in ambient conditions of 28.7°C and 49.6% humidity. This highlights the relative intensity of canicross races; a 12–30-minute race in relatively cool ambient conditions, caused body temperature to elevate to a similar level recorded in dogs exercising for 30 minutes in ambient conditions approaching body temperature. Despite these body temperature elevations, no dogs exhibited any clinical symptoms of heatstroke during any of the canicross race days, again mirroring the findings of Robbins et al. (2017). On several occasions, owners requested additional temperature checks on particularly hot dogs during the period following the race. These dogs all returned to a normal body temperature within 10-20 minutes, suggesting appropriate cooling mechanisms were in place to prevent prolonged hyperthermia. As ambient temperature increases, particularly as it approaches body temperature, cooling mechanisms become less effective (Hemmelgarn & Gannon, 2013). Further investigation into the factors affecting post exercise cooling, particularly the impact ambient conditions have on rate of cooling, may be more required to establish guidance for safe ambient conditions for running.

The combination of canine factors, husbandry factors, exercise factors and environmental factors all influence canine post exercise temperature, meaning any guidelines for “safe” running temperatures are unlikely to apply to all animals and could potentially put some dogs at risk. Instead, owners should be encouraged to understand the factors that can influence their own dog’s performance and heat tolerance in different ambient conditions. Canicross race organisers, and any other organisations promoting running with dogs, should be aware that the recommendation to not run a dog if ‘ambient temperature (°C) x humidity (%) > 1000’ was not supported by the present study, “temperature x humidity” had no significant effect on post-race temperature or post-race hyperthermia so its continued use cannot be recommended for the general pet dog population. As local weather stations only provide estimates of local shade temperatures, this could promote a false sense of security regarding race conditions. Instead, race organisers should make efforts to provide on-site means of monitoring environmental conditions, including ambient temperature, humidity, and wind speed, preferably providing an estimation of UTCI temperature, for instance using a wet bulb globe heat stress monitor. Being able to measure ambient conditions on the racecourse itself, allows owners to make an informed decision regarding their animal’s ability to compete under those conditions. Dog owners need to be aware of the factors that can impact their animal’s exercising body temperature. An unfit, poorly acclimatised, male dog may be at greater risk of heatstroke running in late autumn, than a physically fit female dog in regular training, running in the middle of summer.

A major limitation of this study was the inability to measure body temperature during the race. Previous work using ingestible telemetric thermometry capsules in Labradors, has shown that body temperature increased continuously during a 3.5km, flat run (Angle & Gillette, 2011). One study using treadmill running dogs, suggested that reaching a peak body temperature coincided with the point of exhaustion for the dogs (Nazar et al., 1992), with unconditioned dogs reaching peak temperature and therefore exhaustion faster than conditioned dogs. Phillips et al. (1981) continuously measured rectal temperature in racing sled dogs over a 16km run. They found temperature increased up to around 25 minutes into the run, then tended to plateau following several short rest stops triggered by the trainer’s perception of the dog’s ability to continue.

As intensity of exercise, specifically incline, has been shown to significantly increase canine body temperature (Chapman & Baker, 1984), it is possible canicross racing dogs reach a peak body temperature following a period of incline work, which then plateaus or drops as the work intensity reduces. Anecdotally, canicross runners have reported their dogs slowing down and refusing to pull during races, potentially due to reaching their temperature tolerance threshold. As there are limited non-invasive methods of continuously measuring core body temperature in dogs available in the UK, it is currently difficult to conduct further research on this area under field conditions using pet owned dogs. However, understanding how the dog's body temperature changes throughout the race in response to speed, inclines, and the presence of water obstacles on the course, may help to suggest appropriate race modifications to prevent canine heatstroke, when ambient conditions are considered too warm for all dogs to safely compete.

4.6 Conclusion

This study found that UTCI temperature significantly effects post-race body temperature and post-race hyperthermia in dogs competing in canicross races, and at every race dogs reached post-race temperatures exceeding the heatstroke risk threshold (40.6°C). As the highest UTCI recorded in this study was 11.7°C, race organisers should exercise caution when planning races during warmer weather. Average race speed and sex (male) were also found to have a positive effect on post-race temperature and post-race hyperthermia. . Canine sports associations and dog owners in general should be aware of the potential for inter and intra-dog temperature variations, depending on both husbandry and canine factors, and should be aware of the risk of heatstroke even on relatively cold UK winter days.

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4.7 References

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Section III Appraisal

Canicross continues to grow in popularity, with a recent surge in interest fuelled by the covid-19 pandemic responses such as national lockdowns (Thomas, 2021). When the UK locked down in March 2020, people were initially permitted only one period of outdoor exercise daily, meaning that dog owners were restricted to just one walk or run with their canine companion away from the home. Canicross offered people a source of motivation to exercise and offered the advantage of keeping the dog secured to the owner whilst running, helping to facilitate social distancing (Thomas, 2021). As the sport's popularity rises, so too does the wider awareness of canicross as evidenced by the slowly growing body of research relating to canicross specific sports psychology (Merchant, 2020), sports injuries (Lafuente & Whyle, 2018), exercise physiology (Erjavec et al., 2022) and sport biomechanics (Jendro et al., 2018). Increased participation in the sport also means there are more novice athletes – both human and canine - training and competing in the sport. Novice athletes may not be aware of the threat exertional hyperthermia poses to dogs, and the novice dogs may be unfit and/or overweight which increases their risk of developing heat-related illness (Hall et al., 2020b; Nazar et al., 1992). The results of Chapter Four are therefore particularly important to these novice competitors, as the study recruited pet dogs rather than elite athletes (such as racing Greyhounds) making the results directly applicable to them.

III.2 Critical appraisal of the study methods – Chapter Four

Chapter Four used tympanic membrane temperature (TMT) as an estimate of body temperature. Whilst the studies presented in Section II demonstrate that TMT can provide a reasonable estimation of body temperature (Hall & Carter, 2017a, 2017b), rectal thermometry remains the most accurate method of estimating core temperature (Hall, 2021). However, when designing the study in Chapter Four it was decided that attempting to measure rectal temperature was impractical in a field setting as rectal thermometry is slower that measuring TMT and fewer dogs typically tolerate rectal thermometry (Gomart et al., 2014; Lamb & McBrearty, 2013). As Chapter Four involved canicross sports dogs, two important factors in recruiting participants to the study were ensuring that temperature readings caused no aversion in any of the dogs and ensuring that readings could be performed rapidly to allow dogs and handlers to exit the finish area as quickly as possible to facilitate post-race cooling and warm down activities.

As TMT consistently under-reports body temperature when compared to rectal temperature in dogs (Gomart et al., 2014; Hall & Carter, 2017a; Lamb & McBrearty, 2013; Zanghi, 2016) a TMT specific temperature reference range was developed to ensure that the temperature readings could be interpreted appropriately (Hall & Carter, 2017b). Although using TMT to measure body temperature limits the direct comparison of the results in Chapter Four to other canine studies that have used rectal temperature, the use of TMT improved recruitment of participants so was justified.

A key limitation of the study presented in Chapter Four was the use of single temperature measurements rather than continuous monitoring of core temperature. Davis et al. (2019) used ingestible telemetric thermometry pills to continuously measure internal temperature via the gastrointestinal tract in working dogs and demonstrated that the dogs' body temperatures continued to rise for 10-15 minutes after the cessation of exercise. As the study in Chapter Four included only one single temperature reading per dog when they completed the race, it is probable that some dogs' temperatures continued to rise so the peak temperature was not recorded. Shapiro et al. (1973) demonstrated that both peak body temperature and the duration of time the dog's temperature remained over 43°C were critical to the development of severe heat-related illness (HRI). Without continuous body temperature monitoring it was therefore impossible to truly determine if any of the dogs in the study were at serious risk of developing HRI. Further research using ingestible telemetry pills to monitor canine body temperature throughout the race and recovery period is needed to truly determine the degree of heat stress dogs experience whilst competing and training for canicross events.

Whilst the results of Chapter Four are relevant to all UK dog owners participating in canicross, the generalisability of the results to the wider exercising pet dog population, and indeed international sports dog populations, is limited. For example, European canicross participants frequently run with Eurohounds and Greysters (Erjavec et al., 2022), two hybrid sports crossbreeds that involve breeding Greyhounds, Pointers and Huskies, with the goal of producing large dogs with both explosive sprint and long distance running capability. Although both designer sports crossbreeds were present at the races included in Chapter Four, none of the dogs were included in the study as the only dogs presented by their owners to participate would not tolerate the thermometers. Additionally, only 17 long haired dogs were included in the study, therefore further research is needed to determine how coat type affects canine post-exercise temperature, particularly post-exercise cooling.

The original published version of Chapter Four included a number of statistical analyses that failed to take into consideration the repeated measures in the dataset. Consequently, when the analysis was revised using linear mixed modelling some key results differed, notably UTCI was found to have an effect on post-race temperature, and coat colour was no longer found to significantly affect post-race temperature or post-race temperatures >40.6°C when individual dog was included as a random term. Indeed, the 30 post-race temperatures that exceeded the

40.6°C threshold included just 19 individual dogs, two dogs had four measurements included, four of the nine hottest temperatures recorded.

III.3 Reception of the published work

Following publication of Chapter Four many canicross clubs have now adopted ambient temperature limits for races, with events either shortened in distance or cancelled altogether if the wet bulb globe temperature (WBGT) exceeds the limit. For example, Canicross Midlands (UK) - the club who facilitated the research presented in Chapters Two to Four - have adopted the upper limit of WBGT 20°C for cancelling races and shorten the course if the WBGT is 16-20°C as a direct result of the results presented in Chapter Four (Canicross Midlands, 2022). The Midlands club have always monitored ambient conditions at races but have upgraded their equipment to a device that can measure WBGT. In addition, they have changed from measuring shade temperature to measuring the ambient conditions on the racecourse itself, which is rarely fully shaded from the sun, recognising that it is the conditions on the course that will ultimately affect the dog. The British Sled Sport Federation (the national governing body in the UK) have also made this change. In comparison, the International Federation of Sleddog Sports (IFSS) still currently use shade temperature and humidity to assess race conditions rather than WBGT or UTCI; they shorten races if the temperature exceeds 16°C or humidity exceeds 85% and cancel all races except canicross if the temperature exceeds 22°C (IFSS, 2021). Veterinarians responsible for monitoring canine athlete welfare at IFSS events are actively campaigning for updates to the rules of racing in response to the results presented in Chapter Four.

The work in Chapter Four has been built upon by a recent study that evaluated the effect of two consecutive days racing on the physiological and biochemical parameters of seven experienced canicross dogs (Erjavec et al., 2022). Erjavec et al. (2022) measured rectal temperature and drew blood from the dogs both immediately before and after the two races, with an additional sampling point 24-hours after the second race day. The races took place in Slovenia during April (at the end of the racing season) with ambient temperatures of 13.6-19.1°C (UTCI). The highest post-exercise rectal temperature recorded was 41.7°C, with no dogs showing any symptoms of heat-related illness and, although levels of urea and creatinine increased post-exercise (likely indicative of increased muscle metabolism or mild dehydration), all biochemical parameters remained within normal reference ranges at all sampling points (Erjavec et al., 2022). Erjavec et al. (2022) acknowledge that the small sample size, and inclusion of only experienced, well-conditioned dogs at the end of the race season limit the wider application of these results.

As suggested in Chapter Four, Eravec et al. (2022) recommend further research focusing on the novice canine participants at the start of the racing season, to capture the dogs likely to be at greatest risk of experiencing heat-related illness and oxidative stress from exertion. Unfit dogs have reduced thermoregulation ability (specifically cooling) compared to well-conditioned dogs meaning that their body temperature rises more quickly and they take longer to cool (Nazar et al., 1992; Ready & Morgan, 1984). Furthermore, overweight dogs are more likely to develop heat-related illness (Bruchim et al., 2006; Hall et al., 2020b), meaning that owners who take up canicross with the aim of helping their canine companion lose weight could inadvertently put their dog at risk if they do not recognise the signs of heat-related illness or appreciate the danger of over-exerting in hot weather (Hall et al., 2020a, 2021). Research that includes novice, unfit and overweight dogs competing at canicross events is therefore needed to truly evaluate the physiological and biochemical effects of the sport on the full range of canine participants.

Witnessing canicross events first-hand was a pivotal moment in my own personal professional development. I had treated dogs with heat-related illness whilst working in veterinary practice, and I had examined dogs walked to the practice for routine vaccinations in the summer that arrived with rectal temperatures exceeding 41°C; these dogs were immediately cooled using water and air conditioning and asked to return on a cooler day for their booster. However, I had never previously measured a canine temperature that exceeded 42°C. Every textbook and readily accessible journal article stated that dogs presenting to a veterinary clinic with a temperature above 41°C should be considered to be at high risk for developing heat-related illness (heatstroke) (Bruchim et al., 2006; Drobatz & Macintire, 1996; Flournoy et al., 2003; Hall & Carter, 2016; Hemmelgarn & Gannon, 2013; Johnson et al., 2006; Mazzaferro, 2017; Miller, 2009). However, during the three years that I observed and monitored canine temperatures at Canicross Midland races alongside Dr Anne Carter, no dogs developed moderate or severe heat-related illness. The dogs that finished races with an ear temperature of 42°C or more often dragged their human racing companion to the nearest body of water, and immediately immersed themselves in the water for as long as they wanted/were permitted (Figure III.1).

Figure III.1. Ronin the Dobermann cooling off in a paddling pool post-race during Easter 2019, a particularly hot race day when the course had to be shortened. Ronin sat here for 10 minutes before reluctantly leaving the paddling pool. His ear temperature at the race finish was 40.2°C, after 10 minutes in the paddling pool this had dropped to 38.3°C.

In a follow up study (currently unpublished), Dr Carter and I monitored the temperature of dogs competing and training with Canicross Midlands post-exercise. Figure III.2 illustrates the rate of cooling for the eight hottest dogs at the events. All dogs developed a post-exercise ear temperature over 41.0°C, but within 15 minutes the dogs' temperatures had all dropped to 39.5°C or lower (current guidance recommends active cooling should be stopped once this temperature is reached), towards or below the upper limit of the normal reference range (indicated by the dashed line). As illustrated in Figure III.1, some dogs panted continuously during the initial cooling period, and some lay down either in the available water or upon the ground. It is possible that these dogs were exhibiting early signs of mild heat-related illness (e.g., excessive panting, lethargy) (Hall et al., 2021). However, following cooling, all dogs returned to their normal pre-exercise demeanour and condition. These training or race events were held in the east and west midlands region of the UK between October and August and included ambient temperatures (measured using WBGT) from -0.4 to 12.3°C.

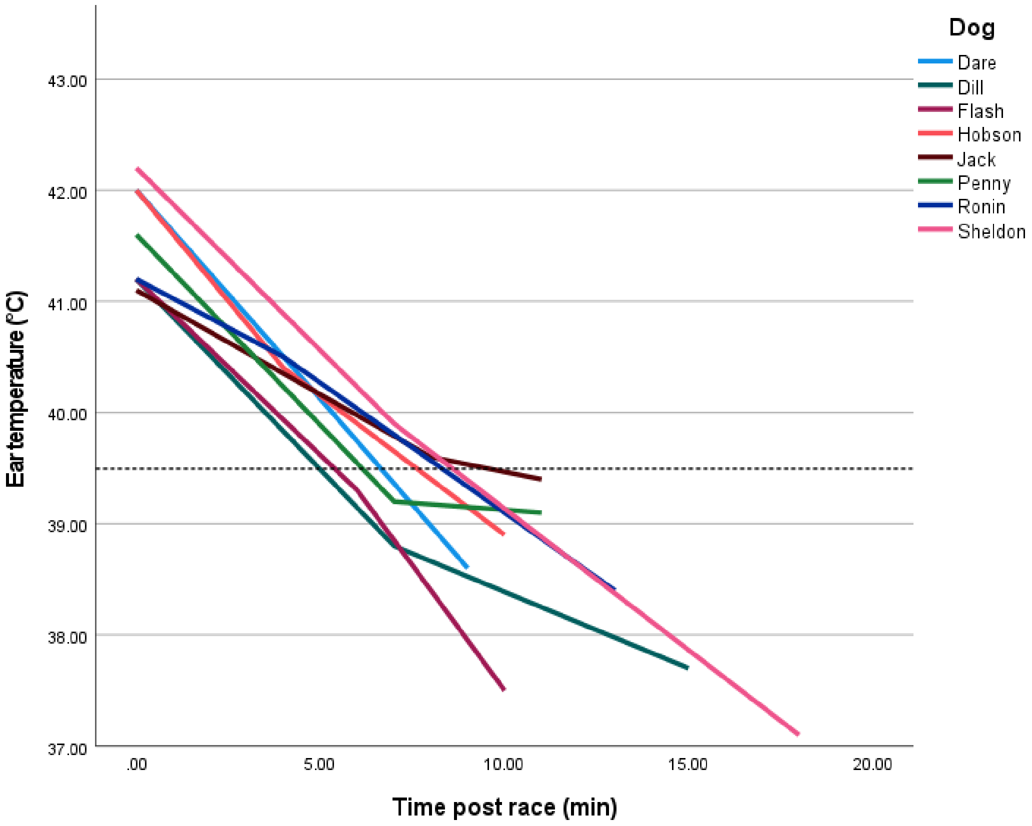

Figure III.2. Post-exercise cooling for eight dogs measured at two canicross events. Time 0 represents the immediate post-exercise ear temperature recorded, with two additional temperature measurements at approximately 5-10 minutes then 10-20 minutes post-exercise (unpublished data). The dashed lined (38.8°C) illustrates the upper limit of the normal canine ear temperature reference range (Hall & Carter, 2017b).

In a study comparing post-exercise cooling methods for working Labrador Retrievers, Davis et al. (2019) reported that when the dogs were not actively cooled (dogs were left in a kennel), core temperature was higher 30 minutes post-exercise than when measured immediately post-exercise for over half the dogs examined. Indeed, experimental studies aiming to induce heat-related illness in dogs reported that the duration the dog's temperature exceeded 43°C predicted death as HRI severity increases the longer a dog's temperature remains elevated above the critical temperature threshold (Shapiro et al., 1973). Therefore, active cooling is vital for reducing the severity of HRI and the risk of death. Certainly, all the dogs in Figure II.2 were cooled post-exercise using a range of methods including drinking cold water, lying on snowy ground, or fully immersing themselves in the nearby lake. These were fit, experienced canicross dogs with practiced owners who were actively participating in the cooling study and knew to cool their dogs after exercise; we did not prescribe the cooling we simply asked owners to treat their dogs as per their usual routine whilst we monitored their temperatures and recorded the cooling interventions used. Had these dogs not been actively cooled, their temperatures may have continued to rise and remained elevated for a prolonged period (Davis et al., 2019). Merchant (2020, page 17) illustrates part of the problem: *"dogs are much more likely to exercise to dangerous levels of exertion than humans, especially if being encouraged to exercise by their human in warm conditions".* If the dog owner does not recognise the danger or does not realise their dog may need active cooling after exercise (including during relatively cool ambient conditions) there is a serious risk of HRI.

The results presented in Chapter Four alongside the research that followed the publication of that study, illustrate the potential for dogs to develop HRI following exercise at relatively low ambient temperatures. Although studies from Israel reported that exertional HRI accounted for almost half of the canine HRI cases presented for treatment at one university veterinary hospital (Bruchim et al., 2006; Bruchim, Ginsburg et al., 2017; Bruchim, Kelmer et al., 2017), it was not known whether the same was true for dogs in the UK. This evidence gap formed the basis of a funding application to Dogs Trust Canine Welfare Grants, and thanks to their generous and ongoing support, the "Hot Dogs - investigating the epidemiology of canine heatstroke presenting to UK primary care veterinary practices" project was launched, leading to the publications presented in Section IV.

Chapter Four Metrics (May 2024):

Google Scholar Citations: 42

Scopus citations: 21

Altmetric: 237

Wider engagement

Popular press articles:

- Hall, E. J., & Carter, A. J. (2018). If your New Year's resolution is to get fit, your dog may be your perfect training partner. The Conversation. https://theconversation.com/if-your-new-years-resolution-is-to-get-fit-your-dog-may-be-your-perfect-training-partner-88578 (9591 reads)

- Hall, E. J., & Carter, A. J. (2018). Dogs don't just die in hot cars – here's how to stop them overheating when exercising. *The Conversation*. https://theconversation.com/dogs-dont-just-die-in-hot-cars-heres-how-to-stop-them-overheating-when-exercising-100266

Invited presentations:

- Carter, A. J., & Hall, E. J. (2017). An update on the canine temperature research. Canicross Midlands Summer Training Camp, August 2017.
- Carter, A. J., & Hall, E. J. (2018). Methods of monitoring temperature and the factors that influence canine hyperthermia during exercise. Canicross Midlands Summer Training Camp, August 2017.

Publications expanding this work:

- Carter, A. J., Hall, E. J., Bradbury, J., Beard, S., Gilbert, S., Barfield, D., & O'Neill, D. G. (2024). Post-exercise management of exertional hyperthermia in dogs participating in dog sport (canicross) events in the UK. Journal of Thermal Biology, 121 (2023), 103827. https://doi.org/10.1016/j.jtherbio.2024.103827

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Section IV: How often and why do dogs develop heat-related illness?

IV.1 Section introduction:

This section presents the results of a retrospective cohort study exploring the incidence, risk factors and triggers of heat-related illness (HRI) in UK dogs. The study is presented in two publications (Chapters Five and Six) which used the VetCompass database to review the anonymised veterinary clinical records of 904,453 dogs under primary veterinary care in the UK during 2016. Chapter Five presents the 2016 incidence risk of HRI in UK dogs and the risk factors for HRI in general (including all grades of illness from mild to severe) at a population level. Chapter Six further examines the same dataset to explore the triggers for HRI events to determine the most common reason UK dogs develop HRI and goes on to identify specific canine risk factors for the three most common HRI triggers. The two chapters address the evidence gap: "*How often and why do dogs develop heat-related illness*?". A critical appraisal of the two studies follows Chapter Six, detailing the impact this work has had on UK-specific initiatives to reduce the occurrence of HRI in pet dogs.

This Section contains edited versions of the following published studies:

Chapter Five:

Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016. *Scientific Reports*, *10*(1), 9128. https://doi.org/10.1038/s41598-020-66015-8

Chapter Six:

Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). Dogs Don't Die Just in Hot Cars—Exertional Heat-Related Illness (Heatstroke) Is a Greater Threat to UK Dogs. *Animals*, *10*(8), 1324. https://doi.org/10.3390/ani10081324

Chapter Five: Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016.

This is an edited version of the article published by Springer Nature, Scientific Reports on 18th June 2020 available online: http://www.nature.com/articles/s41598-020-66015-8

Authors: E. J. Hall, A. J. Carter & D. G. O'Neill

Keywords: VetCompass, electronic patient record, breed, primary-care, canine heatstroke, heat-related illness, heat stress, brachycephalic.

Abbreviations: CI; confidence interval, EPR; electronic patient record, KC; Kennel Club, HRI; heat related illness, OR; odds ratio.

5.1 Abstract

As climate change causes global temperatures to rise, heat-related illness, a potentially fatal condition in dogs, will become an ever-greater threat. This study aimed to report the incidence, fatality and canine risk factors of heat-related illness in UK dogs under primary veterinary care in 2016. The VetCompass^{TM} programme collects de-identified electronic patient records from UK veterinary practices for research. From the clinical records of 905,543 dogs under veterinary care in 2016, 395 confirmed heat-related illness events were identified. The estimated 2016 incidence of heat-related illness was 0.04% (95% CI 0.04-0.05%), with an event fatality rate of 14.18% (95% CI 11.08 – 17.96%). Multivariable analysis identified significant risk factors including breed (e.g., Chow Chow, Bulldog and French Bulldog), higher bodyweight relative to the breed/sex mean and being over two years of age. Dogs with a brachycephalic skull shape and dogs weighing over 50kg were also at greater risk. As we move into an ever-warmer world, veterinary professionals may need to include resistance to heat-related illness amongst their rationales when advising owners on breed selection. Breeding for good respiratory function and maintaining a healthy bodyweight should be considered key welfare priorities for all dogs to limit the risk of heat-related illness.

5.2 Introduction

Climate change is listed among the World Health Organisation's top ten threats to Global Health in 2019, with heat-related illness (HRI) predicted to contribute towards an additional 250,000 human deaths annually by 2030 (WHO, 2019). HRI is a progressive disorder of animals and man caused by core body temperatures that rise above homeostatic limits, resulting in metabolic disturbances (Bouchama & Knochel, 2002). This can lead to decreased cardiac output, fatigue of heat dissipation mechanisms, organ failure and ultimately death (Bouchama & Knochel, 2002; Bruchim, Horowitz, et al., 2017; Hemmelgarn & Gannon, 2013a). Animal welfare organisations in the United Kingdom (UK) and Australia have reported increasing numbers of calls about animals trapped in hot environments over recent years (BVA, 2019; Shih et al., 2019). As the frequency and severity of heat waves is predicted to increase, there is an urgent need for better evidence-based guidance on the risk factors and early recognition of HRI to improve prevention and treatment strategies for both humans and animals (Bruchim, Horowitz, et al., 2017; House of Commons Environmental Audit Committee, 2018).

A deficiency of reliable and current data on the diagnosis, treatment and fatality rate of HRI is a key barrier to mitigating HRI risks in both humans and dogs (Mora et al., 2017). The classical terminology used to define HRI varies, but typically includes terms that describe progression from heat stress, through heat exhaustion to heatstroke (Bouchama & Knochel, 2002). However, these classical terms lack clear explicit definitions and are often used interchangeably as synonyms, leaving their usage open to individual interpretation that creates a confused medical and veterinary literature (Bruchim, Horowitz, et al., 2017). A novel HRI scoring system has been proposed for use in humans, acknowledging that patients can progress through the stages of disease severity depending on the duration and intensity of heat exposure and effectiveness of treatment (Yamamoto et al., 2015). To date, studies of HRI in dogs have included only cases described as suffering from advanced stages of HRI "heatstroke" (Bruchim et al., 2006; Drobatz & Macintire, 1996; Segev et al., 2015; Teichmann et al., 2014). Excluding dogs presenting with less severe forms and stages of HRI from risk factor analysis fails to take the progressive nature of the condition into consideration and biases the results away from the overall HRI caseloads seen in general veterinary practice.

HRI is reported as a relatively common condition in dogs in regions with hot climates (Bruchim, Horowitz, et al., 2017; Drobatz & Macintire, 1996), but cases are reportedly less common in more temperate regions such as the UK. In a BVA survey of over 1000 UK companion animal veterinarians, half reported seeing an average of five canine heat-related illness cases during the summer of 2016 (BVA, 2017). Case reviews from primary-care single centre studies in the

UK often include insufficient cases for robust statistical analyses and are therefore of limited scientific value. For this reason, canine HRI studies to date have tended to rely on referral hospital populations that accumulate caseloads from a broad base of referring practices (Aroch et al., 2009; Bruchim et al., 2006; Bruchim, Ginsburg, et al., 2017; Drobatz & Macintire, 1996; Segev et al., 2015; Teichmann et al., 2014), but referral caseloads self-select for complex and severe cases, and the diagnoses and outcomes will be heavily influenced by the advanced veterinary equipment and care available in such hospitals (Bartlett et al., 2010). The largest heatstroke study in dogs to date included 126 dogs presenting to a hospital in Israel and reported a case fatality rate of 53% (Segev et al., 2015). That study used a retrospective case series analysis from a referral hospital population, preventing extrapolation of fatality rate to the wider canine population because of the inherent referral bias (Bartlett et al., 2010). Consequently, results from such referral studies are not representative of the general canine population, reducing the generalisability and wider world application of the findings (O'Neill et al., 2014).

In recent years, there has been considerable development of 'Big Data' databases combining primary-care clinical records from hundreds or even thousands of individual veterinary practices (Royal Veterinary College, 2019; University of Liverpool, 2019; VetCompass Australia, 2019). In the UK, VetCompass^{TM} has developed an online research platform that provides access to de-identified veterinary patient records from over 15 million companion animals and has been validated as a research resource by 75 peer reviewed publications to date (O'Neill et al., 2014; Royal Veterinary College, 2019).

Study aims

The current study aimed to use the VetCompass database of veterinary health records to (i) estimate the 2016 incidence of HRI in the UK dog population; (ii) identify canine risk factors for HRI and (iii) estimate case-fatality rate for HRI in dogs under primary veterinary care in 2016. It was hypothesised that brachycephalic breeds (specifically the Bulldog) have higher odds of HRI compared to mesocephalic breeds.

5.3 Methods

Data collection and management

The study used data from the VetCompass Programme that provides research access to de-identified electronic patient records (EPRs) from primary-care veterinary practices in the UK as previously described (Anderson et al., 2018; O'Neill, Corah, et al., 2018; O'Neill, Skipper, et al., 2019; O'Neill et al., 2014). The study population included all dogs under primary veterinary care during 2016 in VetCompass. Dogs under veterinary care were defined as those with either a) at least one EPR recorded during 2016 and/or b) at least one EPR recorded during both 2015 and 2017. Data fields available for each dog included a unique animal identifier with breed, sex, neuter status, date of birth and bodyweight, and also clinical information from free-form text clinical notes, treatments and deceased status with relevant dates.

Database search

Pilot study. Pilot investigations were conducted to refine the search terms used to identify candidate HRI cases within the denominator population. Because HRI is neither a definitive diagnosis nor a disorder that can be objectively confirmed through diagnostic testing, the case definition needed to be broad enough to include diagnoses reached by excluding other differential diagnoses and by consideration of the animal's recent history.

The final HRI case definition was:

An event recorded in the EPR that included a history of at least one of the following clinical signs developing specifically after, and being ascribed to, exposure to a hot environment, physical exertion or both.

Clinical signs:

- panting excessively or continuously despite removal from heat/cessation of exercise,
- collapse not subsequently attributed to another cause (e.g., heart failure, Addison's),
- stiffness, lethargy or reluctance to move,
- gastrointestinal disturbance including hypersalivation, vomiting or diarrhoea,
- neurological dysfunction including ataxia, seizures, coma or death,
- haematological disturbances including petechiae or purpura.

Exclusion criteria included:

- subsequent diagnosis of an infectious or inflammatory condition that was not attributed to primary heat exposure such as kennel cough, pyometra or infectious meningitis,
- HRI or synonym listed only as one of a differential list,
- an earlier diagnosis of HRI that was later revised to exclude HRI, for example the dog was diagnosed with epilepsy following further seizure activity.

There are currently no explicit guidelines for accurately staging HRI in dogs and they, like humans, may progress through the stages of HRI depending on their management (Shapiro et al., 1973). Therefore, the HRI cases included in the current study comprised all stages of disease from mild (classically referred to as heat stress) to severe (classically referred to as heatstroke) (Bouchama & Knochel, 2002). Additionally, in recognition of the limitations of using clinical data not recorded for the purpose of research, any dog with an event where the EPR included a final stated veterinary diagnosis of, or insurance claim for HRI (including terms such as heatstroke, heat stress, heat exhaustion or overheating) regardless of clinical history detail was also included as a HRI case (Figure 5.3.1.).

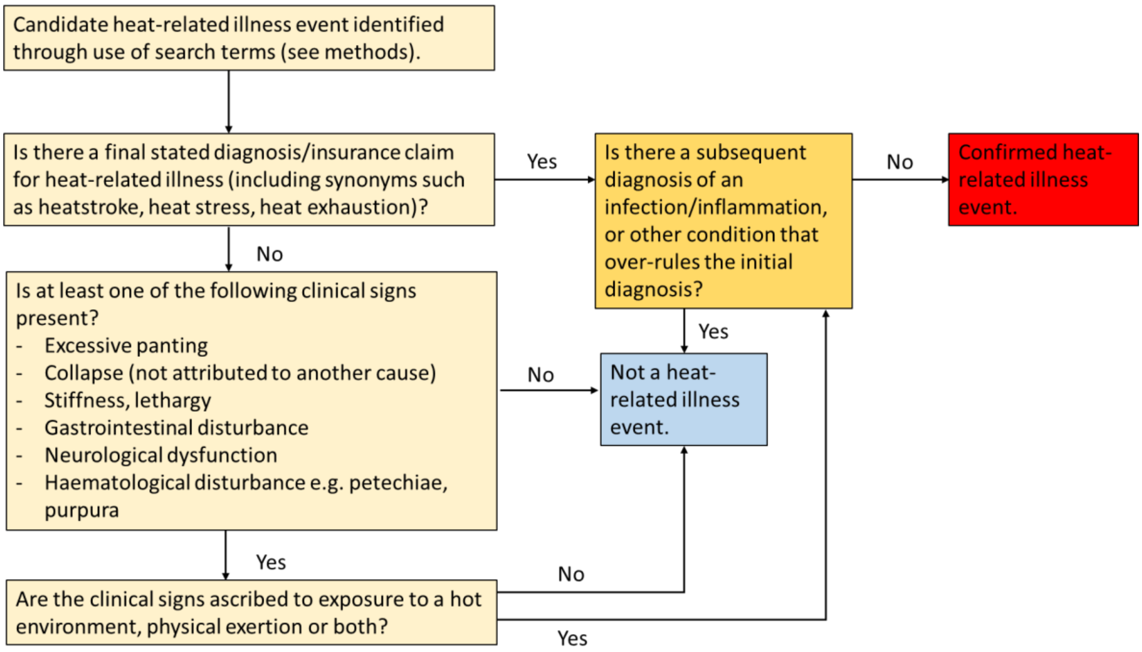

Figure 5.3.1. Flow chart illustrating the application of the heat-related illness case inclusion and exclusion criteria applied to candidate heat-related illness cases identified in the VetCompass database.

Main study. Candidate cases of HRI were identified by searching the EPR free-text fields for the following terms: heat stroke~3, heatst*, hyperthermi*, overheat*, over heated~2, heat exhaustion~2, hot car~2, collapse* + heat, cooling, high ambient temp*. Dogs identified from all searches were merged and randomly ordered. All candidate cases were manually reviewed in detail by two researchers (author one and author two) to identify all confirmed HRI cases that met the study case definition for HRI occurring at any date within the patient's available lifetime EPR (*prevalent HRI cases*), up to the point of data extraction (20th January 2019). Disagreements between the two authors on case inclusion prompted a case discussion centred around the case inclusion/exclusion criteria until a final decision was agreed. From these *prevalent HRI cases*, the subset of *incident 2016 HRI cases* was identified including only dogs with their first HRI event occurring within the 2016 study period. All confirmed *incident 2016 HRI cases* underwent further data extraction including outcome of event (survival or death) and date of heat exposure event. The first event occurring during the study period (2016) was used for the date of exposure event to calculate age at event for dogs with multiple HRI events.

Analysis

Sample size calculations using Epi Info 7 were based on an estimated HRI incidence of 0.29% derived from a survey of the UK veterinary profession that reported an average of five canine HRI cases per practice during 2016 (BVA, 2017). There were approximately 5,000 small animal or mixed practices in the UK during 2016 (Royal College of Veterinary Surgeons, 2016), resulting in an estimated 25,000 HRI events within the 8.5 million dogs in the pet UK population (PFMA, 2016). The Bulldog has previously been reported at greater HRI risk than other dogs (odds ratio (OR) 2.7) (Bruchim et al., 2006), and comprise 0.36% of the UK dog population (O'Neill, Skipper, et al., 2019). Sample size calculations estimated that cross-sectional analysis would require 114,588 dogs (including 1879 Bulldogs) to provide a 2.7 odds ratio estimate for a disorder expected to occur in 0.29% of overall population with a 0.01% confidence limit and 90% power (60:1 ratio of control to exposed).

The study used a cohort design. The denominator population included 905,543 dogs from the VetCompass database. Demographic data were extracted automatically from the database for all study dogs and exported into Microsoft Excel (Office 365) for cleaning and descriptive analysis.

The prevalence of HRI within the cohort was estimated using all confirmed *prevalent HRI cases*. The one-year (2016) incidence was calculated using only *2016 incident HRI cases.* The event fatality rate was calculated using all dogs with at least one HRI event occurring in 2016. The 95% confidence intervals (CI) were calculated using EpiTools (AusVet 2019). The number of incident cases each month was plotted against the mean monthly UK air temperature, retrieved from the Met Office (https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series) to provide a visual representation of the relationship between ambient temperature and HRI incidence.

Risk factor analysis used cohort clinical data from all dogs in the denominator population and was conducted in SPSS v25 using multivariable logistic regression to identify potential risk factors associated with HRI (defined in Table 5.3.1). Binary logistic regression was used to evaluate potential univariable associations between risk factors (*breed type, purebred, skull shape, adult bodyweight, bodyweight relative to breed/sex mean, sex/neuter* and *age*) and HRI diagnosis during 2016 (*2016 incident HRI cases)*. As *breed type* was a factor of primary interest for the study, variables that are highly collinear with breed (*purebred*) or considered a defining characteristic of individual breeds (*adult bodyweight* and *skull shape*) were used in alternative models and not included in the multivariable models using *breed type* as previously described (O'Neill et al., 2014). Risk factors with liberal associations to HRI ($P<0.2$) in univariable modelling were selected for multivariable evaluation. Model development used manual backwards stepwise elimination. Pairwise interactions were tested for all variables in the final multivariable model. The area under the receiver operating characteristic (ROC) curve was used to evaluate the predictive ability of the model (Dohoo et al., 2009) alongside consideration of the underpinning biological plausibility of the model specification. Statistical significance was set at $P < 0.05$.

Table 5.3.1. Potential risk factors assessed for association with heat related illness (HRI) in UK dogs.

Potential risk factor for HRI	Variable definition	Justification
Breed type	Categorical variable including all named breed types (including both KC recognised purebred and non-KC recognised purebred) and designer hybrid types with contrived names (e.g., Cockapoo, Labradoodle, Lurcher) with ≥5 HRI cases and/or ≥5000 dogs in the overall study population. All remaining dogs were assigned to grouped categories of "other purebred", "other designer cross" or "non-designer crossbred".	Belgian Malinois, Golden Retrievers and brachycephalic breeds are reported to have increased odds ratio of HRI compared to small breeds of dog (Bruchim et al., 2006). Labrador Retriever was used as the comparator for this variable as they were the largest breed type in the denominator population (after crossbred) so enabled high statistical power to explore breed risks (Dohoo et al., 2009; Erlen et al., 2018).
Purebred	Categorical variable grouping all dogs of recognisable breeds as "purebred", all recognisable designer crossbreeds as "designer cross" and the remaining dogs as "crossbred".	Purebred dogs are more likely to have an exaggerated conformation such as brachycephaly, thick coat, or giant body size, limiting their ability to thermoregulate (Hemmelgarn & Gannon, 2013b). A higher percentage of purebred dogs presented with heatstroke to one veterinary hospital (Drobatz & Macintire, 1996).
Skull shape	Purebred dogs were categorised by skull shape into three groups, "brachycephalic", "mesocephalic" and dolichocephalic" (see Supplementary note 1 for breeds by category). Designer crossbred dogs including a brachycephalic breed were classified as "brachycephalic cross" and all other dogs listed as crossbred or unrecorded breed were classified as "skull shape unrecorded".	Surface areas of the nasal turbinates and effective ventilation provide the mechanism to enable evaporative heat loss through panting, thus brachycephalic dogs have reduced heat dissipation mechanisms (Bruchim et al., 2006; S. Flournoy et al., 2003; Hemmelgarn & Gannon, 2013b; Lilja-Maula et al., 2017).

Adult bodyweight	Adult bodyweight was defined as the mean of all bodyweight (kg) values recorded for each dog after reaching 18 months old. Bodyweight (kg) was then categorised into seven groups (<10, 10-<20, 20-<30, 30-<40, 40-<50, ≥50), dogs under 18 months or with no recorded adult bodyweight were classified as "unrecorded".	Small breeds of dog are reported to have decreased risk of HRI (Bruchim et al., 2006), dogs with greater body mass have been reported to develop higher post exercise body temperatures (McNicholl et al., 2016).
Bodyweight relative to breed/sex mean	A categorical variable grouping dogs with a mean adult bodyweight "equal or above" or "below" the mean adult bodyweight for their breed and sex (calculated using the overall VetCompass study population). An "unrecorded" variable included all dogs with no adult bodyweight or labelled as crossbred.	Increased bodyweight can be due to increases in either lean muscle mass, or body fat. Obesity limits heat conduction and radiation from the skin and can limit effective cooling via respiration (Hemmelgarn & Gannon, 2013b), overweight animals overheat faster and take longer to cool (Durkot et al., 1986). Dogs with greater lean body mass developed higher post exercise temperatures than lighter dogs (McNicholl et al., 2016).
Sex/neuter	Dogs were classified by sex and neuter status into five categories (female entire, female neutered, male entire, male neutered) with "unrecorded" was used to group any dogs with no recorded sex or neuter status.	Male dogs develop higher body temperature post exercise (Carter & Hall, 2018; McNicholl et al., 2016), and are overrepresented in cases of heatstroke presenting to veterinary hospitals (Segev et al., 2015, 2018; Teichmann et al., 2014).
Age	The age variable described the age of the dog at the end of the study period (31st December 2016) for non-case dogs, or the age at the first HRI event for *2016 incident HRI cases*. Age (years) was categorised into eight groups (<2, 2-<4, 4-<6, 6-<8, 8-<10, 10-<12, ≥12) with "unrecorded" for any dogs with no date of birth recorded in the EPR.	Older animals are more likely to have pre-existing conditions that limit effective heat dissipation such as heart disease, or respiratory diseases e.g., laryngeal paralysis (S. Flournoy et al., 2003).

5.4 Results

The study included 905,543 dogs under veterinary care at 886 UK VetCompass clinics during 2016. EPR searches identified 6531 candidate cases, of which 1222 were classified as *prevalent HRI cases* following manual review giving an estimated prevalence of 0.14% (95% CI 0.13-0.14%). There were 35 dogs identified with two HRI events and one dog with three recorded HRI events from the *prevalent HRI cases*. Data completeness varied between the variables assessed: *breed type* 99.55%, *sex/neuter* 99.53%, *age* 98.63% and *adult bodyweight* 65.70%.

Incidence estimate

There were 390 *2016 incident HRI cases* (with five cases experiencing two events resulting in 395 HRI events) within the denominator population of 905,543 dogs . The incidence risk of HRI in dogs under primary veterinary care during 2016 was 0.04% (95% CI 0.04-0.05%). There were no HRI events during February, October or December, while 40.51% (158/390) of the incident cases were in July (see Figure 5.4.1), corresponding with a heatwave event thought to have been triggered by a particularly strong El Nino (WMO, 2019).

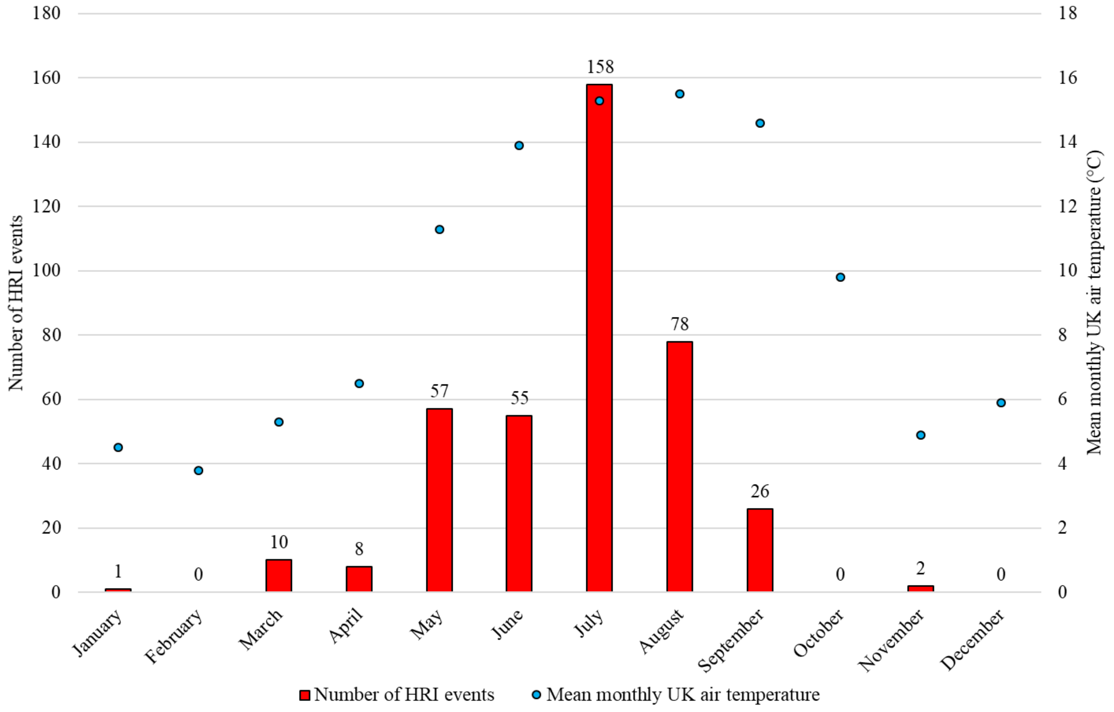

Figure 5.4.1. Heat-related illness cases by month for UK dogs under primary veterinary care at practices in the VetCompass Programme, against mean monthly UK air temperature for 2016.

Breeds with the highest incidence of HRI were the Chow Chow (0.50%, 95% CI 0.21-1.16%), Bulldog (0.42%, 95% CI 0.30-0.58%, French Bulldog (0.18%, 95% CI 0.12-0.25%), Dogue de Bordeaux (0.17%, 95% CI 0.07-0.39%), Greyhound (0.15%, 95% CI 0.07-0.29%) and Cavalier King Charles Spaniel (0.12%, 95% CI 0.08-0.18%) (Figure 5.4.2). The incidence risk of HRI in brachycephalic breeds overall was 0.08% (95% CI 0.07-0.09%) (Figure 5.4.3).

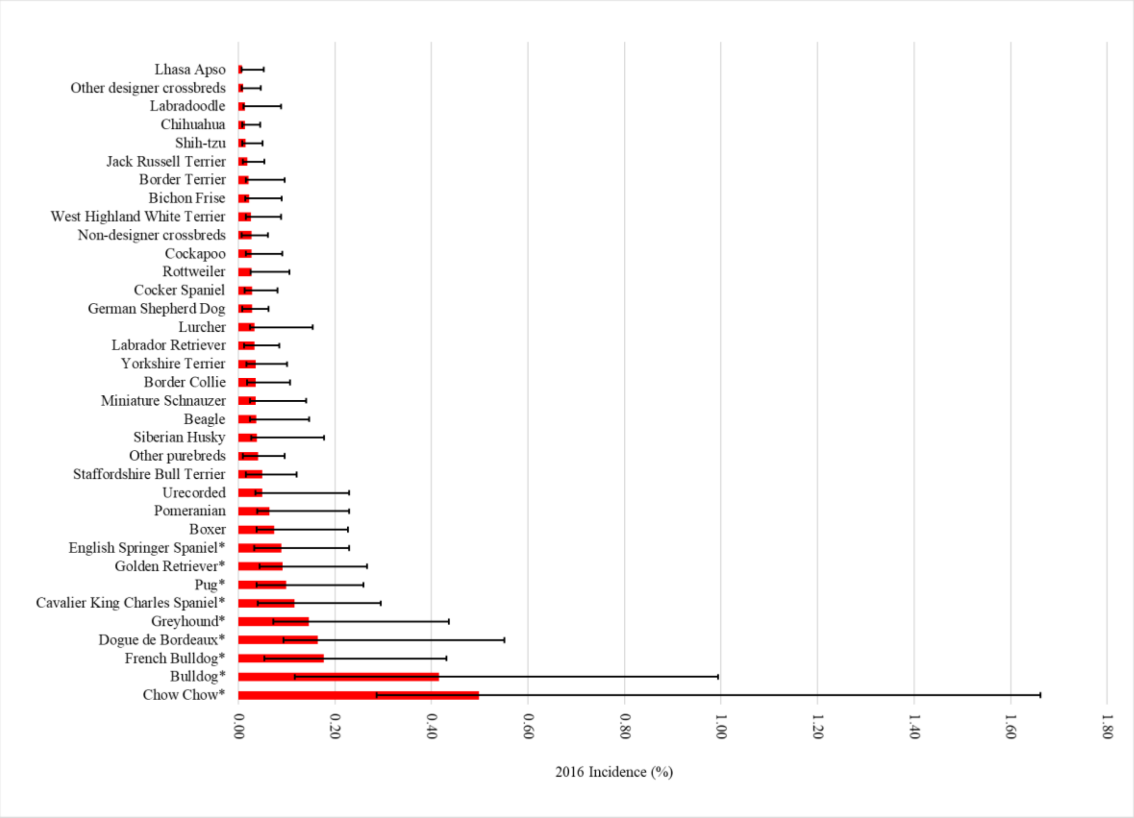

Figure 5.4.2. One-year (2016) incidence risk of heat related illness in dog breeds and designer crossbreeds under primary veterinary care at practices in the VetCompass Programme in the UK. The error bars show the 95% confidence interval. * Indicates breeds with increased odds compare with Labrador Retrievers, identified by multivariable regression analysis.

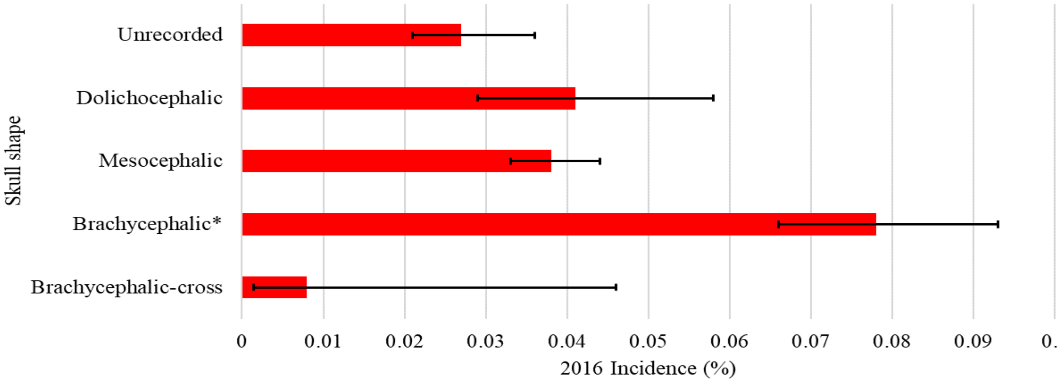

Figure 5.4.3. One-year (2016) incidence risk of heat related illness by *Skull shape* in dogs under primary veterinary care at practices in the VetCompass Programme in the UK. The error bars show the 95% confidence interval. * Indicates skull shapes with increased odds compared with mesocephalic dogs, identified by multivariable regression analysis.

Fatality

During the 2016 period, 56 of the 395 HRI events resulted in death of the dog. The manner of death was not recorded for two cases. Of the remaining 54 deaths, 35 (64.81%) were by euthanasia and 19 (35.19%) were unassisted deaths. The event fatality rate for HRI in dogs during 2016 was 14.18% (95% CI 11.08 – 17.96%).

Risk analysis

Univariable binary logistic regression modelling identified *breed type* (R^2 = 0.040, P<0.001), *purebred* (R^2 = 0.004, P<0.001), *skull shape* (R^2 = 0.009, P<0.001), *adult bodyweight* (R^2 = 0.006, P<0.001), *bodyweight relative to breed/sex mean* (R^2 = 0.002, P<0.001) and *age* (R^2 = 0.002, P = 0.063) as factors liberally associated with HRI, but not *sex/neuter* (R^2 = 0.001, P = 0.459) (see Supplementary note 2 for descriptive and univariable regression results).

The final breed multivariable model retained three risk factors: *breed type, bodyweight relative to breed/sex mean* and *age* (R^2 = 0.045, degrees of freedom = 43). The model showed acceptable discrimination (area under the ROC curve: 0.718). In the final model (Table 5.4.2), nine breeds (Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever) had higher odds of HRI compared to Labrador Retrievers. Crossbreds were not at significantly different odds compared to Labrador Retrievers (OR 0.82, 95% CI 0.49-1.37, p=0.450). No breed types had significantly reduced odds of HRI compared to Labrador Retrievers. Dogs with bodyweight equal to or greater than the relative breed/sex mean had higher odds of HRI (OR 1.42, 95% CI 1.12-1.80) compared to dogs weighing below the relative breed/sex mean. Dogs in the 2-<4 years, 6-<8 years and ≥12 years categories had greater odds compared to dogs <2 years old, dogs ≥12 years had the greatest odds of HRI (OR 1.75, 95% CI 1.14-2.70).

Table 5.4.2. Multivariable binary logistic regression results for risk factors associated with heat related illness in dogs under primary veterinary care in the VetCompass Programme in the UK during 2016.

Independent Variable	**Odds Ratio**	**95% CI**	**P-value**
Breed type			<0.001
Labrador Retriever	Base		
Chow Chow	16.61	6.21-44.44	<0.001
Bulldog	13.95	8.01-24.29	<0.001
French Bulldog	6.49	3.62-11.63	<0.001
Dogue de Bordeaux	5.31	1.99-14.21	0.001
Greyhound	4.26	1.88-9.70	0.001

Cavalier King Charles Spaniel	3.45	1.86-6.42	<0.001
Pug	3.24	1.67-6.29	<0.001
English Springer Spaniel	2.74	1.25-6.01	0.012
Golden Retriever	2.65	1.40-5.01	0.003
Boxer	2.26	0.95-5.34	0.064
Pomeranian	2.12	0.48-9.30	0.319
Missing	2.11	0.72-6.20	0.173
Staffordshire Bull Terrier	1.50	0.84-2.68	0.175
Other purebred	1.28	0.76-2.14	0.358
Siberian Husky	1.18	0.28-5.06	0.822
Beagle	1.15	0.34-3.86	0.827
Miniature Schnauzer	1.08	0.32-3.64	0.900
Border Collie	1.08	0.47-2.44	0.862
Yorkshire Terrier	1.05	0.49-2.25	0.898
Lurcher	1.00	0.24-4.30	0.996
German Shepherd Dog	0.92	0.35-2.48	0.874
Cocker Spaniel	0.88	0.35-2.20	0.788
Rottweiler	0.86	0.20-3.69	0.841
Cockapoo	0.85	0.39-1.87	0.686
Non-designer crossbred	0.82	0.49-1.37	0.450
West Highland White Terrier	0.76	0.28-2.02	0.581
Bichon Frise	0.68	0.20-2.27	0.525
Border Terrier	0.61	0.14-2.60	0.503
Jack Russell Terrier	0.55	0.25-1.21	0.135
Shih-tzu	0.47	0.18-1.24	0.127
Chihuahua	0.44	0.17-1.18	0.102
Labradoodle	0.41	0.06-3.06	0.384
Other designer crossbred	0.33	0.08-1.41	0.133
Lhasa Apso	0.24	0.03-1.76	0.159
Age			0.085
<2 years	Base		
2-<4 years	1.56	1.13-2.14	0.007
4-<6 years	1.41	0.99-2.02	0.058
6-<8 years	1.53	1.05-2.23	0.026
8-<10 years	1.21	0.79-1.86	0.374
10-<12 years	1.16	0.71-1.88	0.559
≥12 years	1.75	1.14-2.70	0.011
Unrecorded	0.70	0.22-2.26	0.552
Bodyweight relative to breed/sex mean			0.001
Below	Base		
At or above	1.42	1.12-1.80	0.004
Unrecorded	0.91	0.69-1.20	0.505

As described in the methods, variables collinear (*purebred*) and definitive of breed types (*bodyweight* and *skull shape*) replaced the *breed type* variable in the final multivariable model (Table 5.4.3). Purebred dogs had 1.86 times (95% CI 1.39-2.49) the odds of crossbred dogs.

Brachycephalic dogs had higher odds of HRI (OR 2.10, 95% CI 1.68-2.64) compared to mesocephalic dogs. Dogs over 50kg in bodyweight had 3.42 times the odds of HRI (95% CI 1.54-7.57) compared to dogs weighing under 10kg.

Table 5.4.3. Results for variables that individually replaced the *breed type* variable in the final multivariable logistic regression model (with *age* and *bodyweight relative to breed/sex mean*) to evaluate risk factors associated with heat related illness in dogs under primary veterinary care in the VetCompass Programme in the UK during 2016.

Variable	**Odds ratio**	**95% CI**	**P-value**
Skull shape			<0.001
Mesocephalic	Base		
Dolichocephalic	1.08	0.74-1.58	0.698
Brachycephalic-cross	0.22	0.03-1.56	0.129
Brachycephalic	2.10	1.68-2.64	<0.001
Unrecorded	0.73	0.53-0.99	0.039
Purebred			<0.001
Crossbred	Base		
Designer Cross	0.72	0.36-1.41	0.337
Purebred	1.86	1.39-2.49	<0.001
Unrecorded	2.41	0.57-10.16	0.233
Bodyweight (kg)			<0.001
<10	Base		
10-<20	1.82	1.31-2.53	<0.001
20-<30	2.13	1.51-3.02	<0.001
30-<40	1.74	1.14-2.65	0.010
40-<50	1.76	0.91-3.40	0.093
≥50	3.42	1.54-7.57	0.002
Unrecorded	0.65	0.16-2.70	0.553

5.5 Discussion

This is the largest primary-care study to report the incidence, risk factors and case fatality for HRI in dogs in the UK. The 0.04% 2016 incidence of HRI in dogs under primary veterinary care based on our real clinical records is considerably lower than the incidence predicted by an opinion survey of veterinary surgeons carried out during the same study period (2016) (BVA, 2017). This highlights the issue of recall bias when using surveys based on belief rather than documented reports of disorders, especially following exposure to media campaigns highlighting hazards that may promote a recency effect to encourage higher 'recall' (Neugebauer & Ng, 1990). That survey was conducted following the launch of the "Dogs die in hot cars" campaign (Duggal, 2018), which could explain the 'prompted' high numbers of cases reported by veterinary surgeons. It should also be noted that the survey included all veterinary surgeons, including those working in referral and out-of-hours emergency hospitals, which may also contribute to the high numbers of cases reported, whereby individual cases could be double, or triple counted.

The current study reports event fatality for HRI events at 14.18%. Our primary-care case fatality rate is lower than previous reports of 36–50% (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014). However, ours is the first study to include all stages of HRI presentation, including early stages which may be managed without hospitalisation, while previous studies tended to include only the more severely affected subset of dogs defined as having "heatstroke" or advanced heat related illness presenting to referral hospitals. This is the first study to use a primary veterinary care population rather than a referral population, highlighting the limitations of using referral populations to estimate incidence and fatality at a population level (Bartlett et al., 2010). The relatively low fatality rate reported in the current study could also reflect the temperate UK climate. As previous studies have primarily been conducted in countries with hotter climates such as Israel (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014), the comparatively higher fatality rates reported in hotter countries should serve as a warning for the UK. As climate change accelerates both the frequency and severity of heat waves (Mora et al., 2017), the incidence and fatality rate of HRI is likely to increase in dogs (House of Commons Environmental Audit Committee, 2018). In the current study, 40.51% of the incident cases were in July, corresponding to a European heatwave. This 2016 July heatwave was attributed to the El Nino effect and was previously the hottest July on record (WMO, 2019). This record has since been broken; July 2019 is currently the hottest on record without the contribution of a particularly strong El Nino effect, highlighting the impact global warming is having on extreme temperature events (WMO, 2019). The number of days per year with extreme heat in Europe have tripled in the last two decades, prompting concerns that global warming is accelerating even more rapidly than predicted (Lorenz et al., 2019).

Compared to Labrador Retrievers in the final multivariable model, nine breeds had significantly higher odds of HRI: Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever. These findings agree with previous studies that reported increased HRI risk to brachycephalic breed types in general (Segev et al., 2015), Bulldogs (Bruchim et al., 2006; Drobatz & Macintire, 1996) and Golden Retrievers (Bruchim et al., 2006). The increased odds ratios for these breeds in the multivariable compared to the univariable models highlights the importance of undertaking multivariable analysis when investigating breed related risk studies (Dohoo et al., 2009). As well as some extremely brachycephalic breeds (Bulldog and French Bulldog), we also identified increased risk in some mesocephalic breeds. The Golden Retriever had 2.67 times the odds compared to the Labrador Retriever despite being of similar size, temperament, and purpose. The Golden Retriever does, however, have a thicker coat than the Labrador which may be the tipping factor for HRI between these two breeds. The Chow Chow, another breed with a very thick coat, had the greatest risk of HRI of all the study breeds (OR = 16.17), although it must be noted the confidence interval for this breed is very wide due to the relatively small sample size. Coat type is potentially an important risk factor for HRI in dogs, but may instead be a complicating factor for dogs with a behavioural or anatomical (e.g., brachycephaly) predisposition to overheating. Other double coated breeds may also have increased risk; however, the current study was under-powered to fully explore these pre-dispositions due to low numbers of these breeds.

The Labrador Retriever has previously been reported with increased risk of HRI (Bruchim et al., 2006), although that study included both Labrador and Golden Retrievers as a single breed and therefore the increased risk may have come from the subset of these dogs that were Golden Retrievers (Bruchim et al., 2006). The current study elected to use the Labrador Retriever as the comparator breed instead of crossbred for similar reasons to those suggested by Erlen et al. (2018). Crossbred dogs show a high level of variability in genetics, bodyweight, skull shape and conformation compared to a single specified purebred breed (Mellanby et al., 2013). This high variability challenges the utility of crossbreds as a standard comparator breed. Second only to crossbreds, the Labrador Retriever was the most common breed in the current study, comprising 6.6% of the total study population and enabling high statistical power to explore breed related risk (Dohoo et al., 2009). In the current study, the odds of HRI were not significantly different between Labrador Retrievers and crossbred dogs.

It has been suggested that racing Greyhounds rarely exhibit HRI (S. W. Flournoy et al., 2003) but our results showed pet Greyhounds to have 4.26 times the odds of HRI when compared to the Labrador Retriever. As a dolichocephalic breed they are not commonly associated with obesity (O’Neill, Rooney, et al., 2019), however they tend to have a high lean muscle mass which has been associated with increased risk of post exercise hyperthermia (McNicholl et al., 2016). Further research is required to explore the underlying reason for this result, but a recent study found “collapse” to be the second most common cause of death in Greyhounds, specifically in animals over 12 years old (O’Neill, Rooney, et al., 2019). A degenerative cardiovascular or respiratory disorder (such as laryngeal paralysis) could potentially promote their increased risk of HRI.

This study included three grouped breed-type variables (other purebred, other designer crossbred and crossbred) and 32 individual breeds and designer hybrid breed types, because breed was a factor of primary interest. Including this many breed-type variables increased the degrees of freedom in the regression model, negatively impacting the statistical power. However, it is important to include as many popular breeds as possible in risk analysis studies to enable identification of breed predispositions to disorders, but also to identify breeds with apparent resistance or protection from disorders. HRI is a disorder that requires extrinsic input; dogs do not develop HRI due an underlying intrinsic factor (unlike osteoarthritis or cancer) and non-disease is the natural internal state. To develop HRI dogs, must be exposed to either a hot environment and/or an activity that induces significant hyperthermia. In support of this theory, there were no individual breed types identified with significantly reduced risk of HRI compared to the Labrador Retriever in this study. The canine risk factor model presented in this study should be considered exploratory, identifying canine features than increase a dog's risk of HRI, rather than predictive. A predictive HRI model would need to include additional non-canine variables such as ambient temperature, humidity, activity levels, fitness and hydration (Carter & Hall, 2018).

This study supports assertions that brachycephaly is associated with increased risk of HRI in dogs. Five of the nine breeds with significantly increased odds of HRI were brachycephalic (Bulldog, French Bulldog, Dogue de Bordeaux, Cavalier King Charles Spaniel and Pug). Compared to mesocephalic dogs in multivariable modelling, brachycephalic dogs had 2.10 times the odds of HRI, with no significant difference in HRI odds between dolichocephalic and mesocephalic dogs. Interestingly, brachycephalic crosses had the lowest incidence of HRI across all skull types including unrecorded (including predominantly crossbred dogs) (see Figure 2). They did not however, have a significantly reduced odds ratio of HRI at multivariable level. This could potentially be due to this group of dogs being comparatively young compared to the rest of the population (O'Neill, Baral, et al., 2018), but could also be attributed to the typically lower bodyweight of designer crossbreds. The mean designer cross bodyweight in this study was 15.6kg, compared to the mean purebred bodyweight of 17.5kg, and mean crossbred bodyweight of 17.4kg. This finding could lend support to the argument for outbreeding to increase muzzle length within extreme brachycephalic breeds to improve the health and welfare of dogs (Ladlow et al., 2018) but requires further research.

Dogs at or above the mean adult bodyweight for their breed/sex showed increased risk of HRI compared to dogs below the mean bodyweight in multivariable analysis. Increased HRI risk in heavier individuals within breeds agrees with findings from previous studies exploring post-race body temperature in Greyhounds; dogs with a greater lean body mass were significantly hotter post-race than lighter dogs (McNicholl et al., 2016). It was not possible to determine whether elevated bodyweight within breed was due to obesity, conformation differences or increased muscle mass in this study as body condition scores were not available from the EPRs. There are several different scales used for measuring body condition score in dogs, meaning it is not possible to make direct comparisons between clinical records when a single unit is used to record a dog's score. As highlighted in a report by Ward et al.(Ward et al., 2018), adopting a single universal score for body condition score in dogs should be considered a key priority for veterinary professionals and canine welfare organisations to allow consistent measurement, recording and monitoring of body composition in dogs.

Dogs weighing over 50kg in absolute bodyweight had the highest odds of HRI, and all bodyweight groups over 10kg had significantly higher odds for HRI than dogs weighing under 10kg. Smaller dogs have a high heat storage to radiative surface area ratio that results in more rapid heat loss compared to larger dogs, meaning they can exercise for longer before overheating (Phillips et al., 1981; Young et al., 1959). This increased efficiency in radiative heat loss could explain why the purebred breeds with the lowest odds of HRI are all small breed dogs (Table 2). Of the breeds analysed, the Lhasa Apso, Shih tzu and Chihuahua had the lowest odds of HRI despite all being brachycephalic breeds. These breeds all typically weigh under 10kg. In comparison, French bulldogs and Cavalier King Charles Spaniels typically weigh over 10kg (O'Neill, Baral, et al., 2018; Summers et al., 2015), whilst Pugs typically weigh around 10kg (O'Neill et al., 2016); the HRI odds for these three breeds appears to be proportional to their typical bodyweights.

Reflecting the findings of Drobatz and Macintire (1996), purebred dogs showed increased risk of HRI compared to crossbred dogs in the current study. Purebred dogs are more likely to have exaggerated features such as thick coats, extreme body size and skull shapes (Hemmelgarn & Gannon, 2013b), all of which were predicted, and subsequently appear to, impact HRI risk. In comparison, wild dogs such as the African Hunting dog, have been shown to tolerate higher core body temperatures than domestic dogs during exercise in hot climates (41°C), and lose a greater proportion of the heat generated through non-evaporative mechanisms effectively conserving water (Taylor et al., 1971).

In the final multivariable model, dogs ≥12 years old had the greatest odds of HRI compared to dogs <2 years old, reflecting the human literature which reports an increased HRI risk to humans of advanced age or with chronic medical conditions (Lewis, 2007). Dogs with pre-existing medical conditions were excluded from previous heatstroke studies (Bruchim et al., 2006; Drobatz & Macintire, 1996; Yamamoto et al., 2018). Older dogs are more likely to be affected by age related conditions such as respiratory or cardiovascular disease, therefore elderly dogs were potentially absent from the previous study populations and subsequent analysis. Old age in humans is associated with increased HRI risk, due to a decreased physiological ability to dissipate heat (notably changes in sweat production and decreased skin blood flow) (Balmain et al., 2018). Further studies should explore the effect of age on canine thermoregulatory ability.

Despite previous studies suggesting male dogs have increased risk of HRI (Carter & Hall, 2018; McNicholl et al., 2016), there was no significant difference in odds for HRI between males and females, or between neutered and entire dogs shown in the current study. Previous HRI studies have reported mixed findings for sex as a risk factor in dogs, varying from no reported difference (Aroch et al., 2009; Bruchim et al., 2006) to male overrepresentation (Segev et al., 2015, 2018; Teichmann et al., 2014). As this is the first study to include multivariable analysis for HRI risk factors in dogs, it is possible that including relative bodyweight in the analysis accounted for the possible confounding effect of increased bodyweight in males.

Alongside the environmental threat to canine health and welfare, the canine population itself is becoming less heat tolerant as proportional obesity (German et al., 2018) and brachycephalism increase (O'Neill et al., 2016; O'Neill, Baral, et al., 2018; O'Neill, Skipper, et al., 2019). The current study found that brachycephalic breeds comprised 18.42% of the total primary-care population in 2016 and the KC reported that the French Bulldog became the most commonly registered pedigree breed in 2018(The Kennel Club, 2018). Increasing popularity of brachycephalic breeds coupled with the increasing frequency of heatwave events poses a significant welfare concern for the modern dog population and is likely to result in increasing incidence of HRI over the coming years.

A recent survey of brachycephalic dog owners found over a third reported that their dog had a problem with heat regulation (Packer et al., 2019). The survey did not differentiate simple overheating from overheating leading to HRI, but nonetheless identified heat regulation as the most common problem perceived by brachycephalic owners (Packer et al., 2019). The comparably lower incidence of HRI reported in this study compared to the owner reports of overheating in the survey conducted by Packer et al. (2019) could be due to several possibilities. Owners of brachycephalic dogs may normalise heat related issues in these breeds and therefore not perceive overheating to be of sufficient concern to either report events or seek treatment from their veterinary surgeon. Similarly, veterinary surgeons may normalise these findings such that they do not consider these events significant enough to warrant recording in the dog's clinical notes. Alternatively, owners of brachycephalic dogs may be more aware of their dog's risk of overheating and take deliberate actions to prevent occurrence, thus preventing their dogs developing severe HRI. Overall, it is probable that the true incidence of HRI in UK dogs, particularly brachycephalics, is likely to be higher than estimated in this current study.

There were some limitations to the study. The study used manual stepwise elimination to select the final breed model, despite mounting opposition to this method of model selection (Antonakis & Dietz, 2011; Burnham & Anderson, 2002; Shtatland et al., 2001). Whilst the automated stepwise method fails to take into account prior knowledge and risks artificially elevating R2 values, this study included consideration of biological plausibility when selecting the final model variables and aimed to produce an explanatory model, rather than a predictive model.

As noted in a previous study, the data used in this study were not recorded for research purposes meaning there are likely to be missing data within the dataset (Conroy et al., 2019; O'Neill, Corah, et al., 2018). Additionally, the inclusion criteria for an HRI case relied upon the accuracy and completeness of the clinical notes associated with the event. As dogs with HRI typically present as an emergency, clinical notes may be less accurately recorded at the time of treatment meaning false negatives are more likely (Radford et al., 2011). The lack of a definitive diagnostic test for HRI meant that by necessity, the inclusion and exclusion criteria for an HRI case could have resulted in some dogs being mis-identified. Thus, for cases where owner treatment preference or finances prevented further diagnostic testing to rule out other non-HRI causes of hyperthermia, these cases could have been misidentified as HRI cases. The study population comprised only dogs under the care of primary veterinary practices, many of which do not offer a full 24-hour emergency service. Whilst it is likely that some cases presented to dedicated out of hours emergency practices which were not included in this study, most out of hours practices send clinical notes on to the patient's first opinion practice so most would still have been included in this study. Additionally, HRI often follows failure of the dog owner to appreciate the risk of a hot environment or of undertaking extreme exercise to the dog, meaning there could often be elements of owner guilt associated with the condition. This may reduce the willingness of an owner to declare the true reason for the dog's illness or death. As previously noted, overheating may be perceived by owners of some breeds as normal or may be managed by the owner, meaning HRI events are not reported or presented to the dog's primary care practice. These limitations combined with the lack of a definitive diagnostic test or definition for HRI suggest that the true incidence of HRI may be much higher than reported in this study.

The current study defined specific breeds by skull morphology as described in the methods and supplementary material. Although the breeds assigned to each skull type category could reasonably be challenged, changing the specific breeds listed in each category is unlikely to change the overall inferences drawn from the analysis (O'Neill et al., 2017). The traditional definitions used to describe canine skull shape with three categories from dolichocephalic to brachycephalic is potentially oversimplified, and the newer cephalic index systems derived from various skull width to length ratios may be more accurate (Georgevsky et al., 2013). However, the variability in cephalic index between individuals of the same breed and between sexes (Carrasco et al., 2014; Georgevsky et al., 2013), and the limited widescale measurement of cephalic index in large numbers of different breeds means it was not possible to use this measurement in place of the traditional skull morphology definitions for the current study. Whilst coat type has been noted as another possible risk factor for HRI in dogs, it was not possible to accurately retrieve coat type for individual dogs from the EPRs in this study, as this is not a characteristic commonly recorded by veterinary practice management software and can often vary widely within individual breeds.

Finally, the current study population included only dogs under care of a primary veterinary practice during the study period of 2016. It was therefore not possible to include HRI events prior to, or after 2016 in the risk factor analysis as this would introduce selection bias because fatal HRI events prior to 2016 would be excluded, and dogs born after 2016 would be excluded from events post 2016. This limited the number of HRI cases for analysis and prevented any investigation into changes in HRI incidence over time. These could be considered as research topics for a future study.

5.6 Conclusions

Extreme heat events are predicted to increase in both frequency and severity, with deaths due to HRI in humans predicted to triple by 2050 (House of Commons Environmental Audit Committee, 2018). This is the first study to explore HRI in a large population of dogs under primary veterinary care and the canine risk factors identified suggest that similar risk factors for HRI apply for both humans and dogs. This study found that increased bodyweight (relative to breed), brachycephaly and age significantly increased the risk of HRI and identified nine breeds at significantly increased risk. Maintaining healthy bodyweight should be considered an important management tool for limiting HRI risk, therefore routine recording of patient body condition score should be highlighted as a key strategy for enabling the monitoring and subsequent management of canine obesity. Prevention is an incredibly important strategy for limiting the welfare implications and mortality caused by HRI in both man and dog. The results of this study can assist veterinary practitioners, breeders and owners in identifying dogs and breeds at greater risk of HRI and therefore with implementation of strategies to reduce the risks of HRI in dogs.

Declarations

Ethics approval: Ethics approval was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652).

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Authors' contributions

All authors (EH, AC and DON) made substantial contributions to the conception and design of the study, acquisition and extraction of data from the VetCompass Programme database, and to analysis and interpretation of the results. All authors (EH, AC and DON) were involved in drafting and revising the manuscript and gave final approval of the version to be published. Each author agrees to be accountable for all aspects of the accuracy or integrity of the work.

Competing interests: The authors have no conflicts of interest to declare.

Data availability: The datasets supporting the current study are publicly available on the RVC data repository: http://researchonline.rvc.ac.uk/id/eprint/12379/.

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5.8 Supplementary Material

Supplementary Note 1: Breed types by skull shape.

All other named breed-types were classified as mesocephalic.

All crossbred, designer crossbred or dogs with no listed breed were classified as *unknown* skull shape.

Table 5.8.1. Breed types defined as brachycephalic skull shape.

Brachycephalic breed types		
Affenpinscher	Cavalier King Charles Spaniel	Miniature Bulldog
Alapaha Blue Blood Bulldog	Chihuahua	Miniture Shih-Tzu
American Bandogge Mastiff	Dogue de Bordeaux	Neopolitan Mastiff
American Bulldog	Dorset Olde Tyme Bulldogge	Old English Mastiff
American Lo-Sze Pugg	English Mastiff	Olde Boston Bulldogge
American Pocket Bully	French Bulldog	Olde English Bulldogge
Australian Bulldog	German Boxer	Olde Victorian Bulldogge
Aylestone Bulldog	Griffon	Pekingese
Boston Terrier	Griffon Bruxellois	Pug
Boxer	Italian Mastiff	Shih-tzu
Bull Boxer	Japanese Chin	Spanish Bulldog
Bull Mastiff	King Charles Spaniel	Valley Bulldog
Bulldog	Lhasa Apso	Victorian Bulldog
Catahoula Bulldog	Mastiff	

Table 5.8.2. Breed types defined as brachycephalic designer-cross skull shape

Brachycephalic-cross breed types		
American Lamalese	Chiweenie	Pugalier
Beaglier	Chug	Puganese
Boxador	Cockalier	Pugapoo
Boxoodle	Jackachi	Puggle
Bug	Jackashit	Pugland
Bullador	Jug	Pugpom
Cavachi	La-Chon	PugTzu
Cavachon	Lha-Cocker	Sharanian
Cavadoodle	Lhasalier	Sharpador
Cavador	Lhasapoo	ShiChi
Cavajack	Malshi	Shichon
Cavapom	Maltalier	Shih-Poo
Cavapoo	Pekepoo	Shiranian
Cavapoochon	Pomapug	Shorkie
Cavatzu	Pomchi	Shug
Chichon	Pooshit	
Chi-Poo	Pugador	

Table 5.8.3. Breed types defined as dolichocephalic skull shape.

Dolichocephalic breed types		
Afghan Hound	Dachsbracke	Miniature Pinscher
Airedale Terrier	Dachshund	Miniature Poodle
American Bull Terrier	Dashapoo	Peruvian Hairless
American White Shepherd Dog	Dutch Sheepdog	Petit Basset Griffon Vendeen
Andalusian Mouse-Hunting Dog	Dutch Shepherd Dog	Pharaoh Hound
Anglos-Francaises de Petite Venerie	English Bull Terrier	Pinscher
Ariege Pointer	English Greyhound	Podenco
Australian Kelpie	English Terrier	Podenco Canario
Azawakh Hound	Fox Terrier	Poodle
Basset Griffon Vendeen	French Basset	Portuguese Podengo
Basset Hound	German Guard Dog	Saarloos Wolfhound
Bavarian Mountain Hound	German Pinscher	Saluki
Beauce Shepherd Dog	German Shepherd Dog	Scottish Collie
Bedlington Terrier	German Shepherd Dog - White	Scottish Deerhound
Belgian Groenendael Shepherd Dog	Grand Basset Griffon Vendeen	Scottish Rough Collie
Belgian Laekenois Shepherd Dog	Grand Griffon Bleu de Gascogne	Scottish Smooth Collie
Belgian Malinois Shepherd Dog	Grand Griffon Vendeen	Scottish Terrier
Belgian Shepherd	Great Dane	Shetland Sheepdog
Belgian Short-Haired Pointer	Greyhound	Sloughi
Belgian Tervuren Shepherd Dog	Ibizan Hound	Smooth Fox Terrier
Black and Tan Coonhound	Irish Terrier	Spanish Greyhound
Bleu de Gascogne Basset	Irish Wolfhound	Spanish Hound
Bloodhound	Italian Greyhound	Spanish Podenco
Bluetick Coonhound	Italian Hound	Standard Doberman Pinscher
Borzoi	Italian Shepherd Dog	Standard Poodle
Bracco Italiano	Kerry Blue Terrier	Swiss White Shepherd Dog
Braque Francais	King Shepherd Dog	Teacup Poodle
British Wolfdog	Lakeland Terrier	Teckel Dachshund
Bruno Jura Hound	Lurcher	Toy Fox Terrier
Bull Terrier	Manchester Terrier	Toy Manchester Terrier
Carlin Pinscher	Mexican Hairless - Intermediate	Toy Poodle
Carpathian Sheepdog	Miniature Bull Terrier	Trail Hound
Chippiparai	Miniature Coloured Bull Terrier	Welsh Terrier
Cirneco Dell 'Etna	Miniature Dachshund	Whippet
Coonhound	Miniature Doberman Pinscher	Wire-Haired Fox Terrier
Croatian Sheepdog	Miniature English Bull Terrier	Wolfhound
Czesky Terrier	Miniature Fox Terrier	Yugoslavian Shepherd Dog

Supplementary note 2: Univariable and descriptive statistics for potential risk factors.

Table 5.8.4. Descriptive and univariable logistic regression results for breed type associated with heat related illness in dogs under primary veterinary care in the VetCompass™ Programme in the UK during 2016.

Independent variable	Case No. (%)	Non-case No. (%)	Odds ratio	95% CI	P-value
Breed type					<0.001
Labrador Retriever	20 (5.13)	59,943 (6.62)	Base		
Chow	5 (1.28)	997 (0.11)	15.03	5.63-40.13	<0.001
Bulldog	35 (8.97)	8375 (0.93)	12.53	7.23-21.71	<0.001
French Bulldog	29 (7.44)	16,368 (1.81)	5.31	3.00-9.39	<0.001
Dogue de Bordeaux	5 (1.28)	3027 (0.33)	4.95	1.86-13.20	0.001
Greyhound	8 (2.05)	5448 (0.60)	4.40	1.94-10.00	<0.001
Cavalier King Charles Spaniel	20 (5.13)	17,237 (1.90)	3.48	1.87-6.47	<0.001
Pug	16 (4.10)	16,198 (1.79)	2.96	1.53-5.71	0.001
English Springer Spaniel	18 (4.62)	20,190 (2.23)	2.76	1.26-6.06	0.012
Golden Retriever	9 (2.31)	9784 (1.08)	2.67	1.41-5.05	0.002
Boxer	7 (1.79)	9435 (1.04)	2.22	0.94-5.26	0.069
Pomeranian	4 (1.03)	6217 (0.69)	1.93	0.66-5.64	0.231
Missing	2 (0.51)	4054 (0.45)	1.48	0.35-6.33	0.598
Staffordshire Bull Terrier	26 (6.67)	53,029 (5.86)	1.47	0.82-2.63	0.196
Other purebred	51 (13.08)	123,018 (13.59)	1.24	0.74-2.08	0.411
Siberian Husky	2 (0.51)	5239 (0.58)	1.14	0.27-4.90	0.856
Beagle	3 (0.77)	8067 (0.89)	1.12	0.33-3.75	0.861
Miniature Schnauzer	3 (0.77)	8393 (0.93)	1.07	0.32-3.61	0.911
Border Collie	8 (2.05)	22,396 (2.47)	1.07	0.47-2.43	0.870
Yorkshire Terrier	10 (2.56)	28,169 (3.11)	1.06	0.50-2.27	0.873
Lurcher	2 (0.51)	6020 (0.67)	1.00	0.23-4.26	0.995
German Shepherd Dog	6 (1.54)	21,334 (2.36)	0.84	0.34-2.10	0.714
Cocker Spaniel	9 (2.31)	32,136 (3.55)	0.84	0.38-1.84	0.663
Rottweiler	2 (0.51)	7283 (0.80)	0.82	0.19-3.52	0.793
Cockapoo	5 (1.28)	18,247 (2.02)	0.82	0.31-2.19	0.694
Non-designer Crossbred	52 (13.33)	193,878 (21.42)	0.80	0.48-1.35	0.407
West Highland White Terrier	5 (1.28)	18,873 (2.09)	0.79	0.30-2.12	0.645
Bichon Frise	3 (0.77)	13,265 (1.47)	0.68	0.20-2.28	0.530
Border Terrier	2 (0.51)	9649 (1.07)	0.62	0.15-2.66	0.521
Jack Russell Terrier	9 (2.31)	48,426 (5.35)	0.56	0.25-1.22	0.145
Shih-tzu	5 (1.28)	32,905 (3.64)	0.46	0.17-1.21	0.116
Chihuahua	5 (1.28)	37,253 (4.12)	0.40	0.15-1.07	0.069
Labradoodle	1 (0.26)	7484 (0.83)	0.40	0.05-2.98	0.372
Other designer crossbred	2 (0.51)	20,268 (2.24)	0.30	0.07-1.27	0.100
Lhasa Apso	1 (0.26)	12,548 (1.39)	0.24	0.03-1.78	0.162

Table 5.8.5. Descriptive and univariable logistic regression results for risk factors associated with heat related illness in dogs under primary veterinary care in the VetCompass^{TM} Programme in the UK during 2016.

Independent Variable	Case No. (%)	Non-case No. (%)	Odds ratio	95% CI	P-value
Purebred					< 0.001
Non-designer Crossbred	52 (13.33)	193,878 (21.42)	Base		
Designer Crossbred	10 (2.56)	52,019 (5.75)	0.72	0.37-1.41	0.335
Purebred	326 (83.59)	655,202 (72.39)	1.86	1.38-2.49	<0.001
Unrecorded	2 (0.51)	4054 (0.45)	1.84	0.45-7.55	0.398
Skull shape					< 0.001
Mesocephalic	173 (44.36)	452,295 (49.97)	Base		
Dolicocephalic	31 (7.95)	75,817 (8.38)	1.07	0.73-1.57	0.732
Brachycephalic-cross	1 (0.26)	12,337 (1.36)	0.21	0.03-1.51	0.122
Brachycephalic	131 (33.59)	166,772 (18.42)	2.05	1.64-2.58	< 0.001
Unknown	54 (13.85)	197,932 (21.86)	0.71	0.53-0.97	0.03
Adult bodyweight (kg)					< 0.001
<10	61 (15.64)	213,291 (23.56)	Base		
10-<20	90 (23.08)	167,689 (18.53)	1.88	1.36-2.60	< 0.001
20-<30	76 (19.49)	117,605 (12.99)	2.26	1.61-3.17	< 0.001
30-<40	37 (9.49)	69,895 (7.72)	1.85	1.23-2.79	0.003
40-<50	11 (2.82)	19,848 (2.19)	1.94	1.02-3.68	0.043
≥50	7 (1.79)	6391 (0.71)	3.83	1.75-8.38	0.001
Unrecorded	108 (27.69)	310,434 (34.3)	1.22	0.89-1.67	0.221
Bodyweight relative to breed/sex mean					< 0.001
Lower	124 (31.79)	317,225 (35.05)	Base		
Equal/Higher	156 (40.00)	275,357 (30.42)	1.45	1.15-1.84	0.002
Unrecorded	110 (28.21)	312,571 (34.53)	0.90	0.70-1.16	0.423
Sex/neuter					0.459
Female-entire	93 (23.85)	233,734 (25.82)	Base		
Female-neutered	89 (22.82)	197,792 (21.85)	1.13	0.85-1.51	0.407
Male-entire	117 (30.00)	259,405 (28.66)	1.13	0.86-1.49	0.367
Male-neutered	91 (23.33)	209,993 (23.20)	1.09	0.82-1.45	0.563
Unrecorded	0 (0.00)	4227 (0.47)	~	~	~
Age					0.063
<2 years	78 (20.00)	234,364 (25.89)	Base		
2-<4 years	94 (24.10)	178,135 (19.68)	1.59	1.17-2.14	0.003
4-<6 years	65 (16.67)	139,916 (15.46)	1.40	1.00-1.94	0.047
6-<8 years	56 (14.36)	113,325 (12.52)	1.49	1.05-2.09	0.024
8-<10 years	36 (9.23)	90,982 (10.05)	1.19	0.80-1.77	0.391
10-<12 years	24 (6.15)	66,241 (7.32)	1.09	0.69-1.72	0.716
≥12 years	34 (8.72)	69,769 (7.71)	1.46	0.98-2.19	0.064
Unrecorded	3 (0.77)	12,421 (1.37)	0.73	0.23-2.30	0.586

Chapter Six: Dogs don't die just in hot cars—exertional heat-related illness (heatstroke) is a greater threat to UK dogs

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6.1 Simple summary and abstract

Simple Summary: Heat-related illness (often called heatstroke) is a potentially fatal condition inflicted on dogs that will become more common as global temperatures rise. Understanding why dogs develop heatstroke can help to refine prevention strategies through owner education and societal changes. This study aimed to determine the most common triggers of heat-related illness in UK dogs, and which types of dogs were at most risk. We reviewed the veterinary records of over 900,000 dogs and identified that exercise was the most common trigger of heat-related illness in dogs. We also found that heatstroke caused by exercise was just as likely to kill as heatstroke from a hot car. Male dogs and younger dogs were more likely to develop heat-related illnesses triggered by exercise. Older dogs and flat-faced dogs were at greater risk of developing heat-related illness just by sitting outside in hot weather. Any dog can develop heatstroke if left in a hot car, but flat-faced breeds were particularly at risk. As the world gets hotter, we need to include our canine companions in our strategies to stay cool, as they can suffer fatal consequences when we fail to keep them safe.

Abstract: Heat-related illness will affect increasing numbers of dogs as global temperatures rise unless effective mitigation strategies are implemented. This study aimed to identify the key triggers of heat-related illness in dogs and investigate canine risk factors for the most common triggers in UK dogs. Using the VetCompass™ programme, de-identified electronic patient records of 905,543 dogs under primary veterinary care in 2016 were reviewed to identify 1259 heat-related illness events from 1222 dogs. Exertional heat-related illness was the predominant trigger (74.2% of events), followed by environmental (12.9%) and vehicular confinement (5.2%). Canine and human risk factors appear similar; young male dogs had greater odds of exertional heat-related illness, older dogs and dogs with respiratory

compromise had the greatest odds of environmental heat-related illness. Brachycephalic dogs had greater odds of all three types of heat-related illness compared with mesocephalic dogs. The odds of death following vehicular heat-related illness (OR 1.47, p = 0.492) was similar to that of exertional heat-related illness. In the UK, exertional heat-related illness affects more dogs, and kills more dogs, than confinement in a hot vehicle. Campaigns to raise public awareness about heat-related illness in dogs need to highlight that dogs don't die just in hot cars.

6.2 Introduction

Heat-related illness (HRI) is a potentially fatal disorder affecting man and animals, and is predicted to become more frequent as climate change increases both the severity and regularity of heatwave events (Macintyre et al., 2018). As mean annual temperatures continue to rise, human populations need to consider mitigation strategies to survive, potentially including migration away from the hottest regions (Xu et al., 2020) or adaptations to heat including air cooling mechanisms and changes to working practices to reduce the risk of HRI to outdoor workers (Kjellstrom et al., 2016). Domestic dogs intertwine with every aspect of human society, from providing simple companionship to fulfilling essential working services such as hearing and visual assistant dogs, medical detection dogs and military working dogs (Hoffman et al., 2018). A deeper understanding of the risk factors for canine HRI is therefore urgently needed to ensure adaptations to rising global temperatures can include consideration of canine companions and colleagues.

From a pathophysiological perspective, HRI can be defined as hyperthermia causing progressive systemic inflammation and multi-organ dysfunction, resulting in neurological derangements and potentially death (Bouchama & Knochel, 2002). However, this gives little information on the underlying causes of the clinical event and, more importantly, offers little information to help prevent these HRI events in the first place. From a causal perspective, two main triggers are described for HRI in humans: exertional and environmental (Bouchama & Knochel, 2002). Exertional HRI typically follows exercise or physical labour in a hot environment or prolonged strenuous exercise in environments of any temperature (Bouchama & Knochel, 2002; Johnson et al., 2006). Environmental HRI, also referred to as classic or non-exertional HRI, typically follows prolonged exposure to high ambient temperatures or shorter exposure to extreme heat (Rogers et al., 2007). Very young children and babies are similar to dogs in that they are generally not agents of their own liberty from confinement (Duzinski et al., 2014). Very young children and babies are also at risk of vehicular HRI (a subtype of environmental HRI) following confinement in a hot vehicle after being left unattended or after accidentally locking themselves inside the vehicle (Duzinski et al., 2014). In human medicine, exertional HRI most commonly affects young active males either working in physically demanding industries such as construction, or participating in sports (Armstrong et al., 2007). Exertional HRI is the third leading cause of death in US high school athletes, and the incidence of HRI in the US Armed Forces has been gradually increasing since 2014 (Rogers et al., 2007). Conversely, environmental HRI is known to typically affect socially vulnerable patients, those with advanced age or chronic medical conditions, who may be confined indoors and less resilient to natural hazards such as heatwaves (Gaudio & Grissom, 2016; Lewis, 2007).

Canine patients are likely to share similar risk factors to humans for the various types of HRI, but there is limited published evidence in the canine literature. Older dogs are more likely to suffer from underlying health conditions that impact thermoregulation such as heart disease (Mattin et al., 2015), which could increase the likelihood of environmental HRI (Kuzuya, 2013). Respiratory diseases such as brachycephalic obstructive airway disorder (BOAS) have been shown to accelerate the increase in body temperature during exercise (Lilja-Maula et al., 2017) and brachycephalic dogs have intrinsically greater odds of developing HRI compared to dogs with longer muzzle (Hall et al., 2020a). Heat regulation problems are reported to affect around a third of brachycephalic dogs (Packer et al., 2019) and obesity has been reported as a significant risk factor for death in dogs presenting with HRI (Bruchim et al., 2006). Reflecting the male predisposition to exertional HRI in humans, male dogs develop a significantly higher body temperature than females during intense exercise (Carter & Hall, 2018; McNicholl et al., 2016). Both dogs trained for military work (e.g., Belgian Malinois) and active playful dogs (e.g., Golden Retriever and Labrador Retriever) have been reported to be at increased risk of exertional HRI (Bruchim et al., 2006), however, that study included only patients referred for specialist care and therefore may not represent the wider canine population. A larger primary-care study reported the Chow Chow and Bulldog with the greatest odds of HRI highlighting the value of primary-care focused research for generalization to the wider companion animal population (Bartlett et al., 2010).

Because the veterinary diagnosis of HRI is heavily dependent upon an accurate history of the events leading up to the animal’s presentation (Bruchim, Horowitz, et al., 2017), greater awareness of the specific risk factors for HRI in dogs could support earlier recognition, diagnosis and appropriate management. However, prevention remains the most important approach to limiting the welfare burden of HRI overall, (Yamamoto et al., 2018) because irreversible organ damage and cellular destruction follow any occasion when the body is heated beyond 49 °C (Bouchama & Knochel, 2002). Reports from Israel suggest exertional HRI may be the more common cause of heatstroke in dogs in that country (Bruchim et al., 2016;

Bruchim, Ginsburg, et al., 2017; Bruchim, Kelmer, et al., 2017). Although there is some evidence that exertion is also the main trigger of HRI in UK dogs (Hall et al., 2020b), current efforts to educate UK dog owners about heatstroke prevention focus almost exclusively on environmental heatstroke, specifically the message that 'dogs die in hot cars' (Hall & Carter, 2016). Generation of a solid evidence base on the predominant trigger of canine HRI, canine risk factors for different HRI types and the seasonality of different HRI types in the UK could support optimized and targeted educational campaigns.

This study aimed to use the VetCompass database of veterinary health records to (i) identify the leading triggers for HRI in the UK general dog population; (ii) identify risk factors for the three key triggers of HRI and (iii) compare the case fatality rate and seasonality between different HRI triggers.

6.3 Materials and methods

Data Collection and Management

This study was an extension of work previously reported in Hall et al. (2020a) and used the same dataset described in that study. The VetCompass Programme (Royal Veterinary College, London, UK) offers a research database providing access to de-identified electronic patient records (EPRs) from primary-care veterinary practices in the UK (Anderson et al., 2018; O'Neill et al., 2018, 2019; O'Neill et al., 2014). The study population included all dogs under veterinary care during 2016 as previously defined. EPRs were searched to identify candidate cases of HRI, using the following terms: heat stroke~3, heatst*, hyperthermi*, overheat*, over heated~2, heat exhaustion~2, hot car~2, collapse* + heat, cooling, high ambient temp*. Dogs identified from all searches were merged and randomly ordered. All candidate cases were manually reviewed in detail by two researchers (author 1 and author 2) to identify all dogs (confirmed HRI cases) meeting the study case definition for HRI occurring at any date within the patient's available EPR (prevalent HRI events). All confirmed HRI events underwent additional data extraction including date of heat exposure event, the trigger for the HRI event (Table 6.3.1) and outcome of each event (survival or death). All events were assigned to a single trigger category. For dogs with multiple HRI events, only events occurring between 1st January 2016–31st December 2018 (2016–2018 HRI events) were included when exploring triggers as risk factors for death and reporting numbers of events by trigger. Whilst events occurring after 2016 were excluded from previous risk factor analysis to avoid introducing potential bias from the aging denominator population (Hall et al., 2020a), they were included in the present study to provide greater event numbers for statistical analysis. The earliest HRI event recorded in the

EPR (first HRI event) was used to calculate age at the event and was included in risk factor analysis (see Figure 6.3.1).

Ethical approval for this study was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652).

Table 6.3.1. Definitions of heat-related illness (HRI) triggers in UK dogs.

Trigger	Definition	Justification
Exertional	Any HRI event where physical activity is identified as the inciting cause regardless of ambient temperature. All types of physical activity are included.	Exertional HRI is reported to affect both humans (Rogers et al., 2007), horses (Brownlow et al., 2016) and dogs (Bruchim, Horowitz, et al., 2017).
Environmental	Any HRI event where the dog was reported to be outdoors in the heat but not exercising.	Environmental HRI typically affects dogs in the summer months but can also be triggered by unseasonable hot spells especially when the dog has not been acclimatized to heat (Bruchim et al., 2006; Drobatz & Macintire, 1996).
Undergoing treatment (vets/groomer)	HRI events that occurred following hospitalisation in a veterinary clinic or following professional grooming.	Frenzied jumping and barking has been reported to trigger HRI in dogs (Drobatz & Macintire, 1996), and can occur following separation from owners in veterinary clinics. Dogs have been reported to suffer HRI following grooming in media reports (Colletti, 2019).
Blanket entrapment	HRI events resulting from the dog becoming entangled in blankets.	Wearing thick or insulating clothing increases the risk of HRI in humans (Gaudio & Grissom, 2016).
Building confinement	HRI events that occurred following confinement in a hot building.	Confinement indoors with no air conditioning is a known risk factor for elderly human HRI patients (Gaudio & Grissom, 2016).
Vehicular confinement	HRI events that occurred following confinement in a hot vehicle, including both dogs left unattended in a hot vehicle and dogs travelling in a hot vehicle.	Enclosed vehicles can reach 54.4 °C (Ondrak et al., 2015) in the summer months. Vehicular confinement was the leading trigger of HRI in dogs presenting to a German veterinary hospital (Teichmann et al., 2014).
Unrecorded	Confirmed HRI events with no record of an inciting cause in the clinical history.	HRI requires urgent treatment, meaning some dogs present as emergencies needing immediate triage and treatment. Clinical notes may not be written at the time of presentation limiting the information recorded. Additionally, some owners may be reluctant to disclose the inciting cause or may not have recognised the condition as HRI.

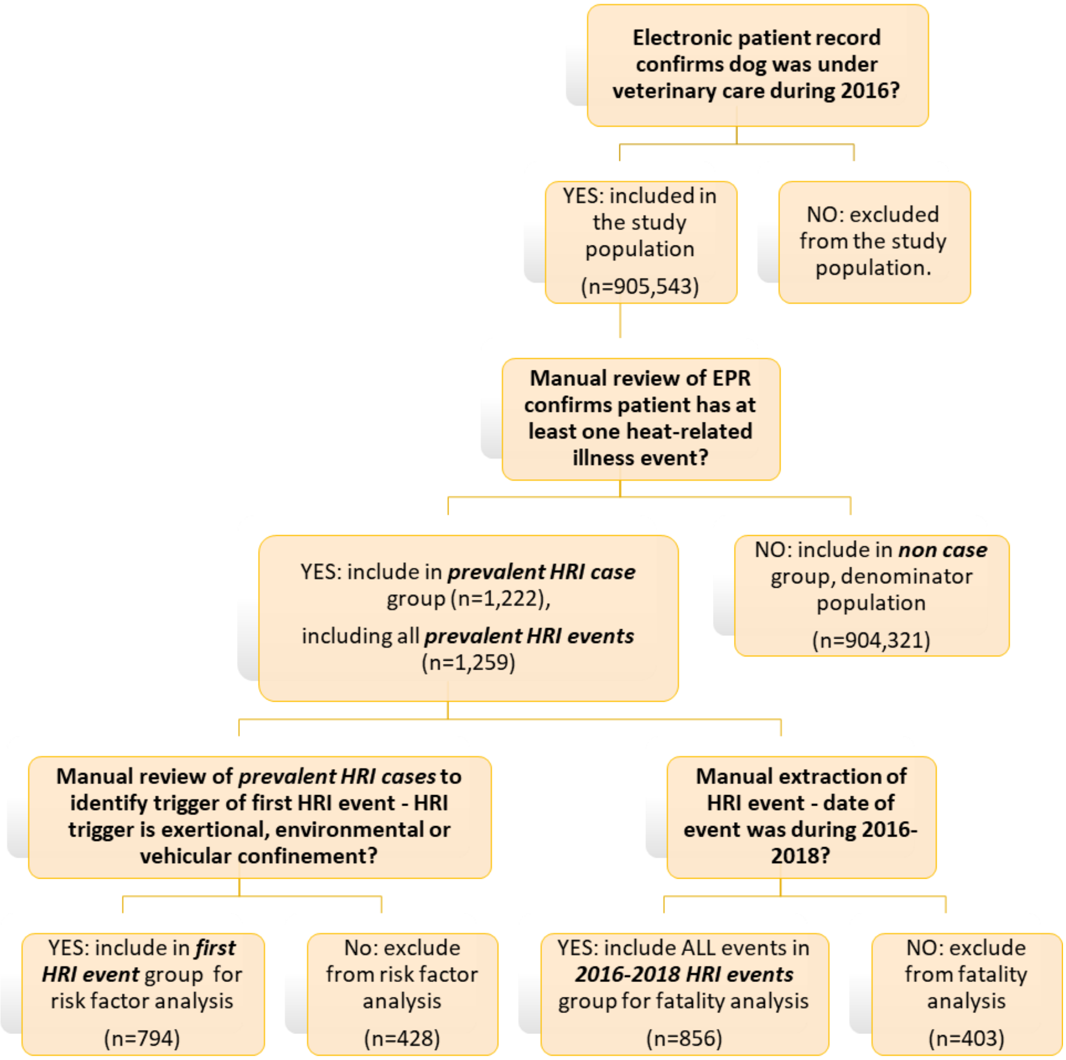

Figure 6.3.1. Flow chart of decisions for inclusion in HRI fatality analysis and risk factor analysis for HRI triggers.

Analysis

The study used a cohort design applied to a denominator population of 905,543 dogs from the VetCompass database under veterinary care in 2016. Demographic data were extracted automatically from the database for all study dogs. Demographic and clinical data were exported into Microsoft Excel (v16, Redmond, Washington, USA) for cleaning and descriptive analysis, risk factor analysis used SPSS v25 (IMB Inc., Armonk, New York, USA).

Summary statistics were calculated using *all HRI events* to determine the number of HRI events per month and to identify the top three triggers for HRI in UK dogs: exertional HRI, environmental HRI and vehicular HRI. The 2016–2018 HRI events were then assigned to a trigger category for risk factor analysis: exertional HRI, environmental HRI, vehicular HRI, unrecorded HRI, building entrapment, blanket entanglement and undergoing treatment.

Risk Factor Analysis for Fatality

Binary logistic regression modelling was used to compare the odds for death between triggers using only 2016–2018 HRI events, using the most numerous trigger (exertional) as the comparator. Events occurring prior to 2016 were excluded from fatality analysis, because any dogs that died from their HRI event prior to 2016 would by definition be excluded from the denominator population, meaning events prior to 2016 would be biased toward survival.

Risk Factor Analysis for Triggers

Risk factor analysis used cohort clinical data to explore potential canine risk factors for HRI triggered by each of the three key categories: exertional HRI, environmental HRI and vehicular HRI, using all dogs in the denominator population not defined as a confirmed HRI case as the "non-case" population. Where the first HRI event was not triggered by one of the three categories above, these cases were excluded from this analysis as they did not meet the inclusion criteria for "non-case". As the purpose of this analysis was to identify canine risk factors for the different triggers, events that occurred prior to 2016 were included to increase the number of events available for statistical analysis.

Separate binary logistic regression modelling of the first HRI events was used to identify risk factors for each trigger: exertional HRI, environmental HRI and vehicular HRI. The variables considered in univariable binary logistic regression analysis included breed type, purebred, skull shape, adult bodyweight, bodyweight relative to breed/sex mean, sex/neuter and age. These risk factors were defined in a previous study (Hall et al., 2020a), but are included in Appendix A, Table 6.A1 for reference. Risk factors with liberal associations in univariable modelling ($p < 0.2$) were selected for multivariable evaluation. As breed type was a factor of primary interest, variables that were highly collinear with breed (purebred) or considered a defining characteristic of individual breeds (adult bodyweight and skull shape) were not included in the multivariable models with breed type but were included in alternative models that swapped out the breed type variable as previously described (Hall et al., 2020a; O'Neill et al., 2014). Model development used manual backwards stepwise elimination, as this was an explanatory model aiming to identify canine risk factors, rather than a predictive model (Hall et al., 2020a). Pairwise interactions were tested for all variables in the final multivariable model. The area under the receiver operating characteristic (ROC) curve was used to evaluate the explanatory ability of the model (Dohoo et al., 2009) alongside consideration of the underpinning biological plausibility of the model specification. Statistical significance was set at $p < 0.05$.

6.4 Results

The study included 905,543 dogs under primary veterinary care at 886 UK VetCompass clinics during 2016. From this population, 1259 HRI events were identified from the EPRs of 1222 dogs; 35 dogs had two HRI events and one dog had three HRI events recorded at the time of the study (2.95% of affected dogs had multiple events). Data completeness, incidence estimate, and case fatality rate have been reported in a previous study (Hall et al., 2020a).

HRI Triggers

There were 380/1259 (30.2%) HRI events with no trigger recorded in the EPR. Of the remaining 879 HRI events, the predominant triggers recorded were exertional HRI (n = 652, 74.2%), followed by environmental HRI (n = 113, 12.9%) and vehicular confinement (n = 46, 5.2%). Other triggers included being under the care of a veterinary clinic or groomer (n = 40, 4.6%), building confinement (n = 24, 2.7%) and blanket entrapment (n = 4, 0.5%).

Of the 652 HRI events triggered by exercise, the type of exercise was not specified for 101 (15.5%) events. Of the remaining 551 events, 372 (67.5%) occurred after walking, 97 (17.6%) after high-intensity activities such as running or cycling, 76 (13.8%) after periods of play and 6 (1.1%) of those events occurred after canine competitions.

Event Fatality and Seasonality

From the 2016–2018 HRI events*,* the event fatality rate for each trigger is shown in Table 6.4.1. Of the events with a known trigger, building confinement (OR 6.06, 95% CI 2.13–17.22) had greater odds for HRI associated fatality when compared to exertional HRI only. Cases with no recorded trigger also had greater odds (OR 2.43, 95% CI 1.49–3.94).

Table 6.4.1. Descriptive and binary logistic regression results for triggers as risk factors for heat-related illness associated fatality in dogs affected between 2016–2018, under primary veterinary care in the VetCompass programme in the UK during 2016.

Trigger	Number of Events (n = 856)	% of Known Events (n = 592)	Event Fatality (Rate)	Odds Ratio	95% Confidence Interval	P-Value
Exertional	420	70.9%	32 (7.6%)	base		
Blanket entrapment	2	0.3%	1 (50.0%)	12.13	0.74–198.43	0.080
Building confinement	18	3.0%	6 (33.3%)	6.06	2.13–17.22	0.001
Environmental	84	14.2%	8 (9.5%)	1.28	0.57–2.88	0.556
Undergoing treatment (vet/groomer)	31	5.2%	3 (9.7%)	1.3	0.37–4.51	0.680
Unrecorded	264		44 (16.7%)	2.43	1.49–3.94	<0.001
Vehicular confinement	37	6.3%	4 (10.8%)	1.47	0.49–4.41	0.492

HRI events occurred during every month of the year, with July (n = 426, 33.84%) showing the highest proportion of events. Although HRI fatalities were recorded in all months from January to October, July accounted for 35/99 (35.35%) of fatalities (Figure 6.4.1). Environmental HRI and vehicular confinement were recorded only between March and September (see Figure 6.4.2), corresponding to the UK’s spring to summer period and typically warmest months. Vehicular HRI fatalities only occurred between March and July, whilst environmental HRI fatalities occurred from May to September. Building confinement triggered HRI across all months except November with fatalities occurring from June to September and undergoing treatment at a vets/groomer triggered HRI in all months except December, January and March with fatalities in June and August. Exertional HRI occurred in all months, however, there was only one exertional HRI fatality (in January) outside the typically warmer UK months of March–October. There were HRI events with no recorded trigger in all months except December, with fatalities from unrecorded triggers occurring between February and September.

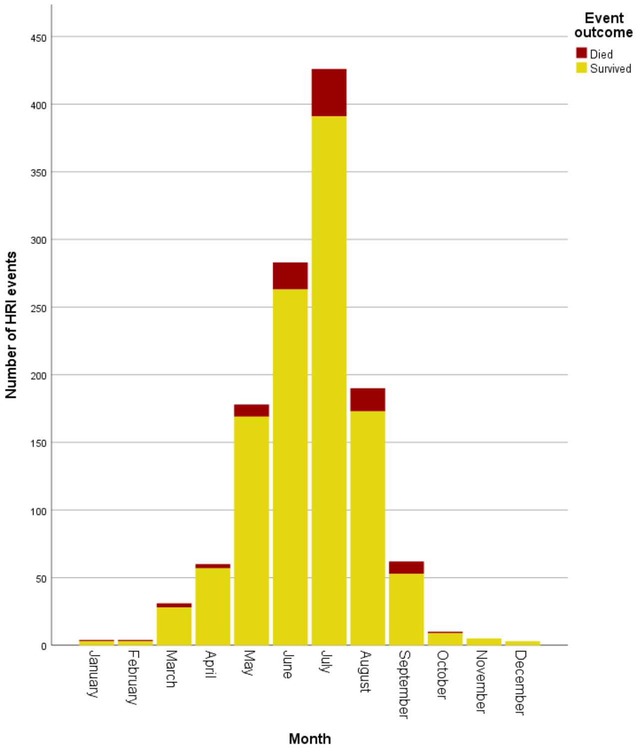

Figure 6.3.1. Histogram showing the number of heat-related illness events by outcome per month.

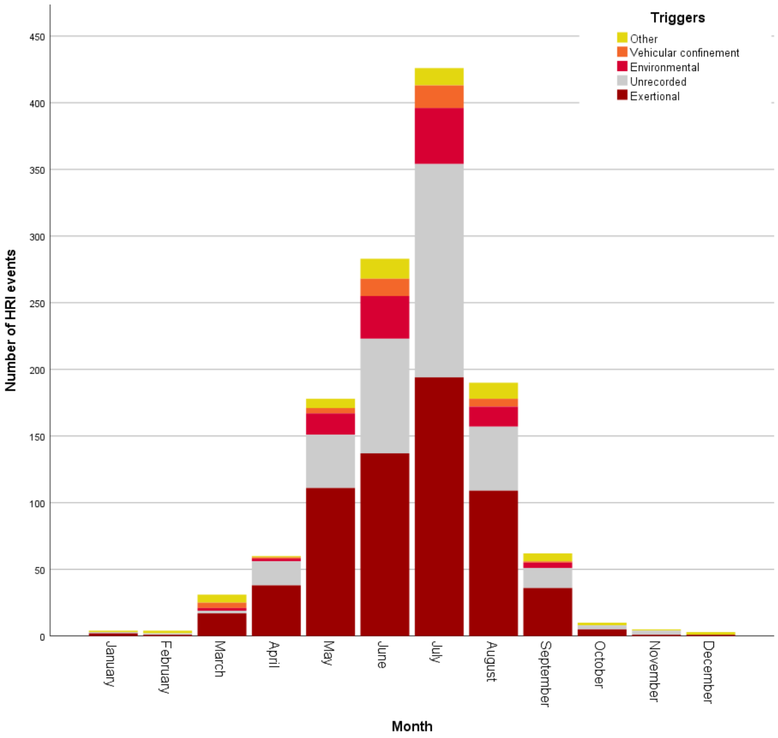

Figure 6.4.2. Histogram showing the number of heat-related illness events by a trigger, per month.

Risk Factor Analysis for Exertional HRI

All risk factors were strongly associated with exertional HRI following univariable binary logistic regression modelling ($p < 0.001$). The final breed multivariable model retained four risk factors: breed type, age, bodyweight relative to breed/sex mean and sex/neuter. The model showed acceptable discrimination ($R^2 = 0.004$, area under the ROC curve: 0.725). In the final model, seven breeds (Chow Chow, Bulldog, French Bulldog, Greyhound, English Springer Spaniel, Cavalier King Charles Spaniel and Staffordshire Bull Terrier) had higher odds of exertional HRI, and eleven breed types (Crossbred, German Shepherd Dog, West Highland White Terrier, Bichon Frise, Lhasa Apso, Jack Russel Terrier, Designer Crossbred, Shih-tzu, Cocker Spaniel, Yorkshire Terrier and Chihuahua) had lower odds of exertional HRI compared to Labrador Retrievers. As crossbred dogs (previously used as the breed type comparator in other VetCompass studies (Anderson et al., 2018; O'Neill et al., 2018; Shoop et al., 2015)) were found to have significantly reduced odds of exertional HRI compared to Labrador Retrievers, the multivariable analysis was repeated using crossbred as the comparator. Labrador Retrievers had 2.1 (95% CI 1.47–2.88) times the odds of exertional HRI compared to non-designer crossbred dogs (the other breeds with significantly greater odds of exertional HRI compared to non-designer crossbred dogs are indicated in Table 3). Dogs aged over 8 years had lower odds of exertional HRI compared to dogs under 2 years of age. Entire females had lower odds of exertional HRI compared to entire males, neutered males and neutered females. Dogs with bodyweight equal to or greater than the breed/sex mean had higher odds of HRI compared to dogs weighing below the relative breed/sex mean (see Table 6.3).

Table 6.4.2. Multivariable binary logistic regression results for risk factors associated with exertional heat-related illness in dogs under primary veterinary care in the VetCompass programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Breed type	Labrador Retriever *	Base		<0.001
	Chow Chow *	7.00	3.00–16.33	<0.001
	Bulldog *	3.73	2.34–5.93	<0.001
	French Bulldog *	2.96	1.96–4.47	<0.001
	Greyhound *	2.11	1.08–4.16	0.030
	English Springer Spaniel *	1.85	1.21–2.84	0.005
	Cavalier King Charles Spaniel *	1.69	1.06–2.67	0.026
	Staffordshire Bull Terrier *	1.56	1.09–2.22	0.015
	Pug *	1.58	0.97–2.56	0.064
	Boxer *	1.31	0.68–2.50	0.418
	Golden Retriever *	1.25	0.65–2.39	0.499
	Border Collie *	1.15	0.71–1.88	0.566

	Dogue de Bordeaux	1.12	0.35–3.59	0.848
	Missing	1.09	0.26–4.57	0.909
	Pomeranian	1.08	0.46–2.51	0.860
	Rottweiler	0.96	0.42–2.24	0.931
	Border Terrier	0.89	0.43–1.88	0.764
	Other purebred *	0.73	0.52–1.03	0.077
	Siberian Husky	0.61	0.19–1.95	0.405
	Cockapoo	0.52	0.26–1.02	0.056
	Miniature Schnauzer	0.49	0.18–1.35	0.168
	Lurcher	0.37	0.09–1.52	0.167
	Beagle	0.25	0.06–1.01	0.052
	Yorkshire Terrier	0.52	0.29–0.96	0.036
	Cocker Spaniel	0.52	0.30–0.91	0.022
	Non-designer Crossbred	0.49	0.35–0.68	<0.001
	Jack Russell Terrier	0.43	0.25–0.73	0.002
	West Highland White Terrier	0.43	0.20–0.94	0.034
	German Shepherd Dog	0.33	0.14–0.76	0.010
	Labradoodle	0.26	0.06–1.06	0.060
	Shih-tzu	0.25	0.12–0.53	<0.001
	Chihuahua **	0.21	0.09–0.45	<0.001
	Other designer crossbred	0.19	0.07–0.52	0.001
	Lhasa Apso	0.17	0.04–0.69	0.013
	Bichon Frise	0.16	0.04–0.64	0.010
Age	<2 years	Base		<0.001
	2– < 4 years	1.23	0.97–1.56	0.090
	4– < 6 years	0.82	0.62–1.08	0.157
	6– < 8 years	0.77	0.57–1.03	0.080
	8– < 10 years	0.48	0.33–0.69	<0.001
	10– < 12 years	0.48	0.32–0.72	<0.001
	≥12 years	0.54	0.36–0.81	0.002
	Unrecorded	1.37	0.63–2.98	0.424
Sex/neuter	Female-entire	Base		<0.001
	Female-neutered	1.63	1.26–2.10	<0.001
	Male-entire	1.49	1.18–1.88	<0.001
	Male-neutered	1.83	1.43–2.33	<0.001
	Unrecorded	0.00	~	0.982
Bodyweight relative to breed/sex mean	Lower	Base		<0.001
	Equal/Higher	1.30	1.09–1.55	0.003
	Unrecorded	0.49	0.30–0.62	<0.001

* Indicates breeds with significantly greater odds of exertional HRI compared to non-designer crossbred dogs. ** Indicates breeds with significantly reduced odds of exertional HRI compared to non-designer crossbred dogs.

As described in the methods, variables collinear (purebred) and definitive of breed types (bodyweight and skull shape) replaced the breed type variable in the final multivariable model. Purebred dogs had 1.84 (95% CI 1.47–2.31) times the odds of exertional HRI than crossbred dogs. Dogs in all bodyweight categories over 10 kg had greater odds of exertional HRI compared to dogs under 10 kg bodyweight. Brachycephalic dogs had 1.32 (95% CI 1.10–1.60) times the odds of exertional HRI, and dolichocephalic dogs and brachycephalic crossbred dogs had lower odds of exertional HRI compared to mesocephalic dogs (Appendix B, Table 6.A2).

Risk Factor Analysis for Environmental HRI

Following univariable analysis, all variables were liberally associated with environmental HRI: breed type ($p = 0.002$), age ($p = 0.051$), sex/neuter ($p = 0.108$), purebred (0.054), skull shape ($p = 0.009$), adult bodyweight ($p = 0.001$) and bodyweight relative to breed/sex mean ($p < 0.001$). The final breed multivariable model retained breed type, age and sex/neuter. The final model showed acceptable discrimination ($R^2 = 0.039$, area under the ROC curve: 0.721). In the final model, four breeds had higher odds of environmental HRI than Labrador Retrievers: Chow Chow (OR 8.41, 95% CI 1.06–66.70), Bulldog (OR 7.52, 95% CI 2.76–20.47), Pug (OR 3.30, 95% CI 1.16–9.41) and French Bulldog (OR 3.16, 95% CI 1.03–9.73). Dogs aged ≥12 years (OR 3.15, 95% CI 1.56–6.37) had greater odds of environmental HRI compared to dogs <2 years old. Female neutered (OR1.92, 95% CI 1.03–3.56) and male entire (OR1.87, 95% CI 1.05–3.33) had greater odds compared to female entire dogs (Table 6.4).

Variables collinear (purebred) and definitive of breed types (bodyweight and skull shape) replaced the breed type variable in the final multivariable model. Purebred dogs had 1.97 the odds (95% CI 1.12–3.47) of environmental HRI compared to crossbred dogs. Brachycephalic dogs had 2.36 the odds (95% CI 1.50–3.72) compared to mesocephalic dogs, and dogs in the 10– < 20 kg and 20– < 30 kg bodyweight categories had greater odds for environmental HRI compared to dogs <10 kg (Appendix B, Table 6.A3).

Table 6.4.3. Multivariable binary logistic regression results for risk factors associated with environmental heat-related illness in dogs under primary veterinary care in the VetCompass programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Breed type	Labrador Retriever	Base		0.002
	Chow Chow	8.41	1.06–66.70	0.044
	Bulldog	7.52	2.76–20.47	<0.001
	Pug	3.30	1.16–9.41	0.025
	French Bulldog	3.16	1.03–9.73	0.045
	Cavalier King Charles Spaniel	2.38	0.85–6.69	0.100
	Boxer	2.22	0.60–8.19	0.233
	Other designer crossbred	1.33	0.36–5.01	0.670
	Jack Russell Terrier	1.29	0.52–3.17	0.583
	West Highland White Terrier	1.21	0.37–3.96	0.748

	Bichon Frise	1.08	0.23–5.00	0.923
	Labradoodle	1.06	0.13–8.38	0.958
	Beagle	0.95	0.12–7.48	0.958
	Staffordshire Bull Terrier	0.88	0.33–2.36	0.798
	Cocker Spaniel	0.88	0.27–2.85	0.829
	Chihuahua	0.71	0.19–2.65	0.612
	Yorkshire Terrier	0.70	0.19–2.59	0.594
	Other purebred	0.69	0.29–1.64	0.404
	German Shepherd Dog	0.69	0.15–3.18	0.629
	Border Terrier	0.67	0.09–5.28	0.703
	Golden Retriever	0.65	0.08–5.11	0.680
	Border Collie	0.58	0.13–2.70	0.490
	Lhasa Apso	0.55	0.07–4.34	0.571
	Cockapoo	0.50	0.06–4.01	0.515
	Non-designer Crossbred	0.50	0.22–1.16	0.105
	Shih-tzu	0.46	0.10–2.13	0.320
	English Springer Spaniel	0.00	~	0.965
	Miniature Schnauzer	0.00	~	0.977
	Rottweiler	0.00	~	0.979
	Pomeranian	0.00	~	0.981
	Lurcher	0.00	~	0.981
	Greyhound	0.00	~	0.981
	Siberian Husky	0.00	~	0.982
	Dogue de Bordeaux	0.00	~	0.987
	Missing	0.00	~	0.984
Age	<2 years	Base		0.081
	2– < 4 years	1.35	0.72–2.50	0.349
	4– < 6 years	1.09	0.53–2.24	0.821
	6– < 8 years	1.67	0.84–3.35	0.146
	8– < 10 years	1.81	0.88–3.73	0.110
	10– < 12 years	1.64	0.71–3.76	0.244
	≥12 years	3.15	1.56–6.37	0.001
	Unrecorded	0.00	~	0.973
Sex/neuter	Female-entire	Base		0.373
	Female-neutered	1.92	1.03–3.56	0.039
	Male-entire	1.87	1.05–3.33	0.033
	Male-neutered	1.72	0.93–3.21	0.086
	Unrecorded	0.00	~	0.984

Risk Factor Analysis for Vehicular HRI

Univariable binary logistic regression modelling identified breed type (*p* = 0.007), sex/neuter (*p* = 0.199) and skull shape (*p* = 0.007), as factors liberally associated with vehicular HRI, but not age (*p* = 0.690), bodyweight relative to breed/sex mean (*p* = 0.269), purebred (*p* = 0.395) or bodyweight (*p* = 0.245). The final breed multivariable model retained two risk factors: breed type and sex/neuter. The model showed good discrimination (R^2 = 0.066, area under the ROC curve: 0.808). In the final model (Table 5) five breeds had increased odds of vehicular HRI compared to the Labrador Retriever: Bulldog (OR 16.63, 95% CI 3.02–91.53), Greyhound (OR 9.59, 95% CI 1.35–68.23), Cavalier King Charles Spaniel (OR 8.52, 95% CI 1.65–43.94), French Bulldog (OR 6.70, 95% CI 1.11–40.65) and Pug (OR 6.29, 95% CI 1.05–37.84) (Table 6.5). Variables definitive of breed types (skull shape) replaced the breed type variable in the final multivariable model. Brachycephalic dogs had greater odds (OR 3.07, 95% CI 1.60–5.87) of vehicular HRI compared to mesocephalic dogs (see Appendix B, Table 6.A4).

Table 6.4.4. Multivariable binary logistic regression results for risk factors associated with vehicular heat-related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Breed type	Labrador Retriever	Base		0.041
	Bulldog	16.63	3.02–91.53	0.001
	Greyhound	9.59	1.35–68.23	0.024
	Cavalier King Charles Spaniel	8.52	1.65–43.94	0.010
	French Bulldog	6.70	1.11–40.65	0.039
	Pug	6.29	1.05–37.84	0.045
	Siberian Husky	6.10	0.55–67.40	0.140
	Pomeranian	5.31	0.48–58.76	0.173
	Labradoodle	3.88	0.35–42.83	0.268
	Boxer	3.22	0.29–35.49	0.340
	Border Terrier	3.07	0.28–33.84	0.360
	Golden Retriever	3.05	0.28–33.63	0.363
	Cocker Spaniel	2.82	0.47–16.90	0.256
	Shih-tzu	1.89	0.27–13.46	0.523
	Cockapoo	1.70	0.15–18.79	0.664
	West Highland White Terrier	1.51	0.14–16.62	0.738
	German Shepherd Dog	1.49	0.14–16.48	0.744
	Border Collie	1.33	0.12–14.65	0.817
	Jack Russell Terrier	1.21	0.17–8.58	0.850
	Non-designer Crossbred	0.90	0.18–4.47	0.901
	Chihuahua	0.89	0.08–9.83	0.923
	Staffordshire Bull Terrier	0.58	0.05–6.39	0.655
	Other purebred	0.50	0.07–3.55	0.489
	Bichon Frise	0.00	~	0.975
	Lhasa Apso	0.00	~	0.976
	English Springer Spaniel	0.00	~	0.969
	Miniature Schnauzer	0.00	~	0.980
	Beagle	0.00	~	0.980
	Rottweiler	0.00	~	0.981
	Lurcher	0.00	~	0.983

	Dogue de Bordeaux	0.00	~	0.988
	Other designer crossbred	0.00	~	0.969
	Missing	0.00	~	0.986
	Yorkshire Terrier	0.00	~	0.963
	Chow Chow	0.00	~	0.993
Sex/neuter	Female-entire	Base		0.239
	Female-neutered	1.49	0.69–3.22	0.316
	Male-entire	0.43	0.16–1.13	0.086
	Male-neutered	1.27	0.58–2.79	0.546
	Unrecorded	0.00	~	0.984

6.5 Discussion

This is the largest primary-care study worldwide to deconstruct and explain HRI triggers in companion dogs. Reflecting the results of previous studies from Israel (Bruchim et al., 2016; Bruchim, Ginsburg, et al., 2017; Bruchim, Kelmer, et al., 2017), the predominant trigger of HRI presenting to UK primary-care practices was exertional HRI (74.2% of events with a known cause). Exertional HRI events occurred year-round, with a 7.6% overall fatality rate. Exertional HRI accounted for the majority of HRI related deaths with known triggers. The odds of death did not differ between exertional HRI, environmental HRI or vehicular HRI.

Seven breed types had greater odds of exertional HRI when compared to Labrador retrievers: Chow Chow, Bulldog, French Bulldog, Greyhound, English Springer Spaniel, Cavalier King Charles Spaniel and Staffordshire Bull Terrier. Six of those breeds have previously been identified with greater odds for HRI in general (Hall et al., 2020a), whereas the Staffordshire Bull Terrier appears to have greater odds specifically for exertional HRI. The Labrador Retriever was chosen as the comparator breed for reasons highlighted previously (Erlen et al., 2018; Hall et al., 2020a) namely that the Labrador Retriever was the most common definitive breed type in the study population. However, the Labrador Retriever had twice the odds for exertional HRI compared to non-designer crossbred dogs, as did several other large active breeds (Boxer, Golden Retriever and Border Collie), along with the Pug, and “other purebred”—namely breeds with either relatively low numbers in the study population or fewer than five confirmed HRI cases. Labrador Retrievers, Golden Retrievers, Border Collies and English Springer Spaniels represent breeds that are commonly used as working or assistance/service dogs including guide dogs for the visually impaired, hearing assistance dogs, medical support dogs, military detection dogs and medical detection dogs. Given the current evidence that these breeds show increased risk of exertional HRI, it is essential that future societal adaptations to increasing ambient temperature include appropriate mitigations to safeguard working and assistance dogs.

German Shepherd Dogs showed just one-third of the odds for exertional HRI compared to the Labrador Retriever in the current study. Both Australian Shepherd Dogs (Drobatz & Macintire, 1996) and Belgian Malinois (Bruchim et al., 2006) have previously been identified with increased risk of exertional HRI, however, these studies used referral hospital populations and thus likely included a relatively higher proportion of military or police working dogs than the present study based on the general population of dogs. German Shepherd Dogs and Belgian Malinois comprised over 70% of the US civilian law enforcement dogs in one study (Stojsih et al., 2014), in which HRI was the second most common cause of traumatic death accounting for approximately a quarter of deaths. However, 75% of those HRI events were triggered by vehicular confinement. The conflicting findings of this study compared to previous reports suggesting an increased risk of exertional HRI in Shepherd type dogs likely reflects the difference in study populations, with the current study population being the first to explore HRI in first opinion veterinary practice. Additionally, the potential for an underlying genetic predisposition for HRI in military working dogs (Belgian Malinois) has been suggested (Gogolski et al., 2020), potentially associated with low levels of expression of heat shock proteins (Romanucci & Della Salda, 2013).

Exertional HRI appears to predominantly affect younger dogs, all age groups of dogs over 8 years had reduced odds compared to dogs less than 2 years of age. This may reflect differing intensity and duration of exercise undertaken by younger dogs whereas older dogs are more likely to suffer from conditions that limit their ability to exercise, such as osteoarthritis (Anderson et al., 2018) and cardiac disease (O’Neill et al., 2013). Male dogs and neutered female dogs had greater odds than entire female dogs for exertional HRI. These findings mirror the human risk factors of exertional HRI, with young male athletes and labourers most likely to be affected (Nakamura & Aruga, 2013). Entire female dogs could have reduced odds for exertional HRI due to their relatively lower bodyweights compared to male and neutered animals (McNicholl et al., 2016), or it could reflect reduced exercise levels during reproductive periods such as pregnancy and lactation. Dogs at or above the mean adult bodyweight for their breed/sex showed an increased risk of exertional HRI compared to dogs below the mean bodyweight, and all dogs weighing 10 kg or over had increased odds of exertional HRI compared to dogs weighing under 10 kg.

Although the precise mechanisms behind the differing odds between categories for exertional HRI was not explored in this study, it is important to note that HRI is a disorder that requires extrinsic (and often human-controlled) input—dogs cannot develop HRI without exposure to a hot environment or exercise that results in overwhelming hyperthermia (Hall et al., 2020a). Exertional HRI requires the dog to have undertaken either exercise in a hot environment

(Johnson et al., 2006), or prolonged or intense exercise sufficient to exceed thermoregulatory capacity. The majority of exertional HRI events in the present study occurred following relatively low-intensity activities such as walking and occurred during the typically warmer spring and summer months. However, as demonstrated in Figure 3, exertional HRI events occurred in every month (albeit with lower numbers between October and February), confirming that exertional HRI is a year-round risk for UK dogs.

Several breeds along with both non-designer crossbred, and designer crossbred dogs were identified with reduced odds for HRI compared to the Labrador Retriever. Conversely, only Chihuahuas were identified with reduced odds (OR 0.42, 95% CI 0.20–0.92) of exertional HRI compared to non-designer crossbred dogs. The Chihuahua is the smallest breed of dog in the world (O'Neill et al., 2020), with owners reportedly more influenced by "convenience" when choosing this breed than owners of other popular dog breeds (Sandøe et al., 2017). Chihuahua ownership and popularity are also reported to be influenced by fashion and celebrity trends, with the breed frequently depicted as a "handbag dog" being carried as a fashion statement (Redmalm, 2014). Their relatively smaller bodyweight is likely to confer a degree of protection from HRI as previously identified (Hall et al., 2020a; Young et al., 1959), which could potentially be augmented by their greater likelihood of being carried than other breeds which could reduce the risk of exertional HRI due to reduced exercise.

Dogs with both dolichocephalic and brachycephalic-cross skull shapes showed reduced odds of exertional HRI, whilst brachycephalic dogs had increased odds of exertional HRI when compared to mesocephalic dogs. This gradient of increasing exertional HRI risk with shortening of the skull is likely due to the differing relative surface area of the nasal turbinates. Evaporative heat loss from panting and respiration is an important aspect of canine thermoregulation (Hemmelgarn & Gannon, 2013), so, therefore, dogs with longer muzzles have more surface area for evaporative heat loss. The reduced odds of exertional HRI for brachycephalic crosses is unexpected but may reflect the diversity of skull conformation types within this ill-defined category. This group is likely to be younger compared to the rest of the study population (Hall et al., 2020a), however, younger dogs have increased odds of exertional HRI. The group is also likely to have relatively lower bodyweight compared to both purebred and non-designer crossbred dogs (Hall et al., 2020a), but could also be subject to similar lifestyle differences, e.g., "handbag dogs", as the Chihuahua due to their small stature and "designer" status.

The second most commonly reported HRI trigger was environmental (12.9% of events with a known cause). Environmental triggers were only recorded between March and September, reflecting the UK's warmer season. The four breeds with increased odds of environmental HRI when compared to the Labrador Retriever were predominantly brachycephalic breeds (Bulldog, Pug and French Bulldog); brachycephalic dogs, in general, had 2.36 the odds compared to mesocephalic breeds. This mirrors the increased risk of environmental HRI for humans with underlying respiratory disorders, and is supported by the findings of Lilja-Maula et al. (2017) that documented Bulldogs developing hyperthermia just standing in ambient room temperature (21 °C). Although the Chow Chow had the greatest odds of both exertional and environmental HRI, it must be noted that the Chow Chow breed group was the smallest in the study population resulting in very wide confidence intervals, and so these results need to be generalized to the wider population with caution.

Dogs aged 12 years or over had over three times the odds of environmental HRI compared to dogs under 2 years, again mirroring human risk factors. Advancing age increases the likelihood of underlying health conditions such as cardiac or respiratory disease, and old age in humans has been shown to increase HRI risk due to decreased physiological thermoregulatory mechanisms such as decreased sweat production and skin blood flow (Balmain et al., 2018; Kuzuya, 2013). Dogs weighing from 10 up to 30 kg had almost twice the odds of environmental HRI compared to dogs weighing less than 10 kg, however, interestingly none of the dogs weighing 50 kg or over were reported with environmental HRI. In general, the risk factor analysis for environmental HRI was the least informative of the three models, with the lowest R^2 and area under the ROC curve values. Environmental HRI requires prolonged exposure to a hot environment, or acute exposure to an extremely hot environment, both traditionally rare events in the UK. Environmental HRI is also the trigger for dogs that is least influenced by human behaviour, whereas both exertional HRI and vehicular HRI are heavily dependent on the actions of the dog’s owner. The much lower levels of environmental HRI compared with exertional HRI offers a substantial welfare gain opportunity by empowering owners with management tools that can limit the exertional HRI risk to their dogs. However, if climate change continues to increase, the frequency of heatwave events in the UK, the number of dogs experiencing environmental HRI is likely to increase without appropriate mitigation strategies.

Five breed types had increased odds of vehicular HRI compared to the Labrador Retriever (Bulldog, Greyhound, Cavalier King Charles Spaniel, French Bulldog and Pug). Brachycephalic dogs overall had three times the odds compared to mesocephalic dogs. However, the relatively low number of vehicular HRI events (37/856) resulted in low statistical power for this analysis, as reflected in the wide confidence intervals. Only two variables remained in the final vehicular HRI risk factor model, likely reflecting the predominantly extrinsic causal structure to vehicular HRI. Any dog subjected to confinement in a hot car will overheat, as their thermoregulatory mechanisms cease to be effective once ambient temperature exceeds body temperature.

Internal car temperature in the UK can exceed 50 °C between May and August, and can exceed 40 °C between April and September (Carter et al., 2020). The duration of confinement and the temperature within the vehicle will determine the severity of HRI (Shapiro et al., 1973), however underlying canine factors that impact thermoregulatory ability (such as a respiratory compromise or disease (Hemmelgarn & Gannon, 2013), acclimatization (Bruchim et al., 2014; Nazar et al., 1992; Ready & Morgan, 1984) and hydration (Baker et al., 1983)) will result in dogs overheating and developing HRI at lower relative temperatures.

Vehicular HRI was the third most common trigger and was reported only between March and September. Welfare charities and UK veterinary organisations run an annual “Dogs die in hot cars campaign”, traditionally launched around May (BVA, 2019; Duggal, 2018). However, Carter et al. (2020), report that internal vehicle temperatures exceeded 35 °C between the months of April and September in a study measuring UK vehicle temperatures for a two-year period. As heat acclimatization is known to impact susceptibility to HRI, sudden warm spells in March and April may be particularly dangerous for dogs left in cars. The findings of the current study, and those of Carter et al. (2020), support an earlier launch of this annual awareness campaign.

There was no significant difference in the odds for HRI related fatality between vehicular and exertional HRI. However, because exertional HRI affected around ten times as many dogs and resulted in eight times as many deaths overall than vehicular HRI, there is now a strong evidential basis to suggest that educational campaigns aimed at owners need to move from focusing purely on the risk of vehicular HRI to dogs and instead to include warnings about the more frequent dangers of exercising in hot weather.

This study identifies some important novel HRI triggers, in particular dogs developing HRI whilst under the care of veterinary practices and professional groomers. Undergoing treatment at a veterinary practice or grooming parlour was the fourth most common trigger for HRI events with a known cause, with a similar fatality rate to both exertional and vehicular HRI. This topic was explored further as part of an abstract presentation, reporting that two-thirds of the HRI events occurred in a veterinary practice (56% brachycephalic dogs) and one third whilst dogs were undergoing professional grooming (45% brachycephalic) (Hall et al., 2020b). The French Bulldog and the Bulldog accounted for a third of the cases occurring under veterinary care, whilst West Highland White Terriers were the most numerous breed type affected during grooming. Both veterinary practice premises and grooming parlours can be warm, stressful environments for dogs, highlighting the need for careful patient monitoring and awareness of the risk of HRI in these situations, especially in predisposed breeds.

Other HRI triggers identified in the current study included building confinement and blanket entrapment. These two triggers had the highest fatalities rates, with building confinement resulting in HRI all year round. Building confinement (OR 6.1) and unrecorded trigger (OR 2.4) HRI events both had significantly greater odds for HRI fatality compared to exertional HRI. Building confinement HRI events included events where central heating had been accidentally left on, or developed a fault, and so resulted in dogs being restricted to hot environments for prolonged periods while owners were unaware of the problem. The HRI events with unrecorded triggers included emergency presentations where the attending veterinary surgeon potentially did not have time to accurately record a history in the EPR and also includes HRI events where a specific trigger was not recognised or reported by the owner. Increasing owner awareness of circumstances that can result in canine HRI should be a priority as global temperatures continue to rise.

Dogs have been proposed as an ideal translational model for studying human morbidity and mortality (Hoffman et al., 2018; Jin et al., 2016). Domestic dogs often share their owners' home and leisure activities including walking, running and other sports (Carter & Hall, 2018). Dogs increasingly accompany their owners to the workplace (Foreman et al., 2017) and are often included in travel and holiday plans. No other species more intimately intertwines with the human lifestyle, meaning dogs potentially face similar levels of both environmental and exertional heat exposure to humans. The results of the current study highlight that dogs share similar risk factors to humans for both exertional and environmental HRI. How dogs are transported, housed and managed will also influence HRI risk. Dogs housed outside, with no access to air conditioning or fans will be at increased risk of environmental HRI as global warming worsens. The vehicular HRI events in the current study included both dogs left in parked vehicles and dogs travelling in hot vehicles, and highlight the danger of transporting dogs in cars without adequate ventilation or air conditioning during hot weather. As the frequency of extreme weather events such as heat waves is increasing, society needs to prepare strategies to mitigate the threat of HRI (House of Commons Environmental Audit Committee, 2018), to protect both human and canine health (Bruchim, Horowitz, et al., 2017).

This study had some limitations. As previously reported, the clinical record data in the VetCompass program were not recorded primarily for research purposes, meaning there are missing data within the dataset and the accuracy of descriptive entries (such as patient histories recording HRI triggers) is reliant upon the history provided to the veterinary surgeon treating the animal and their clinical notetaking (Conroy et al., 2019; O'Neill et al., 2018). Other limitations including the lack of a definitive diagnostic test for HRI, the use of skull shape definitions such as brachycephalic and mesocephalic, and the use of manual stepwise elimination to select the final breed models for the various HRI triggers have been discussed in a previous study (Hall et al., 2020a).

The present study used HRI events recorded at any point within the available clinical records for each dog. This may have selectively biased towards less severe HRI events, because dogs that died as a result of HRI prior to 2016 were by definition not part of the study population. This is reflected in the overall fatality rate of the cases in the present study (7.86%) which is lower than the 2016 incident fatality rate (14.18%) reported previously (Hall et al., 2020a). As the main aims of the present study were to identify the predominant triggers for HRI in UK dogs, and explore risk factors for the top three triggers, the decision to include all HRI events was made to increase the number of events available for analysis, and thus improve the statistical power of the findings.

Finally, the present study aimed to identify potential risk factors for different HRI triggers, producing potentially explanatory models, rather than predictive models. The effect of ambient temperature and humidity, canine behaviour and activity status, heat acclimation, athletic fitness and overall health fitness would all need to be considered to create a truly predictive model for canine HRI. These variables are not recorded in veterinary EPRs, meaning it was not possible to include these factors in the present analysis.

6.6 Conclusions

This study highlights canine risk factors for the three most common triggers of HRI in UK dogs, providing both dog owners and veterinary professionals information that can be used to identify at-risk dogs, tailor HRI education and potentially assist with more rapid recognition and therefore treatment of HRI in dogs. Dogs appear to share similar risk factors to humans for both of the most common HRI triggers: exertional and environmental. Young, active male dogs appear to have the greatest odds for exertional HRI, older dogs and brachycephalic dogs have greater odds for environmental HRI. Exertional HRI is shown to result in almost ten times the health welfare burden for dogs compared with vehicular HRI. It is hoped that these results will help to inform more targeted education campaigns, and catalyse further research to develop canine HRI mitigation strategies in the face of increasing global temperatures.

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Data Availability: https://researchonline.rvc.ac.uk/id/eprint/12745/

6.7 Appendix A

Table 6.A1. Potential canine risk factors for association with HRI in UK dogs (Hall et al., 2020a)**.**

Potential Risk Factor for HRI	Variable Definition	Justification
Breed type	Categorical variable including all named breed types (including both KC recognised purebred and non-KC recognised purebred) and designer hybrid types with contrived names (e.g., Cockapoo, Labradoodle, Lurcher) with ≥5 HRI cases and/or ≥5000 dogs in the overall study population. All remaining dogs were assigned to grouped categories of "other purebred", "other designer cross" or "non-designer crossbred".	Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever breeds have all be identified as having greater odds of HRI in UK dogs (Hall et al., 2020a). Labrador Retriever was used as the comparator for this variable as they were the largest breed type in the denominator population (after crossbred) so enabled high statistical power to explore breed risks (Dohoo et al., 2009; Erlen et al., 2018).
Purebred	Categorical variable grouping all dogs of recognisable breeds as "purebred", all recognisable designer crossbreeds as "designer cross" and the remaining dogs as "crossbred".	Purebred dogs are more likely to have an exaggerated conformation such as brachycephaly, thick coat, or giant body size, limiting their ability to thermoregulate (Hemmelgarn & Gannon, 2013). A higher percentage of purebred dogs presented with heatstroke to one veterinary hospital (Drobatz & Macintire, 1996).
Skull shape	Purebred dogs were categorised by skull shape into three groups, "brachycephalic", "mesocephalic" and dolichocephalic" (see Supplementary note 1 for breeds by category). Designer crossbred dogs including a brachycephalic breed were classified as "brachycephalic cross" and all other dogs listed as crossbred or unrecorded breed were classified as "skull shape unrecorded".	Surface areas of the nasal turbinates and effective ventilation provide the mechanism to enable evaporative heat loss through panting, thus brachycephalic dogs have reduced heat dissipation mechanisms (Bruchim et al., 2006; Flournoy et al., 2003; Hemmelgarn & Gannon, 2013; Lilja-Maula et al., 2017).

Adult bodyweight	Adult bodyweight was defined as the mean of all bodyweight (kg) values recorded for each dog after reaching 18 months old. Bodyweight (kg) was then categorised into seven groups (<10, 10– < 20, 20– < 30, 30– < 40, 40– < 50, ≥50), dogs under 18 months or with no recorded adult bodyweight were classified as "unrecorded".	Small breeds of dog are reported to have decreased risk of HRI (Bruchim et al., 2006), dogs with greater body mass have been reported to develop higher post exercise body temperatures (McNicholl et al., 2016).
Bodyweight relative to breed/sex mean	A categorical variable grouping dogs with a mean adult bodyweight "equal or above" or "below" the mean adult bodyweight for their breed and sex (calculated using the overall VetCompass study population). An "unrecorded" variable included all dogs with no adult bodyweight or labelled as crossbred.	Increased bodyweight can be due to increases in either lean muscle mass, or body fat. Obesity limits heat conduction and radiation from the skin and can limit effective cooling via respiration (Hemmelgarn & Gannon, 2013), overweight animals overheat faster and take longer to cool (Durkot et al., 1986). Dogs with greater lean body mass developed higher post-exercise temperatures than lighter dogs (McNicholl et al., 2016).
Sex/neuter	Dogs were classified by sex and neuter status into five categories (female entire, female neutered, male entire, male neutered) with "unrecorded" was used to group any dogs with no recorded sex or neuter status.	Male dogs develop higher body temperature post exercise (Carter & Hall, 2018; McNicholl et al., 2016), and are over-represented in cases of heatstroke presenting to veterinary hospitals (Segev et al., 2015, 2018; Teichmann et al., 2014).
Age	The age variable described the age of the dog at the end of the study period (31st December 2016) for non-case dogs, or the age at the first HRI event for 2016 incident HRI cases. Age (years) was categorised into eight groups (<2, 2– < 4, 4– < 6, 6– < 8, 8– < 10, 10– < 12, ≥12) with "unrecorded" for any dogs with no date of birth recorded in the EPR.	Older animals are more likely to have pre-existing conditions that limit effective heat dissipation such as heart disease, or respiratory diseases e.g., laryngeal paralysis (Flournoy et al., 2003).

6.8 Appendix B

Table 6.A2. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with age, bodyweight relative to breed/sex mean and sex/neuter) to evaluate risk factors associated with exertional heat-related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Purebred	Non-designer Crossbred	Base		<0.001
	Designer Crossbred	0.68	0.41–1.13	0.134
	Purebred	1.84	1.47–2.31	<0.001
	Unrecorded	2.11	0.51–8.78	0.306
Skull shape	Mesocephalic	Base		<0.001
	Dolichocephalic	0.72	0.52–1.00	0.048
	Brachycephalic-cross	0.19	0.05–0.75	0.018
	Brachycephalic	1.32	1.10–1.60	0.004
	Unknown	0.60	0.47–0.76	<0.001
Adult bodyweight (kg)	<10 kg	Base		<0.001
	10– < 20 kg	2.52	1.97–3.22	<0.001
	20– < 30 kg	2.27	1.73–2.99	<0.001
	30– < 40 kg	2.30	1.68–3.15	<0.001
	40– < 50 kg	2.15	1.31–3.53	0.002
	≥50 kg	2.21	1.02–4.79	0.046
	Unrecorded	0.54	0.13–2.23	0.395

Table 6.A3. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with age and sex/neuter) to evaluate risk factors associated with environmental heat related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Purebred	Non-designer Crossbred	Base		0.127
	Designer Crossbred	1.55	0.55–4.34	0.404
	Purebred	1.97	1.12–3.47	0.018
	Unrecorded	0.00	~	0.985
Skull shape	Mesocephalic	Base		<0.001
	Dolichocephalic	0.81	0.37–1.79	0.606
	Brachycephalic-cross	1.94	0.46–8.16	0.364
	Brachycephalic	2.36	1.50–3.72	<0.001
	Unknown	0.61	0.34–1.09	0.094
Adult bodyweight (kg)	<10 kg	Base		0.005
	10– < 20 kg	1.82	1.07–3.08	0.027
	20– < 30 kg	1.90	1.04–3.45	0.036
	30– < 40 kg	1.61	0.78–3.32	0.200
	40– < 50 kg	1.52	0.45–5.09	0.498
	≥50 kg	0.00	~	0.980
	Unrecorded	0.56	0.29–1.06	0.074

Table 6.A4. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with sex/neuter) to evaluate risk factors associated with vehicular heat related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	P-Value
Skull shape	Mesocephalic	Base		0.003
	Dolichocephalic	1.00	0.29–3.39	0.999
	Brachycephalic-cross	0.00	~	0.975
	Brachycephalic	3.07	1.60–5.87	0.001
	Unknown	0.74	0.29–1.86	0.522

6.9 References

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Section IV Appraisal

IV.2 Critical appraisal of the study methods – Chapters Five and Six

Chapters Five and Six used VetCompass data from a cohort of UK dogs under primary veterinary care during 2016. The data, accessible via the VetCompass programme, are limited to the veterinary practices that participate in the programme and the entries made in the patient's clinical record using free-text and fee charging entries. As reported in both Chapters Five and Six, VetCompass data are not generated primarily for research purposes and are therefore sometimes incomplete or missing (Hall et al., 2020; Hall et al., 2020; OʹNeill et al., 2014). Standard statistical modelling excludes observations with missing data in any variable for complete case analysis (Dohoo et al., 2009). Due to the relatively low incidence risk of heat-related illness, an early decision was made to retain all cases in the analysis by including unknown/missing data in the coding of the variables, to explore as potential risk factors.

Whilst these categories (unknown or missing) may offer little in the way of meaningful conclusions, without them the number of HRI events included in both studies would be reduced resulting in lower precision in the results, particularly for the multivariable analyses. For example, the data completeness for adult bodyweight was 66% therefore excluding any HRI events without a bodyweight record would have reduced the case population by a third. Severe HRI is a true veterinary emergency requiring urgent triage and aggressive management, meaning that obtaining a bodyweight for the patient may be overlooked especially for large breed dogs that are challenging to weigh when unconscious. Additionally, adult was defined as 18 months so any dogs that had not reached this age would not have an adult bodyweight recorded. Excluding cases without a bodyweight could therefore have skewed the remaining cases in the analysis to include fewer severe events or to exclude younger dogs.

An important consideration missing in these veterinary record-based studies are the owner factors potentially influencing a dog's HRI risk. Whilst younger dogs and male dogs were identified as being at increased risk of exertional HRI in Chapter Six, it is possible this increased risk is due to an owner factor rather than a biological factor. Anecdotally, owners participating in certain canine sports (e.g., canicross) may be more likely to acquire a male dog, as they tend to be larger (thus providing more pull when racing), and unlike bitches the dog's sport participation is not interrupted by oestrous. Consequently, the increased risk of exertional HRI for male dogs may be due to their increased exposure to intense exercise due to their owner's lifestyle. The increased risk of exertional HRI for young dogs may also be influenced by people's inclination to acquire dogs as puppies (Diverio et al., 2016; King et al., 2009), and evidence that many people do little to no research prior to acquiring a dog (Holland, 2019). As a result, young dogs owned by first time dog owners may be at increased risk because their owner does not understand how to prevent or recognise HRI. Glanville et al. (2023) propose that this lack of "problem awareness" (e.g., failing to understand the risk factors for HRI) can be a threat to canine welfare, despite most dog owners demonstrating a strong sense of duty of care towards their pet. Further research to explore how owner factors influence canine HRI risk is therefore needed, as owner behaviour change may be a critical factor in preventing HRI in dogs (Glanville et al., 2023).

The absence of a definitive diagnostic test or criteria for identifying HRI in dogs creates an element of uncertainty in the reliability of the data (Hall et al., 2020). The inclusion criteria for the HRI events required the veterinary surgeon to make a diagnosis of HRI and/or report the presentation of clinical signs typical of HRI triggered specifically by exposure to a hot environment, physical exertion, or both (Hall et al., 2020). As reported in Chapter Six, 30% of the HRI events had no specific trigger recorded in the patient history (Hall et al., 2020) meaning that these events were included on the basis of the veterinary surgeon's diagnosis. It is therefore likely that more true HRI events occurred that were not recognised as HRI due to the lack of a patient history that included exposure to a hot environment and/or exercise. This may have been due to owners not recognising the different triggers of HRI. It is also possible that some owners withheld information relating to the trigger of their dog's condition through fear of reprisal or guilt, meaning that the true incidence of HRI was likely higher than reported. Razzak et al., (2022) explored the impact of a human HRI educational campaign targeting at risk populations on hospital visits for HRI during the summer and reported a 38% reduction in visits from communities that received the educational intervention. The educational campaign focused on risk factors, early recognition, and prevention of HRI. Razzak et al., (2022) demonstrated the importance of public awareness of risk factors and recognition of disease when planning strategies to reduce HRI incidence, and the results from Chapter Six suggest that the same strategies could also be of welfare benefit for dogs.

Conversely, it is possible that some of the HRI events included in the current study were misclassified and not true HRI events, but another disorder misdiagnosed by the attending veterinary surgeon. This is an inherent challenge when using primary-care data and when researching a disorder for which there is no definitive diagnostic test. As a result, the incidence reported in Chapter Five fails to take into consideration the effects of false positive and false negative HRI diagnoses. Bayesian statistical techniques take into account data uncertainty and variability to derive true incidence values (Gardner, 2002), and have been used to overcome this challenge (O'Neill et al., 2013). However, as Bayesian techniques rely upon prior knowledge such as previous estimates of incidence and risk factor analysis, where this evidence is limited or lacking the resulting Bayesian analysis may be flawed (Gardner, 2002). Epilepsy - another disorder for which there is no definitive diagnostic test – has an estimated prevalence of 0.62% and is the most common chronic neurological condition in UK dogs (Kearsley-Fleet et al., 2013). The lack of a definitive diagnostic test has potentially acted as a barrier to canine epilepsy research, with few studies exploring canine risk factors for epilepsy or reporting disease prevalence until Kearsley-Fleet et al., (2013) published their study using VetCompass clinical data. Whilst relying upon clinician expertise for diagnosing and identifying true cases introduces uncertainty into the data and may result in both false negative diagnoses being missed and false positive diagnoses being included, ultimately there is no alternative available if these diseases are to be researched.

Learning to manage incomplete and potentially uncertain data was an important part of my personal development throughout the completion of this thesis. My undergraduate scientific training instilled a strong positivist epistemological approach to research methods, with a desire to seek reliable answers and deduce meaning through hypothesis testing using carefully controlled studies. My veterinary education did not formally acknowledge any deviation from this positivist approach, but introduced the concept of uncertainty through evidence-based veterinary practice (Holmes & Cockcroft, 2004). The goal of evidence-based practice is to use the best available scientific evidence to support decision making to optimise patient care, whilst also considering the veterinary professional’s expertise, the wishes of the animal’s carer and the animal’s tolerance of potential interventions to ensure a holistic approach to patient care (Holmes & Cockcroft, 2004). The definition of evidence-based veterinary medicine highlights the importance the veterinary professional and the owner, in other words the importance of people, and thus the need for humanities when considering the practice of veterinary medicine. Veterinary medicine cannot exist without the people who own, farm or care for the animals presented for treatment, nor the veterinary professionals themselves and is therefore subject to the complexity that results from human emotions, motivations and interactions (Desmond, 2022). Studies that use veterinary practice data are therefore also subject to that same human influence and complexity, better suited to a more interpretive ontological approach and constructivist epistemology. I therefore took a pragmatic approach to Sections IV and V of this thesis, acknowledging the complexity and uncertainty of the data whilst interpreting the patient histories to identify HRI events, whilst still retaining a postpositivist desire to quantitatively explore the incidence, fatality rate, triggers and risk factors associated with the condition.

Since completing Chapters Five and Six, I have also used another primary-care veterinary practice research database to explore HRI in companion animals. The Small Animal Veterinary Surveillance Network (SAVSNET) was established by the University of Liverpool in partnership with the British Small Animal Veterinary Association and collects data from both veterinary diagnostic laboratories and data from veterinary practices in the UK (O'Neill et al., 2014). A key difference between the VetCompass program and SAVSNET is that SAVSNET records individual diarised veterinary consultation records rather than broader veterinary patient electronic records that also include non-diarised consultations, surgeries, telephone calls, repeat prescriptions and follow-up clinical notes (Hall, Radford, et al., 2022). This reduces the scope for long-term follow-up of outcomes which limits the estimation of incidence or fatality rate as date of death cannot be confirmed. Despite differences between the two research databases, a review of HRI events presenting to UK veterinary practices participating in SAVSNET between 2013-2018 identified similar findings to those reported in Chapters Five and Six, thus providing validation of the results from the VetCompass studies (Table IV.1).

Table IV.1. A comparison of key findings from studies exploring heat-related illness in UK dogs using two research databases, VetCompass and SAVSNET.

Finding	**Results from Chapters Five and Six using VetCompass data from 2016 and including events from 2016-2018** (Hall et al., 2020; Hall et al., 2020)	**Results from SAVSNET data using data and events from 2013-2018** (Hall, Radford, et al., 2022)
Number of canine HRI events identified	856	146
Estimated incidence risk	0.04% (2016)	Unable to calculate
Event fatality rate	14.18%	Unable to calculate
Event trigger not recorded in patient record	30.2%	32.2%
Common triggers of HRI (% of cases with known triggers)	Exertion: 74.2% Environment: 12.9% Vehicle confinement: 5.2%	Exertion: 73.5% Environment: 19.6% Vehicle confinement: 6.9%
Distribution of clinical grade of HRI events	Mild: 39.9% Moderate:46.1% Severe: 14.0%	Mild: 32.1% Moderate: 53.7% Severe: 14.2%
Seasonality of cases	Events occurred all year round 35.4% of events during July	Events occurred between April and October 42.5% of events during July

In both Chapters Five and Six logistic regression modelling was reported to be used as a method of *exploring* risk factors for HRI in dogs. Potential risk factors were identified from data available about each dog (breed, age, bodyweight etc.), and were tested with the goal of producing the simplest model possible, whilst retaining the model's predictive ability, through stepwise elimination of variables. Attempting to predict outcomes through model development that do not consider the underpinning plausibility of the model variables can lead to important risk factors being rejected from the model if they are less predictive that other variables (Greenland & Pearce, 2015). The models presented in Chapters Five and Six are therefore likely to be overly simple, with potentially important risk factors missing, and confidence intervals that are too narrow.

Chapter Five was originally prepared for publication using an information theory approach to model development (Guthery et al., 2003), and using the Akaike information criterion (AIC) value for final model selection. This approach to model development and selection still favours model simplicity and is likely to result in narrow confidence intervals (Greenland & Pearce, 2015). However, the information theory approach considers a priori knowledge of risk factors for HRI in dogs and formally acknowledges that biological models can only produce an approximation of the explainable information based on the available data (Guthery et al., 2003). The risk factor analyses presented in both Chapters Five and Six use hypothesis testing (p-values) as a basis for model selection, and therefore likely omit important risk factors from the final models (Greenland & Pearce, 2015). Additionally, this approach typically results in overstated significance, with small p-values and narrow confidence intervals which can lead to false positive results being reported and poorer predictive power for the resulting model (Greenland & Pearce, 2015). For example, in Chapter Six in the analysis of risk factors for environmental HRI, the final model excluded bodyweight relative to breed/sex mean, despite obesity/being overweight negatively impacting thermoregulation and heat dissipation (Durkot et al., 1986; Flournoy et al., 2003; Hemmelgarn & Gannon, 2013) and being identified as a risk factor for HRI (regardless of trigger) in Chapter Five and a risk factor for death in dogs with HRI by Bruchim et al. (2006).

IV.3 Reception of the published work

At the time of writing, Chapter Five remains the largest published study to report incidence risk, fatality rate and canine risk factors for HRI using UK primary-care veterinary record data. Prior to the publication of Chapter Five, previous studies predominantly reported only case series of dogs affected by the most severe form of HRI – heatstroke – and used only referral veterinary hospital data (Bruchim et al., 2006; Drobatz & Macintire, 1996; Segev et al., 2015; Teichmann et al., 2014). Chapter Five also included all dogs affected by HRI, including all grades of the conditions (from mild to severe), resulting in a larger HRI case population to use for risk factor analysis than would have been possible using only severe cases. Previous HRI studies have used referral hospital caseloads, meaning that it has not been possible to conduct population level analyses due to the lack of an underlying sampling frame from which these referrals were elicited and that reflects the wider dog population (Bartlett et al., 2010). The use of Big Data via the VetCompass database enabled multivariable analyses from a dataset including approximately 10% of the total UK dog population to identify canine risk factors for HRI applicable to the general population, which aligned with some previously reported risk factors such as brachycephalic skull shape (Bruchim et al., 2006), but differed in relation to the identification of at-risk breeds.

One important outcome from the publication of Chapter Five was the creation of an infographic to help illustrate and disseminate the results of the study (Figure IV.1). This infographic was shared on the Hot Dogs blog site and social media channels and served to provide a visual identification of the breeds with increased risk of HRI. People’s responses to environmental hazards (such as heat waves) depends on the activation of three core perceptions: environmental threat, hazard adjustment and social stakeholders (Lindell & Perry, 2012). These perceptions include the identification of personal relevance - e.g., my dog is a breed that has increased risk of HRI - as a key stage in the risk assessment process which can protect motivation to follow advice that aims to reduce risk from the hazard (Lindell & Perry, 2012).

Individuals must first recognise the hazard communication, attend to it, then process both the risk information and the recommended actions to reduce risk. Visual cues that include colours and text formatting can help to draw attention to hazard communication, increasing the likelihood that the observer will engage with the message (Sutton & Fischer, 2021). Distilling the essential information from Chapter Five into an infographic thus helped to create a visual cue to trigger recognition and personal relevance for dog owners (Figure IV.1). When speaking to canine sports participants at events and HRI webinars, Greyhound and Springer Spaniel owners are quick to highlight that their dog is one of the “at risk breeds”, demonstrating the reach of the infographic and the impact it has had on highlighting risk within the canine sports community.

The 9 dog breeds at increased risk of heatstroke

Dog's don't just overheat in hot cars. Exercising in hot weather can be just as dangerous and can prove fatal.

• Is my dog more at risk of heatstroke? •

Nine breeds at particular risk:

1. Chow Chow
2. Bulldog
3. French Bulldog
4. Dogue de Bordeaux
5. Greyhound
6. Cavalier King Charles Spaniel
7. Pug
8. English Springer Spaniel
9. Golden Retriever

Brachycephalic (flat faced) dogs in general had twice the risk of heatstroke.

For more information and advice on keeping your dog safe, visit

www.heatstroke.dog

The full paper is available at Hall, E.J. Carter, A. and O'Neill, D. (2020) Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016. Scientific Reports.

Infographic designed by www.PawPrintsPosters.com

RVC Royal Veterinary College University of London

NTU

Figure IV.1. The infographic produced following publication of Chapter Five, illustrating the nine breeds at increased risk of heat-related illness. The PDF version includes a link to the published paper.

Chapter Six is the first study to report the most common trigger of HRI of UK dogs, with over 70% of HRI events triggered by exercise - predominantly walking (Hall et al., 2020). Prior to this study, the predominant public awareness campaigns relating to HRI in UK dogs focused exclusively on the message that "Dogs Die in Hot Cars" (BVA, 2019; Duggal, 2018). Following discussions with the organisations that manage this campaign (including the British Veterinary Association, RSPCA, Dogs Trust, Blue Cross and The Kennel Club), in 2022 the national educational campaign was updated to include two core messages:

- Dogs Die in Hot Cars – an active message asking members of the public to take action and call the police if they find a dog trapped in a hot car.
- Dogs Die on Hot Walks (Figure IV.2) – an empowering message asking dog owners to take responsibility for ensuring their dog's health and welfare by making safer decisions relating to the time, type, intensity and duration of exercise they plan for their dog during hot weather (Hall, Carter, et al., 2022).

Figure IV.2. The "Dogs Die on Hot Walks" logo released in the UK for the national 2022 canine heat-related illness awareness campaign.

Updating public education campaign messaging is a key step in putting the research from this thesis into action to protect canine health and welfare amidst rising global temperatures. A third of the HRI events from Chapter Six had no trigger recorded in the dog's veterinary patient record. This could have been due to a lack of detail in the veterinary clinical records or could have been due to the dog's owner either not knowing or not being willing to report the true trigger of their pet's HRI event. However, the absence of trigger reporting for these events likely also reflects the general public's lack of awareness of the wider triggers of HRI in dogs. From personal engagement with dog owners through educational events, social media, and my work in general veterinary practice, the "Dogs Die in Hot Cars" campaign has led to a perception that dogs *only* die from HRI in hot cars. Some dog owners do not realise that their pet can develop HRI from exercise, or simply through exposure to high ambient temperatures either inside (confinement in a hot building such as a conservatory) or outside (environmental HRI). As the diagnosis of HRI is reliant upon both clinical presentation and a patient history that includes exposure to heat either through exercise or exogenous sources, this lack of awareness of the wider triggers of HRI has likely resulted in dog owners failing to recognise that their pet's illness is due to HRI. This could result in delayed veterinary treatment, delayed action to try and cool the dog, and potentially avoidable progression of the condition (or even death). For this reason, it is likely that the 2016 incidence risk reported in Chapter Five (0.04%) underestimates the true incidence of HRI in UK dogs. Owner education is therefore an essential step in mitigating the increasing risk of HRI as extreme heat events become more frequent.

The lack of definitive diagnostic criteria for HRI in dogs was discussed in Chapter One and has been identified as a key limitation in the studies presented in Chapters Five and Six. Highlighting this evidence gap resulted in the "Hot Dogs" research team being awarded additional funding from the Dogs Trust Canine Welfare Grants to extend this research project to include a review of the clinical signs associated with HRI in dogs, and to explore the geographical risk factors for HRI in UK dogs. This additional funding resulted in two further publications, the first of which is presented in Section V, proposing a novel clinical grading tool for HRI in dogs. The second publication is not formally included in this thesis but is included in the general discussion in Section VI.

Chapter Five Metrics (May 2024):	**Chapter Six Metrics (May 2024):**
Google Scholar Citations: 47	Google Scholar Citations: 31
Scopus Citations: 27	Scopus Citations: 14
Altmetric: 2051	Altmetric: 405

Wider engagement:

Popular press article:

- Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). Nine dog breeds at higher risk of heatstroke – and what you can do to prevent it. *The Conversation*. https://theconversation.com/nine-dog-breeds-at-higher-risk-of-heatstroke-and-what-you-can-do-to-prevent-it-139501

Conference presentations and media engagement:

- Hall, E., Carter, A., & O'Neill, D. (2020). Hot dogs — Which dog types have highest risk of heat related illness in the UK? BSAVA Congress Proceedings 2020 – Clinical Abstracts [online]. 14th May 2020. **https://doi.org/10.22233/9781910443774.49.7**
- Hall, E., Carter, A., & O'Neill, D. (2020). Hot dogs – What triggers fan the flames of heat related illness for UK dogs? BSAVA Congress Proceedings 2020 – Clinical Abstracts [online]. 14th May 2020. **https://doi.org/10.22233/9781910443774.49.8**
- Guest blog for the British Veterinary Association: Hall, E. J., Carter, A. J., & O'Neill, D. G. (2020). 'Dogs die in hot cars and on hot walks' – new evidence on heat-related illness in UK dogs. https://www.bva.co.uk/news-and-blog/blog-article/dogs-die-in-hot-cars-and-on-hot-walks-new-evidence-on-heat-related-illness-in-uk-dogs/
- Carter, A. J., & Hall, E. J. (2020). It's getting hot in here, so take off all your fur? Active Dog Academy [Webinar], July.
- June 2020 – BBC Radio Nottingham Interview on the risk factors for HRI in UK dogs.
- June 2020 – The Pet Buzz (https://thepetbuzz.com/) radio interview on the risk factors for HRI in UK dogs.
- July 2020 – The Weather Channel (USA) – online television interview on the risk factors for HRI in dogs.
- Beard, S., Hall, E. J., Bradbury, J., Carter, A. J., Gilbert, S., & O'Neill, D. G. (2024). Hot Dogs: using UK emergency care veterinary records to identify risk factors for heat-related illness in dogs. BSAVA Congress Proceedings 2024 – Clinical Abstracts, Manchester, UK. 21st March 2024. https://www.bsavalibrary.com/content/chapter/10.22233/9781913859411.ch147

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Section V: How can heat-related illness severity be graded?

V.1 Section introduction:

This section contains the final publication of the thesis and proposes a novel clinical grading tool for assisting with diagnosing and managing heat-related illness (HRI) in dogs. The research study presented in Chapter Seven applies the same VetCompass data as Chapters Five and Six, to now review the presenting clinical signs and then uses relative risk analysis to adapt the Japanese Association for Acute Medicine Heat-Related Illness Classification (for humans) for use on canine patients. The study also critically analyses the utility of presenting body temperature as a diagnostic criterion for HRI. Chapter Seven addresses the evidence gap "*How can heat-related illness severity be graded*?" and is followed by a critical review of the impact the study has had on the veterinary profession.

This Section contains an edited version of the following published study:

Chapter Seven:

Hall, E. J., Carter, A. J., Bradbury, J., Barfield, D., & O'Neill, D. G. (2021). Proposing the VetCompass clinical grading tool for heat-related illness in dogs. *Scientific Reports*, *11*(1), 6828. https://doi.org/10.1038/s41598-021-86235-w

Chapter Seven: Proposing the VetCompass Clinical Grading Tool for Heat-Related Illness in Dogs

This is an edited version of the article published by Springer Nature, Scientific Reports on 25TH March 2021 available online: http://www.nature.com/articles/s41598-021-86235-w

Authors: E. J. Hall, A. J. Carter, J. Bradbury, D. Barfield & D. G. O'Neill

Abbreviations: CI; confidence interval, EPR; electronic patient record, HRI; heat related illness.

Keywords: 1; heat-related illness 2; VetCompass 3 hyperthermia 4 heat stroke 5 heat stress 6 heat exhaustion

7.1 Abstract

Heat-related illness is a potentially fatal condition in dogs. Rapid and accurate recognition of the severity can improve clinical management in affected dogs and lead to better outcomes. This study explored retrospective VetCompass veterinary clinical records to investigate the clinical signs recorded for dogs presenting with heat-related illness to primary-care veterinary practice from 2016-2018. The relative risk of death associated with these clinical signs was reported and used to develop a novel clinical grading tool. From the clinical records of 856 heat-related illness events, the most frequently recorded clinical signs were respiratory changes (68.73%) and lethargy (47.79%). The clinical signs with the highest relative risk of death were neurological dysfunction, gastrointestinal haemorrhage and bleeding disorders. The novel VetCompass Clinical Grading Tool for Heat-Related Illness in dogs defines three grades: mild (altered respiration, lethargy), moderate (gastrointestinal signs, a single seizure, episodic collapse) and severe (neurological dysfunction, gastrointestinal haemorrhage, bleeding disorders). This novel grading tool offers a simple, evidence-based device to improve recognition of heat-related illness in dogs and promote improved decision-making for earlier interventions such as cooling and hospitalisation. This could improve outcomes and protect the welfare of dogs in the face of rising global temperatures.

7.2 Introduction

Heat-related illness (HRI) is a potentially fatal disorder that affects dogs when their thermoregulatory capacity is overwhelmed, resulting in hyperthermia and subsequent thermal tissue damage (Bouchama & Knochel, 2002; Johnson et al., 2006). There are three recognised main triggers (though with some overlap) of HRI in dogs; exertional HRI occurs following exercise in a hot environment or following intense activity (Hall et al., 2020a; Johnson et al., 2006), environmental HRI results from exposure to extreme environmental heat or prolonged exposure to a hot environment (Bouchama & Knochel, 2002; Rogers et al., 2007), and vehicular HRI results from either entrapment or travel in a hot vehicle (Hall et al., 2020a). Both dogs and humans show differing risks for each HRI trigger according to their age, sex, and underlying health status. Young, active male humans (Armstrong et al., 2007) and dogs (Hall et al., 2020a) are at particular risk of exertional HRI, with breeds including the Labrador Retriever, Golden Retriever, Springer Spaniel and Staffordshire Bull Terrier at greater risk than crossbred dogs (Hall et al., 2020a). Older dogs and humans have increased risk of environmental HRI (Hall et al., 2020a; Lewis, 2007), in part because elderly individuals are more likely to have underlying health conditions such as respiratory disease and heart failure (Mattin et al., 2015). Additionally, age-related physiological changes reduce peripheral blood flow and sweat gland function, and thereby limit the effectiveness of homeostatic thermoregulatory functions for effective cooling in older individuals (Balmain et al., 2018). Vehicular HRI particularly affects young children and babies, most frequently following accidental entrapment (Fatima Siddiqui et al., 2020). Vehicular HRI can also affect dogs, but brachycephalic (flat-faced) breeds such as the British Bulldog, Pug and French Bulldog appear particularly susceptible (Hall et al., 2020a), likely because of their inherently reduced ability to thermoregulate resulting from their shortened muzzle and narrowed airways (Lilja-Maula et al., 2017).

The diagnosis of HRI in human medicine traditionally relies upon measurement of body temperature and assessment of neurological function using the “Classical” definitions established by Bouchama and Knochel (2002). These Classical Heat Stroke Criteria define three levels of HRI, rising from mild heat stress (perceived discomfort and physiological strain resulting from mild hyperthermia), to heat exhaustion (moderate illness including weakness, anxiety, fainting, headache and a core temperature that may be elevated up to, but not exceeding 40.0°C) and finally heat stroke (severe illness, body temperature exceeding 40.0°C accompanied by profound neurological dysfunction including delirium, seizures and coma) (Bouchama & Knochel, 2002). These classical criteria, using a body temperature threshold of ≥41.0°C, are also used in veterinary medicine for diagnosing and categorising HRI in animals, most frequently dogs (Bruchim et al., 2006; Flournoy et al., 2003; Johnson et al., 2006), despite their reliance upon clinical signs/symptoms that, in humans, require verbal communication from the patient e.g., headache, dizziness, anxiety and delirium. However, a study of experimentally induced heat stroke in dogs reported 43.0°C as the critical body temperature threshold for inducing clinical, haematological, biochemical and pathological indicators of heat-related illness in dogs (Shapiro et al., 1973). The duration that the dog's body temperature exceeded 43.0°C accurately predicted the risk of death (Shapiro et al., 1973). The lack of consensus in the veterinary literature regarding the critical temperature threshold for HRI in dogs highlights uncertainty in the value and reliability of using body temperature as a diagnostic criterion for HRI.

Following recognition of the limitations from using core body temperature measurement as a diagnostic criterion for the Classical Heat Stroke Criteria in human medicine, a novel HRI staging system was proposed but has not yet been widely adopted for use in humans (Yamamoto et al., 2015). Body temperature can fluctuate rapidly in these emergency-care patients and because cooling is recommended as soon as HRI is considered likely, many humans present for medical assessment after they have been cooled and therefore their temperature has already begun to drop. The Japanese Association for Acute Medicine Heat-Related Illness Classification (JAAMHC) has been proposed as an alternative diagnostic and triage tool for use in human patients with HRI (Yamamoto et al., 2018). This novel classification included clinical symptoms that were more objectively defined, removed the reliance upon body temperature and self-reported symptoms as diagnostic criteria, and acknowledged that HRI is a progressive rather than a static disorder within patients where increasingly severe pathology is developed with ongoing exposure to heat or failure to receive appropriate treatment (available http://www.mdpi.com/1660-4601/15/9/1962/s1) (Yamamoto et al., 2018). Crucially, the JAAMHC novel classification appears better at predicting clinical outcomes for human patients with HRI (Kondo et al., 2019; Yamamoto et al., 2018), enabling more appropriate and targeted treatment following initial triage.

Most canine HRI research has applied a variation of the Classical Heat Stroke Criteria when selecting cases for analysis, and generally included only dogs presented to referral hospitals rather than primary-care practices (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014a). This has tended to exclude dogs presenting with milder clinical signs of HRI from inclusion in studies while favouring inclusion of severe cases requiring advanced levels of care, resulting in research findings that may suffer from referral bias (Bartlett et al., 2010). The HRI case fatality rate reported by these earlier referral-based studies ranged from 36-50 % (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014a), whilst a veterinary primary-care study including dogs with all stages of HRI reported a much lower case fatality rate of 14% (Hall et al., 2020b), highlighting the benefits from primary-care focused research for results that are more generalisable to the wider dog population. No specific triggers for HRI were reported in the clinical records for almost a third of the dogs presented in the primary-care study (Hall et al., 2020a) potentially demonstrating a lack of recognition of early signs of HRI by owners or veterinary professionals. Improved awareness of the triggers of HRI, the clinical signs of mild HRI and the actions needed when a dog presents with HRI should be considered as urgent educational priorities for both owners and veterinary professionals to protect canine welfare in the face of rising global temperatures and increasingly frequent extreme heat events (Bruchim et al., 2017; Mora et al., 2017). Use of the Classical Heat Stroke Criteria definitions that rely on body temperature as a diagnostic criterion may promote continued misdiagnosis because HRI cases that have already begun to cool may be misclassified. This can result in missed opportunities to manage mild or early HRI cases, as noted in human medicine (Yamamoto et al., 2018). Therefore, the current paper proposed that a more objective and staged approach for diagnostic criteria should be explored and then used to develop a more reliable HRI clinical grading scheme in dogs.

This study aimed to i) report the clinical presentations and outcomes of dogs presenting to primary-care veterinary clinics in the UK with HRI, and ii) adapt the JAAMHC novel HRI classification system to develop a new clinical grading system that is based on canine first opinion data and therefore more reliable and applicable for use in the wider population of dogs. The study is presented in three phases to reflect the sequential nature of the work.

7.3 Phase 1 – reviewing the clinical presentation data of dogs affected by heat-related illness

Data collection and management

This study continues the work previously reported in Hall et al. (2020a, 2020b) and used the same dataset described in those studies. The VetCompass Programme collects deidentified electronic patient records (EPRs) from affiliated primary-care veterinary practices in the UK, providing a research database for large scale primary-care studies that includes the clinical records of over 9 million dogs (Anderson et al., 2018; O'Neill et al., 2018, 2019; O'Neill et al., 2014). All dogs under veterinary care during 2016 were included in the current study population as previously defined in Hall et al. (2020b). Candidate cases for HRI were identified by searching EPRs for the following terms: heat stroke~3, heatst*, hyperthermi*, overheat*, over heated~2, heat exhaustion~2, hot car~2, collapse* + heat, cooling, high ambient temp*. Candidate cases were manually reviewed by two authors (authors 1 and 2) to identify all dogs meeting the case definition of HRI and presenting between 1st January 2016 and 31st December 2018 (see Table 7.3.1).

Table 7.3.1. Case inclusion and exclusion criteria used for heat-related illness (HRI) events in dogs presenting to primary-care veterinary practice, defined in Hall et al. (2020b)**.**

Inclusion criteria - Evidence for heat-related illness recorded in the patient record:	Final stated diagnosis or insurance claim for a heat-related illness (including heat stroke, heat stress, heat exhaustion or other synonym), and/or History of at least one of the clinical signs listed below, clinical records indicated that these were associated with exposure to these triggers: exposure to a hot environment, physical exertion or both.
Clinical signs:	• Panting excessively (panting continues despite removal from heat/cessation of exercise) • Collapse not subsequently attributed to another cause (e.g., heart failure, Addison's) • Stiffness, lethargy or reluctance to move • Gastrointestinal disturbance including hypersalivation, vomiting or diarrhoea • Neurological dysfunction including ataxia, stupor, seizures, coma or death • Coagulation disturbances (bleeding disorders) including petechiae or purpura
Exclusion criteria:	Subsequent diagnosis of an infectious or inflammatory condition that was not attributed to primary heat exposure such as kennel cough, pyometra or infectious meningitis. HRI or synonym listed only as one of a differential list. An earlier diagnosis of HRI that was later revised to exclude HRI, for example the dog was diagnosed with epilepsy following further seizure activity.

All confirmed HRI events underwent additional data extraction including: date of the event, date of presentation, presenting clinical signs, duration of treatment, and outcome (survived or died including euthanasia, unknown cause of death and unassisted deaths). For this study, only HRI events occurring between 1st January 2016 and 31st December 2018 were included in the analysis, as events that occurred prior to 1st January 2016 resulted in a survival outcome by definition (Figure 7.3.1).

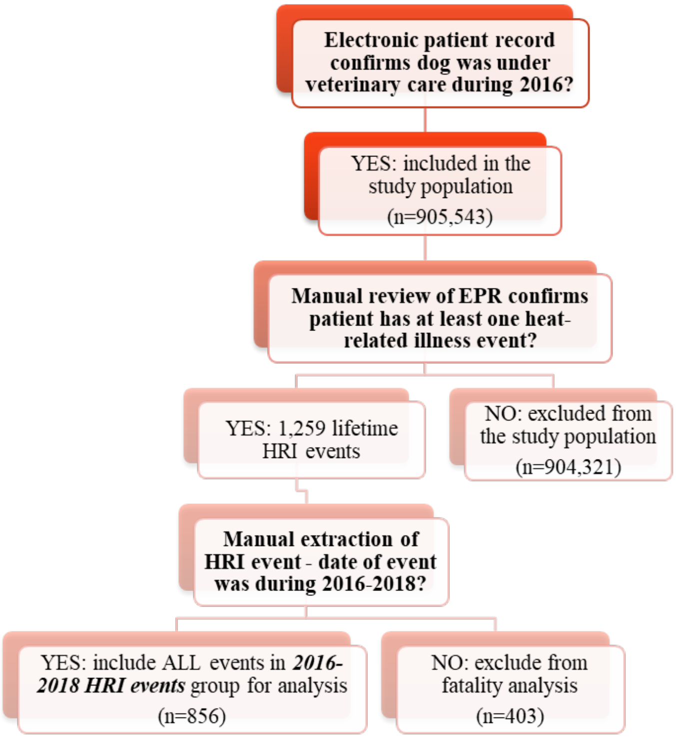


Figure 7.3.1. Flow chart of decisions for event inclusion in heat-related illness (HRI) staging analysis and reporting clinical presentations of HRI in UK dogs.

Investigating the risk of death associated with clinical signs recorded for HRI events

The study included 856 HRI events that occurred between 2016-2018 identified from the EPRs of 828 dogs (28 dogs had two HRI events in this period), from a population of 905,543 dogs presenting to primary-care veterinary clinics in the UK during 2016. The recorded clinical signs extracted for each HRI event were analysed to determine the relative risk of death overall and specifically for unassisted death (see definitions below) for dogs showing each individual clinical sign compared to dogs not showing that clinical sign:

- Death by any mechanism (including unassisted death, unknown method of death and euthanasia)
- Unassisted deaths only (deaths via euthanasia or an unrecorded mechanism were excluded)

Events without at least one clinical sign recorded in the EPR were excluded from the relative risk analysis. Univariable relative risk analysis using the chi squared test was performed using StatCalc v7.2 (Epi Info, Centre for Disease Control and Prevention, https://www.cdc.gov/epiinfo/index.html). Statistical significance was set at $p < 0.05$.

From the 856 HRI events reviewed, 63 events (7.34%) did not have at least one clinical sign recorded and were removed from the analysis. From the 793 EPRs with at least one recorded clinical sign, the most commonly recorded clinical signs were altered respiration (including excessive panting and dyspnoea) (n= 545, 68.73%), lethargy (n = 379, 47.79%) and intermittent collapse (n = 250, 31.5%). Multiple clinical signs were recorded for 560 HRI events (70.6%).

The clinical signs with the highest relative risk of death overall (including euthanasia, unknown method and unassisted deaths) are shown in Table 7.3.2. Dogs presenting with abnormal mentation (including unresponsive, coma, stupor, multiple seizures and status epilepticus), gastrointestinal haemorrhage, petechiae/purpura or ataxia had at least three times the relative risk of death compared to dogs presenting without those clinical signs.

Table 7.3.2. Proportional fatality and relative risk for *death overall* (including euthanasia, unknown method and unassisted) in dogs recorded with specific clinical signs of heat-related illness cases presenting to primary-care veterinary practices in the UK between 2016-2018. Relative risk describes the risk ratio of death in heat-related illness cases recorded with this clinical sign compared to cases without this clinical sign. *CI confidence interval, n = 793

Presenting clinical sign	Clinical sign recorded		Clinical sign not recorded		Relative Risk	95% CI*	P-value
	n	Death n (%)	n	Death n (%)			
Unresponsive	51	43 (84.31)	742	47 (6.33)	13.31	9.85 to 17.98	<0.001
Coma	15	14 (93.33)	778	76 (9.77)	9.55	7.42 to 12.30	<0.001
Stupor	24	17 (70.83)	769	73 (9.49)	7.46	5.33 to 10.45	<0.001
Multiple seizures	12	8 (66.67)	781	82 (10.50)	6.35	4.05 to 9.95	<0.001
Gastrointestinal haemorrhage	27	14 (51.85)	766	76 (9.92)	5.22	3.43 to 7.97	<0.001
Petechiae/ Purpura	18	8 (44.44)	775	82 (10.58)	4.2	2.41 to 7.32	<0.001
Ataxia	14	5 (35.71)	779	85 (10.91)	3.27	1.58 to 6.80	0.002
Respiratory (excessive panting/ dyspnoea)	545	66 (12.11)	248	24 (9.68)	1.25	0.80 to 1.95	0.321
Single seizure	30	4 (13.33)	763	86 (11.27)	1.18	0.47 to 3.01	0.724
Hypersalivation	33	4 (12.12)	760	86 (11.32)	1.07	0.42 to 2.74	0.886
Diarrhoea	76	9 (11.84)	717	81 (11.30)	1.05	0.55 to 2.00	0.887
Vomiting	193	22 (11.40)	600	68 (11.33)	1.01	0.64 to 1.58	0.980
Collapse - intermittent	250	27 (10.80)	543	63 (11.60)	0.93	0.61 to 1.42	0.741
Lethargy	379	21 (5.54)	414	69 (16.67)	0.33	0.21 to 0.53	<0.001

The clinical signs with the highest relative risk of unassisted death are shown in Table 7.3.3. Dogs presenting with abnormal mentation (including unresponsive, coma, profound depression or multiple seizures) also had significantly increased risk of an unassisted death ($p < 0.001$). Dogs with lethargy recorded as a clinical sign for their HRI event had a significantly reduced relative risk of death (overall and unassisted) ($p < 0.001$).

Table 7.3.3. Proportional fatality and relative risk for *unassisted death* (excluding euthanasia) in dogs recorded with specific clinical signs of heat-related illness cases presenting to primary-care veterinary practices in the UK between 2016-2018. Relative risk describes the risk ratio of death in heat-related illness cases recorded with this clinical sign compared to cases without this clinical sign. *CI confidence interval, n = 738

	Clinical sign present		Clinical sign not present				
Presenting clinical sign	n	Unassisted deaths n (%)	n	Unassisted deaths n (%)	Relative Risk	95% CI*	P -value
Unresponsive	29	21 (72.41)	709	14 (1.97)	36.67	20.84 to 64.54	<0.001
Coma	9	8 (88.89)	729	27 (3.70)	24.00	15.51 to 37.13	<0.001
Stupor	12	5 (41.67)	726	30 (4.13)	10.08	4.74 to 21.47	<0.001
Multiple seizures	7	3 (42.86)	731	32 (4.38)	9.79	3.90 to 24.57	<0.001
Gastro- intestinal haemorrhage	15	2 (13.33)	723	33 (4.56)	2.92	0.77 to 11.07	0.115
Single seizure	29	3 (10.34)	709	32 (4.51)	2.29	0.75 to 7.05	0.148
Respiratory (excessive panting/ dyspnoea)	508	29 (5.71)	230	6 (2.61)	2.19	0.92 to 5.20	0.076
Ataxia	10	1 (10.00)	728	34 (4.67)	2.14	0.32 to 14.15	0.429
Petechiae/ Purpura	11	1 (9.09)	727	34 (4.68)	1.95	0.29 to 12.98	0.491
Hyper- salivation	31	2 (6.45)	707	33 (4.67)	1.38	0.35 to 5.50	0.646
Collapse - intermittent	231	8 (3.46)	507	27 (5.33)	0.65	0.30 to 1.41	0.276
Diarrhoea	69	2 (2.90)	669	33 (4.93)	0.59	0.14 to 2.40	0.459
Vomiting	176	5 (2.84)	562	30 (5.34)	0.53	0.21 to 1.35	0.185
Lethargy	363	5 (1.38)	375	30 (8.00)	0.17	0.07 to 0.44	<0.001

Investigating the relative risk of death associated with presenting body temperature measurements for HRI events

Because body temperature at first veterinary presentation is still routinely used as a key criterion for clinical management of HRI in many veterinary settings (Bruchim et al., 2006, 2017; Flournoy et al., 2003; Johnson et al., 2006), the presenting body temperature of survivors versus non survivors was compared using the Mann-Whitney U test following normality testing showing a non-normal distribution of body temperature values. The relative risk of death associated with several body temperature thresholds at presentation was explored as part of the development process for the current novel VetCompass Clinical Grading Tool for Canine Heat-Related Illness (referred to as the VetCompass HRI Grading Tool hereafter). Dogs presenting with a body temperature in one of three critical temperature thresholds (<37.6°C, ≥41.0°C, and ≥43.0°C) were compared to dogs presenting with a normal body temperature: 37.6 – 39.2°C (Werth et al., 2024). For each HRI event, the presenting body temperature was categorised as below, or at/above each of the three thresholds. The relative risk of death overall and the relative risk of unassisted death were calculated for each temperature threshold; HRI events where the presenting body temperature was not recorded in the EPR were excluded from analysis. Dogs that died as a result of euthanasia or unreported mechanisms were excluded from the analysis for relative risk of unassisted death. Associations with hypothermia were also explored because hypothermia has been identified previously as a risk factor for death (Bruchim et al., 2006). The threshold for hypothermia was <37.6°C, aligning with the limit (<37.6°C) used by Bruchim et al. (2006), using 37.6 to 39.2°C as the reference range for normal body temperature; this temperature range was derived from a canine population presenting for routine veterinary care in the UK (Werth et al., 2024).

Body temperature at presentation was recorded for 629 events (73.5%). The median temperature recorded for non-survivors (n = 71), was 41.0°C (IQR: 39.6-42.4°C, range: 35.6-43.3°C) (p<0.001) and was significantly higher than for survivors (n = 558) which was 39.6°C (interquartile range [IQR]: 38.7-40.5°C, range: 34.9-43.4°C). The number of dogs presenting with a body temperature <37.6°C, ≥41.0°C or ≥43.0°C is shown in Table 7.4. Dogs presenting with a body temperature ≥41.0°C or ≥43.0°C had a higher relative risk of death and unassisted death compared to dogs with a normal body temperature on presentation (see Table 7.3.4). Dogs presenting with hypothermia (<37.6°C) did not have a significantly increased relative risk of death (p = 0.110) or unassisted death compared to dogs with a normal body (p = 0.350).

Table 7.3.4. Body temperature category at veterinary presentation as a risk factor for death (all causes) and unassisted death in dogs diagnosed with heat-related illness presenting to primary-care veterinary practices in the UK between 2016-2018. Relative risk describes the risk of death in heat-related illness cases meeting each temperature criterion compared to cases with a normal (37.6 to 39.2°C) temperature. *CI confidence interval.

Temperature	Critical temperature threshold exceeded		Normal temperature		Relative Risk	95% CI*	P -value
	n	Deaths n (%)	n	Deaths n (%)			
<37.6°C	21	3 (14.29)	224	11 (4.91)	2.91	0.88 to 9.62	0.110
≥41.0°C	132	37 (28.03)	224	11 (4.91)	5.71	3.02 to 10.8	<0.001
≥43.0°C	19	14 (73.68)	224	11 (4.91)	15.00	7.94 to 28.34	<0.001
Temperature	**n**	**Unassisted deaths n (%)**	**n**	**Unassisted deaths n (%)**	**Relative Risk**	**95% CI**	**P-value**
<37.6°C	19	1 (5.26)	217	4 (1.84)	2.86	0.34 to 24.28	0.350
≥41.0°C	110	15 (13.64)	217	4 (1.84)	7.40	2.52 to 21.76	<0.001
≥43.0°C	12	7 (58.33)	217	4 (1.84)	31.65	10.72 to 93.4	<0.001

7.4 Phase 2 – adapting the JAAMHC staging criteria for use in canine HRI patients

The clinical symptoms identified in the JAAMHC staging criteria for human HRI were adapted for application to dogs in the current study (see Table 7.4.1) to create the novel VetCompass HRI Grading Tool. This adaptation was based on differences in physiology between the two species (namely thermoregulatory reliance on panting rather than sweating in dogs) and the evidence base generated from the relative risk analysis for presenting clinical signs reported above. The clinical signs that were associated with significantly increased risk of death overall and risk of unassisted death in the current study (p<0.05) were included in the most severe category, notably: altered mentation (including unresponsive, coma, profound depression, multiple seizures and ataxia) gastrointestinal haemorrhage and petechiae/purpura.

Although the current study did not evaluate laboratory diagnostic results, a previous study of post-mortem findings in dogs that died as a result of HRI reported hepatomegaly in all cases, and hepatic parenchymal necrosis in over half the dogs examined (Bruchim et al., 2009). Renal pathology was also noted in all the dogs examined, ranging from interstitial and glomerular congestion to tubular necrosis in both the proximal and distal convoluted tubules (Bruchim et al., 2009). Abnormal renal and hepatic function were therefore retained in the diagnostic criteria for severe HRI in dogs.

Table 7.4.1. Development of the novel VetCompass Clinical Grading Tool for Heat-Related Illness in dogs, based upon the JAAMHC human heat-related illness scale.

Japanese Association of Acute Medicine Heat-Related Illness Classification stages	Human symptoms	VetCompass Clinical Grading Tool for Heat-Related Illness in dogs grades	Adapted canine clinical signs
Stage I	Dizziness, faintness, slight yawning Heavy sweating Muscle pain, stiff muscles (muscle cramps) Impaired consciousness is not observed	Mild	No impaired consciousness observed Lethargy or stiffness Panting heavily or respiratory distress
Stage II	Headache, vomiting, fatigue, sinking feeling Declined concentration and judgement	Moderate	Vomiting and/or diarrhoea (no blood present), hypersalivation Collapse (intermittent only) A single seizure
Stage III	Includes at least one of the following: Central nervous system manifestation (impaired consciousness, cerebellar symptoms, convulsive seizures) Hepatic/renal dysfunction Coagulation disorder	Severe	Includes at least one of the following: Central nervous system impairment (ataxia, two or more seizures, profound depression, unresponsive, coma) Hepatic/renal dysfunction (confirmed on blood tests) Gastrointestinal haemorrhage Coagulation disorder
Unreported	N/A	Unreported	No clinical signs or diagnostic results recorded in the clinical history

7.5 Phase 3 – Retrospective grading of 2016-2018 canine HRI events using the novel VetCompass Grading Tool

Analysis

All HRI events identified during 2016-2018 were retrospectively classified according to the novel VetCompass HRI Grading Tool defined in Table 5. Where an HRI event had insufficient information recorded in the EPR to allow classification, the event was categorised as "unreported" as per the definition in Table 5. Descriptive statistics and the distribution of cases were compared with the distribution of human HRI events.

The utility of temperature thresholds was explored within the VetCompass HRI Grading Tool. The inclusion of temperature threshold ≥43°C as a severe grade criterion within the VetCompass HRI Grading Tool would have changed the grading of three events: one originally graded mild would have changed to severe and two events originally graded moderate would have changed to severe. None of these events resulted in fatality, and only one of the three events resulted in hospitalisation beyond one day. This suggests limited additional value from adding a temperature threshold ≥43.0°C as a severe grade criterion to the grading tool.

The inclusion of temperature threshold ≥41.0°C as a severe grade criterion within the VetCompass HRI Grading Tool would have changed the grading of 83 (9.70%) of the 856 events; 40 (12.62%) of the 317 events originally graded mild would have changed to severe, and 43 (11.75%) of the 366 events originally graded moderate would have changed to severe. From the 40 events originally graded mild, there was one fatality, an elderly animal the owners elected to euthanise. From the 43 dogs originally graded moderate, there were four fatalities – three of which were unassisted deaths. Of these four dogs, one elderly dog was euthanised due to underlying laryngeal paralysis, one of the unassisted deaths was a dog that had experienced multiple HRI events that year and died under sedation, the remaining two dogs were brachycephalic one of which experienced a cardiac arrest and the other died following a tracheostomy. There were an additional 17 events that resulted in hospitalisation beyond one day, however all these events were discharged after one overnight stay.

This review suggests that the application of temperature thresholds add little additional value to the grading tool and therefore body temperature was omitted from the final VetCompass HRI Grading Tool definitions, in line with similar recommendations from Yamamoto et al. (2015) for human HRI patients.

The distribution of HRI event severity using the novel VetCompass Grading Tool

The distribution of HRI events using the VetCompass HRI Grading Tool is shown in Figure 7.5.1. Overall, 39.92% of classified HRI events were graded mild, 46.10% graded moderate and 13.98% graded severe. In comparison, the distribution of human HRI events presenting to 102 Japanese hospitals during the summer of 2012 classified by the JAAMHC in one paper was 48.86% stage I, 33.24% stage II and 17.90% stage III (Yamamoto et al., 2018). The distribution of canine HRI events between the grades of the VetCompass HRI Grading Tool closely reflected the distribution in human HRI patients reported by Yamamoto et al. (2018).

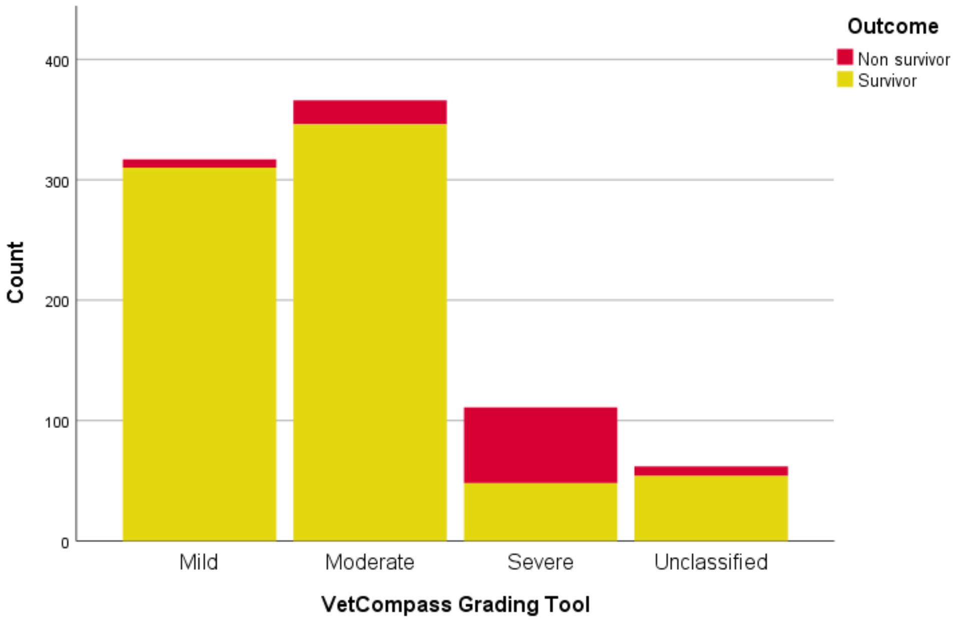


Figure 7.5.1. The event distribution and survival outcomes for HRI grades defined using the VetCompass Clinical Grading Tool for Heat-Related Illness in dogs presenting to primary-care veterinary practices in the UK between 2016-2018.

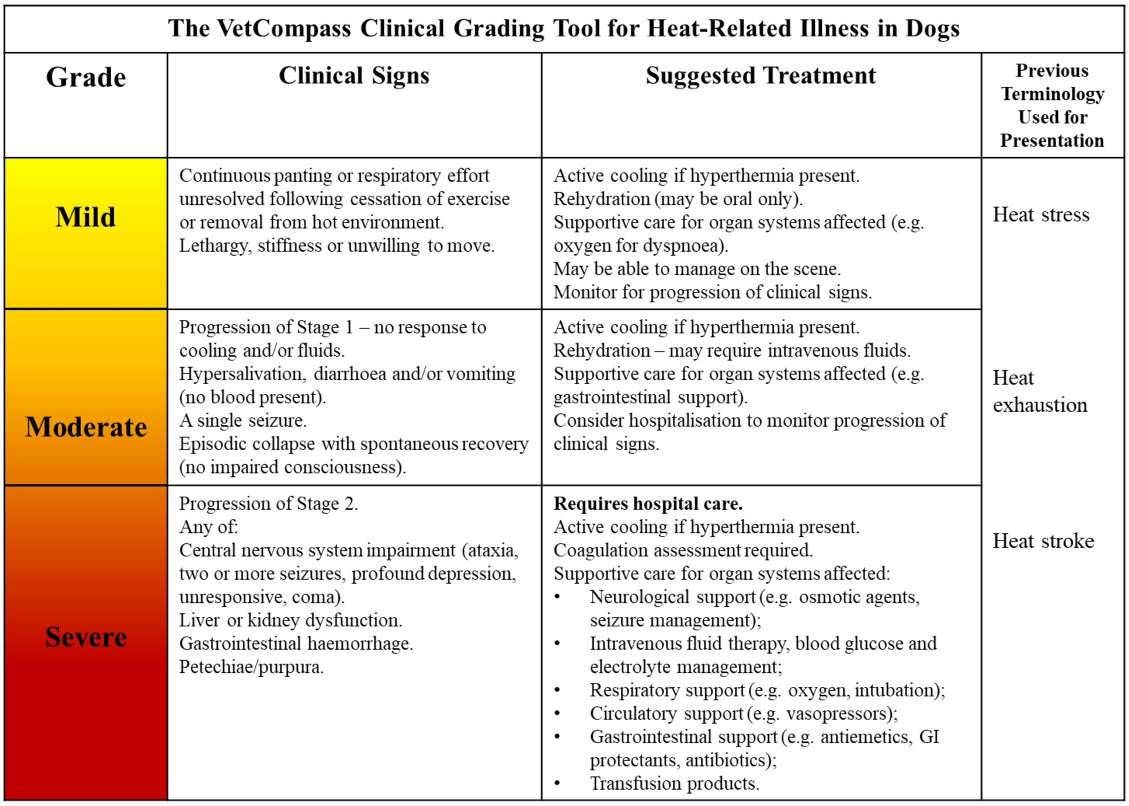
Comparing the fatality rate distribution of canine versus human HRI events

The fatality rate (death overall) for canine HRI events classified using the novel VetCompass HRI Grading Tool was 2.21% for mild events, 5.46% for moderate events and 56.76% for severe events. The unassisted death fatality rate increased from 0.32% in mild events, to 2.19% in moderate events, and 23.42% in severe events.

These fatality rates compare to the findings of a human study using the JAAMHC classification for human HRI events: stage I patients all survived, the fatality rate for stage II patients was 0.7%, increasing to 10.2% for stage III patients (Yamamoto et al., 2018).

The final VetCompass HRI Grading Tool

The final VetCompass Clinical Grading Tool for HRI in dogs (Figure 7.5.2) incorporated clinical signs but excluded presenting body temperature as a defining criterion. Although a presenting body temperature ≥41.0°C and ≥43.0°C were both associated with a significantly increased relative risk of death compared to dogs presenting with lower body temperature, it is the duration of temperature elevation that results in clinical pathology, so a single temperature reading alone is poorly diagnostic of severe illness unless that temperature is above 45.0°C (Shapiro et al., 1973). Clinical management should aim to prevent worsening of the patient's condition through early temperature management, fluid therapy and supportive management of body systems affected (Bruchim & Kelmer, 2018; Hemmelgarn & Gannon, 2013).



The VetCompass Clinical Grading Tool for Heat-Related Illness in Dogs			
Grade	**Clinical Signs**	**Suggested Treatment**	**Previous Terminology Used for Presentation**
Mild	Continuous panting or respiratory effort unresolved following cessation of exercise or removal from hot environment. Lethargy, stiffness or unwilling to move.	Active cooling if hyperthermia present. Rehydration (may be oral only). Supportive care for organ systems affected (e.g. oxygen for dyspnoea). May be able to manage on the scene. Monitor for progression of clinical signs.	Heat stress
Moderate	Progression of Stage 1 – no response to cooling and/or fluids. Hypersalivation, diarrhoea and/or vomiting (no blood present). A single seizure. Episodic collapse with spontaneous recovery (no impaired consciousness).	Active cooling if hyperthermia present. Rehydration – may require intravenous fluids. Supportive care for organ systems affected (e.g. gastrointestinal support). Consider hospitalisation to monitor progression of clinical signs.	Heat exhaustion
Severe	Progression of Stage 2. Any of: Central nervous system impairment (ataxia, two or more seizures, profound depression, unresponsive, coma). Liver or kidney dysfunction. Gastrointestinal haemorrhage. Petechiae/purpura.	**Requires hospital care.** Active cooling if hyperthermia present. Coagulation assessment required. Supportive care for organ systems affected: • Neurological support (e.g. osmotic agents, seizure management); • Intravenous fluid therapy, blood glucose and electrolyte management; • Respiratory support (e.g. oxygen, intubation); • Circulatory support (e.g. vasopressors); • Gastrointestinal support (e.g. antiemetics, GI protectants, antibiotics); • Transfusion products.	Heat stroke

Figure 7.5.2. The novel VetCompass Clinical Grading Tool for Heat-Related Illness in Dogs.

7.6 Discussion

This study reports that the most commonly recorded clinical signs in UK dogs with HRI presenting to primary-care veterinary practices were respiratory changes (excessive panting/dyspnoea) and lethargy. This is a key finding to assist dog owners, as early recognition of these milder clinical signs could allow them to take earlier action to prevent worsening of their pet’s condition and prevent progression of the HRI. We also report that the clinical signs associated with the highest relative risk of death (both overall and unassisted) were abnormal mentation including unresponsive, coma, stupor and multiple seizures (including status epilepticus). The results from relative risk analysis were applied as an evidence base to support an adaptation of the JAAMHC classification for human HRI events to create the novel VetCompass Clinical Grading Tool for HRI in dogs.

Previous veterinary studies of HRI in dogs have tended to focus on the most severe subset of cases, using the Classical Heat Stroke Criteria heat stroke definition to determine case inclusion criteria (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014b). These studies were generally restricted to dogs referred for specialist care, and so are poorly representative of the overall canine population. For this reason, we elected to compare the distribution of canine HRI events in the current study to the distribution of human HRI events reported in a study from Japan (Yamamoto et al., 2018) rather than to previously reported studies in dogs. The progressive nature of HRI should theoretically result in the majority of HRI events being classed as stage I, with fewer events classed as stage II, and the minority of events progressing to stage III, especially as public awareness of HRI has increased the likelihood of early interventions such as cooling and removal from hot environments (Scarneo-Miller et al., 2020). More canine HRI events were classified as moderate than mild compared to the human results, which may represent a variety of owner-related factors. Increased public awareness of HRI through national campaigns may have resulted in more owners managing milder cases at home rather than seeking active veterinary care. The impacts from financial costs of veterinary consultation may also play a role here: owners may preferentially present more severe cases for veterinary care because they perceive the clinical risk justifies the financial outlay whereas they may choose to monitor and manage milder cases on their own. This could drive a relative underreporting of milder HRI in UK dogs. It is also possible that some owners either did not recognise mild HRI events, or as suggested by Packer et al. (2019), brachycephalic owners may in fact perceive mild HRI as “normal for their breed of dog”.

The clinical signs included in the Grading Tool for severe HRI reflect the pathological findings reported in a study of 11 dogs that died (ten unassisted deaths and one euthanasia) as a result of HRI in one referral hospital (Bruchim et al., 2009), namely evidence of a coagulopathy, gastro-intestinal mucosal necrosis, renal damage, hepatopathy and brain damage. The presence of petechiae/purpura suggests a coagulopathy had developed, a consequence of endothelial damage from both thermal injury to cells and also secondary hypoperfusion, shock and systemic inflammatory response (Bouchama & Knochel, 2002; Bruchim et al., 2009). Disseminated intravascular coagulopathy (DIC) is a life-threatening syndrome that occurs when widespread activation of the coagulation system is triggered alongside dysregulation of thrombin generation (e.g. a hypercoagulable to a hypocoagulable state) (Levi & ten Cate, 1999). Heat-related illness can trigger DIC, as reported by Bruchim et al. where all of the dogs examined post-mortem were found to have developed DIC as a result of their HRI (Bruchim et al., 2009). A mortality rate of 62.5% has been reported for dogs with overt DIC (three or more coagulation variable abnormalities detected during clinical screening) triggered by a variety of inciting disorders including HRI (Goggs et al., 2018). It is therefore appropriate that the clinical signs of petechiae/purpura were included in the criteria for severe HRI in dogs, as it is for humans (Yamamoto et al., 2015).

Histopathological examination of the brains and meninges of dogs that died as a result of HRI revealed mild to severe oedema and hyperaemia in all sections examined from all dogs in the previous study (Bruchim et al., 2009). In another study of dogs presenting to a referral hospital with HRI, cases presenting with profoundly altered mentation (obtunded or comatose) had a fatality rate of 70%, and the dogs that presented with disorientation or stupor had a fatality rate of 41% (Bruchim et al., 2006). In the present study, all clinical signs indicative of altered mentation had a significantly increased relative risk of both death overall and unassisted death, and are therefore included in the severe HRI criteria in the current grading tool.

Altered respiration was the most frequently recorded clinical sign for all dogs with HRI in the present study. Pulmonary oedema and hyperaemia were noted in all the deceased dogs examined at post-mortem by Bruchim et al. (2009), and tachypnoea was reported in around 80% of the dogs presented to the same referral hospital with heat stroke (Bruchim et al., 2006). However, altered respiration including panting heavily or respiratory distress, was not associated with an increased relative risk of death or unassisted death in the present study. As panting is a key thermoregulatory mechanism in dogs for cooling, this clinical sign will be present in all conscious dogs with hyperthermia at some point during a HRI event and is therefore included in the criteria for mild HRI in the grading tool. Comatose dogs cease panting, which likely contributes to their reduced rate of cooling when immersed in cold water (Magazanik et al., 1980), and potentially contributes to the increased fatality rate in dogs that developed impaired mentation as a result of HRI.

The findings of the present study support the recommendations of recent human HRI studies (Yamamoto et al., 2015, 2018) that body temperature should no longer be considered a reliable diagnostic criterion for staging HRI in dogs. Body temperature can fluctuate rapidly, especially when active cooling methods have been applied prior to clinical assessment (Demartini et al., 2015). There are also conflicting results on the associations between body temperatures per se and pathological changes in dogs. In a study of anaesthetised dogs, prolonged (90 minutes) whole body hyperthermia at 42.5°C failed to induce histopathological or clinically significant neurological disturbance, when other physiological responses to hyperthermia (for example respiratory alkalosis or reduced blood pressure) were prevented (Oglesbee et al., 2002). Post exercise body temperatures of 42.5°C have also been reported in dogs showing no clinical signs of HRI (Carter & Hall, 2018; Robbins et al., 2017). Experimental heat stroke studies carried out on dogs in the 1970s suggested that 43.0°C is the critical temperature threshold for canine HRI (Shapiro et al., 1973). In a series of inhumane experiments that involved exposing dogs to ambient temperatures of 50.0°C both with and without physical exertion until they collapsed, a body temperature of 43.0°C was reported as the critical limit for clinical effects. Dogs that did not exceed a body temperature of 43.0°C had no clinical or clinicopathological signs of HRI, whilst dogs that developed a body temperature >44.0°C all died of heat stroke. The longer a dog had a body temperature >43.0°C, the greater the likelihood of death. The previously proposed critical body temperature threshold of >41.0°C for diagnosis of HRI can therefore no longer be considered appropriate. Any dog with a temperature approaching 41.0°C should be actively cooled as a matter of urgency, but clinical signs should be used to then determine the severity of HRI present.

Hypothermia on presentation has previously been reported as being associated with an increased fatality rate (Drobatz & Macintire, 1996). However, Drobatz and Macintire (1996) clarified that it was not possible to determine if hypothermia due to cooling contributed to the poor outcome, or if hypothermia was instead an effect of poor tissue perfusion caused by profound clinical disease. In the present study, hypothermia on presentation did not increase the risk of death (overall or unassisted death), reflecting the findings of Bruchim et al. (2006). Many veterinary texts caution against aggressive, rapid cooling of dogs with HRI due to a perceived hazard of hypothermia (Boag & Marshall, 2020; Drobatz, 2015; Newfield, 2019). However, from the current study, it appears hypothermia does not increase the fatality risk for dogs, when compared to dogs with a normal body temperature (37.6 to 39.2°C). In humans with exertional HRI, cold water immersion is the gold standard treatment (Casa et al., 2007). Rapid (within minutes of collapse) initiation of cooling using cold (10°C) water immersion until the patient's body temperature dropped below 38.8°C was associated with 100% survival rate in one study of over 200 HRI events (Demartini et al., 2015). In dogs, work to date has included the use of warm water (30°C) immersion to effectively cool dogs with exertional hyperthermia but not HRI(Davis et al., 2019), and dogs with experimentally induced HRI cooled with a range of water temperatures (Magazanik et al., 1980). The latter study reported that tap water (15-16°C) achieved the fastest rate of cooling in conscious dogs with HRI, but found that comatose dogs cooled at a slower rate due to the cessation of panting (Magazanik et al., 1980). As drowning is a risk to any HRI patient undergoing water immersion, especially patients with central nervous system impairment, constant monitoring is needed to ensure the head remains above the water level (Casa et al., 2007; Hemmelgarn & Gannon, 2013).

A novel severity scoring system has been proposed previously for dogs with HRI by Segev et al.(2015). However, that scoring system required comprehensive laboratory analysis including prothrombin and activated partial thromboplastin time, blood glucose, biochemistry, and haematology analysis, and required the use of a statistical model to determine the overall patient score. This reliance on laboratory tests requires the dog to be physically presented to the veterinary practice in order to take the samples, and the owners to be both willing and able to pay for the tests before the score can be determined. As noted in that study's limitations, the scoring system proposed by Segev et al. is aimed at assisting decision making for only the most severe of cases, and requires further testing before it can be deemed a reliable model (Segev et al., 2015).

In contrast, the novel VetCompass HRI Grading Tool proposed in the present study aimed to create a grading system that could be used by veterinary professionals to triage patients over the telephone or when presenting to the veterinary practice, and that can be used without the need for complex statistical modelling, potentially expensive laboratory testing or indeed any mathematical calculations. The tool could be displayed as a poster (see Figure 3) in veterinary receptions, and be added to the emergency or treatment room as a quick reference guide to assist veterinary staff with decision making and provide advice to owners regarding a potential prognosis for dogs with HRI. It could be adapted as an educational tool to improve public awareness of the early signs of HRI in dogs, to be shared on social media to get to the attention of owners who are the key decision-makers in the early phases of most dogs with HRI. Delayed cooling has been associated with an increased fatality rate in dogs presenting to a referral hospital with HRI (Bruchim et al., 2006), thus improving owners' ability to recognise and promptly respond to signs of HRI in dogs should be considered a priority as global temperatures continue to rise.

This study had some limitations. As noted in previous studies, VetCompass clinical record data are not recorded for research purposes (Hall et al., 2020a, 2020b). As a result, there are missing data within the dataset and descriptive data may be inaccurate or incomplete, because they are reliant upon the history recorded by the attending veterinary surgeon and so can be impacted by factors such as stress and workload, especially when recording clinical notes from emergency patient presentations. For events with an unassisted death, progressive changes in clinical signs may not have been accurately recorded within the electronic clinical history but may instead have been recorded on alternative documentation such as paper-based hospital records or cardiac arrest monitoring charts. Likewise, HRI cases that were euthanised may have limited clinical histories and clinical signs recorded if the owner requested euthanasia early during presentation. Some cases may also have been euthanised before additional clinical signs developed if there were financial constraints on treatment options, or if the dog was elderly or had other underlying health conditions that contributed to the decision to euthanise.

Future evaluation may help to refine the VetCompass HRI Grading Tool further by exploring the tool's predictive ability for other HRI factors such prolonged hospitalisation and dog conformations.

7.7 Conclusion

This study presents the novel VetCompass Clinical Grading Tool developed for dogs with heat-related illness, and aims to improve both owner and veterinary recognition of the progressive clinical signs associated with the disorder. Continued use of the previously available Classical Heat Stroke Criteria should be done with caution because those criteria were not designed for use with canine patients. There is a risk of underestimating the severity of the dog's condition due to a reliance on patient reported symptoms and presenting body temperature rather than observed clinical signs. Continued use of body temperature as a diagnostic criterion cannot be supported, in line with recent human medical advances. The VetCompass HRI Grading Tool offers a quick, practical and evidence-based tool for veterinary professionals to grade HRI cases and should assist in optimising clinical care and the clinical outcomes. As global temperatures continue to rise, uncomplicated triage tools such as the one proposed in this study can help to improve owner understanding and assist in decision making for effective early management when HRI occurs.

Ethics approval: Ethics approval was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652). This project used only data from a research repository, no actual dogs were involved in the project.

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Author Contributions: E.J.H. was responsible for the conception and design of the study, E.J.H., A.J.C. and D.G.O. were responsible for acquisition and extraction of data. E.J.H. carried out the analysis and drafted the manuscript. E.J.H., A.J.C., J.B., D.B., and D.G.O were involved in interpreting the results, revising the manuscript and gave final approval of the version to be published. E.J.H., A.J.C., J.B., D.B., and D.G.O. agree to be accountable for all aspects of the accuracy or integrity of the work.

Data Availability: Original data used for the current study is available: https://researchonline.rvc.ac.uk/id/eprint/13572/

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V.2 Critical appraisal of the study methods – Chapter Seven

This thesis began with the goal of better understanding the risk factors for heatstroke specifically in those dogs participating in human-canine sports. The first stage in commencing this research project was to better understand "*heatstroke*" as a clinical condition, resulting in the recognition that heatstroke is more accurately defined as the most severe (and often fatal) form of the progressive disorder heat-related illness (HRI). This definition has only recently been applied to human medicine (Yamamoto et al., 2015, 2018), and the clinical criteria used to differentiate mild, moderate and severe HRI in humans are subject to ongoing evaluation and refinement (Kondo et al., 2019).

In canine medicine, the majority of clinical textbooks and previous research used the classical heatstroke definition and diagnostic criteria for these more severe HRI cases (Bruchim, 2012; Drobatz & Macintire, 1996; Mazzaferro, 2017), which is based on human heatstroke criteria (Bouchama & Knochel, 2002). As previously noted, these human heatstroke criteria are largely based on patient reported clinical symptoms rather than objective observable clinical signs, meaning that they cannot be readily applied to canine patients. As a result, the initial inclusion criteria used to identify HRI cases in the VetCompass dataset were based on a potentially flawed model that used human heatstroke diagnostic criteria and the results of relatively small canine case series carried out in university teaching hospitals (Bruchim et al., 2006; Drobatz & Macintire, 1996; Teichmann et al., 2014). Therefore, the initial "heatstroke" based inclusion criteria may have resulted in some HRI cases being missed during the initial VetCompass database search. These previous heatstroke diagnostic criteria were also being used by the practicing clinicians, so it is probable that undiagnosed HRI cases went unreported in the dataset. As noted in Section IV, this an inherent challenge when using primary-care data.

Whilst HRI is a growing concern due to rising global temperatures and increasingly frequent and extreme heat-wave events (Raymond et al., 2020), HRI remains a relatively uncommon medical diagnosis in both humans and dogs in the UK. The estimated incidence risk of severe HRI in people living in the UK during 2017-2018 was around 0.005% (NHS, 2019), similar to the 2016 incidence risk of severe HRI in dogs of around 0.006% (95% CI 0.005 to 0.008%) (Hall et al., 2022). With only one in every 12,000-20,000 dogs affected by severe HRI each year, individual veterinary hospitals or clinics may treat only one or two HRI cases annually. Thus, individual clinicians have a limited opportunity to experience managing HRI cases, and there are insufficient cases to generate case series to support clinical research into the condition. As a result, previous canine HRI studies have been limited to regions with a warmer climate, using referral hospital patient populations that accrue severe cases referred from several practices (Bruchim et al., 2006, 2016; Bruchim, Kelmer, et al., 2017; Drobatz & Macintire, 1996). Population level data is critical to generate sufficient case numbers on relatively rare disorders to enable meaningful statistical analyses without substantial selection bias, and this thesis presents the first body of research to use UK population level data for this purpose to explore HRI. The relatively low incidence of canine HRI has therefore created a "chicken and egg" conundrum with the need for population level data to support research exploring the clinical presentation of HRI in dogs, but in order to identify those dogs affected by HRI within that population a set of inclusion criteria needed to be defined which were based on likely flawed human heatstroke criteria. A pragmatist approach was once again needed to approach this conundrum, meaning that Chapter Seven is, as the title suggests, a proposal, not a finalised tool ready for immediate deployment into practice, and therefore in need of further evaluation.

The initial rationale for omitting body temperature within the Clinical Grading Tool was based on body temperature not being included in the JAAMHC staging criteria for human HRI (Yamamoto et al., 2015), and numerous studies highlighting the importance of repeated (or preferably continuous) body temperature measurements for assessing dogs' HRI risk (Davis et al., 2019; Hall et al., 2020; Shapiro et al., 1973). However, as body temperature was included in previous canine heatstroke case criteria, it was included in the analysis. Shapiro et al. (1973) reported that all dogs with a body temperature measurement ≥44.0°C died in their study of dogs with experimentally induced heatstroke, whilst both duration and elevation above 43.0°C contributed to fatal outcomes for dogs with temperatures that did not exceed 44.0°C. As a single point in time temperature measurement can indicate elevation beyond the critical limit, but not the duration of temperature elevation, it could be argued that temperature measurement at presentation is therefore of limited predictive value. The inclusion of temperature thresholds within the Clinical Grading tool was therefore subjected to additional consideration and ultimately rejected. However, by the same reasoning each of the clinical signs evaluated for inclusion in the grading tool can be caused by other aetiologies unrelated to hyperthermia, meaning they are all imperfect as predictors of HRI severity. The rationale for excluding temperature from the grading tool was therefore flawed. As dogs presenting with body temperatures of ≥41.0°C or ≥43.0°C had significantly increased risk of death and unassisted death compared to dogs with a normal body temperature, arguably body temperature ≥41.0°C should have been added to the clinical signs of severe HRI in the Clinical Grading Tool. Whilst hypothermia was included in the evaluation of critical temperatures, it is largely induced following the use of cooling interventions (a treatment for HRI) rather than part of the normal aetiology of HRI. Hypothermia should therefore be omitted from further evaluation for inclusion in the Clinical Grading Tool, and instead be considered separately as a part of ongoing patient monitoring and management rather than initial triage.

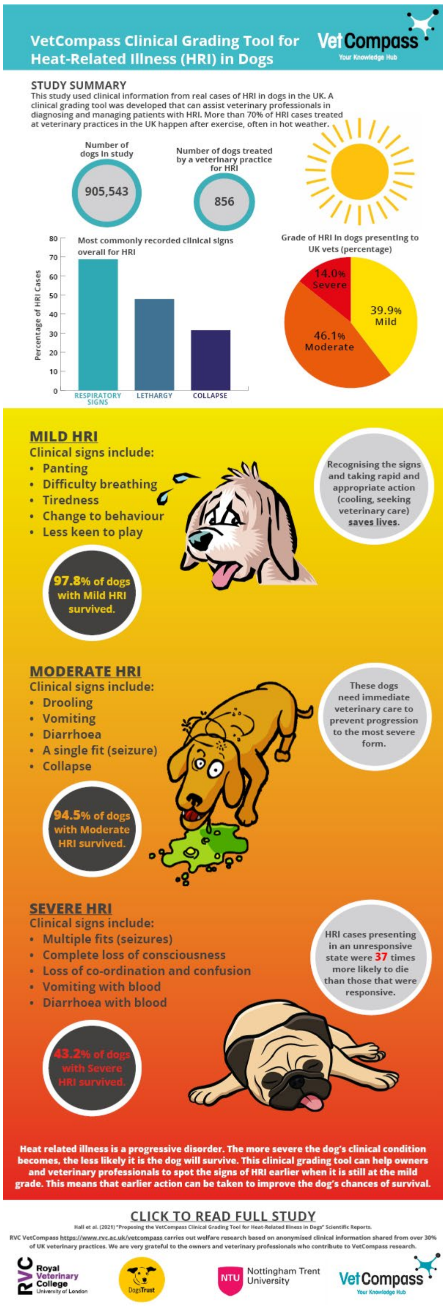
Alongside the need to re-evaluate the inclusion of presenting body temperature thresholds into the HRI grades, a key question remains; whether the proposed VetCompass Clinical Grading Tool for HRI in dogs is more accurate than the Classical Heat Stroke Criteria that has traditionally been used. In particular, the differentiation between moderate and severe HRI cases needs further scrutiny, as the criteria used in the VetCompass Clinical Grading Tool are still based on human criteria for all grades of HRI, albeit observable clinical signs rather than patient reported clinical symptoms. Further research aiming to evaluate the VetCompass Clinical Grading Tool is already underway and will be discussed in more detail in the general discussion in Section VI. Further consideration for the need to include body temperature within the Clinical Grading Tool will form part of this continued work.

V.3 Reception of the published work

In line with the overall aim of disseminating the results from this thesis as rapidly and widely as possible, as with the study from Chapter Five the publication presented in Chapter Seven was followed by an infographic (Figure V.3.1). The VetCompass research group have been using infographics for several years to facilitate the sharing of results in a more accessible format (Royal Veterinary College, 2022). These infographics allow pet owners who contribute their animal's data to the VetCompass to see the resultant evidence generation and impact on improving animal welfare and veterinary practice, and allows the research to reach a wider audience. Alongside the infographic, the study presented in Chapter Seven was also announced via a press release which was published in over 200 UK news outlets. This resulted in widespread subsequent media engagement including national radio interviews and invitations to deliver webinars and podcasts to canine sports groups to present the results in a format dog owners could understand and apply in their own setting (see wider engagements below).

A key outcome from Chapter Seven was the position statement from the UK Brachycephalic Working Group (UK BWG), the Consensus Statement on Preventing and Moderating Heat-related Illness in Dogs (O'Neill et al., 2021). The results of Chapter Seven highlight the importance of recognising and managing HRI during the milder stages of the condition, with survival dropping to less than 50% once the severe grade develops (Hall et al., 2021). Yet, earlier research has worryingly suggested that many owners of brachycephalic dogs perceive the mild signs of HRI as “normal for their breed of dog” (Packer et al., 2019).

The UK BWG includes academia, the veterinary profession, animal welfare charities, The Kennel Club, brachycephalic breed groups and the UK government, and aims to improve the welfare of dogs by eliminating breed-related health problems specifically related to brachycephaly (Brachycephalic Working Group, 2021). The UK BWG Consensus Statement highlights the specific risk of HRI to brachycephalic dogs and outlines measures dog owners can take to reduce that risk, including recognising the early signs of mild HRI. The publication of the Consensus Statement was also reported in the UK popular press and has been promoted by breed clubs to increase the reach to the general public.



VetCompass Clinical Grading Tool for Heat-Related Illness (HRI) in Dogs

STUDY SUMMARY

This study used clinical information from real cases of HRI in dogs in the UK. A clinical grading tool was developed that can assist veterinary professionals in diagnosing and managing patients with HRI. More than 70% of HRI cases treated at veterinary practices in the UK happen after exercise, often in hot weather.

Number of dogs in study: 905,543

Number of dogs treated by a veterinary practice for HRI: 856

MILD HRI

Clinical signs include:
- Panting
- Difficulty breathing
- Tiredness
- Change to behaviour
- Less keen to play

Recognising the signs and taking rapid and appropriate action (cooling, seeking veterinary care) **saves lives.**

97.8% of dogs with Mild HRI survived.

MODERATE HRI

Clinical signs include:
- Drooling
- Vomiting
- Diarrhoea
- A single fit (seizure)
- Collapse

These dogs need immediate veterinary care to prevent progression to the most severe form.

94.5% of dogs with Moderate HRI survived.

SEVERE HRI

Clinical signs include:
- Multiple fits (seizures)
- Complete loss of consciousness
- Loss of co-ordination and confusion
- Vomiting with blood
- Diarrhoea with blood

HRI cases presenting in an unresponsive state were 37 times more likely to die than those that were responsive.

43.2% of dogs with Severe HRI survived.

Heat related illness is a progressive disorder. The more severe the dog’s clinical condition becomes, the less likely it is the dog will survive. This clinical grading tool can help owners and veterinary professionals to spot the signs of HRI earlier when it is still at the mild grade. This means that earlier action can be taken to improve the dog’s chances of survival.

CLICK TO READ FULL STUDY

Hall et al. (2021) "Proposing the VetCompass Clinical Grading Tool for Heat-Related Illness in Dogs" Scientific Reports.

RVC VetCompass https://www.rvc.ac.uk/vetcompass carries out welfare research based on anonymised clinical information shared from over 30% of UK veterinary practices. We are very grateful to the owners and veterinary professionals who contribute to VetCompass research.

Figure V.3.1. The infographic created following publication of Chapter Seven, providing key facts and illustrations to communicate the clinical signs associated with each grade from the VetCompass Clinical Grading Tool for heat-related illness in dogs.

As discussed in Section IV, many dog owners appear to hold the misconception that dogs only develop HRI from vehicular confinement. Those misconceptions were to a lesser extent mirrored by the UK veterinary profession. At the 2020 BSAVA Congress when I presented the clinical abstract that summarised the findings of Chapter Six (What triggers fan the flames of HRI for UK dogs?), many veterinary audience members were shocked by the variety of triggers identified, and that the majority of cases were triggered by exercise. In addition, 578/856 (67.5%) of the HRI events included in Chapter Seven were diagnosed as "heatstroke" in the electronic patient record, yet only 14.0% of those same events were graded as severe by the Clinical Grading Tool. This may be due to the use of presenting body temperature as a diagnostic criterion for heatstroke or may reflect a lack of awareness of the less severe forms of HRI within the wider profession. Improving the veterinary profession's knowledge of HRI is therefore also imperative.

Whilst the VetCompass Clinical Grading Tool requires further evaluation before widespread clinical application, the fundamental principles of the Tool are unlikely to change. Specifically, body temperature at presentation for veterinary treatment should no longer be considered a reliable diagnostic criterion for HRI when considered alone, and presentation for treatment during the mild to moderate stages of the disease improves patient outcome (Hall et al., 2021). To disseminate these findings to the profession as widely as possible, Chapter Seven was published in an open access journal to ensure everyone could read the full article. However, targeting a general science journal such as Scientific Reports had the downside that this is not a journal specifically read by veterinary professionals. I therefore presented the key findings at the 2021 BSAVA Congress as a clinical abstract and have shared the recording of that presentation through the Hot Dogs blog.

The Clinical Grading Tool was also included in a 2022 BSAVA Congress lecture titled "Understanding hyperthermia" that was presented by a research team that was not part of the Hot Dogs team, yet reinforced the key messages regarding the use of body temperature, and recognising mild signs of HRI for improved outcomes (Allerton & Cook, 2022). Two emergency and critical care specialist veterinary surgeons working in two different referral hospitals have therefore engaged with the work presented in Chapter Seven, and further disseminated the Clinical Grading Tool to the veterinary professionals attending the lecture and watching the recording at a later date.

Chapter Seven Metric (May 2024):

Google Scholar Citations: 14

Scopus Citations: 8

Altmetric: 1085

Wider engagement:

Conference presentations and media engagement:

- Hall, E. J., Carter, A. J., & O'Neill, D. G. (2022). How to keep your pets safe in a heatwave. The Conversation. https://theconversation.com/how-to-keep-your-pets-safe-in-a-heatwave-186863
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- Carter, A. J., & Hall, E. J. (2022). What you need to know to beat the heat – heat-related illness in canicross dogs. K9 Trailtime Coach Education [webinar], June 2022.
- Carter, A. J., & Hall, E. J. (2022). Beating the heat – heat-related illness in canicross dogs. Sporty Paws [webinar], July 2022.
- Carter, A. J., & Hall, E. J. (2022). Managing performance dogs in the heat. Mantrailing UK [webinar], July 2022.
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- Hall, E. J. & Carter, A.J. (2023) Heat-related illness in pet and sports dogs. K9 Conservationists Podcast. August 2023.
- Hall, E. J. & Beard, S. (2023). Using quality improvement to enhance the care of patients with heat-related illness. BVNA Congress 2023, Telford, UK. 8th October 2023.

Publications expanding this work:

- Beard, S., Hall, E. J., Bradbury, J., Carter, A. J., Gilbert, S., & O'Neill, D. G. (2024). Epidemiology of heat- related illness in dogs under UK emergency veterinary care in 2022. *Veterinary Record*, e4153. https://doi.org/10.1002/vetr.4153
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Section VI: General Discussion

VI.1 Section introduction:

This final section summarises the overall contribution of the thesis to the wider literature and understanding, and highlights where the published studies and dissemination plans have already influenced practice or directed public campaigns. A summary of an additional study that has followed on from the publication of Chapters Five to Seven is also included here to illustrate how these findings relate to the broader issue of societal adaptations to global warming. This general discussion includes an overview of the key strengths and limitations of the published works presented in this thesis, outlines how the studies have influenced policy and practice to date, and ends by proposing future research that is needed to address remaining evidence gaps including an overview of the next stage of the "Hot Dogs" research project.

Chapter Eight: Advancing the understanding of heat-related illness in dogs

The research presented within this thesis aims to advance our understanding of the epidemiology and recognition of heat-related illness in pet dogs and its role in dog welfare. The works aimed to fill four key evidence gaps identified in the previous literature:

Evidence Gap 1: What is an abnormal canine body temperature?

Evidence Gap 2: What factors influence canine body temperature during exercise?

Evidence Gap 3: How often and why do dogs develop heat-related illness?

Evidence Gap 4: How can heat-related illness severity be graded?

The six published studies presented in this thesis address these evidence gaps. Figure 8.1 demonstrates how the evidence gaps interact to address the overarching research aim of more fully understanding of the epidemiology and recognition of heat-related illness in pet dogs.

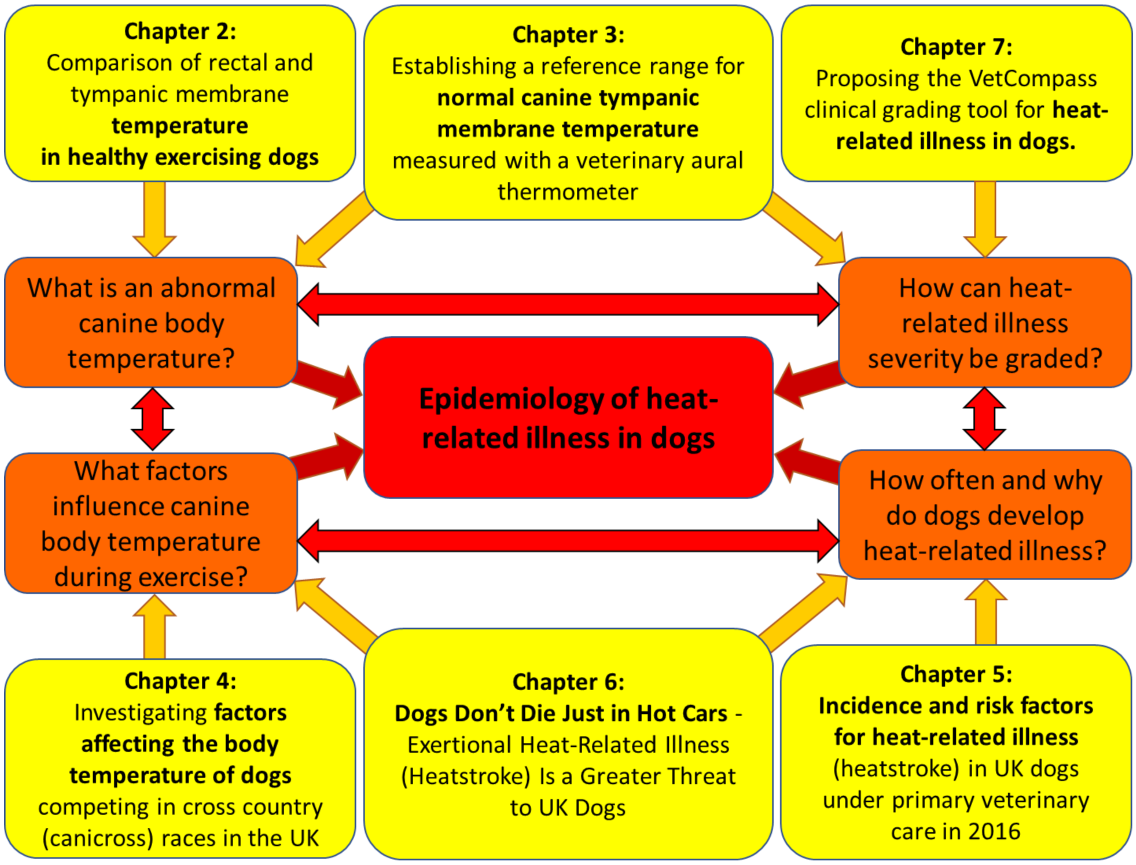


Figure 8.1. How the four key evidence gaps and the six published studies that address those gaps form the overall thesis to address the aim of advancing our understanding of the epidemiology and recognition of heat-related illness in pet dogs.

8.1 Summary of key findings

8.1.1 What is an abnormal canine body temperature?

Chapter Three presents a normal tympanic membrane (ear) temperature reference range for healthy dogs at rest (36.5-38.8°C), and Section II highlights the need for further up to date, statistically derived, anatomical location-specific temperature reference ranges to improve our ability to interpret canine temperature measurements. However, in relation to HRI, Chapter Seven identified that temperature measurement is of limited diagnostic usefulness unless continuous, real-time temperature monitoring is possible (Hall et al., 2021a). As body temperature can change rapidly in response to active cooling or removal from heat (Davis et al., 2019; Magazanik et al., 1980), and as duration of temperature elevation beyond the critical threshold of 43°C predicts the severity of disease (Shapiro et al., 1973), a single body temperature measurement at the time of presentation for veterinary treatment is of limited value in grading HRI. Developing a method of continuously monitoring body temperature in dogs at high risk of HRI (e.g., military working dogs or canine athletes) should be considered a research priority to safeguard the welfare of dogs working in extreme temperatures.

8.1.2 What factors influence canine body temperature during exercise?

Chapter Four identified that increasing ambient temperature, sex (being male) and dogs running at faster speeds were at greater risk of developing hyperthermia following canicross races (Carter & Hall, 2018). However, none of the variables explored were significantly associated with developing a post-race temperature >40.6°C. These results highlight the complexity of predicting HRI risk in canine athletes; both intrinsic (canine factors) and extrinsic (speed and ambient conditions) factors influence the profiles of canine body temperature during exercise. Mitigating HRI risk in canine athletes is therefore challenging and requires consideration of the individual athlete and their management alongside the ambient conditions. For this reason, dog owner education regarding risk factors and how to recognise HRI has been an important outcome from this research.

In the general pet population, specific breeds (Chow Chow, Bulldog, French Bulldog, Greyhound, English Springer Spaniel, Cavalier King Charles Spaniel and Staffordshire Bull Terrier), younger dogs (under 2 years), overweight dogs and male dogs had increased odds of exertional HRI (Hall et al., 2020). Dogs weighing over 10kg and brachycephalic dogs also had increased odds of exertional HRI. These risk factors for exertional HRI likely reflect intrinsic canine factors that impact the dog’s ability to thermoregulate during exercise (obesity and brachycephaly), alongside factors that impact the frequency, duration and intensity of exercise the dogs experience (breed-type and age). In addition, the breed specific risk may be associated with increased prevalence of conditions such as heart disease in Cavalier King Charles Spaniels (Summers et al., 2015), and temperament traits such as the high exercise drive in Springer Spaniels (Coile, 2015). Communicating these additional risk factors to dog owners can support them in better risk assessing for HRI during exercise.

8.1.3 How often and why do dogs develop heat-related illness?

Chapter Five reported that the 2016 incidence of veterinary diagnosis of HRI in UK dogs was 0.04% (95% CI 0.04-0.05%) (Hall et al., 2020). This is the first population level estimate of HRI incidence to be reported using primary-care veterinary data, and thus establishes a benchmark that can be used to monitor changes in disease frequency in the future. Whilst this finding suggests that HRI is not a common disorder affecting UK dogs, it is a preventable but potentially fatal condition; the HRI event fatality rate was 14.18% (95% CI 11.08 – 17.96%) (i.e., 1 in 7 dogs with HRI). Chapter Six presents the variety and frequency of different HRI triggers in UK dogs, which include the following:

- Exertional HRI (74.2%)
- Environmental HRI (12.9%)

- Vehicular HRI (5.2%)
- Undergoing treatment in a veterinary clinic or groomer (4.6%)
- Building confinement (2.7%)
- Blanket entrapment (0.5%)

A key finding from Chapter Six was that 30.2% of HRI events had no trigger recorded in the patient's veterinary history (Hall et al., 2020). Whilst this result may be due to lack of detail in the patient's veterinary record, it is also possible that some owners may not have recognised the underlying cause of their dog's condition. Ensuring that dog owners are aware of the various potential triggers for HRI in dogs, especially the risk of exercising dogs in hot weather, should be important objective for future HRI awareness campaigns.

8.1.4 How can heat-related illness severity be graded?

Chapter Seven proposes the VetCompass Clinical Grading Tool for HRI in dogs, a novel grading tool that uses presenting clinical signs to grade HRI from mild to severe disease and acknowledges the progressive nature of the disease (Hall et al., 2021a). Previous literature and veterinary clinical guidance used adapted human definitions from the Classical Heatstroke criteria (Bouchama & Knochel, 2002; Hall et al., 2021a), which relied heavily upon body temperature measurement at presentation and subjective clinical symptoms related to neurological damage (such as headaches, feeling of fatigue and confusion). Canine HRI was therefore characterised for the VetCompass Clinical Grading Tool by the progression of clinical signs resulting from thermal damage and biochemical disruption to the body, characterised by the following grades of disease:

Mild:

- Continuous panting or respiratory effort unresolved following cessation of exercise or removal from hot environment.
- Lethargy, stiffness or unwilling to move.

Moderate:

- Progression of Stage 1 – no response to cooling and/or fluids.
- Hypersalivation, diarrhoea and/or vomiting (no blood present).
- A single seizure.
- Episodic collapse with spontaneous recovery (no impaired consciousness).

Severe:

- Progression of Stage 2.

- Any of:
    - Central nervous system impairment (ataxia, two or more seizures, profound depression, unresponsive, coma).
    - Liver or kidney dysfunction.
    - Gastrointestinal haemorrhage.
    - Petechiae/purpura.

8.1.5 Additional work following this thesis

Although not presented as part of this thesis, the VetCompass data used in Chapters Five – Seven supported a follow-up publication that identified the intrinsic (canine) and extrinsic (geographical location, ambient temperature, and trigger) risk factors for severe and fatal disease in UK dogs affected by HRI (Hall, Carter, Chico, et al., 2022). Dogs that developed HRI triggered by confinement in a hot vehicle had three times the odds of being severe compared to HRI triggered by exertion. This finding reflects the importance of owners actively monitoring their dogs for signs of heat stress. Dogs left in a hot car may not be found and treated until their HRI has progressed in severity, and as the internal temperature of a car can rapidly exceed 50°C in the summer, dogs can rapidly be exposed to life-threatening temperatures (Carter et al., 2020).

In contrast, when dogs overheat during exercise, the owner is typically present and able to observe clinical signs that indicate the dog is unwell allowing remedial action to be taken. In addition, the dog has some degree of agency during exercise (compared to being restricted in a hot car), meaning the dog can cease the activity, seek shade or seek water to limit the progression of the HRI. As exertional HRI affects over ten times as many dogs as vehicular HRI in the UK (Hall et al., 2020), a key outcome of this thesis has been the launch of the Dogs Die on Hot Walks campaign (Hall, Carter, & O'Neill, 2022). This campaign aims to increase awareness of exertional HRI and encourages dog owners to learn how to recognise mild HRI so they can take immediate action to safeguard canine health and welfare.

Skull shape was associated with increased odds of fatal HRI, but not severe disease (Hall, Carter, Chico, et al., 2022). Brachycephalic dogs with HRI had three times the odds of a fatal outcome compared to mesocephalic dogs with HRI, but skull shape was not associated with severe HRI. Whilst this finding was initially unexpected it suggests an important difference in the pathophysiological impact of HRI on brachycephalic dogs compared to non-brachycephalic dogs. Brachycephalic dogs, especially those affected by obstructive airway disease, are at greater risk of developing respiratory failure either due to worsening airway restrictions or following aspiration pneumonia resulting from vomiting (Boesch et al., 2005), which can lead to cardiac arrest (Fawcett et al., 2018) before the moderate to severe clinical signs can develop (Hall, Carter, Chico, et al., 2022). This finding highlights another challenge to maintaining the welfare of brachycephalic dogs, and adds further weight to the argument that breeding must prioritise health and function over aesthetics in brachycephalic breeds (O'Neill, Sahota, et al., 2022). Despite numerous studies documenting the health and welfare issues affecting brachycephalic dogs (O'Neill et al., 2018, 2019; O'Neill, Sahota, et al., 2022; O'Neill, Skipper, et al., 2022) their popularity continues to rise (The Kennel Club, 2021). Current messaging to the public about the harms of brachycephaly to dogs does not appear to be having to desired effect, thus new approaches need to be considered (Farnworth, 2022).

Although the ambient temperature on days of HRI events was associated with both severe and fatal HRI following univariable analysis, ambient temperature was not retained in either multivariable model (Hall, Carter, Chico, et al., 2022). Whilst elevated ambient temperature increases the likelihood of HRI occurring, predicting HRI occurrence is complicated by a number of factors. Alongside the HRI trigger (exercise, hot vehicle or hot ambient conditions), the individual dog's physiological ability to thermoregulate impacts both the profile and duration of temperature elevation, and thus the individual plays an important role in mitigating or increasing the risk of HRI development (Brownlow & Mizzi, 2022). The severity or frequency of extreme heatwave events cannot be controlled, yet the work in the current thesis suggests that veterinary professionals, breeders and owners can usefully improve canine health and a dog's ability to tolerate higher temperatures by promoting responsible breeding practices and reducing canine obesity. Educating dog owners to ensure they understand the risk factors for HRI, how to recognise HRI, and the importance of taking action during the mild stages of the condition can also limit the severity of the disease and reduce mortality (Hall et al., 2021a).

8.2 Key strengths and limitations of the studies

All six published papers presented in this thesis embraced pragmatism within the epistemological approach, situating the research within the real-world (as opposed to a controlled laboratory or simulated environment) and acknowledging uncertainty and complexity as part of the study designs. Whilst this has resulted in limitations and missing data, this approach generates results that are applicable to the general pet dog population and can be applied directly to practice.

For example, Chapters Two-Four used ear thermometers to promote increased numbers of dogs participating in the studies. Whilst ear thermometers do not perform as reliably as rectal thermometers (Hall, 2021), canine tolerance of the thermometer was considered to be more important to ensure dogs did not develop any negative associations with being examined during the study periods and to increase participant recruitment. This resulted in temperature measurements from 157 dogs in Chapter Three, and over 200 temperature measurements from 108 dogs in Chapter Four. Whilst temperature studies involving racing Greyhounds can recruit over 200 dogs (McNicholl et al., 2016), studies using pet, working or laboratory dog populations typically include fewer than 20 animals (Lopedote et al., 2020; Piccione et al., 2011; Rizzo et al., 2017; Robbins et al., 2017).

Chapters Five to Seven purposefully used Big Data via the VetCompass database, including the veterinary records of over 900,000 individual dogs, to estimate population level incidence risk and fatality rate for diagnosed HRI in pet dogs. Whilst HRI is not a common veterinary diagnosis in UK dogs (Hall et al., 2020), such a large denominator population ensured sufficient case numbers were identified to allow risk factor analysis and a review of the clinical presentation. Using primary-care veterinary data also had the advantage of better representing the general pet population of the UK as almost 80% of pet dogs are registered with a veterinary practice (Asher et al., 2011). However, the limitations of using veterinary patient records must be acknowledged. The records collated within the VetCompass database are not generated for the purpose of research meaning they are sometimes incomplete as highlighted in Chapter Five; just 66% of patient records included bodyweight (Hall et al., 2020). Additionally, the confidence in the HRI diagnosis is dependent upon a number of factors including clinical acumen, owner willingness to share a complete patient history, and quality of the written records (O'Neill et al., 2014).

For HRI there is also the issue of poor understanding of the disease aetiology. For example, prior to the publication of Chapter Six confinement in a hot vehicle was often considered to be the predominant cause of HRI in UK dogs meaning there are likely events that were misdiagnosed due to a lack of history of heat exposure during exercise (Hall et al., 2020). Indeed, 30% of the HRI events identified in the VetCompass dataset had no trigger recorded in the patient history. This could be attributed to missing data in the written history, but likely also reflects the owner's lack of awareness of the variety of triggers for canine HRI (Hall et al., 2020). Public education is therefore a priority for preventing and managing HRI in dogs, as owners can reduce their pet's risk of the disease if they recognise when their pet is potentially in danger.

Mild HRI events may not require veterinary treatment and owners unwilling or unable to pay for veterinary care may be less likely to seek treatment for some events. Over a third of brachycephalic dog owners have reported that their dog has issues regulating temperature (Packer et al., 2019), suggesting that mild HRI may even be considered typical for some breeds.

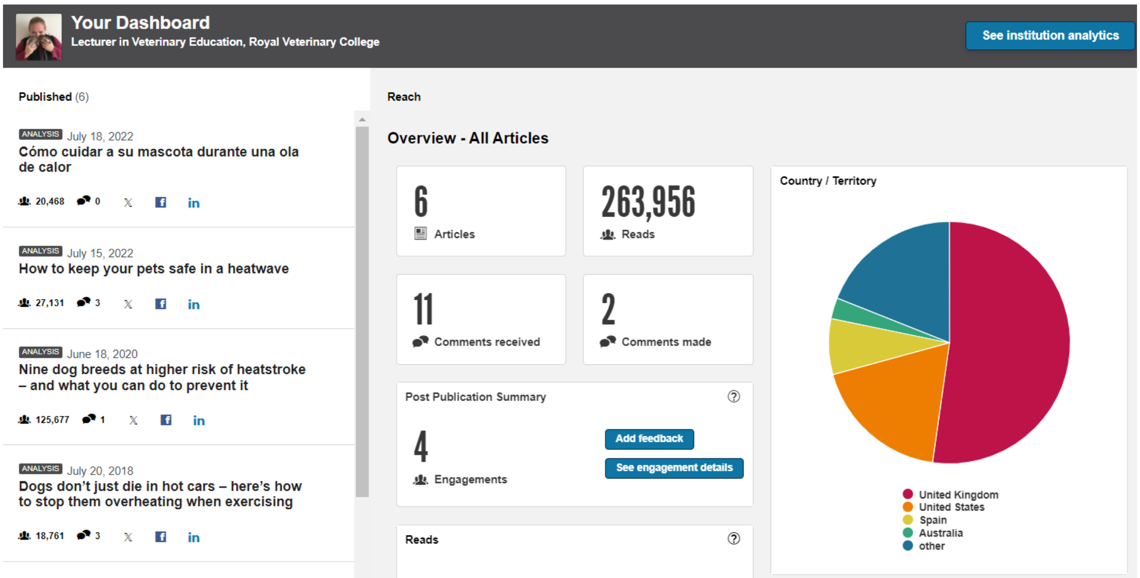
Additionally, dogs found dead may never reach the veterinary clinic, or if they are presented to the clinic already deceased the cause of death may not be recognised or recorded. As veterinary practice records only include data from events that triggered contact with the practice, any events that were managed by the owner at home without veterinary advice or awareness are missing from this dataset. Therefore the incidence risk of HRI in UK dogs (0.04%) reported in Chapter Five is likely an underestimate of the true annual incidence (Hall et al., 2020).

The multivariable models used to investigate and identify risk factors for HRI in Chapters Five and Six are limited to variables that could be readily identified within the veterinary patient records. There are additional intrinsic variables such as fitness (Nazar et al., 1992), coat length (Dawson et al., 2014), coat colour (Carter & Hall, 2018; McNicholl et al., 2016), heat acclimation (Bruchim et al., 2014) and hydration status (M. A. Baker et al., 1983) alongside extrinsic variables such as local weather conditions and duration of heat exposure that could not be identified within the patient records. Consequently, the final models are unlikely to be fully predictive models as evidenced by the low R^2 values reported (Hall et al., 2020; Hall et al., 2020). Additionally, the small number of dogs included within some categories (such as some breed types) resulted in wide confidence intervals that illustrate low precision, but as the results from these models are being used to identify risk and increase owner awareness of HRI risk in general there is little risk of these limitations causing any harm.

The model development used in these Chapters (backward stepwise elimination) is criticised for inflating R^2 values (Antonakis & Dietz, 2011; Shtatland et al., 2001) and Bayesian modelling with an information theory approach to model development could offer more reliable results by incorporating prior knowledge (Guthery et al., 2003; Jeffery et al., 2022). However, in order to include prior knowledge within statistical analyses there must be prior knowledge available, and as this thesis demonstrates when the previous veterinary literature relating to body temperature measurements and HRI was examined the prior knowledge was often based on poor quality evidence and weak assumptions (Hall et al., 2020; Hall et al., 2020, 2021a; Hall & Carter, 2017).

8.3 Impact on public campaigns and practice

As all the studies included in this thesis by publication were of an applied nature, disseminating the findings in an accessible format for both professionals and the public was a key goal. Chapter Three (Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer) was published in the British Veterinary Nursing Association’s Veterinary Nursing Journal to ensure the findings would be immediately accessible to a large proportion of the UK's veterinary nursing profession, those practitioners best able to utilise and apply the findings to their clinical practice. Chapters Four to Seven were all publicised more widely via press releases from Nottingham Trent University's press office, with Chapter Five reaching a global audience following media engagement from over 300 news outlets including the New York Times. This led to both national and international press engagement, with the US Weather Channel sharing a feature on risk factors for HRI in dogs as part of their heatwave programming. Findings from the thesis have also been shared by The Conversation, a non-profit independent news organisation that partners with academics to create evidence-driven news stories for international audiences. The Conversation articles that reported the findings of this thesis had over 260,000 reads in digital format but have also been published in print format across the globe (Figure 8.3.1).


Your Dashboard
Lecturer in Veterinary Education, Royal Veterinary College

Published (6)

ANALYSIS July 18, 2022
Cómo cuidar a su mascota durante una ola de calor
20,468 0

ANALYSIS July 15, 2022
How to keep your pets safe in a heatwave
27,131 3

ANALYSIS June 18, 2020
Nine dog breeds at higher risk of heatstroke – and what you can do to prevent it
125,677 1

ANALYSIS July 20, 2018
Dogs don't just die in hot cars – here's how to stop them overheating when exercising
18,761 3

Reach

Overview - All Articles

6 Articles

263,956 Reads

11 Comments received

2 Comments made

Post Publication Summary

4 Engagements

Reads

Country / Territory

Figure 8.3.1. Distribution statistics for The Conversation articles based on the works published in this thesis as of May 2024.

Following publication of Chapter Four (Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK), Dr Carter and I received numerous requests for copies of the publication from canicross competitors around the world. As Chapter Four received no external funding, we were unable to publish this paper in an open access format which we quickly realised would limit the potential audience the research could reach. Replying to individual requests for article access was time consuming, leading us to explore options available to authors for dissemination of studies published behind a paywall. The desire to provide open access to our work alongside more accessible interpretations of the journal articles (lay summaries) led to the creation of our blog – Hot Dogs heatstroke education for dog owners [https://heatstroke.dog/] - which has to date reached a global audience of over 68,000 readers (Figure 8.3.2). Dr Carter and I also shared the results from

Chapter Four directly with the canicross community that supported our research by delivering seminars at the club's annual summer training camps during 2017-2018 and through online webinars to UK canine sports clubs as part of coach education programmes. The findings published in Chapter Four resulted in canicross clubs updating their HRI risk assessments and temperature limits for canine competitors as discussed in Section III.

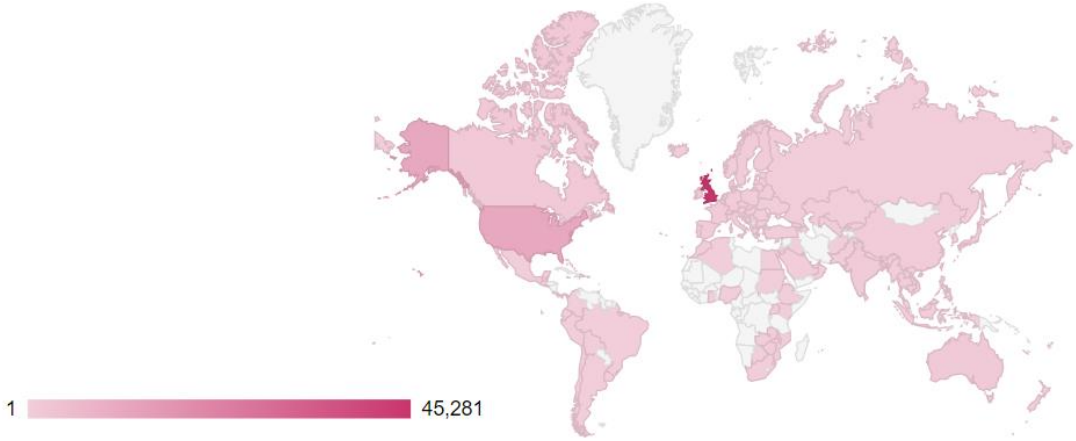


Figure 8.3.2. The location of readers accessing the "Hot Dogs – heatstroke education for dog owners" blog [https://heatstroke.dog/] from the blog launch in 2018 to present (May 2024).

The Hot Dogs blog is distributed by two key social media channels on Facebook [https://www.facebook.com/hotdogscanineheatstroke/] and Twitter [https://twitter.com/HotDogsResearch]. These channels are followed by a mixture of dog owners, canine sports participants, canine professionals (including dog walkers, dog boarding and rescue kennels and groomers) and veterinary practitioners. However, they are also followed by larger organisations such as Dogs Trust, RSPCA, British Veterinary Association, and the Universities Federation for Animal Welfare allowing us to reach a mixture of scientists, veterinary professionals, policy makers and the general public. This has been instrumental in raising awareness of the key findings from this thesis, in particular relating to the most common trigger of HRI in UK dogs, exertional HRI. From 2022 the annual Dogs Die in Hot Cars educational campaign has been updated to include a second message, Dogs Die on Hot Walks as a direct result of the work presented in Chapter Six. Whilst vehicular HRI is associated with increased odds of severe disease when compared to exertional HRI (Hall, Carter, Chico, et al., 2022), the risk of exertional HRI is higher than vehicular HRI in UK dogs meaning more dogs are affected overall (Hall et al., 2020). Raising awareness of the range of triggers for HRI in dogs (but especially exercise) to dispel the public perception that dogs only die from HRI in hot cars therefore has the potential to significantly reduce the incidence of this potentially fatal condition in the future.

As brachycephalic dogs have been identified as being at increased risk of all forms of HRI (Hall et al., 2020) and increased risk of severe HRI (Hall, Carter, Chico, et al., 2022), increasing owner awareness of the risk factors, clinical signs and measures for preventing HRI was considered an urgent priority. A consensus statement on preventing and moderating HRI in dogs was therefore published in collaboration with the UK Brachycephalic Working Group to directly target breeders and owners of brachycephalic breeds (O'Neill et al., 2021). This consensus statement was also reported in the national press (in print), targeting pet owners in the general public, which ensured the messaging reached a wider audience than would be possible through on-line publication of the consensus statement alone.

Whilst the VetCompass Clinical Grading Tool for HRI in dogs requires further evaluation and validation, the key findings have been recognised by the veterinary emergency and critical care community and were discussed in a session delivered to veterinary professionals at the BSAVA Congress 2022 (Allerton & Cook, 2022). Practitioners were urged to recognise the limitations of using body temperature at initial veterinary presentation as a diagnostic criterion for HRI severity, and were reminded of the importance of educating clients about the wider triggers and canine specific risk factors for HRI identified in Chapters Five and Six. The Clinical Grading Tool has also been shared to the Working and Performance Dog Vets Facebook group (a closed group for veterinary professionals managing or treating sports, service and working dogs around the world), with the US Veterinary Tactical Group recommending the tool for anyone managing working dogs in hot environments.

Figure 8.3.3 illustrates the various methods I have used to disseminate the research presented in this thesis to key target audiences.

Figure 8.3.3. The methods used to disseminate the research findings presented in this thesis to a wider audience.

8.4 Future work

Whilst the work presented in this thesis has begun to address the four major evidence gaps identified in Section I, further research is needed to consolidate the understanding of HRI in dogs and to develop robust guidelines for diagnosing and managing dogs affected by HRI when presented to veterinary practitioners. There are three key areas to address with future work: identification of effective cooling methods for hyperthermic dogs; evaluating and refining the VetCompass Clinical Grading Tool for HRI in dogs; and improving public facing educational campaigns relating to HRI in dogs.

8.4.1 How to cool a hot dog

One of the questions I am asked most frequently through the Hot Dogs social media accounts and public engagement activities is “how should I cool a hot dog?”. This question could not be answered through this thesis, although the VetCompass HRI data was used to benchmark the cooling methods used by primary-care veterinary professions during 2016-2018 and was presented at BSAVA Congress 2021 as a clinical abstract (Hall et al., 2021b), and has now been published as an open access article (Hall et al., 2023). The results of this benchmarking study demonstrated that many veterinary professionals were still using outdated cooling methods such as cold water enemas, alcohol application to footpads, and covering patients in wet towels (Hall et al., 2023). As discussed in Chapter Seven, many veterinary texts currently recommend using tepid (not cold) water to cool dogs and actively caution against used cold water due a fear that this could induced vasoconstriction or shivering which could limit cooling (Boag & Marshall, 2020; Drobatz, 2015; Newfield, 2019). However, there is no robust evidence to support these statements. This has resulted in conflicting messages being communicated to both veterinary professionals and dog owners, with anecdotal evidence of owners being afraid to use water to cool their dog for fear of doing more harm, which ultimately delays effective cooling and may contribute to worsening of the dog’s condition. Rapid, effective cooling is a primary therapeutic objective when managing a patient affected by HRI (Casa et al., 2007), therefore identifying safe and effective cooling methods for dogs should be a priority research aim for future work.

As discussed in Section III, Dr Carter and I have collected canine cooling data from dogs participating in canicross events, using a pragmatic field-based observational approach. We have now published this study, reporting that housing dogs in vehicles post cooling reduces cooling effectiveness, and cold-water immersion (down to 0.1°C) can effectively cool dogs with exertional hyperthermia with no observed adverse effects (Carter et al., 2024). Possible associations between rapid cooling and extreme post-cooling hypothermia, and organ failure and increased mortality in human HRI patients has been raised in the human medical literature (Chen et al., 2023), further highlighting the need for more research on safe and effective cooling methods for canine HRI patients.

8.4.2 Evaluating the VetCompass Clinical Grading Tool for heat-related illness in dogs

The results presented in Chapter Seven (Proposing the VetCompass clinical grading tool for heat-related illness in dogs) highlighted that the previous grading schemes of HRI in dogs based on Bouchama & Knochel's (2002) Classical Heatstroke Criteria were flawed. In particular, the use of presenting body temperature as a diagnostic criterion for grading HRI should no longer be supported due to the limitations of interpreting a single body temperature measurement from a single time point (Hall et al., 2021a). The novel VetCompass Clinical Grading Tool proposed in Chapter Seven offers canine specific HRI grading criteria that are based on the largest retrospective analysis of canine HRI events published to date, however the Tool requires evaluation using a novel dataset to determine its suitability for clinical application.

Dogs Trust Canine Welfare Grants have awarded additional funding to support a Master of Research project that will evaluate the VetCompass Clinical Grading Tool using a clinical audit methodology. The Grading Tool has now been introduced to the UK’s largest veterinary emergency and critical care provider (Vets Now) since 2022. Both quantitative and qualitative analysis will be used to evaluate the Grading Tool’s ability to identify severe cases at presentation, to explore the clinical application of the Tool and if it affects patient management, and to critically analyse how veterinary staff perceive the useability and usefulness of the Tool. This project will continue to use VetCompass data but will use only Vets Now clinical data, so the project will no longer focus purely on primary-care patient management. The primary aim of this follow-up project is to evaluate and if necessary, refine the Clinical Grading Tool to produce a triage tool that can support veterinary professionals with decision making in relation to management of canine HRI cases. The follow-up project also aims to support the development of another veterinary researcher through the Royal Veterinary College’s post graduate research programme, and to showcase how quality improvement initiatives such as clinical audit activity can enhance and progress the veterinary profession. I am supervising and supporting the Master of Research student throughout this additional project alongside my supervisors Dr Anne Carter and Dr Dan O’Neill.

8.4.3 Effective communication of heat-related illness risk to dog owners

Climate change is already adversely impacting human and animal health through changes to weather patterns and increasingly frequent extreme weather events (Brackett, 2019; Raymond et al., 2020). Community-based educational interventions have been shown to significantly reduce (human) HRI related hospital admissions in high risk communities (Razzak et al., 2022), demonstrating the potential impact of educational mitigation strategies that aim to prevent morbidity and mortality associated with extreme heat exposure. The results presented in Chapters Five to Seven demonstrate the similarities between dogs and humans affected by HRI in relation to incidence (Hall et al., 2020, 2021a; Hall, Carter, Chico, et al., 2022), risk factors (Hall et al., 2020; Hall et al., 2020), triggers (Hall et al., 2020), and outcomes (Hall et al., 2021a). As dogs play an important role in human society, it may be possible to develop educational interventions that can communicate HRI risk relating to both humans and dogs. Research to evaluate the most effective means of disseminating such educational interventions is needed to ensure messaging reaches the most at-risk groups, which would likely include groups with limited internet access or exposure to veterinary clinic based educational opportunities (Macintyre et al., 2018).

8.4.4 Application of current heat-related illness research to working dogs

Whilst numerous studies have explored risk factors for, and incidence of, HRI in military and police working dogs (Baker et al., 2012; Benito et al., 2022; Davis et al., 2019; Miller et al., 2018; Stojsih et al., 2014), comparatively little research focuses on the impact working in the heat has on other types of working dogs, such as guide dogs for the blind, hearing dogs for the deaf, medical detection dogs, or dogs working with livestock/wildlife. Several of the breeds identified in Chapters Five and Six as being at increased risk of HRI (both in general and specifically exertional or vehicular HRI) are commonly used as working or service dogs, including the Golden Retriever, Springer Spaniel and Border Collie (Hall et al., 2020; Hall et al., 2020). Therefore, it is likely that many service dogs have an increased risk of developing HRI. For example, as a key pathophysiological feature of HRI is impairment of the nervous system (Bouchama & Knochel, 2002; Bruchim et al., 2017; Hall et al., 2021a), there is the potential for mild HRI to impact working dogs' cognitive ability, which could reduce their physical, mental and olfactory ability (Otto et al., 2017). In addition, dogs working in medical or guiding service roles may be primarily cared for by people with sensory impairments that could prevent recognition of mild signs of HRI (Hall, Carter, Chico, et al., 2022). Furthermore, types of housing associated with the greatest risk of heat stress are frequently associated with more vulnerable members of society who may rely on service dogs.

If service dogs are at increased risk of HRI, this could erode the social license to operate if the public perceive these dogs to be suffering due to their work (Hampton et al., 2020). Research is therefore needed to better understand how to ensure the health and welfare of service dogs amidst rising global temperatures. Developing mitigation strategies to minimise HRI risk in all working dogs, and methods to detect mild HRI quickly, should therefore be considered urgent priorities to protect both canine welfare and to ensure working dogs can continue to perform their vital roles in society.

8.5 Overall conclusion

The body of work presented in this thesis provides an initial benchmark of the incidence risk of HRI in UK dogs (0.04% in 2016), alongside the predominant triggers of HRI (exertional, environmental, and vehicular HRI) and canine risk factors for the disorder (breed, bodyweight, age, being overweight and skull shape). These benchmarks provide a means of monitoring the disease incidence in the face of rising global temperatures and increasingly frequent extreme heat events. They also provide a means of monitoring the impact of educational interventions.

Each of the evidence gaps identified and at least partially filled in this thesis highlight the need for improved guidance in the educational veterinary literature (textbooks and practitioner focused articles) and continuing professional education resources (such as webinars and conferences) to support evidence-based practice in relation to temperature monitoring, interpretation of elevated body temperature measurements, recognising dogs at risk of HRI and diagnosing HRI in dogs. Improved education for veterinary professionals is a priority, as they are at the frontline both treating dogs with HRI and educating pet owners on HRI risk factors. Alongside improved veterinary education, more dog owner and canine professional focused HRI educational inventions are needed to ensure they can recognise mild HRI to facilitate early intervention and improve outcomes. In addition, dog owners and canine professionals need to be aware of the different triggers of HRI so they can make safer decisions relating to canine management in the face of rising global temperatures.

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Appendices

Contents

Temperature conversion table for °C to °F

°C	°F
36.0	96.8
36.1	97.0
36.2	97.2
36.3	97.3
36.4	97.5
36.5	97.7
36.6	97.9
36.7	98.1
36.8	98.2
36.9	98.4
37.0	98.6
37.1	98.8
37.2	99.0
37.3	99.1
37.4	99.3
37.5	99.5
37.6	99.7
37.7	99.9
37.8	100.0
37.9	100.2
38.0	100.4
38.1	100.6
38.2	100.8
38.3	100.9
38.4	101.1
38.5	101.3
38.6	101.5
38.7	101.7
38.8	101.8
38.9	102.0
39.0	102.2
39.1	102.4
39.2	102.6
39.3	102.7
39.4	102.9
39.5	103.1
39.6	103.3
39.7	103.5
39.8	103.6
39.9	103.8
40.0	104.0
40.1	104.2
40.2	104.4
40.3	104.5
40.4	104.7

°C	°F
40.5	104.9
40.6	105.1
40.7	105.3
40.8	105.4
40.9	105.6
41.0	105.8
41.1	106.0
41.2	106.2
41.3	106.3
41.4	106.5
41.5	106.7
41.6	106.9
41.7	107.1
41.8	107.2
41.9	107.4
42.0	107.6
42.1	107.8
42.2	108.0
42.3	108.1
42.4	108.3
42.5	108.5
42.6	108.7
42.7	108.9
42.8	109.0
42.9	109.2
43.0	109.4
43.1	109.6
43.2	109.8
43.3	109.9
43.4	110.1
43.5	110.3
43.6	110.5
43.7	110.7
43.8	110.8
43.9	111.0
44.0	111.2
44.1	111.4
44.2	111.6
44.3	111.7
44.4	111.9
44.5	112.1
44.6	112.3
44.7	112.5
44.8	112.6
44.9	112.8

Statements of joint authorships and contributions to the research

Record of author contribution to Chapter Two

Article:	Comparison of rectal and tympanic membrane temperature in healthy exercising dogs.	
Journal:	Comparative Exercise Physiology	
Submitted:	18.08.2016	
Accepted (published):	22.12.16 (06.03.2017)	
Principal author:	Emily Hall	
Additional author(s):	Anne Carter	
Article contribution by Emily J Hall:	Design of the project:	70%
	Conduct of the research:	50%
	Analysis of the results:	70%
	Preparation of the publication (including revisions):	70% (revisions 50%)

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Record of author contribution to Chapter Three

Article:	Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer	
DOI	https://doi.org/10.1080/17415349.2017.1377133	
Journal:	Veterinary Nursing Journal	
Submitted:	04.07.2017	
Accepted (published):	02.09.2017 (16.11.2017)	
Principal author:	Emily Hall	
Additional author(s):	Anne Carter	
Article contribution by Emily J Hall:	Design of the project:	90%
	Conduct of the research:	50%
	Analysis of the results:	80%
	Preparation of the publication (including revisions):	70% (revisions 50%)

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Record of author contribution to Chapter Four

Article:	Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK	
DOI	https://doi.org/10.1016/j.jtherbio.2017.12.006	
Journal:	Journal of Thermal Biology	
Submitted:	31.10.2017	
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Record of author contribution to Chapter Five

Article:	Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016	
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Record of author contribution to Chapter Six

Article:	Dogs Don’t Die Just in Hot Cars—Exertional Heat-Related Illness (Heatstroke) Is a Greater Threat to UK Dogs	
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Article contribution by Emily J Hall:	Design of the project:	70%
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	Analysis of the results:	80%
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Record of author contribution to Chapter Seven

Article:	Proposing the VetCompass clinical grading tool for heat-related illness in dogs	
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Article contribution by Emily J Hall:	Design of the project:	80%
	Conduct of the research:	70%
	Analysis of the results:	90%
	Preparation of the publication (including revisions):	60% (revisions 70%)

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Chapter Two: Comparison of rectal and tympanic membrane temperature in healthy exercising dogs.

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2.1 Abstract

The ability to monitor body temperature in athletes at risk of hyperthermia is essential in all species. Currently, the only commonly accepted temperature monitoring site in dogs is the rectum. This is impractical in field situations as it takes time, requires additional handlers to restrain the dog and is not tolerated by all animals. Tympanic membrane temperature (TMT) monitoring may provide a rapid measure of body temperature to facilitate identification of heat stress and heat stroke in canine athletes. In human studies, TMT diverges from rectal temperature (RT) as body temperature increases during exercise induced hyperthermia so is not recommended for monitoring human athletes. If the same divergence occurs in dogs, TMT may not be suitable for use when monitoring the temperature of canine athletes.

The aim of the study was to determine if TMT diverged from RT following exercise in healthy dogs.

24 healthy dogs were recruited to the study. Body temperature was measured using a veterinary auricular infrared thermometer (VetTemp) to record tympanic membrane temperature and an electric predictive rectal thermometer. Temperatures were recorded pre and post exercise in a non-clinical setting, familiar to the dogs.

The mixed model approach showed that exercise had no effect on the difference between RT and TMT ($F_{(1,201)}$ =0.026, P=0.872). The overall mean difference of RT minus TMT was 0.39°C (n = 116). 68.4% of readings fell within the accepted 0.5°C difference in temperature recording method.

In line with previously reported TMT to RT comparison studies in dogs, this study found that TMT measured consistently lower than RT. Using a correction factor of 0.4°C minimised the difference. The hypothesis that dogs would show greater differences between TMT and RT following exercise was not supported, suggesting that TMT could be used to monitor body temperature in exercising dogs where RT is not possible.

2.2 Introduction

Exertional heat stroke occurs when core temperature exceeds the body's thermoregulatory mechanism, typically after strenuous exercise, when athletes are not appropriately acclimatised to the ambient conditions, or when exercising in high ambient temperatures (Reniker & Mann, 2002). As the popularity of canine sports continues to increase (The Kennel Club, 2017) there is an increased risk of exertional heat stroke occurring (Hall & Carter, 2016). The ability to measure canine athlete temperatures during training and racing events is essential for identifying those at risk of heat injury, as rapid treatment has been shown to reduce mortality (Bruchim et al., 2006).

The ability to estimate body temperature is essential for animal welfare, as core temperature measurements from the trachea, oesophagus or a central vascular space require the use of invasive and potentially painful techniques which are impractical for most field or clinical settings (Miller, 2009). There are a number of non-invasive body temperature monitoring devices, however the literature to support their use is lacking.

Rectal temperature (RT) is the most widely used method of estimating core temperature in veterinary medicine (Greer et al., 2007; Southward et al., 2006), however this method is not tolerated in all dogs (Lamb & McBrearty, 2013) and can prove impractical in non-clinical situations. Where rectal temperature is tolerated, assistance is often required in order to restrain the patient for temperature measurement. Lamb and McBrearty (2013) reported that 45.5% of conscious canine patients required additional restraint. For these reasons there has been continued interest in alternative methods of estimating core temperature, such as infrared auricular thermometers, axillary temperature recording and the use of infrared thermography (Lamb & McBrearty, 2013; Yanmaz et al., 2015). Infrared auricular thermometers measure the tympanic membrane temperature (TMT) and provide an attractive alternative to RT measurement, both in terms of speed (Greer et al., 2007) and patient tolerance. Lamb and McBrearty (2013) found that conscious canine patients were less likely to require additional restraint for TMT measurement than RT measurement.

However, auricular thermometers have been found to vary in accuracy at predicting RT with mean RT minus TMT differences ranging from -0.015°C to 1.27°C (Huang & Huang, 1999; Huang & Shih, 1998; Konietschke et al., 2014; Piccione et al., 2011; Sousa et al., 2011, 2013; Southward et al., 2006; Yanmaz et al., 2015). This variation may be due to the use of non-veterinary specific auricular thermometers. The veterinary specific devices appear to be more reliable with mean differences ranging from -0.015 °C to 0.77 °C (Gomart et al., 2014; Gonzalez et al., 2002; Greer et al., 2007; Lamb & McBrearty, 2013; Piccione et al., 2011; Rexroat et al., 1999; Smith et al., 2015; Wiedemann et al., 2006). The majority of these studies report that TMT measures consistently lower than rectal temperature. Improved accuracy of the veterinary specific thermometer has been reported in hypothermic patients when compared to hyperthermic patients in a clinical setting (Greer et al., 2007). Southward *el al*. (2006) hypothesised that the device would be less accurate in hyperthermic patients, based on results from the human literature. The findings of Greer *et al.* (2007) were in support of this theory, however, they investigated anaesthetised laboratory animals with endotoxin induced hyperthermia. To date, the effects of physiological, exercise induced hyperthermia on device accuracy have not been investigated in canine athletes.

Within the human medicine literature, a review of TMT versus RT in exercising, hyperthermic athletes, found that TMT increasingly diverges from RT as athlete temperature increases (Huggins et al., 2012). Due to the potential risk of under reporting hyperthermia, it has been suggested that TMT is not a suitable method of monitoring body temperature in human athletes. If this divergence is also present in canine athletes, the same limitations will apply to the tympanic membrane (TM) thermometer, namely underreporting hyperthermia.

The need to monitor canine temperature is not restricted to veterinary settings. Where activities take place in warmer climates, there is an increased risk of both environmental and exertional heat stroke (Johnson et al., 2006). Non-invasive methods of monitoring temperature should ideally be available to ensure rapid identification of animals suffering from heat stress and heat stroke, as morbidity and mortality both reduce if the animal is presented quickly for veterinary care(Bruchim et al., 2006). Increasingly pet owners are becoming aware of the technology available for monitoring their pets’ vital signs, including animal specific health monitoring devices such as the PetPace collar, the Voyce Health Monitor collar, and animal specific TM thermometers such as the Pet-Temp Instant Ear Thermometers. As participation in canine sporting activities increases, owner interest in canine athletic performance and health monitoring is also likely to increase. Within canine sport, owners are beginning to be encouraged to monitor temperature as a sign of performance (Canine Health Foundation, 2015). Internet forums also show that owners are monitoring their dog's temperature using these devices when deciding whether to seek veterinary advice for a sick animal. It is therefore essential that pet owners and professionals are made aware of any potential limitations of this method of temperature measurement. If aural thermometers are to be used by pet owners in a non-clinical setting, a normal temperature range for TMT is necessary in order to prevent hyperthermia going undetected.

Gomart *et al*. (2014) published a table of correction factors for use with the Pet-Temp, to predict RT from TMT measurement, but do not comment on statistical impact of applying these factors. However, their study was limited to hospitalised, clinical canine patients and concluded that further investigation was needed to evaluate these techniques in hyperthermic dogs. To date, no other TMT to RT comparison study has used healthy exercising dogs, away from a clinical veterinary setting. As body temperature can increase with anxiety (Levy et al., 2015), this study was conducted in a non-clinical setting to ensure dogs were not stressed by an unfamiliar environment.

The aim of the study was to determine if TMT diverged from RT following routine daily exercise, in a group of healthy dogs in a non-veterinary environment. The effect of a correction factor on TMT was also investigated, to determine if this improved detection of hyperthermia when compared to RT. The impact of ambient conditions on the difference between the two thermometers was also monitored.

2.3 Material and Methods

The study was approved by the Nottingham Trent University's School of Animal, Rural and Environmental Science's ethics approval group.

Animals

Dogs were recruited from a population of university staff owned pets and members of a local canine sporting club. Owners were required to confirm that their dogs were fit and healthy, not undergoing veterinary treatment and showing no clinical evidence of otitis externa. Sample size was determined by pre study power analysis, at least 22 dogs were needed to achieve a study power of 80%, with an error = 0.05, to detect a 0.6 °C (SD 1 °C) difference between the two methods. This was based on the mean TMT of the sample population reported by Gomart *et al*. (2014). Twenty-four dogs (15 males, 9 females) were recruited, representing eight breed types: cocker spaniel (n=4), Labrador retrievers (n=4), lurchers (n=4), Welsh springer spaniels (n=2), pugs (n=2), collie (n=1), pointer (n=1), springer spaniel (n=1) and cross breeds (n=5). Ages ranged from 6 months to 15 years. All temperature recordings were taken during periods of the dogs' routine exercise, taking place in the East Midlands, UK, throughout a twelve-month period. The purpose of the period of exercise was to elevate body temperature in a non-clinical, physiological manner. In order to limit the impact of the study on the dog's normal routine, the duration, type and intensity of exercise completed was not standardised. The types of exercise included brisk walking on lead, free running off lead and off lead play but was of at least 20 minutes duration.

Temperature measurements

TMT was recorded using one new Vet-Temp VT-150 Instant Ear Thermometer (Advanced Monitors Corporation, California, USA), covered by a single use Vet-Temp DPC-500 probe cover (Advanced Monitors Corporation, California, USA). The Vet-Temp thermometer measures temperatures between 32.2-43.3°C, with an accuracy of ±0.2°C. The thermometer was used as per the manufacturer's instructions (see Figure 2.3.1), with no lubrication and a reading being obtained following the audible alarm. If a reading reported an error code, the probe cover was changed, and the process repeated.

Figure 2.3.1. A Vet-Temp auricular thermometer being used: the dog's ear is pulled out and down, with the probe angled towards the opposite jaw (a probe cover is in place but not visible in this picture).

Rectal temperature was recorded using a V966F Vicks Comfortflex Digital Thermometer (KAZ Incorporated, New York, USA), which alarms once a stable peak temperature is reached. The Comfortflex Digital Thermometer measures temperatures between 32-42.9 °C with an accuracy of ±0.2°C at room temperature. Prior to the study, the thermometer was tested in water baths of 35°C and 40°C and found to be within 0.1°C of the reference mercury thermometer. The thermometer was lubricated using K-Y jelly (Johnson & Johnson, France), inserted at least 2cm into the rectum and held against the rectal wall until the alarm sounded.

All readings were collected by one author to remove any operator bias, and both thermometers were familiar to the author through routine use in clinical practice. All dogs were lightly restrained by an assistant for both temperature recordings. Individuals involved in taking temperature and restraint of the dogs were familiar to the dogs. In all cases, TMT was recorded first, to limit any influence stress response to the RT recording could have on the results. Left or right ears were selected at random depending on the positioning of the patient following restraint, to reflect the likely situation in a clinical practice or home environment.

Both TMT and RT recordings were taken at rest, and immediately following a period of exercise to elevate core temperature. Where geographical location allowed, repeated measures were taken (17/24 dogs) in order to assess any consistency of variation in individual animals. The ambient temperature, relative humidity and wind speed were recorded for every period of exercise. Over the course of the study, mean value for ambient temperature was 12.5°C (range 4.9-20.5 °C), windspeed was 2.44m/s (range 0.36-6.64m/s) and relative humidity was 68.4% (range 42.5-92.9%). Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK), and RD 506-9650 Anemometer (R.S. Components Ltd., Northamptonshire, UK). In order to evaluate the overall impact of these environmental conditions, the results were used to calculate Universal Thermal Comfort Index (UTCI) values (Jendritzky et al., 2012). UTCI was calculated from ambient temperature (°C), relative humidity (%) and wind speed (m/s) using the UTCI calculator (http://www.utci.org/) and varied from -2.6°C to 15.6 °C.

Statistical analysis

Statistics were calculated using SPSS 23.0 (SPSS Inc., Chicago, USA). Mixed linear model was used to compare RT and TMT. The measurement site (ear (TMT) and rectum (RT)) and exercise (pre and post exercise) were included as fixed effects. Dog was included as a random effect. Comparisons were made between temperature pre and post exercise, RT and TMT and the interaction between site and exercise.

Mixed linear model was also used to compare the difference in temperature (RT minus TMT) pre and post exercise. Exercise was included as a fixed effect and dog as a random effect. Spearman's rho test was used to assess correlation between ambient conditions (UTCI) and RT minus TMT, as UTCI was not normally distributed.

As the number of repeat measures per individual was not constant (due to availability and exercise regime of the animals) and the repeated measures were taken on different days and under different environmental conditions (resulting in variable resting body temperatures), the use of a Bland-Altman plot was deemed inappropriate (Hartnack, 2014). A scatter plot was instead used to provide a visual assessment of the difference between the two sites. Significance was indicated at $P<0.05$ for all tests. In line with previous studies an acceptable limit of difference between the two temperature recording sites was set at ±0.5°C.

2.4 Results

A total of 116 paired temperature measurements were recorded, ranging from 1 to 8 paired measurements per dog (median = 6, mean = 4.6). Pre exercise RT readings ranged from 37.4°C to 39.1°C (mean= 38.3°C) and TMT ranged from 36.7°C to 38.8°C (mean = 37.9°C). Post exercise RT readings ranged from 38.3°C to 40.0°C (mean= 39.0°C) and TMT ranged from 37.4°C to 39.7°C (mean= 38.6°C). The range of RT increase recorded following exercise was 0.1-1.4 °C (mean = 0.7 °C, n=58). TMT under reported body temperature when compared to RT in 95 of the pair measurements (82%), 80 pairs of readings (68.4%) fell within the accepted 0.5°C difference in temperature recording method (Figure 2.4.1).

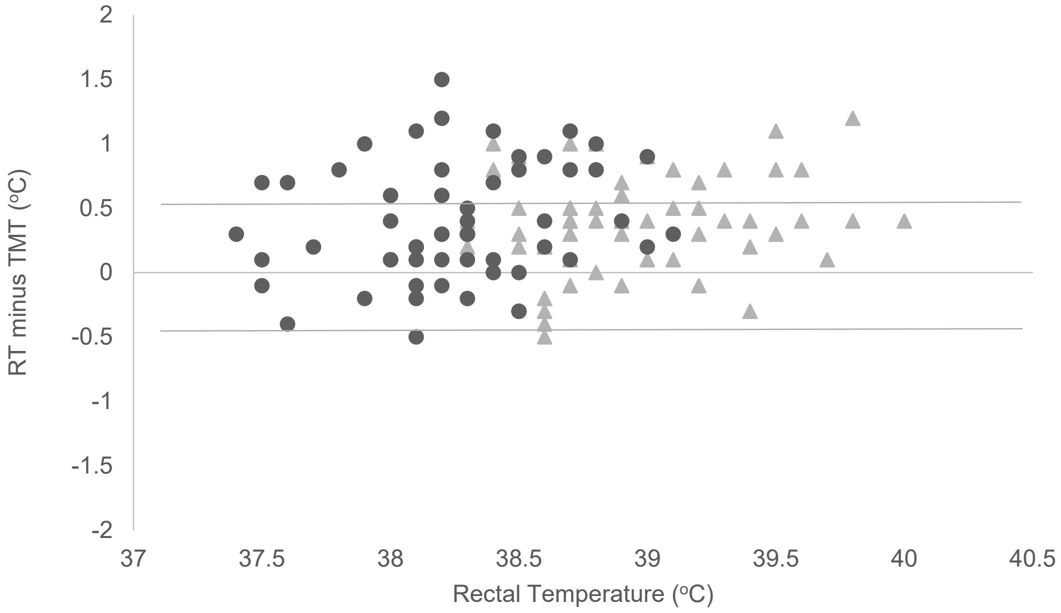

Figure 2.4.1. Rectal temperature (RT) plotted against the rectal temperature minus tympanic membrane temperature (RT minus TMT). Circles represent readings pre exercise, triangles represent readings post exercise. The solid lines represent the clinically acceptable limits of agreement between two temperature recording devices (±0.5°C).

The mixed model approach was used as RT minus TMT was normally distributed, this showed a significant effect of exercise ($F_{(1,203)}$ =173.1, p<0.0001) and measurement site ($F_{(1,201)}$ =52.2, p<0.0001) on temperature. There was no significant interaction between exercise and measurement site ($F_{(1,201)}$ =0.026, P=0.872).

For all data, RT minus TMT ranged from -0.5°C to 1.5°C (mean = 0.39°C, n=116). Pre exercise RT minus TMT ranged from -0.5°C to 1.5°C (mean = 0.38°C, n=58). Post exercise RT minus

TMT ranged from -0.5°C to 1.2°C (mean = 0.39, n=58). Table 2.4.1 shows the descriptive statistics for the two temperature measurement sites pre and post exercise. Descriptive statistics for RT minus TMT following correction of TMT by the addition of 0.4°C are also shown in table 1. The overall mean difference for RT minus corrected TMT+0.4°C was -0.01°C (n=116).

Table 2.4.1. Descriptive statistics for (1) temperature measurement (°C) at different sites, rectal temperature (RT) and tympanic membrane temperature (TMT) pre and post exercise, (2) the difference between RT and TMT pre and post exercise, (3) the difference between RT minus corrected TMT +0.4°C pre and post exercise in healthy exercising dogs (24 dogs, 116 paired temperature measurements).

Time of reading	**Temperature recorded (°C)**	**Mean**	**Median**	**Standard deviation**	**Minimum**	**Maximum**
Pre exercise	RT	38.3	38.3	0.39	37.4	39.1
	TMT	37.9	37.9	0.53	36.7	38.8
	RT minus TMT	0.38	0.3	0.45	-0.4	1.5
	RT minus TMT+0.4°C	-0.02	-0.1	0.45	-0.8	1.1
Post exercise	RT	39.0	38.9	0.41	38.3	40
	TMT	38.6	38.6	0.50	37.4	39.7
	RT minus TMT	0.39	0.4	0.38	-0.5	1.2
	RT minus TMT+0.4°C	-0.01	0	0.38	-0.9	0.8

Figure 2.4.2 shows the RT minus TMT for each individual dog, for each repeated sample pair, and demonstrates the variability within each individual. The mean RT minus TMT for each dog ranged from 0.14°C to 0.87°C, and there was no consistent difference in RT minus TMT for any animal.

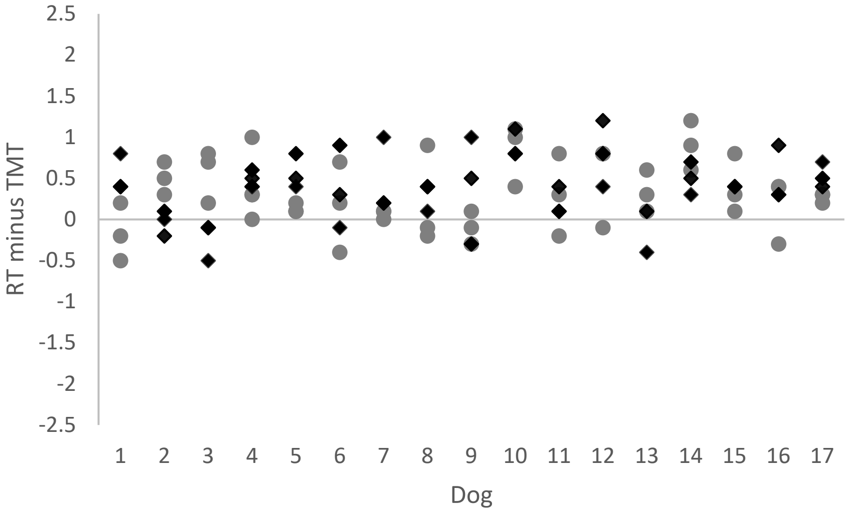

Figure 2.4.2. Rectal temperature minus tympanic membrane temperature (RT minus TMT) values for each individual dog. Circles represent readings pre-exercise, triangles represent readings post exercise.

Use of a correction factor

The results of the present study (overall mean RT minus TMT = 0.39°C) would support using a correction factor of 0.4°C for all dogs. Application of the correction factor TMT+0.4°C, resulted in 92/116 (79.3%) readings falling within the accepted ±0.5°C RT minus TMT difference (previously 68.4%). Repeating analysis using a mixed model approach on the TMT +0.4°C showed there was then no effect of measurement site (rectal versus ear) on temperature ($F_{(1,201)} = 0.067$, $P = 0.797$).

Identification of hyperthermia

Post exercise, hyperthermia was detected using RT on 14/58 (24%) occasions, hyperthermia was defined as a rectal temperature ≥39.3°C (Miller, 2009). Hyperthermia was detected using TMT on 5/58 (9%) occasions. The TMT thermometer identified one individual as being hyperthermic that was normothermic on RT (RT = 39.2°C). The sensitivity and specificity of TMT in detecting hyperthermia were 33.33% and 97.73% respectively.

Application of the correction factor increased the TMT identification of the hyperthermia to 17/58 (29%) occasions. TMT+0.4°C identified seven individuals as being hyperthermic that were normothermic on RT (RT range 38.6°C to 39.2°C). The identification of hyperthermia using TMT+0.4°C had a sensitivity of 71.43% and a specificity of 84.09%.

Impact of environmental conditions

No significant correlation was found between UTCI and RT minus TMT (R_s = 0.47. n = 116, P = 0.615).

2.5 Discussion

Human research shows that TMT diverges from RT during exercise induced hyperthermia (Huggins et al., 2012). In contrast, the present study in dogs found no significant difference in RT minus TMT between pre and post exercise. This suggests that TMT may be suitable as an alternative means of monitoring body temperature in exercising dogs.

The acceptable limit of difference between two temperature monitoring devices is generally reported as ±0.5°C in both human and animal studies (Greer et al., 2007; Lamb & McBrearty, 2013; Niven et al., 2015; Sousa et al., 2011). Using the raw data collected in this study, 31.6% of TMT readings fell outside the accepted 0.5°C difference, similar to the findings reported by Lamb and McBrearty (2013). Therefore, it could be argued this method of temperature measurement is not clinically acceptable.

Rectal temperature does not represent core blood temperature. Rectal temperature readings can be influenced by the presence of faecal material, rectal inflammation and changes in blood supply to the rectum. Greer *et al.*, (2007) demonstrated that canine pulmonary artery temperature differed to simultaneous RT recordings by more than 0.5°C in 5.72% of readings and found that RT frequently recorded temperatures higher than true core temperature (189/297 readings). In human paediatric patients, rectal temperature has been shown to lag behind temporal artery temperature as cooling occurs (Greenes & Fleisher, 2004). In exercising adults TMT has been shown to peak earlier than RT, with RT continuing to increase 5-10 minutes after the cessation of exercise (Newsham et al., 2002). To the author's knowledge there are no published studies investigating this potential lag between rectal and blood temperature during post exercise cooling in dogs. Greer *et al.* (2007) suggested that a lag could be responsible for the differences between rectal and pulmonary artery temperature recordings in anaesthetised dogs, however this was not specifically analysed or investigated. Osinchuk *et al.* (2014) used ingestible telemetry devices to compare rectal to core gastrointestinal temperature in exercising dogs. They reported that core temperature increased and decreased faster than rectal temperature, suggesting that rectal temperature lags behind core temperature in strenuously exercising dogs.

As the type and duration of exercise being undertaken by the dogs in this study was not controlled, it is possible that some dogs could have begun cooling prior to temperature measurement. This could potentially explain some of the differences seen between RT and TMT. The tympanic membrane unlike the rectal mucosa, is also in contact with the air so could potentially be influenced by ambient conditions. The temperature readings in this study were taken all year round, in all seasons and types of weather, resulting in a wide range of ambient conditions and no correlation was found between ambient conditions and RT minus TMT.

When evaluating body temperature in any animal, it is standard practice to make a comparison to the normal reference range for that species in order to categorise the patient as normothermic, hypothermic or hyperthermic. Normal reference ranges for canine rectal temperature vary amongst the literature and the data to support these ranges is not always referenced. For example, one text states a normal range of 38.3-38.7°C (Seymour, 2007), then states a range of 38.3-39.2°C (Goddard & Phillips, 2011) in the following edition, with no reference to the primary sources of information. The range of RT recorded in resting healthy dogs in this study was 37.4-39.1°C, possibly a reflection of the low stress, familiar environment in which the temperatures were measured. In the present study, a short period of exercise increased RT by up to 1.4 °C. This is comparable to dogs undertaking a short walk to the practice or experiencing a period of stress whilst in the waiting room, therefore temperatures recorded in a clinical setting have the potential to be elevated beyond the dog's normal resting temperature. Konietschke *et al*., (2014) highlighted the lack of consistent reference ranges for dogs, in particular at the lower limit, and reported a similar range of temperatures from healthy dogs, 37.2-39.2°C, perhaps suggesting the need for a review of the standard canine rectal temperature reference range. A review of normal rectal temperatures in cats, highlighted a similar lack of consistent reference ranges, and suggested a new reference interval of 36.7-38.9°C following examination of healthy adult cats acclimatised to their environments (Levy et al., 2015).

Of particular importance is the upper limit for normal temperature, most commonly stated as 39.2°C (Miller, 2009). Heat stroke, is a potentially fatal condition in all species, and in dogs can occur once core body temperature exceeds 41°C (Romanucci & Della Salda, 2013). Rapid diagnosis, cooling and presentation to a veterinary hospital in under 1.5hrs have been shown to be critical factors in patient survival (Bruchim et al., 2006). This study has shown that healthy dogs completing short periods of routine exercise in the UK can reach a

RT of 40°C, highlighting the potential risks facing dogs exercising over longer periods during the warmer spring and summer months.

Gomart *et al*., (2014) suggested using correction factors to improve the reliability of the TMT when compared to RT, but did not report how significant these improvements were. This required using three different correction factors ranging from +0.2°C to +0.6°C determined by gender and coat type. In practice, this would be impractical to recommend to owners. These factors also assume that RT minus TMT is consistent for every dog, which is not supported by the findings of this study. The results of the present study would support using a correction factor of 0.4°C for all dogs, as this resulted in no significant difference between RT and TMT+0.4°C. This suggests that TMT+0.4°C is a suitable alternative indicator of body temperature, when rectal thermometry is not practical.

As most studies comparing RT to TMT have found that TMT underreports body temperature, a simpler method of ensuring non-veterinary professionals (e.g. pet owners) are aware of this difference, would be to establish normal TMT reference ranges. The PetTemp instruction manual and company website currently reports a normal ear temperature range of 37.7 to 39.4°C (Admon, 2016). The findings of this study suggest that this "normal" range would result in hyperthermia going undetected 79 % of the time, and suggest a normal resting TMT range of 36.7°C to 38.8°C. Konietschke *et al.* (2014) used 62 dogs to establish a normal rectal temperature range, the reported range of aural temperatures in those animals was 37.1 to 39.1°C, however they did not use a veterinary specific aural thermometer and the measurements were obtained in a clinical setting. Additional research is required to establish a normal TMT reference range in dogs.

The main reasons pet owners measure their dog's temperature are to identify signs of ill health, or when exercising a dog at risk of developing exertional hyperthermia. In both situations identification of hyperthermia is the trigger for action by the owner. The dog owner either seeks veterinary attention for their animal in the case of illness, or stops exercising and begins cooling their animal in the event of exertional hyperthermia. In this study the TMT+0.4°C correction factor improved identification of hyperthermia, but also then identified seven dogs as hyperthermic who were normothermic on RT. In a clinical setting this over reporting of body temperature could complicate patient care, however rectal thermometry is still gold standard for patient monitoring, so it is unlikely this would actually harm any patients. In a non-clinical setting over reporting body temperature might result in owners seeking veterinary attention or stopping a dog's exercise needlessly, but neither of these situations would cause any harm to the dog. Conversely, if owners continue to rely on the current “normal” ear temperature range, they may be reassured that their dog’s temperature is normal, when in fact it could be hyperthermic. If they failed to seek veterinary care or continued exercising their dog, this could have dangerous consequences. It could therefore be argued that under-reporting hyperthermia is more dangerous than over-reporting hyperthermia, especially for animals at risk of heatstroke where delaying seeking veterinary treatment increases the risk of (Bruchim et al., 2006).

At present, the main temperature monitoring method available to owners is rectal thermometry, and as previously mentioned, RT is not tolerated in all dogs, and often requires additional restraint by an assistant (Lamb & McBrearty, 2013). RT monitoring may therefore not be possible for many dog owners wishing to monitor their pet’s body temperature at home, or whilst exercising. The Vet-Temp and Pet-Temp auricular thermometers, offer a potential solution to that problem, and are tolerated well in most dogs (211/212 dogs), with only 24% requiring additional restraint in a veterinary setting (Lamb & McBrearty, 2013). For owners of athletic dogs completing strenuous exercise, or competing in hot climates, the aural thermometers offer a method of monitoring their dog for heatstroke, a potentially fatal condition. However, they should be advised to use a correction factor or specific ear temperature reference range to prevent under reporting of hyperthermia.

Whilst power analysis was used to determine the number of dogs recruited, the sample size was relatively small compared to some of the previous veterinary hospital-based sample populations. As the study recruited a range of dog breeds, ages, sizes and coat types, the effects of these differences could not be evaluated due to the small number of dogs. Ideally, TMT would be compared to blood temperature in healthy dogs with exertional hyperthermia to fully evaluate this temperature recording method, however this would be both impractical and unethical.

Due to the variable types, intensities and duration of exercise undertaken, only 14 dogs reached a temperature considered to be hyperthermic. This limited the evaluation of the aural device for identifying hyperthermia. Recruiting a group of dogs all completing the same type and duration of intense exercise could potentially standardise the elevation in temperature, however individual variation would still impact the overall change in body temperature as reported by Angle and Gillette (2011). Such selective canine recruitment, would also potentially limit the application of any results generated, as intensive canine sporting activities often attract specific breeds or ages of dogs, meaning the younger, older or less sporting breeds would not be represented.

2.6 Conclusion

In line with previous research reported in a clinical setting, this study found that TMT measured consistently lower than RT. The hypothesis that dogs, like humans, would show greater differences in RT minus TMT following exercise, has not been supported by the findings of this study. This suggests that auricular devices could offer a less invasive, better tolerated method of monitoring body temperature in exercising animals, where RT is not possible. Using a correction factor of TMT+0.4°C improves the identification of hyperthermia, and results in no significant difference in RT minus TMT. Perhaps the simplest way to prevent hyperthermia going undetected, would be to establish a normal reference range for canine tympanic membrane temperature, and ensure this reference range is communicated to dog owners using aural thermometers. The results from this study would suggest a normal resting TMT range of 36.7°C to 38.8°C, however more research is needed to validate this range.

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Chapter Three: Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer.

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Keywords: Dog, body temperature, ear thermometer.

3.1 Abstract

Studies have shown that tympanic membrane temperature (TMT) under reports body temperature when compared to rectal temperature. This could lead to misinterpretation of the TMT, if comparing the result to a rectal temperature range. The aim of this study was to establish a normal canine TMT reference range. Four hundred and sixteen TMTs were taken from 157 healthy dogs, in a range of ambient temperatures. The normal reference range for canine TMT was found to be 36.6-38.8°C. This range should be considered by pet owners and veterinary professionals when interpreting TMT measured with a veterinary aural thermometer, to avoid misinterpretation of the results.

3.2 Introduction

In both human and veterinary medicine measuring body temperature remains an important part of any thorough clinical examination. Abnormal body temperature can indicate a range of critical conditions, so it is essential that devices used to measure body temperature are reliable and accurate. Despite considerable scientific advances in digital thermometry and thermography, rectal thermometers remain the gold standard for less-invasive body temperature measurement in veterinary patients, with pulmonary artery, oesophageal and urinary bladder temperatures providing more invasive, but true core temperature measurements. As rectal thermometry can cause stress and require additional restraint in some veterinary patients (Lamb & McBrearty, 2013) there is on-going interest in developing a reliable, less invasive method of accurately measuring body temperature. Aural thermometry remains the most promising alternative method of temperature measurement, but recent studies suggest their readings should be interpreted with caution when compared to rectal temperature reference ranges (Gomart et al., 2014; Hall & Carter, 2017; Zanghi, 2016)

There are numerous studies evaluating the use of aural thermometers in dogs, namely the animal specific PetTemp® and VetTemp® (Advanced Monitors Corporation, California, USA). TMT measurement has been shown to be better tolerated by canine patients in a veterinary setting when compared to rectal thermometry (Gomart et al., 2014; Lamb & McBrearty, 2013), suggesting that for patients where rectal thermometry is impossible due to pathology or patient temperament, TMT can provide a suitable alternative for measuring body temperature (Gomart et al., 2014; Gonzalez et al., 2002; Greer et al., 2007; Hall & Carter, 2017; Lamb & McBrearty, 2013; Rexroat et al., 1999; Southward et al., 2006; Zanghi, 2016). Four of these studies report that TMT underestimates rectal temperature (Gomart et al., 2014; Hall & Carter, 2017; Southward et al., 2006; Zanghi, 2016) mirroring the findings of Yeoh et al. (2017) in primates. This has important implications when using TMT to measure canine body temperature as improper interpretation of the readings could result in misdiagnosis and inappropriate treatment.

The PetTemp® manufacturer guidelines recommend using a normal canine and feline TMT range of 37.7-39.4°C (Admon, 1999). This range is not comparable (specifically at the upper limit) to other published temperature reference ranges (see Table 3.2.1). This lack of consistency defining the normal temperature range is problematic particularly for pet owners trying to interpret their own dog’s body temperature. This variation could reflect the populations of animals used to define “normal canine temperature”. If the dogs’ temperatures were measured in a veterinary setting, rather than a familiar home environment, stress could increase the animal’s body temperature, resulting in an artificially elevated temperature being incorporated into the normal range.

Table 3.2.1. Published normal canine rectal reference ranges, their sources and accessibility to pet owners.

Source	Accessibility of source	Lower temperature limit	Upper temperature limit
Fielder (2016)	On-line veterinary manual open access	37.9°C	39.9°C
Miller (2009)	Textbook		39.2$^{\circ\mathrm{C}}$
Goddard and Phillips (2011)	Textbook	38.2$^{\circ\mathrm{C}}$	39.2$^{\circ\mathrm{C}}$
Konietschke et al. (2014)	Open access article	37.2°C	39.2 °C

The aim of this study was to determine the normal canine TMT reference range (when measured with a veterinary aural device) using healthy dogs. To provide a suitable sample size, data were pooled from previous projects measuring TMT in resting, healthy dogs. The effect of ambient temperature on TMT was also investigated.

3.3 Materials and Methods

This study and all previous projects have been approved by Nottingham Trent University's School of Animal, Rural and Environmental Science's ethics approval group.

Animals

The reference population was recruited to try and reflect the general population of pet dogs within the UK including a range of ages (juvenile to geriatric), both entire and neutered animals of both sex, half of the top 20 pedigree dog breeds in the UK (The Kennel Club, 2017) and a number of crossbreeds. All animals recruited to the study were deemed to be fit and healthy by their owner, with no obvious clinical signs or recent history to suggest systemic disease; shivering dogs were not included in the reference population. If otitis externa was present in one ear, the unaffected ear was used for temperature measurement. Although a previous study has shown that there is no significant difference between the TMT measured in dog's ears with and without otitis externa (Gonzalez et al., 2002), the authors of this paper have found that excessive cerumen or aural discharge can obscure the VetTemp® lens and impact the accuracy. Animals with bilateral ear disease were excluded from the study. All TMT measurements were taken at rest, in a non-veterinary environment. Two study populations were used for data collection, the first group includes pet dogs owned largely by members of staff at Nottingham Trent University. These animals were examined indoors, in a familiar environment between June 2015 and June 2017. The second study group were examined outside, prior to competing in a canicross race (dogs harnessed to their owner either running, biking or scootering over approximately 4km cross country courses) between November 2015 and April 2017. All data collection took place within the East and West Midlands, UK.

The pet dog population consisted of 32 dogs including 12 females (9 neutered) and 20 males (11 neutered), aged 6 months to 16 years (mean = 6 years). 10 breed types were represented in this sample: spaniel (n=7), cross breeds (n=6), Labrador retriever (n=5), lurcher (n=3), collie (n=3), whippet (n=2), pug (n=2), terrier (n=2), Chihuahua (n=1) and pointer (n=1). Body weight was not recorded. TMT measurements were taken in a temperature-controlled environment, dogs were acclimatised to the temperature prior to thermometry.

The canicross dog population consisted of 125 dogs including 52 females (22 neutered) and 73 males (31 neutered), aged 1 -10 years old (mean = 4 years). Twenty-five breed types were represented in the sample population, the most numerous being: cross breed (n=19), pointer (n=17), collie (n=15), spaniel (n=15), lurcher (n=7), husky (n=6), Hungarian vizsla (n=5), Weimaraner (n=5) other breed types (n=36). Body weight was not recorded. Ambient temperature was measured prior to TMT measurement, dogs were acclimatised to the ambient conditions prior to thermometry.

In total, the study population included 157 dogs, representing 28 breed types. Some dogs had multiple TMT measurements recorded, range 1- 9 readings per dog (mean = 3 readings per dog). For dogs with multiple readings, as each TMT was recorded on a separate day, at a different ambient temperature, for the purpose of analysis each TMT was treated as a separate data point.

An additional 30 dogs were recruited at an outdoor canine event in the West Midlands, UK, held in August 2017 to validate the reference range. The dogs' TMTs were measured at rest using the same selection criteria as the main study population. The validation population included 10 females (4 neutered) and 20 males (10 neutered), aged 5.5 months to 14 years (mean = 5 years) and included 14 breed types.

Ambient conditions

Prior to TMT measurement, ambient temperature was recorded. Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK).

Tympanic membrane temperature measurement

Four new VetTemp® VT-150 Instant Ear Thermometers (Advanced Monitors Corporation, California, USA) were used to measure TMT, as per manufacturer's instructions (see Figure 3.3.1) covered by a single use VetTemp® DPC-500 probe cover (Advanced Monitors Corporation, California, USA). The VetTemp® thermometer measures body temperatures between 32.2-43.3°C, with an accuracy of ±0.2°C, within ambient temperatures of 0-40°C. All thermometers were tested reading the surface temperature of a water bath filled with opaque liquid (in an attempt to mimic the surface of the tympanic membrane), and were found to read within ±0.2°C of 36.0°C, 37.0°C and 38.0°C.

Figure 3.3.1. A VetTemp® aural thermometer in use.

All TMT readings were performed by the same investigator, following a standardised method used to examine animals in veterinary practice. Ears used for measurement were chosen based on presentation and restraint of the dog, to reflect the likely situation in practice. Operator accuracy was not formally assessed as part of this study.

Statistical analysis

Statistics were calculated using SPSS 23.0 (SPSS Inc., Chicago, USA). The two populations of dogs were first analysed separately, both populations were found to have a non-parametric distribution and were compared using a Mann-Whitney test, correlation was tested using

Spearman Ranked correlation. The TMTs were then analysed to determine the reference interval, using methods described by Friedrichs et al. (2012). Significance was indicated at P<0.05 for all tests. A histogram was plotted to identify potential outliers, using Dixon's range statistic to determine if outliers should be eliminated from further analysis. As the sample size was over 120 and non-parametric, the percentile method using 90% confidence limits was used to establish the reference limit (Friedrichs et al., 2012). A direct validation method was used, comparing the results from an additional 30 healthy individuals to the calculated reference interval (Friedrichs et al., 2012). More than three readings outside this range would be cause for rejection of the reference interval.

3.4 Results

The median indoor temperature was 21.2°C (range 19.0-21.2°C). For outdoor measurements, the median ambient temperature was 8.9°C (range 3.3-16.2°C). During the validation data collection the median temperature was 19.5°C (range 15.4-24.7°C).

108 TMT measurements were recorded from the indoor dog population, median TMT = 37.9°C (range 34.3-38.9°C). 309 TMT measurements were recorded from the outdoor dog population, median TMT = 37.7°C (range 36.2-39.1°C).

There was no significant difference between indoor versus outdoor TMT measurements (Z = - 1.679, P = 0.093), therefore all data were pooled for further analysis.

The pooled data were then analysed to establish a reference range, with one outlier removed (TMT = 34.3°C) following identification using Dixon's outlier range statistic (Friedrichs et al., 2012). 416 TMT readings were used for the reference interval calculation. The reference interval for healthy canine TMT was calculated from 416 TMT readings, and was shown to range from 36.6 – 38.8°C (confidence interval [CI] = 36.5–36.7°C at the lower limit, CI = 38.8–38.9°C at the upper limit). There was no significant correlation between ambient temperature and TMT (R_s = -0.007 P = 0.894) (see Figure 3.4.1). Additionally, there was no significant difference between the resting TMTs of males and females (Z= -0.578, P= 0.564).

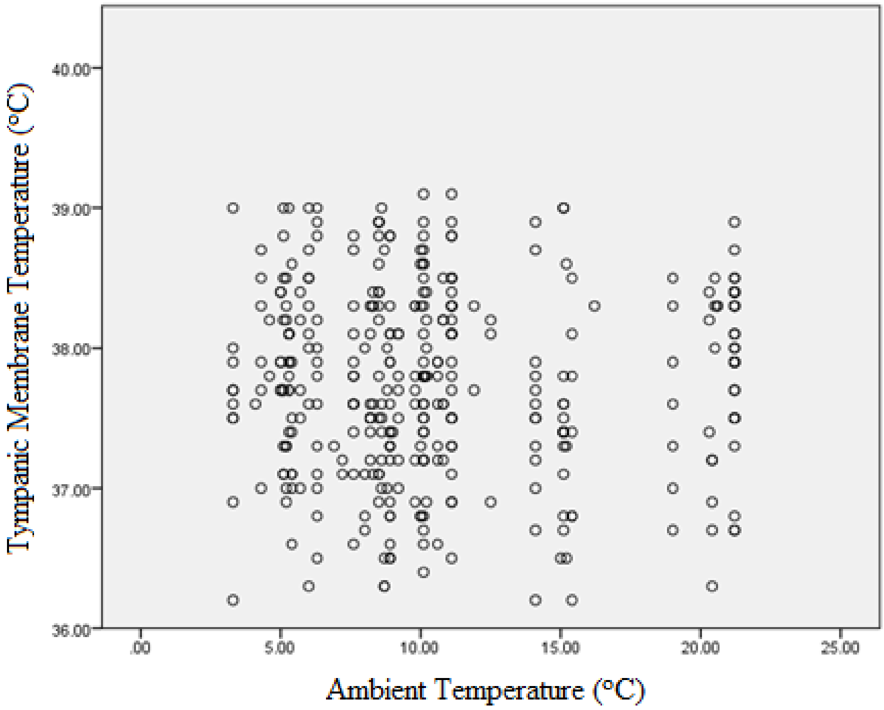

Figure 3.4.1. Scatter plot of the ambient temperature versus tympanic membrane temperature of healthy dogs.

Validation

TMT readings from the 30 dogs in the validation population all fell within this reference interval (36.6 – 38.8°C), with a median TMT of 37.9°C (range 37.0-38.5°C). The reference interval was therefore accepted.

3.5 Discussion

When measured with a veterinary aural thermometer, the normal range of TMT in healthy dogs was found to be 36.6-38.8°C. This is lower than the range of 37.7-39.4°C stated by the thermometer manufacturer (Admon, 2016). Continued use of the manufacturers recommended temperature range, or published canine rectal temperature ranges could result in hypothermia being over diagnosed, hyperthermia being missed and patients being inappropriately treated.

As the PetTemp® is marketed specifically to pet owners as a means of measuring their dog's temperature it is essential that owners understand how to interpret the results for their animal. Global warming is impacting the frequency of unseasonal heat waves (WMO, 2016), increasing the risk of heatstroke in all species, but particularly dogs as their ability to lose heat is quickly impaired as temperature and humidity increase (Hemmelgarn & Gannon, 2013). A dog owner may use their animal's body temperature to reach a decision about seeking veterinary advice for heat related diseases, or how to manage their animals' competition or training. The reference range for canine TMT suggested in this study should reduce the likelihood of hyperthermia being missed, ensuring owners are not falsely reassured by a "normal" temperature measurement potentially putting their animal at risk.

As this study only recorded TMT, with no rectal, or core temperature measurement to compare the results to, there is a possibility some of the animals measured were not normothermic when assessed. Therefore, nothing can be said about the accuracy of the thermometry device from this study alone. Ideally, TMT would have been measured alongside rectal thermometry, however this could have affected the dog's body temperature through stress. Additionally, requiring dogs to have rectal thermometry and aural thermometry performed would have limited the number of dogs recruited to the outdoor study.

Whilst the establishment of a normal canine TMT reference range should improve the interpretation of TMT, it is important to acknowledge the limitations of TMT measurement as a clinical tool. Aural thermometers have been shown to result in more variation than rectal thermometry when operator accuracy has been investigated formally (Greer et al., 2007). This degree of inaccuracy is one of the reasons aural thermometers cannot replace rectal thermometers as the routine method of measuring body temperature in clinical patients. The tympanic membrane does not have a consistent temperature in primates (Yeoh et al., 2017), 2017), and variations between the anatomy of different dog breeds could result in a lack of consistency of probe placement. These factors could explain the reported variability of TMT when compared to rectal temperature (Lamb & McBrearty, 2013). It is also essential that the disposable probe covers are used and changed between every patient. This not only prevents potential transmission of infections between patients, but also protects the probe from accumulation of debris which can reduce accuracy of the device (Admon, 2016).

Although the use of human aural thermometers has been investigated in dogs, the shape of the probe is considerably different to that of the veterinary specific devices (see Figure 3.5.1), meaning in many dogs the human thermometer is likely to be reading the skin lining the ear canal, rather than the tympanic membrane (Greer et al., 2007). The reference range established in this study is therefore unlikely to be accurate when used to interpret results from a human ear thermometer.

Figure 3.5.1. A human aural thermometer alongside a VetTemp® aural thermometer with probe cover in place.

As this study measured TMT in a non-veterinary setting, additional work establishing a reference range in veterinary patients would be beneficial. The stress of visiting a veterinary practice can elevate body temperature, establishing how this affects the upper end of the reference range could aid veterinary professionals in interpretation of the temperature measurements.

3.6 Conclusion

The findings of this study would support a normal canine TMT reference range of 36.6-38.8°C. This is in line with previous research reporting that TMT reads approximately 0.4°C below rectal temperature (Gomart et al., 2014; Hall & Carter, 2017; Zanghi, 2016), when using a normal rectal temperature range of 37.2-39.2°C (Konietschke et al., 2014). TMT is a useful screening tool to assess body temperature in dogs; however, as TMT is not as reliable as rectal thermometry, when monitoring clinical patients TMT measurement should be followed up by rectal thermometry should hypo- or hyperthermia be detected.

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Chapter Four: Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK.

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Keywords: Exercise-induced hyperthermia, canine heatstroke, running with dogs, aural thermometer, canine athlete

Highlights

- Canicross races are typically run over winter to avoid running dogs in hot weather.
- Ambient temperature alone did not correlate with dogs' post-race temperatures.
- Average race speed had a positive effect on canine post-race temperature.
- Dogs exceeding heatstroke associated temperatures were mainly male with dark coats.

4.1 Abstract

Increasing numbers of people are running with their dogs, particularly in harness through the sport canicross. Whilst canicross races are typically held in the winter months, some human centred events are encouraging running with dogs in summer months, potentially putting dogs at risk of heat related injuries, including heatstroke. The aim of this project was to investigate the effects of ambient conditions and running speed on post-race temperature of canicross dogs in the UK, and investigate the potential risk of heatstroke to canicross racing dogs. The effects of canine characteristics (e.g., gender, coat colour) were explored in order to identify factors that could increase the risk of exercise-induced hyperthermia (defined as body temperature exceeding the upper normal limit of

38.8°C).108 dogs were recruited from 10 race days, where ambient conditions ranged from -5 - 11°C measured as universal thermal comfort index (UTCI). 281 post race tympanic membrane temperatures were recorded, ranging from 37.0 - 42.5°C. There was a weak correlation between speed and post-race temperature ($r = 0.269$, $P < 0.001$). Whilst no correlation between any single environmental factor or UTCI and post-race temperature was found, the proportion of dogs developing exercise-induced hyperthermia during the race increased with UTCI ($r = 0.688$, $P = 0.028$). Male dogs ($\chi(1) = 18.286$, $P < 0.001$), and dark coated dogs ($\chi(2) = 8.234$, $P = 0.014$), were significantly more likely to finish the race with a temperature exceeding 40.6°C. Prolonged elevation of body temperature above this temperature is likely to cause heatstroke. At every race dogs exceeded this critical temperature, with 10.7% ($n = 30$) of the overall study population exceeding this temperature throughout the study period. The results suggest male dogs, dark coloured dogs, and increased speed of running all increase the risk of heatstroke in racing canicross dogs. Further research is required to investigate the impact of environmental conditions on post-race cooling, to better understand safe running conditions for dogs.

4.2 Introduction

The sport canicross involves competitors completing a cross country style race either running, cycling or scootering, whilst harnessed to dogs (see Figure 1). The dogs normally run ahead, taking up the slack in the bungee line and providing some assistance to the runner. Canicross is an effective means of exercising both runner and dog over relatively short ‘sprint’ distances of approximately 5km (although longer competitive distances are run). Now formally recognised by The Kennel Club, the sport has been run competitively in the UK since 2000, with increasing numbers of competitors taking part in races around the country (The Kennel Club, 2017). As race results are ultimately linked to both human and dog speed, the sport can promote increased physical activity, encouraging people to exercise with their dog to improve their race times, competitive performance, health and fitness in both species.

Figure 1: One dog canicross competitor on the left, one dog bikejor competitor on the right.

There have been several studies exploring ways of encouraging dog owners to spend more time walking and exercising with their dogs (Rhodes et al., 2012; Schneider et al., 2015; Westgarth et al., 2014, 2015), however studies exploring the impact of this advice (both positive and negative) on the dog are lacking. Encouraging owners to increase their activity levels through dog walking or running, could place the dog at risk of conditions such as heatstroke, as unfit dogs show significantly reduced exercise endurance and increased rate of temperature rise (Nazar et al., 1992) compared to healthy dogs. As heatstroke is a potentially fatal condition, and has been reported following just six minutes of exercise in hot ambient conditions (Bruchim et al., 2006), advising owners to start exercising with their unfit dog in spring or summer months could prove extremely dangerous for the dog. At present advice regarding safe ambient temperature thresholds for exercising with dogs is lacking.

Heatstroke is defined as a systemic inflammatory response leading to multi organ dysfunction and brain damage, associated with hyperthermia (Bouchama & Knochel, 2002), in dogs heatstroke is typically associated with rectal temperatures exceeding 41°C (Flournoy et al., 2003). One veterinary hospital has reported an increase in the number of dogs presenting with exertional heatstroke (caused by exercise) compared to environmental heatstroke (typically following vehicle confinement), with 73% of recent cases being categorised as exertional heatstroke (Bruchim et al., 2017), compared to 58% of cases previously reported (Aroch et al., 2009). The increase in popularity of amateur canine sports participation in the UK, combined with increasing episodes of warm weather during traditionally colder months in autumn and early spring (WMO, 2017), could potentially increase the risk of canine exertional heatstroke occurring (Hall & Carter, 2016).

Traditionally canicross races are run during the autumn-spring, to avoid warm weather for both the runners' and the dogs' benefit. Dogs are more likely to develop heatstroke following prolonged exercise in warm conditions, as they can only sweat through their paw pads, relying mainly on convection and radiation of heat, then panting to allow evaporative heat loss for thermoregulation (Johnson et al., 2006). As ambient temperature increases, heat loss through convection and radiation is limited (Johnson et al., 2006). When competing at canicross events owners are reminded to monitor their own dogs for signs of over-heating, and many canicross clubs have their own informal rules on safe competition conditions. Guidelines on suitable working temperatures are limited, and are reliant on personal experience and anecdote. One such recommendation used by canicross groups and on-line discussion forums is "do not run your dog if ambient temperature (°C) x humidity(%) > 1000", where multiplying the ambient temperature by the relative humidity is used to determine if it is safe to run with your dog (Cani-Sports Edinburgh, n.d.; Highlan Canicrossers, n.d.). Studies investigating the validity of this guideline are lacking, and to date, there have been no studies investigating body temperature in pet dogs competing in canicross races. Whilst the effect of exercise on body temperature has been investigated in both long distance sled racing dogs (Phillips et al., 1981), and in greyhounds competing in shorter sprint races under 1km (McNicholl et al., 2016) there has been no research investigating the temperature of pet dogs racing over middle distances such a canicross race (around 3-5km),

To develop more robust guidelines for safe environmental conditions for canine sports, additional investigation into the effect of ambient conditions on canine athlete body temperature is needed. Physical exercise can exceed thermoregulatory mechanisms, potentially impacting animal health and performance (Piccione et al., 2012; Robbins et al., 2017). Monitoring body temperature is therefore important to monitor the health, physiological status and welfare of exercising, competing or working animals (Rizzo et al., 2017). As temperature, humidity and wind speed all influence body temperature, it is important to consider the thermal impact of the combined effect of all three, when investigating environmental impact on body temperature. Universal thermal comfort index (UTCI) incorporates all of these factors to calculate a "feels like" temperature that reflects the ambient conditions as a whole (Jendritzky et al., 2012). This allows individual environmental conditions to be measured in the field, then combined using the UTCI calculation to provide an ambient temperature that reflects the overall impact of the conditions present.

Aural thermometers measuring tympanic membrane temperature (TMT) have been investigated in comparison with rectal thermometers, and have been found to be an effective alternative for monitoring temperature in dogs pre- and post-exercise (Hall & Carter, 2017a; Robbins et al., 2017; Zanghi, 2016). As aural thermometers are faster and often better tolerated that rectal thermometers (Gomart et al., 2014; Lamb & McBrearty, 2013) they offer an ideal means of monitoring immediate post-race body temperature in the canine athlete under field conditions. Aural thermometers under-report body temperature when compared to rectal temperature in dogs, by around 0.4°C when measured with an animal specific device (Gomart et al., 2014; Hall & Carter, 2017b; Zanghi, 2016), and by around 1.3°C using a human aural thermometer (Piccione et al., 2011). It is therefore important to use an animal specific thermometer and an appropriate reference range when interpreting ear temperature readings (Hall & Carter, 2017b).

The aims of the study were to investigate the effects of varying ambient conditions on the tympanic membrane temperature (TMT) of privately owned pet dogs competing in middle distance canicross races, and the incidence of post-race temperatures associated with heatstroke. In addition, the effects of race speed, gender and coat colour on post-race temperature were also explored to identify canine characteristics that could increase the risk of exercise-induced hyperthermia.

4.3 Methods

This study was approved by Nottingham Trent University's School of Animal, Rural and Environmental Sciences ethics committee.

4.3.1 The race courses

Canicross runners, scooter and bikejor competitors competed with their dogs over a course 3.8 - 4.5km in length over two consecutive days (the course was identical on both days). All dogs had previously competed in canicross races and were at least one year of age for canicross, and two years for scooter and bikejor races. Data were collected at five race weekends (10 individual races) over the 2015-16 and 2016-17 Canicross Midlands race seasons, run between November and April at four venues in the East and West Midlands, UK.

4.3.2 The animals

Canine participants were recruited opportunistically from those competing at the canicross events. Between 18 and 35 dogs were examined on each race day, providing data for 108 dogs (59 male, 49 female) aged 1-10 years old (mean 4.4 years) over the 10 races. Breed types represented were: Pointer (n = 31), Collie (n = 22), Spaniel (n = 13), Husky (n = 10), Retriever (n = 8) and other (n = 24). Across the multiple race dates, dogs' temperatures were recorded pre and post-race between one and nine times (mean 2.6 times per dog) to give 281 post-race temperature data points, of which 210 also had pre-race temperature recorded. For the purpose of analysis, each of the dog's race dates were treated as a separate data point.

4.3.3 Temperature Measurements

TMT was measured pre-race in each dog in the two-hour period prior to competition and post-race, immediately after crossing the finish line of the race. As sampling was opportunistic it was not possible to obtain pre-race TMT readings for all dogs. Left or right ears were selected depending on the positioning of the dog following light restraint. TMT was recorded using a Vet-Temp VT-150 Instant Ear Thermometer (Advanced Monitors Corporation, California, USA), covered by a single use Vet-Temp DPC-500 probe cover. The Vet-Temp thermometer measures temperatures between 32.2 and 43.3°C, with an accuracy of ±0.2°C. The thermometer was used as per the manufacturer's instructions with no lubrication, and a reading being obtained following the audible alarm. If a reading reported an error code, the probe cover was changed, and the process repeated. If an error code occurred a second time, the reading was discounted.

Hyperthermia was defined as TMT greater than the upper normal limit of 38.8°C, using the previously established normal canine TMT range of 36.8-38.8°C. The number of dogs' temperatures exceeding 40.6°C was also noted, as this is equivalent to a rectal temperature of 41°C considered to be the critical body temperature over which heatstroke is likely; TMT has been shown to measure approximately 0.4°C lower than rectal temperature following exercise (Hall & Carter, 2017a; Zanghi, 2016).

4.3.4 Ambient conditions

Ambient conditions (temperature, humidity and wind speed) were recorded prior to collecting the pre-race TMT and at approximately 30-minute intervals until the last post-race temperature had been recorded. Measurements were taken using a HI 9564 Thermo Hygrometer (Hanna Instruments Lid, Bedfordshire, UK), and RD 506-9650 Anemometer (R.S.

Components Ltd., Northamptonshire, UK). To evaluate the overall impact of these environmental conditions, the results were used to calculate Universal Thermal Comfort Index (UTCI) values (Jendritzky et al., 2012). UTCI was calculated from ambient temperature (°C), relative humidity (%) and wind speed (m/s) using the UTCI calculator (http://www.utci.org/). The mean UTCI temperature for the duration of the race period was then calculated. Additionally, the mean 'ambient temperature x humidity' was calculated for each race event.

The shade temperature recorded at the nearest Met Office weather station was also recorded for the duration of the race, to allow comparison between this and the non-shade on-site temperature measurement.

4.3.5 Additional information

Time to complete the course was used to calculate average race speed (km/h), age of the dog, breed, coat colour and coat length and were recorded for all participants.

4.3.6 Statistical analysis

Data were checked for normality using Kolmogorov-Smirnov tests and statistics were calculated using SPSS 23.0 (SPSS Inc., Chicago, IL). The study was a within subject design to accommodate for the range of breeds that participated in each location. This ensured that individual baseline temperature differences were accounted for. Paired t-tests were used to determine the effect of gender on pre-race temp, post-race TMT and temperature difference. ANOVA and post hoc (Bonferroni) tests were used to assess the effect of coat colour and coat length on pre-race TMT, post-race TMT and temperature difference.

To determine the effects of UTCI and speed on post-race temperature, a general linear model (GLM) was carried out, with gender included as a fixed effect and UTCI and speed included as covariates. This GLM was rerun using TMT increase to determine the effects of UTCI and speed on TMT increase. A GLM was also used to look at impact of separate ambient conditions on post-race TMT, with gender as a fixed effect and ambient temperature, humidity and windspeed were included as covariates. This GLM was rerun using TMT increase to determine the effects of separate ambient conditions on TMT increase.

In addition, to investigate the effect of 'ambient temperature x humidity' values, a GLM was run on post-race TMT, with gender as a fixed effect, and speed and 'ambient temperature x humidity' values as covariates. This GLM was rerun using TMT increase.

Chi squared was used to look at the association between gender, coat length and coat colour respectively on the proportion of dogs with post-race TMT > 38.8°C then > 40.6°C. Pearson's correlations were used to determine the relationships between the proportion of dogs reaching post-race TMT > 38.8°C and race ambient temperature, humidity, wind speed or 'ambient temperature x humidity'. Pearson's correlations were calculated to determine the relationship between the proportion of dogs with a post-race TMT > 40.6°C and UTCI, and the proportion of dogs with a post-race TMT > 40.6 °C and 'ambient temperature x humidity' value.

4.4 Results

4.4.1 Ambient conditions

Across the 10 race days the mean ambient temperature recorded was 8.8°C (range 3.3 - 15.4°C), the mean shade temperature recorded by the Met Office weather station was 7.5°C (range 2.5 - 13.5°C) with the Met Office temperature recording a lower temperature on all but one occasion and reading up to 5.5°C lower than the site temperature. Mean site humidity was 70.3% (range 55.0 - 96.1%), mean site wind speed was 1.7m/s (range 0 - 7.4m/s). The mean calculated UTCI temperature for all race days was 7.3°C (range -5.0 - 11.7°C).

4.4.2 Effect of canine characteristics on tympanic membrane temperature

The pre-race TMT varied by 3.1°C across all readings, and was consistent across gender ($Z = -0.527$, $P = 0.598$), coat colour ($F = 0.176$, $P = 0.839$) and coat length ($F = 1.042$, $P = 0.355$). Male dogs had a significantly greater TMT increase from pre to post-race than female dogs ($Z = -4.510$, $P < 0.001$). There was no effect of coat colour ($F = 1.743$, $P = 0.178$) or coat length ($F = 1.713$, $P = 0.183$) on TMT increase (see table 1).

Table 1: Descriptive statistics of pre-race tympanic membrane temperature and temperature increase, for each category of dog.

Study population	Mean (range) pre-race temperature (°C)	Mean (range) temperature increase (°C)
All dogs (n = 210)	37.9 (36.2 - 39.1)	1.8 (-1.4 - 5.0)
Male (n = 113)	37.7 (36.2 - 39.0)	2.1 (-0.4 - 4.1) [a]
Female (n = 97)	37.7 (36.3 - 39.1)	1.4 (-1.4 - 5.0)
Dark coat colour (n = 124)	37.7 (36.2 - 39.1)	1.8 (-0.9 - 5.0)
Medium coat colour (n = 34)	37.7 (36.3 - 39.0)	1.5 (-0.1 - 3.4)
Pale coat colour (n = 52)	37.6 (36.2 - 38.9)	1.9 (-1.4 - 3.8)
Short coat (n = 105)	37.6 (36.3 - 39.0)	1.7 (-0.9 - 4.9)
Medium coat (n = 101)	37.8 (36.2 - 39.1)	1.8 (-1.4 - 5.0)
Long coat (n = 4)	37.6 (37.2 - 38.3)	2.7 (2.0 - 3.6)

Significances ($P < 0.05$): (effect of gender) [a] vs female

The post-race TMT varied by 5.2°C across all readings, with male dogs getting significantly hotter than female dogs (Z = -4.048, P < 0.001) (see table 2). Coat colour also affected post-race TMT (F = 4.312, P = 0.014), post hoc tests using the Bonferroni correction revealed that dogs with medium colour coats had lower post-race TMT than dark coated dogs, they also showed a tendency towards a lower TMT than dogs with pale coats. No difference was seen between dark and pale coats on TMT. Coat length did not affect post-race temperature (F = 2.206, P = 0.112).

Table 2: Descriptive statistics of post-race tympanic membrane temperature, for each category of dog.

Study population	**Mean (range) pre-race temperature (°C)**
All dogs (n = 281)	39.4 (37.0 - 42.5)
Male (n = 157, 55.9%)	39.6 (37.6 - 42.5) ^{a}
Female (n = 124, 44.1%)	39.1 (37.0 - 42.4)
Dark coat colour (n = 161, 57.3%)	39.5 (3701 - 42.5)
Medium coat colour (n = 48, 17.1%)	39.0 (37.4 - 41.1) ^{b}
Pale coat colour (n = 72, 25.6%)	39.5 (37.0 - 40.9)
Short coat (n = 135, 48.0%)	39.3 (37.1 - 42.5)
Medium coat (n = 130, 46.3%)	39.5 (37.0 - 42.5)
Long coat (n = 16, 5.7%)	39.6 (37.5 - 41.9)

Significances ($P < 0.05$): (effect of gender) ^{a} vs female, (effect of coat colour) ^{b} vs dark

4.4.3 Effects of speed and ambient conditions on tympanic membrane temperature

The average speed (mean = 15.58 km/h, range 7.82 - 28.58 km/h) of the dog during the race had a significant effect on the post-race TMT (F = 7.729, P = 0.006) but no effect on TMT increase (F = 2.843, P = 0.093). Speed was found to have a weak correlation with post-race TMT (r = 0.269, n=279, P<0.001). UTCI had no effect on either post-race TMT (F = 0.478, P = 0.490) or TMT increase (F = 0.137, P = 0.712). Individual environmental conditions of temperature, humidity, wind speed and 'ambient temperature x humidity' values had no effect on either post-race TMT or TMT increase (P > 0.05).

4.4.4 Critical temperatures

The proportion of dogs reaching post-race TMT > 38.8^{o}C was calculated for each individual race day. As race day average UTCI temperature increased, the proportion of dogs reaching post-race TMT > 38.8°C increased (r = 0.688, n = 10, P = 0.028) (see figure 2). However, there was no correlation between proportion of dogs reaching post-race TMT >

38.8°C and race ambient temperature (r = 0.356, n = 10, P = 0.312), humidity (r = -0.204, P = 0.571) or wind speed (r = -0.512, n = 10, P = 0.131). In addition, no correlation occurred between proportion of dogs reaching post-race TMT > 38.8°C and 'ambient temperature x humidity' (r = 0.194, n = 10, P = 0.592).

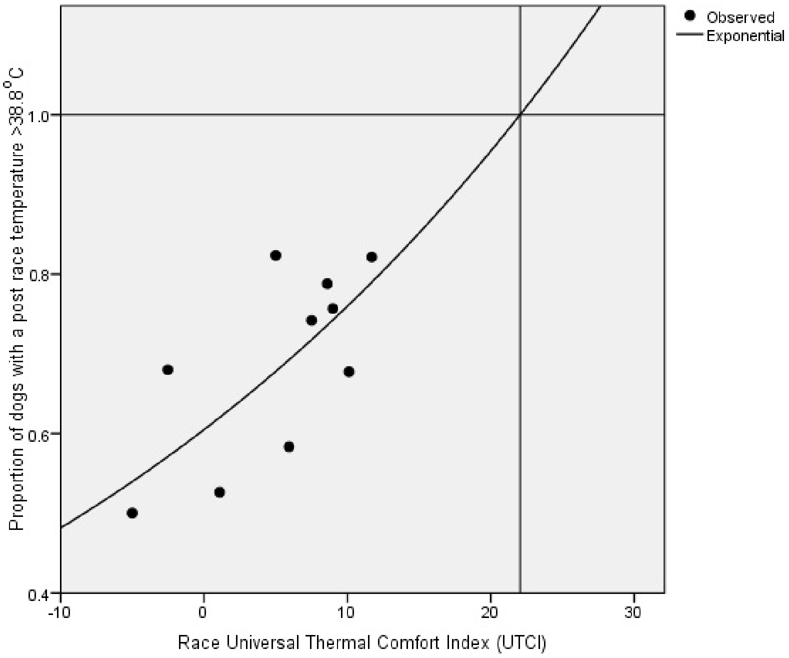

Figure 2: Scatter plot showing race universal thermal comfort index temperature against the proportion of dogs developing post-race hyperthermia (temperature > 38.8°C). The theoretical point at which all dogs would develop post-race hyperthermia is 22.0°C.

No association was found between gender (χ(1) = 0.386, P = 0.224), or coat length (χ(2) = 0.222, P = 0.217) and proportion of dogs with post-race TMT > 38.8°C. Fewer medium colour and more pale dogs that expected had a post-race TMT > 38.8°C (χ(2) = 9.196, P = 0.010).

The dogs reaching the critical temperature of greater than 40.6°C, comprised the top 10.7% of all post-race TMT readings recorded across the 10 race days (n = 30, 24 male dogs and six female dogs). More male dogs (80%) were present than expected (χ(1) = 18.286, P < 0.001). There was no correlation between proportion of dogs reaching post-race TMT > 40.6°C and race UTCI (r=0.221, n=10, P = 0.539). Additionally, no correlation occurred between proportion of dogs reaching post-race TMT > 40.6°C and 'ambient temperature x humidity' (r = -0.063, n = 10, P = 0.862). No association was found between coat length and proportion of dogs exceeding the critical temperature 40.6 °C (χ(2) = 2.571, P = 0.091).

More dark coated dogs (76.7%) and fewer pale coated dogs (13.3%) were found to exceed post-race TMT > 40.6°C than expected ($\chi(2) = 8.234$, $P < 0.05$).

4.5 Discussion

This study found no effect of ambient temperature alone on post-race TMT in dogs exercising in ambient conditions ranging from -5.0 - 11.7°C (UTCI), which is in line with a previously published study investigating strenuous exercise tests on Labradors (Matwichuk et al., 1999). In contrast, McNicholl et al. (2016) found a small effect of ambient temperature on greyhound post-race temperatures, and Phillips et al. (1981) found a strong effect of ambient temperature on mean post-race rectal temperature in sled dogs. These conflicting findings could be explained by differences in canine management between these four studies. The greyhounds and sled dogs were all managed by professional dog trainers, so would have been prepared for each of their races in a similar manner to ensure performance, with similar feeding, hydration and specific conditioning for the type of work being undertaken. In contrast, the dogs in this study, and the Labradors undergoing exercise tests, were all privately owned pet dogs likely managed in very different ways.

The body temperature of exercising dogs is known to be influenced by many non-environmental factors. The results of this study support the findings of McNicholl et al. (2016); male dogs were significantly hotter post-race compared to female dogs, dark dogs developed significantly higher temperatures post-race compared to medium coloured dogs (but not pale dogs), and dog's exceeding the post-race temperature of 40.6^{o}C were more likely to be male, and dark coated. This study also supports the findings of Chapman & Baker (1984), increasing exercise intensity - in this case speed - had a positive effect on post-race temperature. Body size (McNicholl et al., 2016; Phillips et al., 1981), conditioning (Ferasin & Marcora, 2009; Nazar et al., 1992; Ready & Morgan, 1984), hydration (Baker et al., 1983) and diet (Ober et al., 2016) have all be found to influence post exercise body temperature. Although these factors were not investigated as part of this project, they are likely to have influenced the results. It is probable that the pet dogs taking part in this study, would have experienced variations in their feeding, hydration, and conditioning both between different dogs, and between races for individual dogs. Additionally, the different racecourses had different terrains and inclines at different points in the race, also known to influence rate of temperature elevation in exercising dogs (Chapman & Baker, 1984). The combination of these varying factors could have influenced both rate of temperature increase, and post-race temperature and may explain the lack of correlation between UTCI temperature, and post-race temperature of the dogs.

Measuring a single environmental parameter cannot represent the true thermal environment experienced by a human, this led to development of the UTCI calculation (Jendritzky et al., 2012). It is therefore unsurprising there were no correlations between either post-race TMT, or proportion of dogs developing exercise-induced hyperthermia post-race, and any one environmental condition – wind speed, humidity or temperature – or even the combination of temperature and humidity. Whilst no direct correlation was found between UTCI temperature and post-race canine TMT, there was a significant correlation between UTCI and the proportion of dogs finishing the race with exercise-induced hyperthermia. Extrapolating the "line of best fit" in figure 2, theoretically all racing dogs would develop hyperthermia once the UTCI temperature reaches 22.0°C. Whilst hyperthermia in itself is not dangerous, prolonged hyperthermia particularly above 41°C increases the likelihood of long-term damage from heatstroke.

At every race in this study, at least one dog developed a post-race body temperature that would be considered at risk for developing heatstroke (TMT > 40.6°C). The highest recorded post-race TMT was 42.5°C. This is comparable to the highest TMT (42.4 °C) reported by Robbins et al. (2017), following 30 minutes of intermittent exercise in ambient conditions of 28.7°C and 49.6% humidity. This highlights the relative intensity of canicross races; a 12-30 minute race in relatively cool ambient conditions, caused body temperature to elevate to a similar level recorded in dogs exercising for 30 minutes in ambient conditions approaching body temperature. Despite these body temperature elevations, no dogs exhibited any clinical symptoms of heatstroke during any of the canicross race days, again mirroring the findings of Robbins et al. (2017). On several occasions, owners requested additional temperature checks on particularly hot dogs during the period following the race. These dogs all returned to a normal body temperature within 10-20 minutes, suggesting appropriate cooling mechanisms were in place to prevent prolonged hyperthermia. As ambient temperature increases, particularly as it approaches body temperature, cooling mechanisms become less effective (Hemmelgarn & Gannon, 2013). Further investigation into the factors affecting post exercise cooling, particularly the impact ambient conditions have on rate of cooling, may be more required to establish guidance for safe ambient conditions for running.

The combination of canine factors, husbandry factors, exercise factors and environmental factors all influence canine post exercise temperature, meaning any guidelines for "safe" running temperatures are unlikely to apply to all animals and could potentially put dogs at risk. Instead, owners should be encouraged to understand the factors that can influence their own dog's performance and heat tolerance in different ambient conditions. Canicross race organisers, and any other organisations promoting running with dogs, should be aware that the recommendation to not run a dog if 'ambient temperature (°C) x humidity (%) > 1000' did not correlate to canine body temperature or the proportion of dog's developing hyperthermia, or the proportion of dogs developing a temperature considered at risk of heatstroke, so its continued use cannot be recommended for the general pet dog population. As local weather stations only provide estimates of local shade temperatures, this could promote a false sense of security regarding race conditions. Instead, race organisers should make efforts to provide on-site means of monitoring environmental conditions, including ambient temperature, humidity and wind speed, preferably providing an estimation of UTCI temperature, for instance using a wet bulb globe heat stress monitor. Being able to measure ambient conditions on the racecourse itself, allows owners to make an informed decision regarding their animal's ability to compete under those conditions. Dog owners need to be aware of the factors that can impact their animal's exercising body temperature. An unfit, poorly acclimatised, dark coated male dog may be at greater risk of heatstroke running in late autumn, than a pale coated, female dog in regular training, running in the middle of summer.

A major limitation of this study, was the inability to measure body temperature during the race. Previous work using ingestible telemetric thermometry capsules in Labradors, has shown that body temperature increased continuously during a 3.5km, flat run (Angle & Gillette, 2011). One study using treadmill running dogs, suggested that reaching a peak body temperature coincided with the point of exhaustion for the dogs (Nazar et al., 1992), with unconditioned dogs reaching peak temperature and therefore exhaustion faster than conditioned dogs. Phillips et al. (1981) continuously measured rectal temperature in racing sled dogs over a 16km run. They found temperature increased up to around 25 minutes into the run, then tended to plateau following several short rest stops triggered by the trainer's perception of the dog's ability to continue.

As intensity of exercise, specifically incline, has been shown to significantly increase canine body temperature (Chapman & Baker, 1984), it is possible canicross racing dogs reach a peak body temperature following a period of incline work, which then plateaus or drops as the work intensity reduces. Anecdotally, canicross runners have reported their dogs slowing down and refusing to pull during races, potentially due to reaching their temperature tolerance threshold. As there are limited non-invasive methods of continuously measuring core body temperature in dogs available in the UK, it is currently difficult to conduct further research on this area under field conditions using pet owned dogs. However, understanding how the dog's body temperature changes throughout the race in response to speed, inclines, and the presence of water obstacles on the course, may help to suggest appropriate race modifications to prevent canine heatstroke, when ambient conditions are considered too warm for all dogs to safely compete.

4.6 Conclusion

This study found no direct correlation between ambient conditions or UTCI temperature and post-race body temperature of dogs competing in canicross races, and at every race dogs reached post-race temperatures exceeding the heatstroke risk threshold (40.6°C). Average race speed was found to have a positive effect on post-race temperature, and a positive correlation between UTCI (°C) and the proportion of dogs developing exercise-induced hyperthermia during the race was also found. The lack of a clear relationship between environmental factors and canine body temperature highlights the difficulty of trying to establish guidelines for safe running temperatures for dogs. Canine sports associations, and dog owners in general should be aware of the potential for inter and intra-dog temperature variations, depending on both husbandry and canine factors, and should be aware of the risk of heatstroke even on relatively cold UK winter days.

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Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016

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As climate change causes global temperatures to rise, heat-related illness, a potentially fatal condition in dogs, will become an ever-greater threat. This study aimed to report the incidence, fatality and canine risk factors of heat-related illness in UK dogs under primary veterinary care in 2016. The VetCompass™ programme collects de-identified electronic patient records from UK veterinary practices for research. From the clinical records of 905,543 dogs under veterinary care in 2016, 395 confirmed heat-related illness events were identified. The estimated 2016 incidence of heat-related illness was 0.04% (95% CI 0.04-0.05%), with an event fatality rate of 14.18% (95% CI 11.08 – 17.96%). Multivariable analysis identified significant risk factors including breed (e.g. Chow Chow, Bulldog and French Bulldog), higher bodyweight relative to the breed/sex mean and being over two years of age. Dogs with a brachycephalic skull shape and dogs weighing over 50 kg were also at greater risk. As we move into an ever-warmer world, veterinary professionals may need to include resistance to heat-related illness amongst their rationales when advising owners on breed selection. Breeding for good respiratory function and maintaining a healthy bodyweight should be considered key welfare priorities for all dogs to limit the risk of heat-related illness.

Climate change is listed among the World Health Organisation's top ten threats to Global Health in 2019, with heat-related illness (HRI) predicted to contribute towards an additional 250,000 human deaths annually by 2030[1]. HRI is a progressive disorder of animals and man caused by core body temperatures that rise above homeostatic limits, resulting in metabolic disturbances[2]. This can lead to decreased cardiac output, fatigue of heat dissipation mechanisms, organ failure and ultimately death[2–4]. Animal welfare organisations in the United Kingdom (UK) and Australia have reported increasing numbers of calls about animals trapped in hot environments over recent years[5,6]. As the frequency and severity of heat waves is predicted to increase, there is an urgent need for better evidence-based guidance on the risk factors and early recognition of HRI to improve prevention and treatment strategies for both humans and animals[3,7].

A deficiency of reliable and current data on the diagnosis, treatment and fatality rate of HRI is a key barrier to mitigating HRI risks in both humans and dogs[8]. The classical terminology used to define HRI varies, but typically includes terms that describe progression from heat stress, through heat exhaustion to heatstroke[2]. However, these classical terms lack clear explicit definitions and are often used interchangeably as synonyms, leaving their usage open to individual interpretation that creates a confused medical and veterinary literature[3]. A novel HRI scoring system has been proposed for use in humans, acknowledging that patients can progress through the stages of disease severity depending on the duration and intensity of heat exposure and effectiveness of treatment[9]. To date, studies of HRI in dogs have included only cases described as suffering from advanced stages of HRI "heatstroke"[10–13]. Excluding dogs presenting with less severe forms and stages of HRI from risk factor analysis fails to take the progressive nature of the condition into consideration and biases the results away from the overall HRI caseloads seen in general veterinary practice.

HRI is reported as a relatively common condition in dogs in regions with hot climates[3,12], but cases are reportedly less common in more temperate regions such as the UK. In a BVA survey of over 1000 UK companion

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animal veterinarians, half reported seeing an average of five canine heat-related illness cases during the summer of 2016[14]. Case reviews from primary-care single centre studies in the UK often include insufficient cases for robust statistical analyses and are therefore of limited scientific value. For this reason, canine HRI studies to date have tended to rely on referral hospital populations that accumulate caseloads from a broad base of referring practices[10–13,15,16], but referral caseloads self-select for complex and severe cases, and the diagnoses and outcomes will be heavily influenced by the advanced veterinary equipment and care available in such hospitals[17]. The largest heatstroke study in dogs to date included 126 dogs presenting to a hospital in Israel and reported a case fatality rate of 53%[10]. That study used a retrospective case series analysis from a referral hospital population, preventing extrapolation of fatality rate to the wider canine population because of the inherent referral bias[17]. Consequently, results from such referral studies are not representative of the general canine population, reducing the generalisability and wider world application of the findings[18].

In recent years, there has been considerable development of 'Big Data' databases combining primary-care clinical records from hundreds or even thousands of individual veterinary practices[19–21]. In the UK, VetCompass™ has developed an online research platform that provides access to de-identified veterinary patient records from over 15 million companion animals and has been validated as a research resource by 75 peer reviewed publications to date[18,20].

Study aims

The current study aimed to use the VetCompass database of veterinary health records to (i) estimate the 2016 incidence of HRI in the UK dog population; (ii) identify canine risk factors for HRI and (iii) estimate case-fatality rate for HRI in dogs under primary veterinary care in 2016. It was hypothesised that brachycephalic breeds (specifically the Bulldog) have higher odds of HRI compared to mesocephalic breeds.

Methods

Data collection and management.

The study used data from the VetCompass Programme that provides research access to de-identified electronic patient records (EPRs) from primary-care veterinary practices in the UK as previously described[22–25]. The study population included all dogs under primary veterinary care during 2016 in VetCompass. Dogs under veterinary care were defined as those with either a) at least one EPR recorded during 2016 and/or b) at least one EPR recorded during both 2015 and 2017. Data fields available for each dog included a unique animal identifier with breed, sex, neuter status, date of birth and bodyweight, and also clinical information from free-form text clinical notes, treatments and deceased status with relevant dates.

Database search.

Pilot study. Pilot investigations were conducted to refine the search terms used to identify candidate HRI cases within the denominator population. Because HRI is neither a definitive diagnosis nor a disorder that can be objectively confirmed through diagnostic testing, the case definition needed to be broad enough to include diagnoses reached by excluding other differential diagnoses and by consideration of the animal's recent history. The final HRI case definition included any dog with strong evidence for HRI recorded in the EPR including a final stated diagnosis or insurance claim for a heat related illness (including terms such as heatstroke, heat stress, heat exhaustion or overheating) and/or a history of at least one of the following clinical signs developing specifically after, and being ascribed to, exposure to a hot environment, physical exertion or both.

Clinical signs:

- panting excessively or continuously despite removal from heat/cessation of exercise,
- collapse not subsequently attributed to another cause (e.g. heart failure, Addison's),
- stiffness, lethargy or reluctance to move,
- gastrointestinal disturbance including hypersalivation, vomiting or diarrhoea,
- neurological dysfunction including ataxia, seizures, coma or death,
- haematological disturbances including petechiae or purpura.

Exclusion criteria included:

- subsequent diagnosis of an infectious or inflammatory condition that was not attributed to primary heat exposure such as kennel cough, pyometra or infectious meningitis,
- HRI or synonym listed only as one of a differential list,
- an earlier diagnosis of HRI that was later revised to exclude HRI, for example the dog was diagnosed with epilepsy following further seizure activity.

There are currently no explicit guidelines in dogs for accurately staging heat related illness and dogs, like humans, may progress through the stages of HRI depending on their treatment[26]. The HRI case definition in the current study included all stages of disease from mild (classically referred to as heat stress) to severe (classically referred to as heatstroke)[2].

Main study. Candidate cases of HRI were identified by searching the EPR free-text fields for the following terms: heat stroke~3, heatst*, hyperthermi*, overheat*, over heated~2, heat exhaustion~2, hot car~2, collapse* + heat, cooling, high ambient temp*. Dogs identified from all searches were merged and randomly ordered. All candidate cases were manually reviewed in detail by two researchers (author 1 and author 2) to identify all confirmed HRI cases that met the study case definition for HRI occurring at any date within the patient's available lifetime EPR (*prevalent HRI cases*), up to the point of data extraction (20th January 2019). From these prevalent cases, the subset of *incident 2016 HRI cases* was identified with HRI events occurring only within the 2016 study period.

All confirmed prevalent cases underwent further data extraction including outcome of event (survival or death) and date of heat exposure event. The first event occurring during the study period (2016) was used for the date of exposure event to calculate age at event for dogs with multiple HRI events.

Analysis.

Sample size calculations using Epi Info 7 were based on an estimated HRI incidence of 0.29% derived from a survey of the UK veterinary profession that reported an average of five canine HRI cases per practice during 2016[14]. There were approximately 5,000 small animal or mixed practices in the UK during 2016[27], resulting in an estimated 25,000 HRI events within the 8.5 million dogs in the pet UK population[28]. The Bulldog has previously been reported at greater HRI risk than other dogs (odds ratio (OR) 2.7)[11], and comprise 0.36% of the UK dog population[25]. Sample size calculations estimated that cross-sectional analysis would require 114,588 dogs (including 1879 Bulldogs) to provide a 2.7 odds ratio estimate for a disorder expected to occur in 0.29% of overall population with a 0.01% confidence limit and 90% power (60:1 ratio of control to exposed).

The study used a cohort design. The denominator population included 905,543 dogs from the VetCompass database. Demographic data were extracted automatically from the database for all study dogs and exported into Microsoft Excel (Office 365) for cleaning and descriptive analysis.

The prevalence of HRI within the cohort was estimated using all confirmed *prevalent HRI cases*. The one-year (2016) incidence was calculated using only *2016 incident HRI cases*. The event fatality rate was calculated using all dogs with at least one HRI event occurring in 2016. The 95% confidence intervals (CI) were calculated using EpiTools (AusVet 2019). The number of incident cases each month was plotted against the mean monthly UK air temperature, retrieved from the Met Office (https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series) to provide a visual representation of the relationship between ambient temperature and HRI incidence.

Risk factor analysis used cohort clinical data to classify dogs as a case (*2016 incident HRI cases*) or non-case (all dogs in the denominator population not defined as a *2016 incident HRI case*) for HRI during the 2016 study period. Risk factor analysis was conducted in SPSS v25 using multivariable logistic regression to identify potential risk factors associated with HRI (defined in Table 1). Binary logistic regression was used to evaluate potential univariable associations between risk factors (*breed type, purebred, skull shape, adult bodyweight, bodyweight relative to breed/sex mean, sex/neuter* and *age*) and HRI diagnosis during 2016. As *breed type* was a factor of primary interest for the study, variables that are highly collinear with breed (*purebred*) or considered a defining characteristic of individual breeds (*adult bodyweight* and *skull shape*) were used in alternative models and not included in the multivariable models using *breed type,* as previously described[22]. Risk factors with liberal associations in univariable modelling ($P < 0.2$) were selected for multivariable evaluation. Model development used manual backwards stepwise elimination. Pairwise interactions were tested for all variables in the final multivariable model. The area under the receiver operating characteristic (ROC) curve was used to evaluate the predictive ability of the model[29] alongside consideration of the underpinning biological plausibility of the model specification. Statistical significance was set at $P < 0.05$.

Results

The study included 905,543 dogs under veterinary care at 886 UK VetCompass clinics during 2016. EPR searches identified 6531 candidate cases, of which 1222 were classified as *prevalent HRI cases* following manual review giving an estimated prevalence of 0.14% (95% CI 0.13-0.14%). There were 35 dogs identified with two HRI events and one dog with three recorded HRI events from the *prevalent HRI cases*. Data completeness varied between the variables assessed: *breed type* 99.55%, *sex/neuter* 99.53%, *age* 98.63% and *adult bodyweight* 65.70%.

Incidence estimate.

There were 395 HRI events recorded in 2016 from 390 individual dogs. The incidence risk of HRI in dogs under primary veterinary care during 2016 was 0.04% (95% CI 0.04-0.05%). There were no HRI events during February, October or December, while 40% (158/395) of the incident cases were in July (see Fig. 1), corresponding with a heatwave event thought to have been triggered by a particularly strong El Nino[38].

Breeds with the highest incidence of HRI were the Chow Chow (0.50%, 95% CI 0.21-1.16%), Bulldog (0.42%, 95% CI 0.30-0.58%, French Bulldog (0.18%, 95% CI 0.12-0.25%), Dogue de Bordeaux (0.17%, 95% CI 0.07-0.39%), Greyhound (0.15%, 95% CI 0.07-0.29%) and Cavalier King Charles Spaniel (0.12%, 95% CI 0.08-0.18%) (Fig. 2). The incidence risk of HRI in brachycephalic breeds overall was 0.08% (95% CI 0.07-0.09%) (Fig. 3).

Fatality.

During the 2016 period, 56 of the 395 HRI events resulted in death of the dog. The manner of death was not recorded for two cases. Of the remaining 54 deaths, 35 (64.81%) were by euthanasia and 19 (35.19%) were unassisted deaths. The event fatality rate for HRI in dogs during 2016 was 14.18% (95% CI 11.08 – 17.96%).

Risk analysis.

Univariable binary logistic regression modelling identified *breed type* ($R^2 = 0.040$, $P < 0.001$), *purebred* ($R^2 = 0.004$, $P < 0.001$), *skull shape* ($R^2 = 0.009$, $P < 0.001$), *adult bodyweight* ($R^2 = 0.006$, $P < 0.001$), *bodyweight relative to breed/sex mean* ($R^2 = 0.002$, $P < 0.001$) and *age* ($R^2 = 0.002$, $P = 0.063$) as factors liberally associated with HRI, but not *sex/neuter* ($R^2 = 0.001$, $P = 0.459$) (see Supplementary Note 2 for descriptive and univariable regression results).

The final breed multivariable model retained three risk factors: *breed type, bodyweight relative to breed/sex mean* and *age* ($R^2 = 0.045$, degrees of freedom = 43). The model showed acceptable discrimination (area under the ROC curve: 0.718). In the final model (Table 2), nine breeds (Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever) had higher odds of HRI compared to Labrador Retrievers. Crossbreds were not at significantly different odds compared to Labrador Retrievers (OR 0.82, 95% CI 0.49-1.37, $p = 0.450$). No breed types had significantly reduced odds of HRI compared to Labrador Retrievers. Dogs with bodyweight equal to or greater than the relative breed/sex mean had higher odds of HRI (OR 1.42, 95% CI 1.12-1.80) compared to dogs weighing below the relative

Potential risk factor for HRI	Variable definition	Justification
Breed type	Categorical variable including all named breed types (including both KC recognised purebred and non-KC recognised purebred) and designer hybrid types with contrived names (e.g. Cockapoo, Labradoodle, Lurcher) with ≥5 HRI cases and/or ≥5000 dogs in the overall study population. All remaining dogs were assigned to grouped categories of "other purebred", "other designer cross" or "non-designer crossbred".	.Belgian Malinois, Golden Retrievers and brachycephalic breeds are reported to have increased odds ratio of HRI compared to small breeds of dog[11]. Labrador Retriever was used as the comparator for this variable as they were the largest breed type in the denominator population (after crossbred) so enabled high statistical power to explore breed risks[29,30]
Purebred	Categorical variable grouping all dogs of recognisable breeds as "purebred", all recognisable designer crossbreeds as "designer cross" and the remaining dogs as "crossbred".	Purebred dogs are more likely to have an exaggerated conformation such as brachycephaly, thick coat, or giant body size, limiting their ability to thermoregulate[31]. A higher percentage of purebred dogs presented with heatstroke to one veterinary hospital[12].
Skull shape	Purebred dogs were categorised by skull shape into three groups, "brachycephalic", "mesocephalic" and dolichocephalic" (see Supplementary Note 1 for breeds by category). Designer crossbred dogs including a brachycephalic breed were classified as "brachycephalic cross" and all other dogs listed as crossbred or unrecorded breed were classified as "skull shape unrecorded".	.Surface areas of the nasal turbinates and effective ventilation provide the mechanism to enable evaporative heat loss through panting, thus brachycephalic dogs have reduced heat dissipation mechanisms[11,31–33]
Adult bodyweight	Adult bodyweight was defined as the mean of all bodyweight (kg) values recorded for each dog after reaching 18 months old. Bodyweight (kg) was then categorised into seven groups (<10, 10-<20, 20-<30, 30-<40, 40-<50, ≥50), dogs under 18 months or with no recorded adult bodyweight were classified as "unrecorded".	Small breeds of dog are reported to have decreased risk of HRI[11], dogs with greater body mass have been reported to develop higher post exercise body temperatures[34].
Bodyweight relative to breed/sex mean	A categorical variable grouping dogs with a mean adult bodyweight "equal or above" or "below" the mean adult bodyweight for their breed and sex (calculated using the overall VetCompass study population). An "unrecorded" variable included all dogs with no adult bodyweight or labelled as crossbred.	Increased bodyweight can be due to increases in either lean muscle mass, or body fat. Obesity limits heat conduction and radiation from the skin and can limit effective cooling via respiration[31], overweight animals overheat faster and take longer to cool[35]. Dogs with greater lean body mass developed higher post exercise temperatures than lighter dogs[34].
Sex/neuter	Dogs were classified by sex and neuter status into five categories (female entire, female neutered, male entire, male neutered) with "unrecorded" was used to group any dogs with no recorded sex or neuter status.	Male dogs develop higher body temperature post exercise[34,36], and are over represented in cases of heatstroke presenting to veterinary hospitals[10,13,37].
Age	The age variable described the age of the dog at the end of the study period (31st December 2016) for non-case dogs, or the age at the first HRI event for *2016 incident HRI cases*. Age (years) was categorised into eight groups (<2, 2-<4, 4-<6, 6-<8, 8-<10, 10-<12, ≥12) with "unrecorded" for any dogs with no date of birth recorded in the EPR.	Older animals are more likely to have pre-existing conditions that limit effective heat dissipation such as heart disease, or respiratory diseases e.g. laryngeal paralysis[32].

Table 1. Potential risk factors assessed for association with heat related illness (HRI) in UK dogs.

breed/sex mean. Dogs in the 2-<4 years, 6-<8 years and ≥12 years categories had greater odds compared to dogs <2 years old, dogs ≥12 years had the greatest odds of HRI (OR 1.75, 95% CI 1.14-2.70).

As described in the methods, variables collinear (*purebred*) and definitive of breed types (*bodyweight* and *skull shape*) replaced the *breed type* variable in the final multivariable model (Table 3). Purebred dogs had 1.86 times (95% CI 1.39-2.49) the odds of crossbred dogs. Brachycephalic dogs had higher odds of HRI (OR 2.10, 95% CI 1.68-2.64) compared to mesocephalic dogs. Dogs over 50 kg in bodyweight had 3.42 times the odds of HRI (95% CI 1.54-7.57) compared to dogs weighing under 10 kg.

Discussion

This is the largest primary-care study to report the incidence, risk factors and case fatality for HRI in dogs in the UK. The 0.04% annual incidence of HRI in dogs under primary veterinary care based on our real clinical records is considerably lower than the incidence predicted by an opinion survey of veterinary surgeons carried out during the same study period (2016)[14]. This highlights the issue of recall bias when using surveys based on belief rather than documented reports of disorders, especially following exposure to media campaigns highlighting hazards that may promote a recency effect to encourage higher 'recall'[39]. That survey was conducted following the launch of the "Dogs die in hot cars" campaign[40], which could explain the 'prompted' high numbers of cases reported by veterinary surgeons. It should also be noted that the survey included all veterinary surgeons, including those working in referral and out-of-hours emergency hospitals, which may also contribute to the high numbers of cases reported, whereby individual cases could be double, or triple counted.

The current study reports event fatality for HRI events at 14.18%. Our primary-care case fatality rate is lower than previous reports of 36–50%[11–13]. However, ours is the first study to include all stages of HRI presentation, including early stages which may be managed without hospitalisation, while previous studies tended to include only the more severely affected subset of dogs defined as having "heatstroke" or advanced heat related illness presenting to referral hospitals. This is the first study to use a primary veterinary care population rather than a referral population, highlighting the limitations of using referral populations to estimate incidence and fatality at a population level[17]. The relatively low fatality rate reported in the current study could also reflect the temperate UK climate. As previous studies have primarily been conducted in countries with hotter climates such as Israel[11–13], the comparatively higher fatality rates reported in hotter countries should serve as a warning for the UK. As climate change accelerates both the frequency and severity of heat waves[8], the incidence and fatality rate of HRI is likely to increase in dogs[7]. In the current study, 40% of the incident cases were in July, corresponding

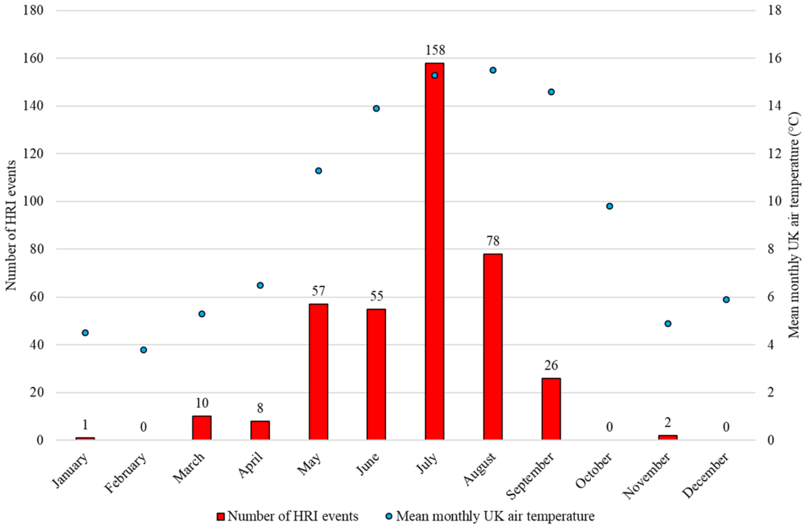

Figure 1. Heat-related illness cases by month for UK dogs under primary veterinary care at practices in the VetCompass Programme, against mean monthly UK air temperature for 2016.

to a European heat-wave. This 2016 July heat-wave was attributed to the El Nino effect and was previously the hottest July on record[38]. This record has since been broken; July 2019 is currently the hottest on record without the contribution of a particularly strong El Nino effect, highlighting the impact global warming is having on extreme temperature events[38]. The number of days per year with extreme heat in Europe have tripled in the last two decades, prompting concerns that global warming is accelerating even more rapidly than predicted[41].

Compared to Labrador Retrievers in the final multivariable model, nine breeds had significantly higher odds of HRI: Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever. These findings agree with previous studies that reported increased HRI risk to brachycephalic breed types in general[10], Bulldogs[11,12] and Golden Retrievers[11]. The increased odds ratios for these breeds in the multivariable compared to the univariable models highlights the importance of undertaking multivariable analysis when investigating breed related risk studies[29]. As well as some extremely brachycephalic breeds (Bulldog and French Bulldog), we also identified increased risk in some mesocephalic breeds. The Golden Retriever had 2.67 times the odds compared to the Labrador Retriever despite being of similar size, temperament and purpose. The Golden Retriever does, however, have a thicker coat than the Labrador which may be the tipping factor for HRI between these two breeds. The Chow Chow, another breed with a very thick coat, had the greatest risk of HRI of all the study breeds (OR = 16.17), although it must be noted the confidence interval for this breed is very wide due to the relatively small sample size. Coat type is potentially an important risk factor for HRI in dogs, but may instead be a complicating factor for dogs with a behavioural or anatomical (e.g. brachycephaly) predisposition to overheating. Other double coated breeds may also have increased risk, however the current study was under-powered to fully explore these pre-dispositions due to low numbers of these breeds.

The Labrador Retriever has previously been reported with increased risk of HRI[11], although that study included both Labrador and Golden Retrievers as a single breed and therefore the increased risk may have come from the subset of these dogs that were Golden Retrievers[11]. The current study elected to use the Labrador Retriever as the comparator breed instead of crossbred for similar reasons to those suggested by Erlen *et al.* (2018)[30]. Crossbred dogs show a high level of variability in genetics, bodyweight, skull shape and conformation compared to a single specified purebred breed[42]. This high variability challenges the utility of crossbreds as a standard comparator breed. Second only to crossbreds, the Labrador Retriever was the most common breed in the current study, comprising 6.6% of the total study population and enabling high statistical power to explore breed related risk[29]. In the current study, the odds of HRI were not significantly different between Labrador Retrievers and crossbred dogs.

It has been suggested that racing Greyhounds rarely exhibit HRI[43] but our results showed pet Greyhounds to have 4.26 times the odds of HRI when compared to the Labrador Retriever. As a dolichocephalic breed, they are not commonly associated with obesity[44], however they tend to have a high lean muscle mass which has been associated with increased risk of post exercise hyperthermia[34]. Further research is required to explore the underlying reason for this result, but a recent study found "collapse" to be the second most common cause of death in Greyhounds, specifically in animals over 12 years old[44]. A degenerative cardiovascular or respiratory disorder (such as laryngeal paralysis) could potentially promote their increased risk of HRI.

This study included three grouped breed-type variables (other purebred, other designer crossbred and crossbred) and 32 individual breeds and designer hybrid breed types, because breed was a factor of primary interest. Including this many breed-type variables increased the degrees of freedom in the regression model, negatively impacting the statistical power. However, it is important to include as many popular breeds as possible in risk analysis studies to enable identification of breed predispositions to disorders, but also to identify breeds with

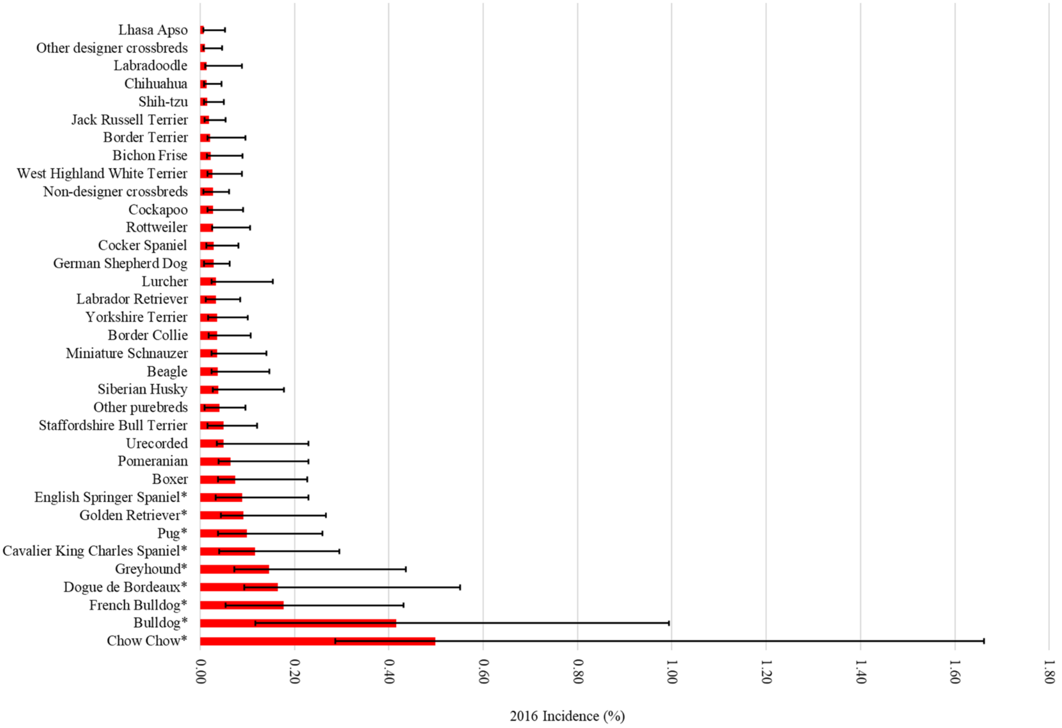

Figure 2. One-year (2016) incidence risk of heat related illness in dog breeds and designer crossbreeds under primary veterinary care at practices in the VetCompass Programme in the UK. The error bars show the 95% confidence interval. *Indicates breeds with increased odds identified by multivariable regression analysis.

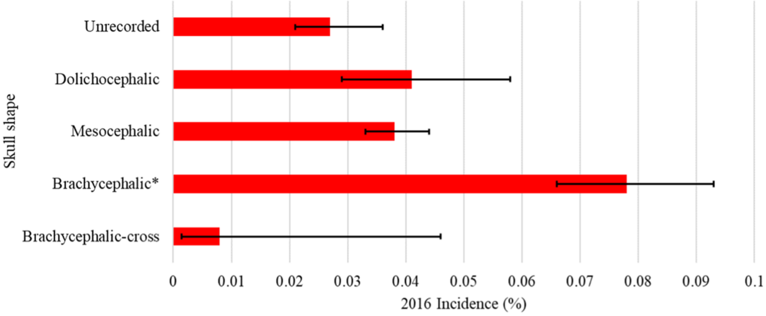

Figure 3. One-year (2016) incidence risk of heat related illness by Skull shape in dogs under primary veterinary care at practices in the VetCompass Programme in the UK. The error bars show the 95% confidence interval. *Indicates skull shapes with increased odds identified by multivariable regression analysis.

apparent resistance or protection from disorders. HRI is a disorder that requires extrinsic input; dogs do not develop HRI due an underlying intrinsic factor (unlike osteoarthritis or cancer) and non-disease is the natural internal state. To develop HRI dogs, must be exposed to either a hot environment and/or an activity that induces significant hyperthermia. In support of this theory, there were no individual breed types identified with significantly reduced risk of HRI compared to the Labrador Retriever in this study. Additionally, whilst the multiple regression model including breed-type showed acceptable discrimination, the model R^2 value (0.045) is very low, suggesting there are key (likely non-canine) factors missing from this model such as ambient temperature and the dog's acclimatisation to heat. The canine risk factor model explored in this study should be considered explanatory, identifying canine features than increase a dog's risk of HRI, rather than predictive. A predictive HRI model would need to include additional non-canine variables such as ambient temperature, humidity, activity levels, fitness and hydration[36].

This study supports assertions that brachycephaly is associated with increased risk of HRI in dogs. Five of the nine breeds with significantly increased odds of HRI were brachycephalic (Bulldog, French Bulldog, Dogue de Bordeaux, Cavalier King Charles Spaniel and Pug), additionally the Boxer (OR 2.26, 95%CI 0.95-5.34), another brachycephalic breed trended towards increased odds. Compared to mesocephalic dogs in multivariable modelling, brachycephalic dogs had 2.10 times the odds of HRI, with no significant difference in HRI odds between dolichocephalic and mesocephalic dogs. Interestingly, brachycephalic crosses had the lowest incidence of HRI

Independent Variable	Odds Ratio	95% CI	P-value
Breed type			<0.001
Labrador Retriever	Base		
Chow Chow	16.61	6.21–44.44	<0.001
Bulldog	13.95	8.01–24.29	<0.001
French Bulldog	6.49	3.62–11.63	<0.001
Dogue de Bordeaux	5.31	1.99–14.21	0.001
Greyhound	4.26	1.88–9.70	0.001
Cavalier King Charles Spaniel	3.45	1.86–6.42	<0.001
Pug	3.24	1.67–6.29	<0.001
English Springer Spaniel	2.74	1.25–6.01	0.012
Golden Retriever	2.65	1.40–5.01	0.003
Boxer	2.26	0.95–5.34	0.064
Pomeranian	2.12	0.48–9.30	0.319
Missing	2.11	0.72–6.20	0.173
Staffordshire Bull Terrier	1.50	0.84–2.68	0.175
Other purebred	1.28	0.76–2.14	0.358
Siberian Husky	1.18	0.28–5.06	0.822
Beagle	1.15	0.34–3.86	0.827
Miniature Schnauzer	1.08	0.32–3.64	0.900
Border Collie	1.08	0.47–2.44	0.862
Yorkshire Terrier	1.05	0.49–2.25	0.898
Lurcher	1.00	0.24–4.30	0.996
German Shepherd Dog	0.92	0.35–2.48	0.874
Cocker Spaniel	0.88	0.35–2.20	0.788
Rottweiler	0.86	0.20–3.69	0.841
Cockapoo	0.85	0.39–1.87	0.686
Non-designer crossbred	0.82	0.49–1.37	0.450
West Highland White Terrier	0.76	0.28–2.02	0.581
Bichon Frise	0.68	0.20–2.27	0.525
Border Terrier	0.61	0.14–2.60	0.503
Jack Russell Terrier	0.55	0.25–1.21	0.135
Shih-tzu	0.47	0.18–1.24	0.127
Chihuahua	0.44	0.17–1.18	0.102
Labradoodle	0.41	0.06–3.06	0.384
Other designer crossbred	0.33	0.08–1.41	0.133
Lhasa Apso	0.24	0.03–1.76	0.159
Age			0.085
<2 years	Base		
2-<4 years	1.56	1.13–2.14	0.007
4-<6 years	1.41	0.99–2.02	0.058
6-<8 years	1.53	1.05–2.23	0.026
8-<10 years	1.21	0.79–1.86	0.374
10-<12 years	1.16	0.71–1.88	0.559
≥12 years	1.75	1.14–2.70	0.011
Unrecorded	0.70	0.22–2.26	0.552
Bodyweight relative to breed/sex mean			0.001
Below	Base		
At or above	1.42	1.12–1.80	0.004
Unrecorded	0.91	0.69–1.20	0.505

Table 2. Multivariable binary logistic regression results for risk factors associated with heat related illness in dogs under primary veterinary care in the VetCompass Programme in the UK during 2016.

across all skull types including unrecorded (including predominantly crossbred dogs) (see Fig. 2). They did not however, have a significantly reduced odds ratio of HRI at multivariable level. This could potentially be due to this group of dogs being comparatively young compared to the rest of the population[45], but could also be attributed

Variable	Odds ratio	95% CI	P-value
Skull shape			<0.001
Mesocephalic	Base		
Dolichocephalic	1.08	0.74–1.58	0.698
Brachycephalic-cross	0.22	0.03–1.56	0.129
Brachycephalic	2.10	1.68–2.64	<0.001
Unrecorded	0.73	0.53–0.99	0.039
Purebred			<0.001
Crossbred	Base		
Designer Cross	0.72	0.36–1.41	0.337
Purebred	1.86	1.39–2.49	<0.001
Unrecorded	2.41	0.57–10.16	0.233
Bodyweight (kg)			<0.001
<10	Base		
10-<20	1.82	1.31–2.53	<0.001
20-<30	2.13	1.51–3.02	<0.001
30-<40	1.74	1.14–2.65	0.010
40-<50	1.76	0.91–3.40	0.093
≥50	3.42	1.54–7.57	0.002
Unrecorded	0.65	0.16–2.70	0.553

Table 3. Results for variables that individually replaced the *breed type* variable in the final multivariable logistic regression model (with *age* and *bodyweight relative to breed/sex mean*) to evaluate risk factors associated with heat related illness in dogs under primary veterinary care in the VetCompass Programme in the UK during 2016.

to the typically lower bodyweight of designer crossbreds. The mean designer cross bodyweight in this study was 15.6 kg, compared to the mean purebred bodyweight of 17.5 kg, and mean crossbred bodyweight of 17.4 kg. This finding could lend support to the argument for outbreeding to increase muzzle length within extreme brachycephalic breeds to improve the health and welfare of dogs[46] but requires further research.

Dogs at or above the mean adult bodyweight for their breed/sex showed increased risk of HRI compared to dogs below the mean bodyweight in multivariable analysis. Increased HRI risk in heavier individuals within breeds agrees with findings from previous studies exploring post-race body temperature in Greyhounds; dogs with a greater lean body mass were significantly hotter post-race than lighter dogs[34]. It was not possible to determine whether elevated bodyweight within breed was due to obesity, conformation differences or increased muscle mass in this study as body condition scores were not available from the EPRs. There are several different scales used for measuring body condition score in dogs, meaning it is not possible to make direct comparisons between clinical records when a single unit is used to record a dog's score. As highlighted in a report by Ward *et al.*[47], adopting an single universal score for body condition score in dogs should be considered a key priority for veterinary professionals and canine welfare organisations to allow consistent measurement, recording and monitoring of body composition in dogs.

Dogs weighing over 50 kg in absolute bodyweight had the highest odds of HRI, and all bodyweight groups over 10 kg had significantly higher odds for HRI than dogs weighing under 10 kg. Smaller dogs have a high heat storage to radiative surface area ratio that results in more rapid heat loss compared to larger dogs, meaning they can exercise for longer before overheating[48,49]. This increased efficiency in radiative heat loss could explain why the purebred breeds with the lowest odds of HRI are all small breed dogs (Table 2). Of the breeds analysed, the Lhaso Apso, Shih tzu and Chihuhua had the lowest odds of HRI despite all being brachycephalic breeds. These breeds all typically weigh under 10 kg. In comparison, French bulldogs and Cavalier King Charles Spaniels typically weigh over 10 kg[45,50], whilst Pugs typically weigh around 10 kg;[51] the HRI odds for these three breeds appears to be proportional to their typical bodyweights.

Reflecting the findings of Drobatz and Macintire (1996), purebred dogs showed increased risk of HRI compared to crossbred dogs in the current study. Purebred dogs are more likely to have exaggerated features such as thick coats, extreme body size and skull shapes[31], all of which were predicted, and subsequently appear to, impact HRI risk. In comparison, wild dogs such as the African Hunting dog, have been shown to tolerate higher core body temperatures than domestic dogs during exercise in hot climates (41 °C), and lose a greater proportion of the heat generated through non-evaporative mechanisms effectively conserving water[52].

In the final multivariable model, dogs ≥12 years old had the greatest odds of HRI compared to dogs <2 years old, reflecting the human literature which reports an increased HRI risk to humans of advanced age or with chronic medical conditions[53]. Dogs with pre-existing medical conditions were excluded from previous heatstroke studies[11,12,54]. Older dogs are more likely to be affected by age related conditions such as respiratory or cardiovascular disease, therefore elderly dogs were potentially absent from the previous study populations and subsequent analysis. Old age in humans is associated with increased HRI risk, due to a decreased physiological ability to dissipate heat (notably changes in sweat production and decreased skin blood flow)[55]. Further studies should explore the effect of age on canine thermoregulatory ability.

Despite previous studies suggesting male dogs have increased risk of HRI[34,36], there was no significant difference in odds for HRI between males and females, or between neutered and entire dogs shown in the current study. Previous HRI studies have reported mixed findings for sex as a risk factor in dogs, varying from no reported difference[11,16] to male overrepresentation[10,13,37]. As this is the first study to include multivariable analysis for HRI risk factors in dogs, it is possible that including relative bodyweight in the analysis accounted for the possible confounding effect of increased bodyweight in males.

Alongside the environmental threat to canine health and welfare, the canine population itself is becoming less heat tolerant as proportional obesity[56] and brachycephalism increase[25,45,51]. The current study found that brachycephalic breeds comprised 18.42% of the total primary-care population in 2016 and the KC reported that the French Bulldog became the most commonly registered pedigree breed in 2018[57]. Increasing popularity of brachycephalic breeds coupled with the increasing frequency of heatwave events poses a significant welfare concern for the modern dog population and is likely to result in increasing incidence of HRI over the coming years.

A recent survey of brachycephalic dog owners found over a third reported that their dog had a problem with heat regulation[58]. The survey did not differentiate simple overheating from overheating leading to HRI, but nonetheless identified heat regulation as the most common problem perceived by brachycephalic owners[58]. The comparably lower incidence of HRI reported in this study compared to the owner reports of overheating in the survey conducted by Packer *et al.*[58] could be due to several possibilities. Owners of brachycephalic dogs may normalise heat related issues in these breeds and therefore not perceive overheating to be of sufficient concern to either report events or seek treatment from their veterinary surgeon. Similarly, veterinary surgeons may normalise these findings such that they do not consider these events significant enough to warrant recording in the dog's clinical notes. Alternatively, owners of brachycephalic dogs may be more aware of their dog's risk of overheating and take deliberate actions to prevent occurrence, thus preventing their dogs developing severe HRI. Overall, it is probable that the true incidence of HRI in UK dogs, particularly brachycephalics, is likely to be higher than estimated in this current study.

There were some limitations to the study. The study used manual stepwise elimination to select the final breed model, despite mounting opposition to this method of model selection[59–61]. Whilst the automated stepwise method fails to take into account prior knowledge and risks artificially elevating R^2 values, this study included consideration of biological plausibility when selecting the final model variables and aimed to produce an explanatory model, rather than a predictive model.

As noted in a previous study, the data used in this study were not recorded for research purposes meaning there are likely to be missing data within the dataset[24,62]. Additionally, the inclusion criteria for an HRI case relied upon the accuracy and completeness of the clinical notes associated with the event. As dogs with HRI typically present as an emergency, clinical notes may be less accurately recorded at the time of treatment meaning false negatives are more likely[63]. The lack of a definitive diagnostic test for HRI meant that by necessity, the inclusion and exclusion criteria for an HRI case could have resulted in some dogs being mis-identified. Thus, for cases where owner treatment preference or finances prevented further diagnostic testing to rule out other non-HRI causes of hyperthermia, these cases could have been misidentified as HRI cases. The study population comprised only dogs under the care of primary veterinary practices, many of which do not offer a full 24-hour emergency service. Whilst it is likely that some cases presented to dedicated out of hours emergency practices which were not included in this study, most out of hours practices send clinical notes on to the patient's first opinion practice so most would still have been included in this study. Additionally, HRI often follows failure of the dog owner to appreciate the risk of a hot environment or of undertaking extreme exercise to the dog, meaning there could often be elements of owner guilt associated with the condition. This may reduce the willingness of an owner to declare the true reason for the dog's illness or death. As previously noted, overheating may be perceived by owners of some breeds as normal or may be managed by the owner, meaning HRI events are not reported or presented to the dog's primary care practice. These limitations combined with the lack of a definitive diagnostic test or definition for HRI suggest that the true incidence of HRI may be much higher than reported in this study.

The current study defined specific breeds by skull morphology as described in the methods and Supplementary Material. Although the breeds assigned to each skull type category could reasonably be challenged, changing the specific breeds listed in each category is unlikely to change the overall inferences drawn from the analysis[64]. The traditional definitions used to describe canine skull shape with three categories from dolichocephalic to brachycephalic is potentially oversimplified, and the newer cephalic index systems derived from various skull width to length ratios may be more accurate[65]. However the variability in cephalic index between individuals of the same breed and between sexes[65,66], and the limited widescale measurement of cephalic index in large numbers of different breeds means it was not possible to use this measurement in place of the traditional skull morphology definitions for the current study. Whilst coat type has been noted as another possible risk factor for HRI in dogs, it was not possible to accurately retrieve coat type for individual dogs from the EPRs in this study, as this is not a characteristic commonly recorded by veterinary practice management software and can often vary widely within individual breeds.

Finally, the current study population included only dogs under care of a primary veterinary practice during the study period of 2016. It was therefore not possible to include HRI events prior to, or after 2016 in the risk factor analysis as this would introduce selection bias because fatal HRI events prior to 2016 would be excluded, and dogs born after 2016 would be excluded from events post 2016. This limited the number of HRI cases for analysis and prevented any investigation into changes in HRI incidence over time. These could be considered as research topics for a future study.

Conclusions

Extreme heat events are predicted to increase in both frequency and severity, with deaths due to HRI in humans predicted to triple by 2050[7]. This is the first study to explore HRI in a large population of dogs under primary veterinary care and the canine risk factors identified suggest that similar risk factors for HRI apply for both humans and dogs. This study found that increased bodyweight (relative to breed), brachycephaly and age significantly increased the risk of HRI and identified nine breeds at significantly increased risk. Maintaining healthy bodyweight should be considered an important management tool for limiting HRI risk, therefore routine recording of patient body condition score should be highlighted as a key strategy for enabling the monitoring and subsequent management of canine obesity. Prevention is an incredibly important strategy for limiting the welfare implications and mortality caused by HRI in both man and dog. The results of this study can assist veterinary practitioners, breeders and owners in identifying dogs and breeds at greater risk of HRI and therefore with implementation of strategies to reduce the risks of HRI in dogs.

Ethics approval. Ethics approval was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652).

Data availability

The datasets supporting the current study are publicly available on the RVC data repository: http://researchonline.rvc.ac.uk/id/eprint/12379/.

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Author contributions

All authors (E.H., A.C. and D.O.N.) made substantial contributions to the conception and design of the study, acquisition and extraction of data from the VetCompass Programme database, and to analysis and interpretation of the results. All authors (E.H., A.C. and D.O.N.) were involved in drafting and revising the manuscript and gave final approval of the version to be published. Each author agrees to be accountable for all aspects of the accuracy or integrity of the work.

Competing interests

The authors declare no competing interests.

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animals

Article

Dogs Don’t Die Just in Hot Cars—Exertional Heat-Related Illness (Heatstroke) Is a Greater Threat to UK Dogs

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Simple Summary: Heat-related illness (often called heatstroke) is a potentially fatal condition inflicted on dogs that will become more common as global temperatures rise. Understanding why dogs develop heatstroke can help to refine prevention strategies through owner education and societal changes. This study aimed to determine the most common triggers of heat-related illness in UK dogs, and which types of dogs were at most risk. We reviewed the veterinary records of over 900,000 dogs and identified that exercise was the most common trigger of heat-related illness in dogs. We also found that heatstroke caused by exercise was just as likely to kill as heatstroke from a hot car. Male dogs and younger dogs were more likely to develop heat-related illnesses triggered by exercise. Older dogs and flat-faced dogs were at greater risk of developing heat-related illness just by sitting outside in hot weather. Any dog can develop heatstroke if left in a hot car, but flat-faced breeds were particularly at risk. As the world gets hotter, we need to include our canine companions in our strategies to stay cool, as they can suffer fatal consequences when we fail to keep them safe.

Abstract: Heat-related illness will affect increasing numbers of dogs as global temperatures rise unless effective mitigation strategies are implemented. This study aimed to identify the key triggers of heat-related illness in dogs and investigate canine risk factors for the most common triggers in UK dogs. Using the VetCompass™ programme, de-identified electronic patient records of 905,543 dogs under primary veterinary care in 2016 were reviewed to identify 1259 heat-related illness events from 1222 dogs. Exertional heat-related illness was the predominant trigger (74.2% of events), followed by environmental (12.9%) and vehicular confinement (5.2%). Canine and human risk factors appear similar; young male dogs had greater odds of exertional heat-related illness, older dogs and dogs with respiratory compromise had the greatest odds of environmental heat-related illness. Brachycephalic dogs had greater odds of all three types of heat-related illness compared with mesocephalic dogs. The odds of death following vehicular heat-related illness (OR 1.47, p = 0.492) was similar to that of exertional heat-related illness. In the UK, exertional heat-related illness affects more dogs, and kills more dogs, than confinement in a hot vehicle. Campaigns to raise public awareness about heat-related illness in dogs need to highlight that dogs don’t die just in hot cars.

Keywords: VetCompass; primary-care; canine heatstroke; heat-related illness; heat stress; brachycephalic; exertional hyperthermia

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1. Introduction

Heat-related illness (HRI) is a potentially fatal disorder affecting man and animals, and is predicted to become more frequent as climate change increases both the severity and regularity of heatwave events [1]. As mean annual temperatures continue to rise, human populations need to consider mitigation strategies to survive, potentially including migration away from the hottest regions [2] or adaptations to heat including air cooling mechanisms and changes to working practices to reduce the risk of HRI to outdoor workers [3]. Domestic dogs intertwine with every aspect of human society, from providing simple companionship to fulfilling essential working services such as hearing and visual assistant dogs, medical detection dogs and military working dogs [4]. A deeper understanding of the risk factors for canine HRI is therefore urgently needed to ensure adaptations to rising global temperatures can include consideration of canine companions and colleagues.

From a pathophysiological perspective, HRI can be defined as hyperthermia causing progressive systemic inflammation and multi-organ dysfunction, resulting in neurological derangements and potentially death [5]. However, this gives little information on the underlying causes of the clinical event and, more importantly, offers little information to help prevent these HRI events in the first place. From a causal perspective, two main triggers are described for HRI in humans: exertional and environmental [5]. Exertional HRI typically follows exercise or physical labor in a hot environment or prolonged strenuous exercise in environments of any temperature [5,6]. Environmental HRI, also referred to as classic or non-exertional HRI, typically follows prolonged exposure to high ambient temperatures or shorter exposure to extreme heat [7]. Very young children and babies are similar to dogs in that they are generally not agents of their own liberty from confinement [8]. Very young children and babies are also at risk of vehicular HRI (a subtype of environmental HRI) following confinement in a hot vehicle after being left unattended or after accidentally locking themselves inside the vehicle [8]. In human medicine, exertional HRI most commonly affects young active males either working in physically demanding industries such as construction, or participating in sports [9]. Exertional HRI is the third leading cause of death in US high school athletes, and the incidence of HRI in the US Armed Forces has been gradually increasing since 2014 [10]. Conversely, environmental HRI is known to typically affect socially vulnerable patients, those with advanced age or chronic medical conditions, who may be confined indoors and less resilient to natural hazards such as heatwaves [11,12].

Canine patients are likely to share similar risk factors to humans for the various types of HRI, but there is limited published evidence in the canine literature. Older dogs are more likely to suffer from underlying health conditions that impact thermoregulation such as heart disease [13], which could increase the likelihood of environmental HRI [14]. Respiratory diseases such as brachycephalic obstructive airway disorder (BOAS) have been shown to accelerate the increase in body temperature during exercise [15] and brachycephalic dogs have intrinsically greater odds of developing HRI compared to dogs with longer muzzle [16]. Heat regulation problems are reported to affect around a third of brachycephalic dogs [17] and obesity has been reported as a significant risk factor for death in dogs presenting with HRI [18]. Reflecting the male predisposition to exertional HRI in humans, male dogs develop a significantly higher body temperature than females during intense exercise [19,20]. Both dogs trained for military work (e.g., Belgian Malinois) and active playful dogs (e.g., Golden Retriever and Labrador Retriever) have been reported to be at increased risk of exertional HRI [18], however, that study included only patients referred for specialist care and therefore may not represent the wider canine population. A larger primary-care study reported the Chow Chow and Bulldog with the greatest odds of HRI highlighting the value of primary-care focused research for generalization to the wider companion animal population [21].

Because the veterinary diagnosis of HRI is heavily dependent upon an accurate history of the events leading up to the animal’s presentation [22], greater awareness of the specific risk factors for HRI in dogs could support earlier recognition, diagnosis and appropriate management. However, prevention remains the most important approach to limiting the welfare burden of HRI overall, [23] because irreversible organ damage and cellular destruction follow any occasion when the body is heated beyond 49 °C [5]. Reports from Israel suggest exertional HRI may be the more common cause of heatstroke in dogs in that country [24–26]. Although there is some evidence that exertion is also the main trigger of HRI in UK dogs [27], current efforts to educate UK dog owners about heatstroke prevention focus almost exclusively on environmental heatstroke, specifically the message that 'dogs die in hot cars' [28]. Generation of a solid evidence base on the predominant trigger of canine HRI, canine risk factors for different HRI types and the seasonality of different HRI types in the UK could support optimized and targeted educational campaigns.

This study aimed to use the VetCompass database of veterinary health records to (i) identify the leading triggers for HRI in the UK general dog population; (ii) identify risk factors for the three key triggers of HRI and (iii) compare the case fatality rate and seasonality between different HRI triggers.

2. Materials and Methods

2.1. Data Collection and Management

This study was an extension of work previously reported in Hall et al. [16] and used the same dataset described in that study. The VetCompass Programme (Royal Veterinary College, London, UK) offers a research database providing access to de-identified electronic patient records (EPRs) from primary-care veterinary practices in the UK [29–32]. The study population included all dogs under veterinary care during 2016 as previously defined. EPRs were searched to identify candidate cases of HRI, using the following terms: heat stroke~3, heatst*, hyperthermi*, overheat*, over heated~2, heat exhaustion~2, hot car~2, collapse* + heat, cooling, high ambient temp*. Dogs identified from all searches were merged and randomly ordered. All candidate cases were manually reviewed in detail by two researchers (author 1 and author 2) to identify all dogs (confirmed HRI cases) meeting the study case definition for HRI occurring at any date within the patient's available EPR (prevalent HRI events). All confirmed prevalent HRI events underwent additional data extraction including date of heat exposure event, the trigger for the HRI event (Table 1) and outcome of each event (survival or death). All events were assigned to a single trigger category. For dogs with multiple HRI events, only events occurring between 1st January 2016–31st December 2018 (2016–2018 HRI events) were included when exploring triggers as risk factors for death and reporting numbers of events by trigger. Whilst events occurring after 2016 were excluded from previous risk factor analysis to avoid introducing potential bias from the aging denominator population [16], they were included in the present study to provide greater event numbers for statistical analysis. The earliest HRI event recorded in the EPR (first HRI event) was used to calculate age at the event and was included in risk factor analysis (see Figure 1).

Ethical approval for this study was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652).

Table 1. Definitions of heat-related illness (HRI) triggers in UK dogs.

Trigger	Definition	Justification
Exertional	Any HRI event where physical activity is identified as the inciting cause regardless of ambient temperature. All types of physical activity are included.	Exertional HRI is reported to affect both humans [10], horses [33] and dogs [22].
Environmental	Any HRI event where the dog was reported to be outdoors in the heat but not exercising.	Environmental HRI typically affects dogs in the summer months, but can also be triggered by unseasonable hot spells especially when the dog has not been acclimatized to heat [18,34].
Undergoing treatment (vets/groomer)	HRI events that occurred following hospitalisation in a veterinary clinic, or following professional grooming.	Frenzied jumping and barking has been reported to trigger HRI in dogs [34], and can occur following separation from owners in veterinary clinics. Dogs have been reported to suffer HRI following grooming in media reports [35].
Blanket entrapment	HRI events resulting from the dog becoming entangled in blankets.	Wearing thick or insulating clothing increases the risk of HRI in humans [12].

Building confinement	HRI events that occurred following confinement in a hot building.	Confinement indoors with no air conditioning is a known risk factor for elderly human HRI patients [12].
Vehicular confinement	HRI events that occurred following confinement in a hot vehicle, including both dogs left unattended in a hot vehicle and dogs travelling in a hot vehicle.	Enclosed vehicles can reach 54.4 °C [36] in the summer months. Vehicular confinement was the leading trigger of HRI in dogs presenting to a German veterinary hospital [37].
Unrecorded	Confirmed HRI events with no record of an inciting cause in the clinical history.	HRI requires urgent treatment, meaning some dogs present as emergencies needing immediate triage and treatment. Clinical notes may not be written at the time of presentation limiting the information recorded. Additionally, some owners may be reluctant to disclose the inciting cause or may not have recognised the condition as HRI.

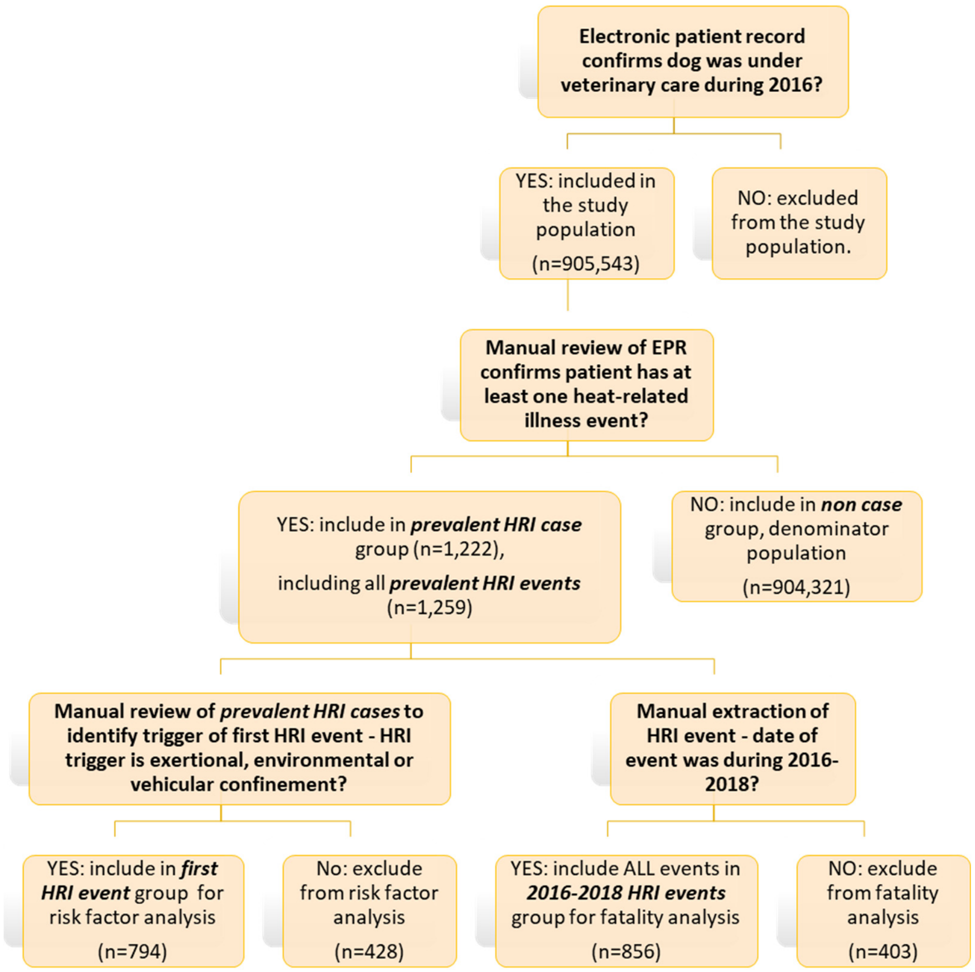

Figure 1. Flow chart of decisions for inclusion in HRI fatality analysis and risk factor analysis for HRI triggers.

2.2. *Analysis*

The study used a cohort design applied to a denominator population of 905,543 dogs from the VetCompass database under veterinary care in 2016. Demographic data were extracted automatically from the database for all study dogs. Demographic and clinical data were exported into Microsoft Excel (v16, Redmond, WA, USA) for cleaning and descriptive analysis, risk factor analysis used SPSS v25 (IMB Inc., Armonk, NY, USA).

Summary statistics were calculated using all prevalent HRI events to determine the number of HRI events per month and to identify the top three triggers for HRI in UK dogs: exertional HRI, environmental HRI and vehicular HRI. The 2016–2018 HRI events were then assigned to a trigger category for risk factor analysis: exertional HRI, environmental HRI, vehicular HRI, unrecorded HRI, building entrapment, blanket entanglement and undergoing treatment.

2.2.1. Risk Factor Analysis for Fatality

Binary logistic regression modelling was used to compare the odds for death between triggers using only 2016–2018 HRI events, using the most numerous trigger (exertional) as the comparator. Events occurring prior to 2016 were excluded from fatality analysis, because any dogs that died from their HRI event prior to 2016 would by definition be excluded from the denominator population, meaning events prior to 2016 would be biased toward survival.

2.2.2. Risk Factor Analysis for Triggers

Risk factor analysis used cohort clinical data to explore potential canine risk factors for HRI triggered by each of the three key categories: exertional HRI, environmental HRI and vehicular HRI, using all dogs in the denominator population not defined as a confirmed HRI case as the "non-case" population. Where the first HRI event was not triggered by one of the three categories above, these cases were excluded from this analysis as they did not meet the inclusion criteria for "non-case". As the purpose of this analysis was to identify canine risk factors for the different triggers, events that occurred prior to 2016 were included to increase the number of events available for statistical analysis.

Separate binary logistic regression modelling of the first HRI events was used to identify risk factors for each trigger: exertional HRI, environmental HRI and vehicular HRI. The variables considered in univariable binary logistic regression analysis included breed type, purebred, skull shape, adult bodyweight, bodyweight relative to breed/sex mean, sex/neuter and age. These risk factors were defined in a previous study [16], but are included in Appendix A, Table A1 for reference. Risk factors with liberal associations in univariable modelling ($p < 0.2$) were selected for multivariable evaluation. As breed type was a factor of primary interest, variables that were highly collinear with breed (purebred) or considered a defining characteristic of individual breeds (adult bodyweight and skull shape) were not included in the multivariable models with breed type but were included in alternative models that swapped out the breed type variable as previously described [16,29]. Model development used manual backwards stepwise elimination, as this was an explanatory model aiming to identify canine risk factors, rather than a predictive model [16]. Pairwise interactions were tested for all variables in the final multivariable model. The area under the receiver operating characteristic (ROC) curve was used to evaluate the explanatory ability of the model [38] alongside consideration of the underpinning biological plausibility of the model specification. Statistical significance was set at $p < 0.05$.

3. Results

The study included 905,543 dogs under primary veterinary care at 886 UK VetCompass clinics during 2016. From this population, 1259 HRI events were identified from the EPRs of 1222 dogs; 35 dogs had two HRI events and one dog had three HRI events recorded at the time of the study (2.95% of affected dogs had multiple events). Data completeness, incidence estimate and case fatality rate have been reported in a previous study [16].

3.1. HRI Triggers

There were 380/1259 (30.2%) prevalent HRI events with no trigger recorded in the EPR. Of the remaining 879 prevalent HRI events, the predominant triggers recorded were exertional HRI (n = 652, 74.2%), followed by environmental HRI (n = 113, 12.9%) and vehicular confinement (n = 46, 5.2%). Other triggers included being under the care of a veterinary clinic or groomer (n = 40, 4.6%), building confinement (n = 24, 2.7%) and blanket entrapment (n = 4, 0.5%).

Of the 652 prevalent HRI events triggered by exercise, the type of exercise was not specified for 101 (15.5%) events. Of the remaining 551 events, 372 (67.5%) occurred after walking, 97 (17.6%) after high-intensity activities such as running or cycling, 76 (13.8%) after periods of play and 6 (1.1%) of those events occurred after canine competitions.

3.2. Event Fatality and Seasonality

From the 2016–2018 HRI events, the event fatality rate for each trigger is shown in Table 2. Of the events with a known trigger, building confinement (OR 6.06, 95% CI 2.13–17.22) had greater odds for HRI associated fatality when compared to exertional HRI only. Cases with no recorded trigger also had greater odds (OR 2.43, 95% CI 1.49–3.94).

Table 2. Descriptive and binary logistic regression results for triggers as risk factors for heat-related illness associated fatality in dogs affected between 2016–2018, under primary veterinary care in the VetCompass programme in the UK during 2016.

Trigger	Number of Events (n = 856)	% of Known Events (n = 592)	Event Fatality (Rate)	Odds Ratio	95% Confidence Interval	*p*-Value
Exertional	420	70.9%	32 (7.6%)	base		
Blanket entrapment	2	0.3%	1 (50.0%)	12.13	0.74–198.43	0.080
Building confinement	18	3.0%	6 (33.3%)	6.06	2.13–17.22	0.001
Environmental	84	14.2%	8 (9.5%)	1.28	0.57–2.88	0.556
Undergoing treatment (vet/groomer)	31	5.2%	3 (9.7%)	1.3	0.37–4.51	0.680
Unrecorded	264		44 (16.7%)	2.43	1.49–3.94	<0.001
Vehicular confinement	37	6.3%	4 (10.8%)	1.47	0.49–4.41	0.492

HRI events occurred during every month of the year, with July (n = 426, 33.84%) showing the highest proportion of events. Although HRI fatalities were recorded in all months from January to October, July accounted for 35/99 (35.35%) of fatalities (Figure 2). Environmental HRI and vehicular confinement were recorded only between March and September (see Figure 3), corresponding to the UK's spring to summer period and typically warmest months. Vehicular HRI fatalities only occurred between March and July, whilst environmental HRI fatalities occurred from May to September. Building confinement triggered HRI across all months except November with fatalities occurring from June to September, and undergoing treatment at a vets/groomer triggered HRI in all months except December, January and March with fatalities in June and August. Exertional HRI occurred in all months, however, there was only one exertional HRI fatality (in January) outside the typically warmer UK months of March–October. There were HRI events with no recorded trigger in all months except December, with fatalities from unrecorded triggers occurring between February and September.

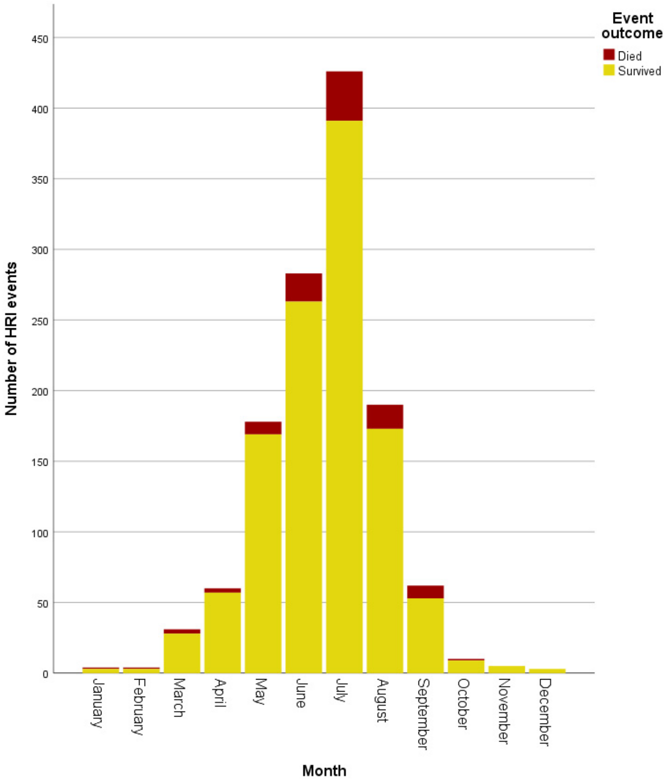

Figure 2. Histogram showing the number of heat-related illness events by outcome per month.

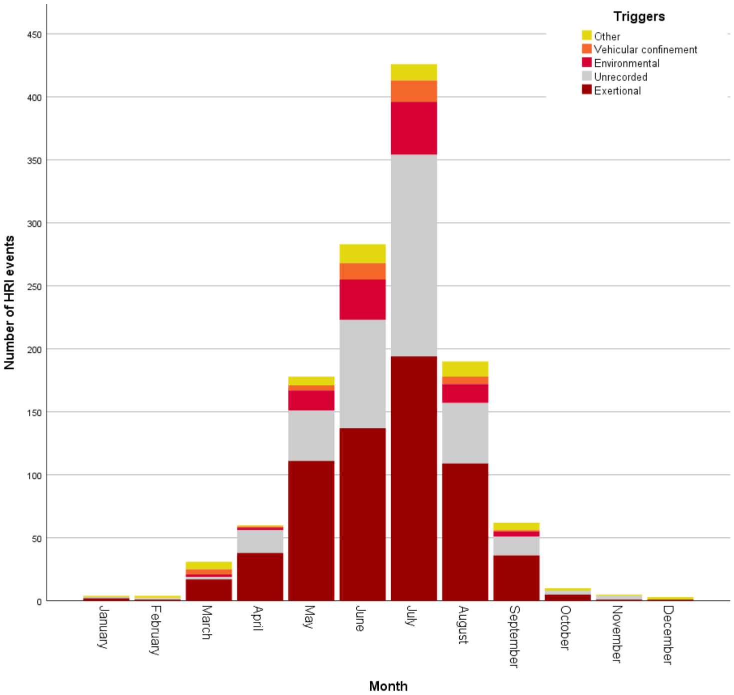

Figure 3. Histogram showing the number of heat-related illness events by a trigger, per month.

3.3. Risk Factor Analysis for Exertional HRI

All risk factors were strongly associated with exertional HRI following univariable binary logistic regression modelling ($p < 0.001$). The final breed multivariable model retained four risk factors: breed type, age, bodyweight relative to breed/sex mean and sex/neuter. The model showed acceptable discrimination ($R^2 = 0.004$, area under the ROC curve: 0.725). In the final model, seven breeds (Chow Chow, Bulldog, French Bulldog, Greyhound, English Springer Spaniel, Cavalier King Charles Spaniel and Staffordshire Bull Terrier) had higher odds of exertional HRI, and eleven breed types (Crossbred, German Shepherd Dog, West Highland White Terrier, Bichon Frise, Lhasa Apso, Jack Russel Terrier, Designer Crossbred, Shih-tzu, Cocker Spaniel, Yorkshire Terrier and Chihuahua) had lower odds of exertional HRI compared to Labrador Retrievers. As crossbred dogs (previously used as the breed type comparator in other VetCompass studies [30,31,39]) were found to have significantly reduced odds of exertional HRI compared to Labrador Retrievers, the multivariable analysis was repeated using crossbred as the comparator. Labrador Retrievers had 2.1 (95% CI 1.47–2.88) times the odds of exertional HRI compared to non-designer crossbred dogs (the other breeds with significantly greater odds of exertional HRI compared to non-designer crossbred dogs are indicated in Table 3). Dogs aged over 8 years had lower odds of exertional HRI compared to dogs under 2 years of age. Entire females had lower odds of exertional HRI compared to entire males, neutered males and neutered females. Dogs with bodyweight equal to or greater than the breed/sex mean had higher odds of HRI compared to dogs weighing below the relative breed/sex mean (see Table 3).

Table 3. Multivariable binary logistic regression results for risk factors associated with exertional heat-related illness in dogs under primary veterinary care in the VetCompass programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Breed type	Labrador Retriever *	Base		
	Chow Chow *	7.00	3.00–16.33	<0.001
	Bulldog *	3.73	2.34–5.93	<0.001
	French Bulldog *	2.96	1.96–4.47	<0.001
	Greyhound *	2.11	1.08–4.16	0.03
	English Springer Spaniel *	1.85	1.21–2.84	0.005
	Cavalier King Charles Spaniel *	1.69	1.06–2.67	0.026
	Staffordshire Bull Terrier *	1.56	1.09–2.22	0.015
	Pug *	1.58	0.97–2.56	0.064
	Boxer *	1.31	0.68–2.50	0.418
	Golden Retriever *	1.25	0.65–2.39	0.499
	Border Collie *	1.15	0.71–1.88	0.566
	Dogue de Bordeaux	1.12	0.35–3.59	0.848
	Missing	1.09	0.26–4.57	0.909
	Pomeranian	1.08	0.46–2.51	0.86
	Rottweiler	0.96	0.42–2.24	0.931
	Border Terrier	0.89	0.43–1.88	0.764
	Other purebred *	0.73	0.52–1.03	0.077
	Siberian Husky	0.61	0.19–1.95	0.405
	Cockapoo	0.52	0.26–1.02	0.056
	Miniature Schnauzer	0.49	0.18–1.35	0.168
	Lurcher	0.37	0.09–1.52	0.167
	Beagle	0.25	0.06–1.01	0.052
	Yorkshire Terrier	0.52	0.29–0.96	0.036
	Cocker Spaniel	0.52	0.30–0.91	0.022
	Non-designer Crossbred	0.49	0.35–0.68	<0.001
	Jack Russell Terrier	0.43	0.25–0.73	0.002
	West Highland White Terrier	0.43	0.20–0.94	0.034
	German Shepherd Dog	0.33	0.14–0.76	0.01
	Labradoodle	0.26	0.06–1.06	0.06
	Shih-tzu	0.25	0.12–0.53	<0.001
	Chihuahua **	0.21	0.09–0.45	<0.001
	Other designer crossbred	0.19	0.07–0.52	0.001
	Lhasa Apso	0.17	0.04–0.69	0.013
	Bichon Frise	0.16	0.04–0.64	0.01
Age	<2 years	Base		
	2– < 4 years	1.23	0.97–1.56	0.09
	4– < 6 years	0.82	0.62–1.08	0.157
	6– < 8 years	0.77	0.57–1.03	0.08
	8– < 10 years	0.48	0.33–0.69	<0.001

	10– < 12 years	0.48	0.32–0.72	<0.001
	≥12 years	0.54	0.36–0.81	0.002
	Unrecorded	1.37	0.63–2.98	0.424
Sex/neuter	Female-entire	Base		
	Female-neutered	1.63	1.26–2.10	<0.001
	Male-entire	1.49	1.18–1.88	<0.001
	Male-neutered	1.83	1.43–2.33	<0.001
	Unrecorded	0	~	0.982
Bodyweight relative to breed/sex mean	Lower	Base		
	Equal/Higher	1.30	1.09–1.55	0.003
	Unrecorded	0.49	0.30–0.62	<0.001

* Indicates breeds with significantly greater odds of exertional HRI compared to non-designer crossbred dogs. ** Indicates breeds with significantly reduced odds of exertional HRI compared to non-designer crossbred dogs.

As described in the methods, variables collinear (purebred) and definitive of breed types (bodyweight and skull shape) replaced the breed type variable in the final multivariable model. Purebred dogs had 1.84 (95% CI 1.47–2.31) times the odds of exertional HRI than crossbred dogs. Dogs in all bodyweight categories over 10 kg had greater odds of exertional HRI compared to dogs under 10 kg bodyweight. Brachycephalic dogs had 1.32 (95% CI 1.10–1.60) times the odds of exertional HRI, and dolichocephalic dogs and brachycephalic crossbred dogs had lower odds of exertional HRI compared to mesocephalic dogs (Appendix B, Table A2).

3.4. Risk Factor Analysis for Environmental HRI

Following univariable analysis, all variables were liberally associated with environmental HRI: breed type ($p = 0.002$), age ($p = 0.051$), sex/neuter ($p = 0.108$), purebred (0.054), skull shape ($p = 0.009$), adult bodyweight ($p = 0.001$) and bodyweight relative to breed/sex mean ($p < 0.001$). The final breed multivariable model retained breed type, age and sex/neuter. The final model showed acceptable discrimination ($R^2 = 0.039$, area under the ROC curve: 0.721). In the final model, four breeds had higher odds of environmental HRI than Labrador Retrievers: Chow Chow (OR 8.41, 95% CI 1.06–66.70), Bulldog (OR 7.52, 95% CI 2.76–20.47), Pug (OR 3.30, 95% CI 1.16–9.41) and French Bulldog (OR 3.16, 95% CI 1.03–9.73). Dogs aged ≥12 years (OR 3.15, 95% CI 1.56–6.37) had greater odds of environmental HRI compared to dogs <2 years old. Female neutered (OR1.92, 95% CI 1.03–3.56) and male entire (OR1.87, 95% CI 1.05–3.33) had greater odds compared to female entire dogs (Table 4).

Variables collinear (purebred) and definitive of breed types (bodyweight and skull shape) replaced the breed type variable in the final multivariable model. Purebred dogs had 1.97 the odds (95% CI 1.12–3.47) of environmental HRI compared to crossbred dogs. Brachycephalic dogs had 2.36 the odds (95% CI 1.50–3.72) compared to mesocephalic dogs, and dogs in the 10– < 20 kg and 20– < 30 kg bodyweight categories had greater odds for environmental HRI compared to dogs <10 kg (Appendix B, Table A3).

Table 4. Multivariable binary logistic regression results for risk factors associated with environmental heat-related illness in dogs under primary veterinary care in the VetCompass programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Breed type	Labrador Retriever	Base		0.002
	Chow Chow	8.41	1.06–66.70	0.044
	Bulldog	7.52	2.76–20.47	<0.001
	Pug	3.30	1.16–9.41	0.025
	French Bulldog	3.16	1.03–9.73	0.045
	Cavalier King Charles Spaniel	2.38	0.85–6.69	0.100
	Boxer	2.22	0.60–8.19	0.233
	Other designer crossbred	1.33	0.36–5.01	0.67
	Jack Russell Terrier	1.29	0.52–3.17	0.583
	West Highland White Terrier	1.21	0.37–3.96	0.748
	Bichon Frise	1.08	0.23–5.00	0.923
	Labradoodle	1.06	0.13–8.38	0.958
	Beagle	0.95	0.12–7.48	0.958

	Staffordshire Bull Terrier	0.88	0.33–2.36	0.798
	Cocker Spaniel	0.88	0.27–2.85	0.829
	Chihuahua	0.71	0.19–2.65	0.612
	Yorkshire Terrier	0.70	0.19–2.59	0.594
	Other purebred	0.69	0.29–1.64	0.404
	German Shepherd Dog	0.69	0.15–3.18	0.629
	Border Terrier	0.67	0.09–5.28	0.703
	Golden Retriever	0.65	0.08–5.11	0.680
	Border Collie	0.58	0.13–2.70	0.490
	Lhasa Apso	0.55	0.07–4.34	0.571
	Cockapoo	0.50	0.06–4.01	0.515
	Non-designer Crossbred	0.50	0.22–1.16	0.105
	Shih-tzu	0.46	0.10–2.13	0.320
	English Springer Spaniel	0.00	~	0.965
	Miniature Schnauzer	0.00	~	0.977
	Rottweiler	0.00	~	0.979
	Pomeranian	0.00	~	0.981
	Lurcher	0.00	~	0.981
	Greyhound	0.00	~	0.981
	Siberian Husky	0.00	~	0.982
	Dogue de Bordeaux	0.00	~	0.987
	Missing	0.00	~	0.984
Age	<2 years	Base		0.081
	2– < 4 years	1.35	0.72–2.50	0.349
	4– < 6 years	1.09	0.53–2.24	0.821
	6– < 8 years	1.67	0.84–3.35	0.146
	8– < 10 years	1.81	0.88–3.73	0.110
	10– < 12 years	1.64	0.71–3.76	0.244
	≥12 years	3.15	1.56–6.37	0.001
	Unrecorded	0.00	~	0.973
Sex/neuter	Female-entire	Base		0.373
	Female-neutered	1.92	1.03–3.56	0.039
	Male-entire	1.87	1.05–3.33	0.033
	Male-neutered	1.72	0.93–3.21	0.086
	Unrecorded	0.00	~	0.984

3.5. Risk Factor Analysis for Vehicular HRI

Univariable binary logistic regression modelling identified breed type (p = 0.007), sex/neuter (p = 0.199) and skull shape (p = 0.007), as factors liberally associated with vehicular HRI, but not age (p = 0.690), bodyweight relative to breed/sex mean (p = 0.269), purebred (p = 0.395) or bodyweight (p = 0.245). The final breed multivariable model retained two risk factors: breed type and sex/neuter. The model showed good discrimination (R^2 = 0.066, area under the ROC curve: 0.808). In the final model (Table 5) five breeds had increased odds of vehicular HRI compared to the Labrador Retriever: Bulldog (OR 16.63, 95% CI 3.02–91.53), Greyhound (OR 9.59, 95% CI 1.35–68.23), Cavalier King Charles Spaniel (OR 8.52, 95% CI 1.65–43.94), French Bulldog (OR 6.70, 95% CI 1.11–40.65) and Pug (OR 6.29, 95% CI 1.05–37.84) (Table 5).

Variables definitive of breed types (skull shape) replaced the breed type variable in the final multivariable model. Brachycephalic dogs had greater odds (OR 3.07, 95% CI 1.60–5.87) of vehicular HRI compared to mesocephalic dogs (see Appendix B, Table A4).

Table 5. Multivariable binary logistic regression results for risk factors associated with vehicular heat-related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Breed type	Labrador Retriever	Base		
	Bulldog	16.63	3.02–91.53	0.001
	Greyhound	9.59	1.35–68.23	0.024
	Cavalier King Charles Spaniel	8.52	1.65–43.94	0.010
	French Bulldog	6.70	1.11–40.65	0.039
	Pug	6.29	1.05–37.84	0.045
	Siberian Husky	6.10	0.55–67.40	0.140

	Pomeranian	5.31	0.48–58.76	0.173
	Labradoodle	3.88	0.35–42.83	0.268
	Boxer	3.22	0.29–35.49	0.340
	Border Terrier	3.07	0.28–33.84	0.360
	Golden Retriever	3.05	0.28–33.63	0.363
	Cocker Spaniel	2.82	0.47–16.90	0.256
	Shih-tzu	1.89	0.27–13.46	0.523
	Cockapoo	1.70	0.15–18.79	0.664
	West Highland White Terrier	1.51	0.14–16.62	0.738
	German Shepherd Dog	1.49	0.14–16.48	0.744
	Border Collie	1.33	0.12–14.65	0.817
	Jack Russell Terrier	1.21	0.17–8.58	0.850
	Non-designer Crossbred	0.90	0.18–4.47	0.901
	Chihuahua	0.89	0.08–9.83	0.923
	Staffordshire Bull Terrier	0.58	0.05–6.39	0.655
	Other purebred	0.50	0.07–3.55	0.489
	Bichon Frise	0.00	~	0.975
	Lhasa Apso	0.00	~	0.976
	English Springer Spaniel	0.00	~	0.969
	Miniature Schnauzer	0.00	~	0.980
	Beagle	0.00	~	0.980
	Rottweiler	0.00	~	0.981
	Lurcher	0.00	~	0.983
	Dogue de Bordeaux	0.00	~	0.988
	Other designer crossbred	0.00	~	0.969
	Missing	0.00	~	0.986
	Yorkshire Terrier	0.00	~	0.963
	Chow Chow	0.00	~	0.993
Sex/neuter	Female-entire	Base		
	Female-neutered	1.49	0.69–3.22	0.316
	Male-entire	0.43	0.16–1.13	0.086
	Male-neutered	1.27	0.58–2.79	0.546
	Unrecorded	0.00	~	0.984

4. Discussion

This is the largest primary-care study worldwide to deconstruct and explain HRI triggers in companion dogs. Reflecting the results of previous studies from Israel [24–26], the predominant trigger of HRI presenting to UK primary-care practices was exertional HRI (74.2% of events with a known cause). Exertional HRI events occurred year-round, with a 7.6% overall fatality rate. Exertional HRI accounted for the majority of HRI related deaths with known triggers. The odds of death did not differ between exertional HRI, environmental HRI or vehicular HRI.

Seven breed types had greater odds of exertional HRI when compared to Labrador retrievers: Chow Chow, Bulldog, French Bulldog, Greyhound, English Springer Spaniel, Cavalier King Charles Spaniel and Staffordshire Bull Terrier. Six of those breeds have previously been identified with greater odds for HRI in general [16], whereas the Staffordshire Bull Terrier appears to have greater odds specifically for exertional HRI. The Labrador Retriever was chosen as the comparator breed for reasons highlighted previously [16,40] namely that the Labrador Retriever was the most common definitive breed type in the study population. However, the Labrador Retriever had twice the odds for exertional HRI compared to non-designer crossbred dogs, as did several other large active breeds (Boxer, Golden Retriever and Border Collie), along with the Pug, and "other purebred"—namely breeds with either relatively low numbers in the study population or fewer than five confirmed HRI cases. Labrador Retrievers, Golden Retrievers, Border Collies and English Springer Spaniels represent breeds that are commonly used as working or assistance/service dogs including guide dogs for the visually impaired, hearing assistance dogs, medical support dogs, military detection dogs and medical detection dogs. Given the current evidence that these breeds show increased risk of exertional HRI, it is essential that future societal adaptations to increasing ambient temperature include appropriate mitigations to safeguard working and assistance dogs.

German Shepherd Dogs showed just one-third of the odds for exertional HRI compared to the Labrador Retriever in the current study. Both Australian Shepherd Dogs [34] and Belgian Malinois

[18] have previously been identified with increased risk of exertional HRI, however, these studies used referral hospital populations and thus likely included a relatively higher proportion of military or police working dogs than the present study based on the general population of dogs. German Shepherd Dogs and Belgian Malinois comprised over 70% of the US civilian law enforcement dogs in one study [41], in which HRI was the second most common cause of traumatic death accounting for approximately a quarter of deaths. However, 75% of those HRI events were triggered by vehicular confinement. The conflicting findings of this study compared to previous reports suggesting an increased risk of exertional HRI in Shepherd type dogs likely reflects the difference in study populations, with the current study population being the first to explore HRI in first opinion veterinary practice. Additionally, the potential for an underlying genetic predisposition for HRI in military working dogs (Belgian Malinois) has been suggested [42], potentially associated with low levels of expression of heat shock proteins [43].

Exertional HRI appears to predominantly affect younger dogs, all age groups of dogs over 8 years had reduced odds compared to dogs less than 2 years of age. This may reflect differing intensity and duration of exercise undertaken by younger dogs whereas older dogs are more likely to suffer from conditions that limit their ability to exercise, such as osteoarthritis [30] and cardiac disease [44]. Male dogs and neutered female dogs had greater odds than entire female dogs for exertional HRI. These findings mirror the human risk factors of exertional HRI, with young male athletes and labourers most likely to be affected [45]. Entire female dogs could have reduced odds for exertional HRI due to their relatively lower bodyweights compared to male and neutered animals [19], or, it could reflect reduced exercise levels during reproductive periods such as pregnancy and lactation. Dogs at or above the mean adult bodyweight for their breed/sex showed an increased risk of exertional HRI compared to dogs below the mean bodyweight, and all dogs weighing 10 kg or over had increased odds of exertional HRI compared to dogs weighing under 10 kg.

Although the precise mechanisms behind the differing odds between categories for exertional HRI was not explored in this study, it is important to note that HRI is a disorder that requires extrinsic (and often human-controlled) input—dogs cannot develop HRI without exposure to a hot environment or exercise that results in overwhelming hyperthermia [16]. Exertional HRI requires the dog to have undertaken either exercise in a hot environment [6], or prolonged or intense exercise sufficient to exceed thermoregulatory capacity. The majority of exertional HRI events in the present study occurred following relatively low-intensity activities such as walking and occurred during the typically warmer spring and summer months. However, as demonstrated in Figure 3, exertional HRI events occurred in every month (albeit with lower numbers between October and February), confirming that exertional HRI is a year-round risk for UK dogs.

Several breeds along with both non-designer crossbred and designer crossbred dogs were identified with reduced odds for HRI compared to the Labrador Retriever. Conversely, only Chihuahuas were identified with reduced odds (OR 0.42, 95% CI 0.20–0.92) of exertional HRI compared to non-designer crossbred dogs. The Chihuahua is the smallest breed of dog in the world [46], with owners reportedly more influenced by "convenience" when choosing this breed than owners of other popular dog breeds [47]. Chihuahua ownership and popularity are also reported to be influenced by fashion and celebrity trends, with the breed frequently depicted as a "handbag dog" being carried as a fashion statement [48]. Their relatively smaller bodyweight is likely to confer a degree of protection from HRI as previously identified [16,49], which could potentially be augmented by their greater likelihood of being carried than other breeds which could reduce the risk of exertional HRI due to reduced exercise.

Dogs with both dolichocephalic and brachycephalic-cross skull shapes showed reduced odds of exertional HRI, whilst brachycephalic dogs had increased odds of exertional HRI when compared to mesocephalic dogs. This gradient of increasing exertional HRI risk with shortening of the skull is likely due to the differing relative surface area of the nasal turbinates. Evaporative heat loss from panting and respiration is an important aspect of canine thermoregulation [50], so, therefore, dogs with longer muzzles have more surface area for evaporative heat loss. The reduced odds of exertional HRI for brachycephalic-crosses is unexpected but may reflect the diversity of skull conformation types within this ill-defined category. This group is likely to be younger compared to the rest of the study population [16], however, younger dogs have increased odds of exertional HRI. The group is also likely to have relatively lower bodyweight compared to both purebred and non-designer crossbred dogs [16], but could also be subject to similar lifestyle differences, e.g., "handbag dogs", as the Chihuahua due to their small stature and "designer" status.

The second most commonly reported HRI trigger was environmental (12.9% of events with a known cause). Environmental triggers were only recorded between March and September, reflecting the UK's warmer season. The four breeds with increased odds of environmental HRI when compared to the Labrador Retriever were predominantly brachycephalic breeds (Bulldog, Pug and French Bulldog); brachycephalic dogs, in general, had 2.36 the odds compared to mesocephalic breeds. This mirrors the increased risk of environmental HRI for humans with underlying respiratory disorders, and is supported by the findings of Lilja-Maula et al. [15] that documented Bulldogs developing hyperthermia just standing in ambient room temperature (21 °C). Although the Chow Chow had the greatest odds of both exertional and environmental HRI, it must be noted that the Chow Chow breed group was the smallest in the study population resulting in very wide confidence intervals, and so these results need to be generalized to the wider population with caution.

Dogs aged 12 years or over had over three times the odds of environmental HRI compared to dogs under 2 years, again mirroring human risk factors. Advancing age increases the likelihood of underlying health conditions such as cardiac or respiratory disease, and old age in humans has been shown to increase HRI risk due to decreased physiological thermoregulatory mechanisms such as decreased sweat production and skin blood flow [14,51]. Dogs weighing from 10 up to 30 kg had almost twice the odds of environmental HRI compared to dogs weighing less than 10 kg, however, interestingly none of the dogs weighing 50 kg or over were reported with environmental HRI. In general, the risk factor analysis for environmental HRI was the least informative of the three models, with the lowest R^2 and area under the ROC curve values. Environmental HRI requires prolonged exposure to a hot environment, or acute exposure to an extremely hot environment, both traditionally rare events in the UK. Environmental HRI is also the trigger for dogs that is least influenced by human behaviour, whereas both exertional HRI and vehicular HRI are heavily dependent on the actions of the dog's owner. The much lower levels of environmental HRI compared with exertional HRI offers a substantial welfare gain opportunity by empowering owners with management tools that can limit the exertional HRI risk to their dogs. However, if climate change continues to increase, the frequency of heatwave events in the UK, the number of dogs experiencing environmental HRI is likely to increase without appropriate mitigation strategies.

Five breed types had increased odds of vehicular HRI compared to the Labrador Retriever (Bulldog, Greyhound, Cavalier King Charles Spaniel, French Bulldog and Pug). Brachycephalic dogs overall had three times the odds compared to mesocephalic dogs. However, the relatively low number of vehicular HRI events (37/856) resulted in low statistical power for this analysis, as reflected in the wide confidence intervals. Only two variables remained in the final vehicular HRI risk factor model, likely reflecting the predominantly extrinsic causal structure to vehicular HRI. Any dog subjected to confinement in a hot car will overheat, as their thermoregulatory mechanisms cease to be effective once ambient temperature exceeds body temperature. Internal car temperature in the UK can exceed 50 °C between May and August, and can exceed 40 °C between April and September [52]. The duration of confinement and the temperature within the vehicle will determine the severity of HRI [53], however underlying canine factors that impact thermoregulatory ability (such as a respiratory compromise or disease [50], acclimatization [54–56] and hydration [57]) will result in dogs overheating and developing HRI at lower relative temperatures.

Vehicular HRI was the third most common trigger and was reported only between March and September. Welfare charities and UK veterinary organisations run an annual "Dogs die in hot cars campaign", traditionally launched around May [58,59]. However, Carter et al. [52], report that internal vehicle temperatures exceeded 35 °C between the months of April and September in a study measuring UK vehicle temperatures for a two-year period. As heat acclimatization is known to impact susceptibility to HRI, sudden warm spells in March and April may be particularly dangerous for dogs left in cars. The findings of the current study, and those of Carter et al. [52], support an earlier launch of this annual awareness campaign.

There was no significant difference in the odds for HRI related fatality between vehicular and exertional HRI. However, because exertional HRI affected around ten times as many dogs and resulted in eight times as many deaths overall than vehicular HRI, there is now a strong evidential basis to suggest that educational campaigns aimed at owners need to move from focusing purely on the risk of vehicular HRI to dogs and instead to include warnings about the more frequent dangers of exercising in hot weather.

This study identifies some important novel HRI triggers, in particular dogs developing HRI whilst under the care of veterinary practices and professional groomers. Undergoing treatment at a veterinary practice or grooming parlour was the fourth most common trigger for HRI events with a known cause, with a similar fatality rate to both exertional and vehicular HRI. This topic was explored further as part of an abstract presentation, reporting that two-thirds of the HRI events occurred in a veterinary practice (56% brachycephalic dogs) and one third whilst dogs were undergoing professional grooming (45% brachycephalic) [27]. The French Bulldog and the Bulldog accounted for a third of the cases occurring under veterinary care, whilst West Highland White Terriers were the most numerous breed type affected during grooming. Both veterinary practice premises and grooming parlours can be warm, stressful environments for dogs, highlighting the need for careful patient monitoring and awareness of the risk of HRI in these situations, especially in predisposed breeds.

Other HRI triggers identified in the current study included building confinement and blanket entrapment. These two triggers had the highest fatalities rates, with building confinement resulting in HRI all year round. Building confinement (OR 6.1) and unrecorded trigger (OR 2.4) HRI events both had significantly greater odds for HRI fatality compared to exertional HRI. Building confinement HRI events included events where central heating had been accidentally left on, or developed a fault, and so resulted in dogs being restricted to hot environments for prolonged periods while owners were unaware of the problem. The HRI events with unrecorded triggers included emergency presentations where the attending veterinary surgeon potentially did not have time to accurately record a history in the EPR and also includes HRI events where a specific trigger was not recognised or reported by the owner. Increasing owner awareness of circumstances that can result in canine HRI should be a priority as global temperatures continue to rise.

Dogs have been proposed as an ideal translational model for studying human morbidity and mortality [4,60]. Domestic dogs often share their owners' home and leisure activities including walking, running and other sports [20]. Dogs increasingly accompany their owners to the workplace [61] and are often included in travel and holiday plans. No other species more intimately intertwines with the human lifestyle, meaning dogs potentially face similar levels of both environmental and exertional heat exposure to humans. The results of the current study highlight that dogs share similar risk factors to humans for both exertional and environmental HRI. How dogs are transported, housed and managed will also influence HRI risk. Dogs housed outside, with no access to air conditioning or fans will be at increased risk of environmental HRI as global warming worsens. The vehicular HRI events in the current study included both dogs left in parked vehicles and dogs travelling in hot vehicles, and highlight the danger of transporting dogs in cars without adequate ventilation or air conditioning during hot weather. As the frequency of extreme weather events such as heat waves is increasing, society needs to prepare strategies to mitigate the threat of HRI [62], to protect both human and canine health [22].

This study had some limitations. As previously reported, the clinical record data in the VetCompass programme were not recorded primarily for research purposes, meaning there are missing data within the dataset and the accuracy of descriptive entries (such as patient histories recording HRI triggers) is reliant upon the history provided to the veterinary surgeon treating the animal and their clinical note-taking [31,63]. Other limitations including the lack of a definitive diagnostic test for HRI, the use of skull shape definitions such as brachycephalic and mesocephalic, and the use of manual stepwise elimination to select the final breed models for the various HRI triggers have been discussed in a previous study [16].

The present study used prevalent HRI events recorded at any point within the available clinical records for each dog. This may have selectively biased towards less severe HRI events, because dogs that died as a result of HRI prior to 2016 were by definition not part of the study population. This is reflected in the overall fatality rate of the prevalent cases in the present study (7.86%) which is lower than the 2016 incident fatality rate (14.18%) reported previously [16]. As the main aims of the present study were to identify the predominant triggers for HRI in UK dogs, and explore risk factors for the top three triggers, the decision to include all prevalent HRI events was made to increase the number of events available for analysis, and thus improve the statistical power of the findings.

Finally, the present study aimed to identify potential risk factors for different HRI triggers, producing potentially explanatory models, rather than predictive models. The low R^2 values for all three risk factor models highlight the impact of non-canine variables as important driving forces for HRI in dogs. The effect of ambient temperature and humidity, canine behaviour and activity status, heat acclimation, athletic fitness and overall health fitness would all need to be considered to create a truly predictive model for canine HRI. These variables are not recorded in veterinary EPRs, meaning it was not possible to include these factors in the present analysis.

5. Conclusions

This study highlights canine risk factors for the three most common triggers of HRI in UK dogs, providing both dog owners and veterinary professionals information that can be used to identify at-risk dogs, tailor HRI education and potentially assist with more rapid recognition and therefore treatment of HRI in dogs. Dogs appear to share similar risk factors to humans for both of the most common HRI triggers: exertional and environmental. Young, active male dogs appear to have the greatest odds for exertional HRI, older dogs and brachycephalic dogs have greater odds for environmental HRI. Exertional HRI is shown to result in almost ten times the health welfare burden for dogs compared with vehicular HRI. It is hoped that these results will help to inform more targeted education campaigns, and catalyse further research to develop canine HRI mitigation strategies in the face of increasing global temperatures.

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Data Availability: https://researchonline.rvc.ac.uk/id/eprint/12745/.

Appendix A

Table A1. Potential canine risk factors for association with HRI in UK dogs [16].

Potential Risk Factor for HRI	Variable Definition	Justification
Breed type	Categorical variable including all named breed types (including both KC recognised purebred and non-KC recognised purebred) and designer hybrid types with contrived names (e.g., Cockapoo, Labradoodle, Lurcher) with ≥5 HRI cases and/or ≥5000 dogs in the overall study population. All remaining dogs were assigned to grouped categories of "other purebred", "other designer cross" or "non-designer crossbred".	Chow Chow, Bulldog, French Bulldog, Dogue de Bordeaux, Greyhound, Cavalier King Charles Spaniel, Pug, English Springer Spaniel and Golden Retriever breeds have all be identified as having greater odds of HRI in UK dogs [16]. Labrador Retriever was used as the comparator for this variable as they were the largest breed type in the denominator population (after crossbred) so enabled high statistical power to explore breed risks [38,40].
Purebred	Categorical variable grouping all dogs of recognisable breeds as "purebred", all recognisable designer crossbreeds as "designer cross" and the remaining dogs as "crossbred".	Purebred dogs are more likely to have an exaggerated conformation such as brachycephaly, thick coat, or giant body size, limiting their ability to thermoregulate [50]. A higher percentage of purebred dogs presented with heatstroke to one veterinary hospital [34].
Skull shape	Purebred dogs were categorised by skull shape into three groups, "brachycephalic", "mesocephalic" and dolichocephalic" (see Supplementary note 1 for breeds by category). Designer crossbred dogs including a brachycephalic breed were classified as "brachycephalic cross" and all other dogs listed as crossbred or unrecorded breed were classified as "skull shape unrecorded".	Surface areas of the nasal turbinates and effective ventilation provide the mechanism to enable evaporative heat loss through panting, thus brachycephalic dogs have reduced heat dissipation mechanisms [15,18,50,64].
Adult bodyweight	Adult bodyweight was defined as the mean of all bodyweight (kg) values recorded for each dog after reaching 18 months old. Bodyweight (kg) was then categorised into seven groups (<10, 10– < 20, 20– < 30, 30– < 40, 40– < 50, ≥50), dogs under 18 months or with no recorded adult bodyweight were classified as "unrecorded".	Small breeds of dog are reported to have decreased risk of HRI [18], dogs with greater body mass have been reported to develop higher post exercise body temperatures [19].
Bodyweight relative to breed/sex mean	A categorical variable grouping dogs with a mean adult bodyweight "equal or above" or "below" the mean adult bodyweight for their breed and sex (calculated using the overall VetCompass study population). An "unrecorded" variable included all dogs with no adult bodyweight or labelled as crossbred.	Increased bodyweight can be due to increases in either lean muscle mass, or body fat. Obesity limits heat conduction and radiation from the skin and can limit effective cooling via respiration [50], overweight animals overheat faster and take longer to cool [65]. Dogs with greater lean body mass developed higher post-exercise temperatures than lighter dogs [19].
Sex/neuter	Dogs were classified by sex and neuter status into five categories (female entire, female neutered, male entire, male neutered) with "unrecorded" was used to group any dogs with no recorded sex or neuter status.	Male dogs develop higher body temperature post exercise [19,20], and are over-represented in cases of heatstroke presenting to veterinary hospitals [37,66,67].
Age	The age variable described the age of the dog at the end of the study period (31st December 2016) for non-case dogs, or the age at the first HRI event for 2016 incident HRI cases. Age (years) was categorised into eight groups (<2, 2– < 4, 4– < 6, 6– < 8, 8– < 10, 10– < 12, ≥12) with "unrecorded" for any dogs with no date of birth recorded in the EPR.	Older animals are more likely to have pre-existing conditions that limit effective heat dissipation such as heart disease, or respiratory diseases e.g., laryngeal paralysis [64].

Appendix B

Table A2. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with age, bodyweight relative to breed/sex mean and sex/neuter) to evaluate risk factors associated with exertional heat-related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Purebred	Non-designer Crossbred	Base		
	Designer Crossbred	0.68	0.41–1.13	0.134
	Purebred	1.84	1.47–2.31	<0.001
	Unrecorded	2.11	0.51–8.78	0.306
Skull shape	Mesocephalic	Base		
	Dolichocephalic	0.72	0.52–1.00	0.048
	Brachycephalic-cross	0.19	0.05–0.75	0.018
	Brachycephalic	1.32	1.10–1.60	0.004
	Unknown	0.60	0.47–0.76	<0.001
Adult bodyweight (kg)	<10 kg	Base		
	10– < 20 kg	2.52	1.97–3.22	<0.001
	20– < 30 kg	2.27	1.73–2.99	<0.001
	30– < 40 kg	2.30	1.68–3.15	<0.001
	40– < 50 kg	2.15	1.31–3.53	0.002
	≥50 kg	2.21	1.02–4.79	0.046
	Unrecorded	0.54	0.13–2.23	0.395

Table A3. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with age and sex/neuter) to evaluate risk factors associated with environmental heat related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Purebred	Non-designer Crossbred	Base		
	Designer Crossbred	1.55	0.55–4.34	0.404
	Purebred	1.97	1.12–3.47	0.018
	Unrecorded	0.00	~	0.985
Skull shape	Mesocephalic	Base		
	Dolichocephalic	0.81	0.37–1.79	0.606
	Brachycephalic-cross	1.94	0.46–8.16	0.364
	Brachycephalic	2.36	1.50–3.72	<0.001
	Unknown	0.61	0.34–1.09	0.094
Adult bodyweight (kg)	<10 kg	Base		
	10– < 20 kg	1.82	1.07–3.08	0.027
	20– < 30 kg	1.90	1.04–3.45	0.036
	30– < 40 kg	1.61	0.78–3.32	0.200
	40– < 50 kg	1.52	0.45–5.09	0.498
	≥50 kg	0.00	~	0.980
	Unrecorded	0.56	0.29–1.06	0.074

Table A4. Results for variables that individually replaced the breed type variable in the final multivariable logistic regression model (with sex/neuter) to evaluate risk factors associated with vehicular heat related illness in dogs under primary veterinary care in the VetCompass Programme.

Risk Factor	Category	Odds Ratio	95% CI	*p*-Value
Skull shape	Mesocephalic	Base		
	Dolichocephalic	1.00	0.29–3.39	0.999
	Brachycephalic-cross	0.00	~	0.975
	Brachycephalic	3.07	1.60–5.87	0.001
	Unknown	0.74	0.29–1.86	0.522

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Proposing the VetCompass clinical grading tool for heat-related illness in dogs

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Heat-related illness is a potentially fatal condition in dogs. Rapid and accurate recognition of the severity can improve clinical management in affected dogs and lead to better outcomes. This study explored retrospective VetCompass veterinary clinical records to investigate the clinical signs recorded for dogs presenting with heat-related illness to primary-care veterinary practice from 2016 to 2018. The relative risk of death associated with these clinical signs was reported and used to develop a novel clinical grading tool. From the clinical records of 856 heat-related illness events, the most frequently recorded clinical signs were respiratory changes (68.73%) and lethargy (47.79%). The clinical signs with the highest relative risk of death were neurological dysfunction, gastrointestinal haemorrhage and bleeding disorders. The novel VetCompass Clinical Grading Tool for Heat-Related Illness in dogs defines three grades: mild (altered respiration, lethargy), moderate (gastrointestinal signs, a single seizure, episodic collapse) and severe (neurological dysfunction, gastrointestinal haemorrhage, bleeding disorders). This novel grading tool offers a simple, evidence-based device to improve recognition of heat-related illness in dogs and promote improved decision-making for earlier interventions such as cooling and hospitalisation. This could improve outcomes and protect the welfare of dogs in the face of rising global temperatures.

Abbreviations

CI	Confidence interval
EPR	Electronic patient record
HRI	Heat related illness

Heat-related illness (HRI) is a potentially fatal disorder that affects dogs when their thermoregulatory capacity is overwhelmed, resulting in hyperthermia and subsequent thermal tissue damage[1,2]. There are three recognised main triggers (though with some overlap) of HRI in dogs; exertional HRI occurs following exercise in a hot environment or following intense activity[2,3], environmental HRI results from exposure to extreme environmental heat or prolonged exposure to a hot environment[1,4], and vehicular HRI results from either entrapment or travel in a hot vehicle[3]. Both dogs and humans show differing risks for each HRI trigger according to their age, sex, and underlying health status. Young, active male humans[5] and dogs[3] are at particular risk of exertional HRI, with breeds including the Labrador Retriever, Golden Retriever, Springer Spaniel and Staffordshire Bull Terrier at greater risk than crossbred dogs[3]. Older dogs and humans have increased risk of environmental HRI[3,6], in part because elderly individuals are more likely to have underlying health conditions such as respiratory disease and heart failure[7]. Additionally, age-related physiological changes reduce peripheral blood flow and sweat gland function, and thereby limit the effectiveness of homeostatic thermoregulatory functions for effective cooling in older individuals[8]. Vehicular HRI particularly affects young children and babies, most frequently following accidental entrapment[9]. Vehicular HRI can also affect dogs, but brachycephalic (flat-faced) breeds such as the British Bulldog, Pug and French Bulldog appear particularly susceptible[3], likely because of their inherently reduced ability to thermoregulate resulting from their shortened muzzle and narrowed airways[10].

The diagnosis of HRI in human medicine traditionally relies upon measurement of body temperature and assessment of neurological function using the "Classical" definitions established by Bouchama and Knochel[1]. These Classical Heat Stroke Criteria define three levels of HRI, rising from mild heat stress (perceived discomfort and physiological strain resulting from mild hyperthermia), to heat exhaustion (moderate illness including

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weakness, anxiety, fainting, headache and a core temperature that may be elevated up to, but not exceeding 40 °C) and finally heat stroke (severe illness, body temperature exceeding 40 °C accompanied by profound neurological dysfunction including delirium, seizures and coma)[1]. These classical criteria, using a body temperature threshold of ≥ 41 °C, are also used in veterinary medicine for diagnosing and categorising HRI in animals, most frequently dogs[2,11,12], despite their reliance upon clinical signs/symptoms that, in humans, require verbal communication from the patient e.g. headache, dizziness, anxiety and delirium. However, a study of experimentally induced heat stroke in dogs reported 43 °C as the critical body temperature threshold for inducing clinical, haematological, biochemical and pathological indicators of heat-related illness in dogs[13]. The duration that the dog's body temperature exceeded 43 °C accurately predicted the risk of death[13]. The lack of consensus in the veterinary literature regarding the critical temperature threshold for HRI in dogs highlights uncertainty in the value and reliability of using body temperature as a diagnostic criterion for HRI.

Following recognition of the limitations from using core body temperature measurement as a diagnostic criterion for the Classical Heat Stroke Criteria in human medicine, a novel HRI staging system was proposed but has not yet been widely adopted for use in humans[14]. Body temperature can fluctuate rapidly in these emergency-care patients and because cooling is recommended as soon as HRI is considered likely, many humans present for medical assessment after they have been cooled and therefore their temperature has already begun to drop. The Japanese Association for Acute Medicine Heat-Related Illness Classification (JAAMHC) has been proposed as an alternative diagnostic and triage tool for use in human patients with HRI[15]. This novel classification included clinical symptoms that were more objectively defined, removed the reliance upon body temperature and self-reported symptoms as diagnostic criteria, and acknowledged that HRI is a progressive rather than a static disorder within patients where increasingly severe pathology is developed with ongoing exposure to heat or failure to receive appropriate treatment (available http://www.mdpi.com/1660-4601/15/9/1962/s1)[15]. Crucially, the JAAMHC novel classification appears better at predicting clinical outcomes for human patients with HRI[15,16], enabling more appropriate and targeted treatment following initial triage.

Most canine HRI research has applied a variation of the Classical Heat Stroke Criteria when selecting cases for analysis, and generally included only dogs presented to referral hospitals rather than primary-care practices[11,17,18]. This has tended to exclude dogs presenting with milder clinical signs of HRI from inclusion in studies while favouring inclusion of severe cases requiring advanced levels of care, resulting in research findings that may suffer from referral bias[19]. The HRI case fatality rate reported by these earlier referral-based studies ranged from 36 to 50%[11,17,18], whilst a veterinary primary-care study including dogs with all stages of HRI reported a much lower case fatality rate of 14%[20], highlighting the benefits from primary-care focused research for results that are more generalisable to the wider dog population. No specific triggers for HRI were reported in the clinical records for almost a third of the dogs presented in the primary-care study[3], potentially demonstrating a lack of recognition of early signs of HRI by owners or veterinary professionals. Improved awareness of the triggers of HRI, the clinical signs of mild HRI and the actions needed when a dog presents with HRI should be considered as urgent educational priorities for both owners and veterinary professionals to protect canine welfare in the face of rising global temperatures and increasingly frequent extreme heat events[21,22]. Use of the Classical Heat Stroke Criteria definitions that rely on body temperature as a diagnostic criterion may promote continued misdiagnosis because HRI cases that have already begun to cool may be misclassified. This can result in missed opportunities to manage mild or early HRI cases, as noted in human medicine[15]. Therefore, the current paper proposed that a more objective and staged approach for diagnostic criteria should be explored and then used to develop a more reliable HRI clinical grading scheme in dogs.

This study aimed to (i) report the clinical presentations and outcomes of dogs presenting to primary-care veterinary clinics in the UK with HRI, and (ii) adapt the JAAMHC novel HRI classification system to develop a new clinical grading system that is based on canine first opinion data and therefore more reliable and applicable for use in the wider population of dogs. The study is presented in three phases to reflect the sequential nature of the work.

Phase 1: reviewing the clinical presentation data of dogs affected by heat-related illness

Data collection and management. This study continues the work previously reported in Hall et al.[3,20] and used the same dataset described in those studies. The VetCompass Programme collects deidentified electronic patient records (EPRs) from affiliated primary-care veterinary practices in the UK, providing a research database for large scale primary-care studies that includes the clinical records of over 9 million dogs[23–26]. All dogs under veterinary care during 2016 were included in the current study population as previously defined in Hall et al.[20]. Candidate cases for HRI were identified by searching EPRs for the following terms: heat stroke ~ 3, heatst*, hyperthermi*, overheat*, over heated ~ 2, heat exhaustion ~ 2, hot car ~ 2, collapse* + heat, cooling, high ambient temp*. Candidate cases were manually reviewed by two authors (authors 1 and 2) to identify all dogs meeting the case definition of HRI and presenting between 1st January 2016 and 31st December 2018 (see Table 1).

All confirmed HRI events underwent additional data extraction including: date of the event, date of presentation, presenting clinical signs, duration of treatment, and outcome (survived or died including euthanasia, unknown cause of death and unassisted deaths). For this study, only HRI events occurring between 1st January 2016 and 31st December 2018 were included in the analysis, as events that occurred prior to 1st January 2016 resulted in a survival outcome by definition (Fig. 1).

Investigating the relative risk of death associated with clinical signs recorded for HRI events. The study included 856 HRI events that occurred between 2016 and 2018 identified from the EPRs

Inclusion criteria—Evidence for heat-related illness recorded in the patient record	Final stated diagnosis or insurance claim for a heat-related illness (including heat stroke, heat stress, heat exhaustion or other synonym), and/or History of at least one of the clinical signs listed below, clinical records indicated that these were associated with exposure to these triggers: exposure to a hot environment, physical exertion or both
Clinical signs	• Panting excessively (panting continues despite removal from heat/cessation of exercise) • Collapse not subsequently attributed to another cause (e.g. heart failure, Addison's) • Stiffness, lethargy or reluctance to move • Gastrointestinal disturbance including hypersalivation, vomiting or diarrhoea • Neurological dysfunction including ataxia, stupor, seizures, coma or death • Coagulation disturbances (bleeding disorders) including petechiae or purpura
Exclusion criteria	Subsequent diagnosis of an infectious or inflammatory condition that was not attributed to primary heat exposure such as kennel cough, pyometra or infectious meningitis HRI or synonym listed only as one of a differential list An earlier diagnosis of HRI that was later revised to exclude HRI, for example the dog was diagnosed with epilepsy following further seizure activity

Table 1. Case inclusion and exclusion criteria used for heat-related illness (HRI) events in dogs presenting to primary-care veterinary practice, defined in Hall et al.[20].

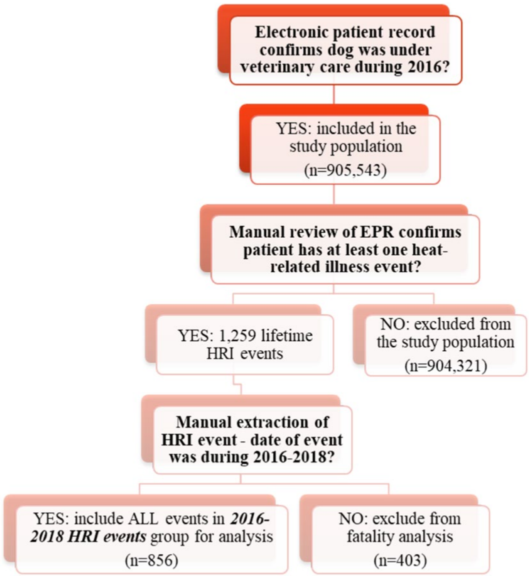


Figure 1. Flow chart of decisions for event inclusion in heat-related illness (HRI) staging analysis and reporting clinical presentations of HRI in UK dogs.

of 828 dogs (28 dogs had two HRI events in this period), from a population of 905,543 dogs presenting to primary-care veterinary clinics in the UK during 2016. The recorded clinical signs extracted for each HRI event were analysed to determine the relative risk of death overall and specifically for unassisted death (see definitions below) for dogs showing each individual clinical sign compared to dogs not showing that clinical sign:

- Death by any mechanism (including unassisted death, unknown method of death and euthanasia).
- Unassisted deaths only (deaths via euthanasia or an unrecorded mechanism were excluded).

Events without at least one clinical sign recorded in the EPR were excluded from the relative risk analysis. Univariable relative risk analysis using the chi squared test was performed using StatCalc v7.2 (Epi Info, Centre for Disease Control and Prevention, https://www.cdc.gov/epiinfo/index.html). Statistical significance was set at $p < 0.05$.

From the 856 HRI events reviewed, 63 events (7.34%) did not have at least one clinical sign recorded and were removed from the analysis. From the 793 EPRs with at least one recorded clinical sign, the most commonly

Presenting clinical sign	Clinical sign recorded			Clinical sign not recorded			Relative Risk	95% CI*	*p*-value
	n	Deaths	% Fatality Rate	n	Deaths	% Fatality Rate			
Unresponsive	51	43	84.31	742	47	6.33	13.31	9.85 to 17.98	< 0.001
Coma	15	14	93.33	778	76	9.77	9.55	7.42 to 12.30	< 0.001
Stupor	24	17	70.83	769	73	9.49	7.46	5.33 to 10.45	< 0.001
Multiple seizures	12	8	66.67	781	82	10.5	6.35	4.05 to 9.95	< 0.001
Gastrointestinal haemorrhage	27	14	51.85	766	76	9.92	5.22	3.43 to 7.97	< 0.001
Petechiae/purpura	18	8	44.44	775	82	10.58	4.2	2.41 to 7.32	< 0.001
Ataxia	14	5	35.71	779	85	10.91	3.27	1.58 to 6.80	0.002
Respiratory (excessive panting/dyspnoea)	545	66	12.11	248	24	9.68	1.25	0.80 to 1.95	0.321
Single seizure	30	4	13.33	763	86	11.27	1.18	0.47 to 3.01	0.724
Hypersalivation	33	4	12.12	760	86	11.32	1.07	0.42 to 2.74	0.886
Diarrhoea	76	9	11.84	717	81	11.30	1.05	0.55 to 2.00	0.887
Vomiting	193	22	11.40	600	68	11.33	1.01	0.64 to 1.58	0.980
Collapse-intermittent	250	27	10.80	543	63	11.60	0.93	0.61 to 1.42	0.741
Lethargy	379	21	5.54	414	69	16.67	0.33	0.21 to 0.53	< 0.001

Table 2. Proportional fatality and relative risk for **death overall** (including euthanasia, unknown method and unassisted) in dogs recorded with specific clinical signs of heat-related illness cases presenting to primary-care veterinary practices in the UK between 2016 and 2018. Relative risk describes the risk ratio of death in heat-related illness cases recorded with this clinical sign compared to cases without this clinical sign. *CI confidence interval, n = 793.

Presenting clinical sign	Clinical sign present			Clinical sign not present			Relative Risk	95% CI*	*p* -value
	n	Unassisted deaths	% Fatality Rate	n	Unassisted deaths	% Fatality Rate			
Unresponsive	29	21	72.41	709	14	1.97	36.67	20.84 to 64.54	< 0.001
Coma	9	8	88.89	729	27	3.70	24.00	15.51 to 37.13	< 0.001
Stupor	12	5	41.67	726	30	4.13	10.08	4.74 to 21.47	< 0.001
Multiple seizures	7	3	42.86	731	32	4.38	9.79	3.90 to 24.57	< 0.001
Gastro- intestinal haemorrhage	15	2	13.33	723	33	4.56	2.92	0.77 to 11.07	0.115
Single seizure	29	3	10.34	709	32	4.51	2.29	0.75 to 7.05	0.148
Respiratory (excessive panting/ dyspnoea)	508	29	5.71	230	6	2.61	2.19	0.92 to 5.20	0.076
Ataxia	10	1	10.00	728	34	4.67	2.14	0.32 to 14.15	0.429
Petechiae/ Purpura	11	1	9.09	727	34	4.68	1.95	0.29 to 12.98	0.491
Hyper- salivation	31	2	6.45	707	33	4.67	1.38	0.35 to 5.50	0.646
Collapse—intermittent	231	8	3.46	507	27	5.33	0.65	0.30 to 1.41	0.276
Diarrhoea	69	2	2.90	669	33	4.93	0.59	0.14 to 2.40	0.459
Vomiting	176	5	2.84	562	30	5.34	0.53	0.21 to 1.35	0.185
Lethargy	363	5	1.38	375	30	8.00	0.17	0.07 to 0.44	< 0.001

Table 3. Proportional fatality and relative risk for **unassisted death** (excluding euthanasia) in dogs recorded with specific clinical signs of heat-related illness cases presenting to primary-care veterinary practices in the UK between 2016 and 2018. Relative risk describes the risk ratio of death in heat-related illness cases recorded with this clinical sign compared to cases without this clinical sign. *CI confidence interval, n = 738.

recorded clinical signs were altered respiration (including excessive panting and dyspnoea) (n = 545, 68.73%), lethargy (n = 379, 47.79%) and intermittent collapse (n = 250, 31.5%). Multiple clinical signs were recorded for 560 HRI events (70.6%).

The clinical signs with the highest relative risk of death overall (including euthanasia, unknown method and unassisted deaths) are shown in Table 2. Dogs presenting with abnormal mentation (including unresponsive, coma, stupor, multiple seizures and status epilepticus), gastrointestinal haemorrhage, petechiae/purpura or ataxia had at least three times the relative risk of death compared to dogs presenting without those clinical signs.

The clinical signs with the highest relative risk of unassisted death are shown in Table 3. Dogs presenting with abnormal mentation (including unresponsive, coma, profound depression or multiple seizures) also had significantly increased risk of an unassisted death ($p < 0.001$). Dogs with lethargy recorded as a clinical sign for their HRI event had a significantly reduced relative risk of death (overall and unassisted) ($p < 0.001$).

	Clinical sign present			Clinical sign not present					
Temperature	n	Deaths	% Fatality Rate	n	Deaths	% Fatality Rate	Relative Risk	95% CI*	*p*-value
< 37.2 °C	14	2	14.29	483	32	6.63	2.16	0.54 to 28.79	0.256
≥ 41 °C	132	37	28.03	483	32	6.63	4.23	2.75 to 6.52	< 0.001
≥ 43 °C	19	14	73.68	596	55	9.23	7.98	5.52 to 11.54	< 0.001
Temperature	n	Unassisted deaths	% Fatality Rate	n	Unassisted deaths	% Fatality Rate	Relative Risk	95% CI	p-value
< 37.2 °C	13	1	7.70	460	9	1.96	3.93	0.54 to 28.79	0.256
≥ 41 °C	110	15	13.64	460	9	1.96	7.06	3.17 to 15.71	< 0.001
≥ 43 °C	12	7	58.33	558	17	3.05	19.15	9.81 to 37.39	< 0.001

Table 4. Body temperature at veterinary presentation as a risk factor for death (all causes) and unassisted death in dogs diagnosed with heat-related illness presenting to primary-care veterinary practices in the UK between 2016 and 2018. Relative risk describes the risk of death in heat-related illness cases meeting each temperature criterion compared to cases that did not meet this criterion. *CI confidence interval n = 629 for overall death analysis, n = 583 for unassisted death analysis.

Investigating the relative risk of death associated with presenting body temperature measurements for HRI events. Because body temperature at first veterinary presentation is still routinely used as a key criterion for clinical management of HRI in many veterinary settings[2,11,12,22], the presenting body temperature of survivors versus non survivors was compared using the Mann-Whitney U test following normality testing showing a non-normal distribution of body temperature values. The relative risk of death associated with several body temperature thresholds at presentation was explored as part of the development process for the current novel VetCompass Clinical Grading Tool for Canine Heat-Related Illness (referred to as the VetCompass HRI Grading Tool hereafter). Three temperature thresholds were compared: < 37.2 °C versus 37.2–40.9 °C, ≥ 41 °C versus 37.2–40.9 °C, and ≥ 43 °C versus 37.2–42.9 °C. For each HRI event, the presenting body temperature was categorised as below, or at/above each of the three thresholds. The relative risk of death overall and the relative risk of unassisted death were calculated for each temperature threshold; HRI events where the presenting body temperature was not recorded in the EPR were excluded from analysis. Dogs that died as a result of euthanasia or unreported mechanisms were excluded from the analysis for relative risk of unassisted death. Associations with hypothermia were also explored because hypothermia has been identified previously as a risk factor for death[11]. The threshold for hypothermia was < 37.2 °C, as defined by Konietschke et al.[27]. Whilst this threshold is lower than the limit (< 37.6 °C) used by Bruchim et al.[11], this temperature range was derived from a canine population living in a similar climate to the UK.

Body temperature at presentation was recorded for 629 events (73.5%). The median temperature recorded for non-survivors (n = 71), was 41.0 °C (IQR: 39.6–42.4 °C, range: 35.6–43.3 °C) ($p < 0.001$) and was significantly higher than for survivors (n = 558) which was 39.6 °C (interquartile range [IQR]: 38.7–40.5 °C, range: 34.9–43.4 °C). The number of dogs presenting with a body temperature < 37.2 °C, ≥ 41 °C or ≥ 43 °C is shown in Table 4. Dogs presenting with a body temperature ≥ 43 °C had a higher relative risk of death and unassisted death compared to dogs with a temperature ≥ 41 °C (see Table 4). Dogs presenting with hypothermia (< 37.2 °C) did not have a significantly increased relative risk of death ($p = 0.256$) or unassisted death compared to dogs without hypothermia ($p = 0.256$).

Phase 2: adapting the JAAMHC staging criteria for use in canine HRI patients

The clinical symptoms identified in the JAAMHC staging criteria for human HRI were adapted for application to dogs in the current study (see Table 5) to create the novel VetCompass HRI Grading Tool. This adaptation was based on differences in physiology between the two species (namely thermoregulatory reliance on panting rather than sweating in dogs) and the evidence base generated from the relative risk analysis for presenting clinical signs reported above. The clinical signs that were associated with significantly increased risk of death overall and risk of unassisted death in the current study ($p < 0.05$) were included in the most severe category, notably: altered mentation (including unresponsive, coma, profound depression, multiple seizures and ataxia) gastrointestinal haemorrhage and petechiae/purpura.

Although the current study did not evaluate laboratory diagnostic results, a previous study of post mortem findings in dogs that died as a result of HRI reported hepatomegaly in all cases, and hepatic parenchymal necrosis in over half the dogs examined[28]. Renal pathology was also noted in all the dogs examined, ranging from interstitial and glomerular congestion to tubular necrosis in both the proximal and distal convoluted tubules[28]. Abnormal renal and hepatic function were therefore retained in the diagnostic criteria for severe HRI in dogs.

Phase 3: retrospective grading of 2016–2018 canine HRI events using the novel VetCompass grading tool

Analysis. All HRI events identified during 2016–2018 were retrospectively classified according to the novel VetCompass HRI Grading Tool defined in Table 5. Where an HRI event had insufficient information recorded in the EPR to allow classification, the event was categorised as "unreported" as per the definition in Table 5. Descriptive statistics and the distribution of cases were compared with the distribution of human HRI events.

Japanese Association of Acute Medicine Heat-Related Illness Classification stages	Human symptoms	VetCompass Clinical Grading Tool for Heat-Related Illness in dogs grades	Adapted canine clinical signs
Stage I	Dizziness, faintness, slight yawning Heavy sweating Muscle pain, stiff muscles (muscle cramps) Impaired consciousness is not observed	Mild	No impaired consciousness observed Lethargy or stiffness Panting heavily or respiratory distress
Stage II	Headache, vomiting, Fatigue, sinking feeling Declined concentration and judgement	Moderate	Vomiting and/or diarrhoea (no blood present), hypersalivation Collapse (intermittent only) A single seizure
Stage III	Includes at least one of the following: Central nervous system manifestation (impaired consciousness, cerebellar symptoms, convulsive seizures) Hepatic/renal dysfunction Coagulation disorder	Severe	Includes at least one of the following: Central nervous system impairment (ataxia, two or more seizures, profound depression, unresponsive, coma) Hepatic/renal dysfunction (confirmed on blood tests) Gastrointestinal haemorrhage Coagulation disorder
Unreported	N/A	Unreported	No clinical signs or diagnostic results recorded in the clinical history

Table 5. Development of the novel VetCompass Clinical Grading Tool for Heat-Related Illness in dogs, based upon the JAAMHC human heat-related illness scale.

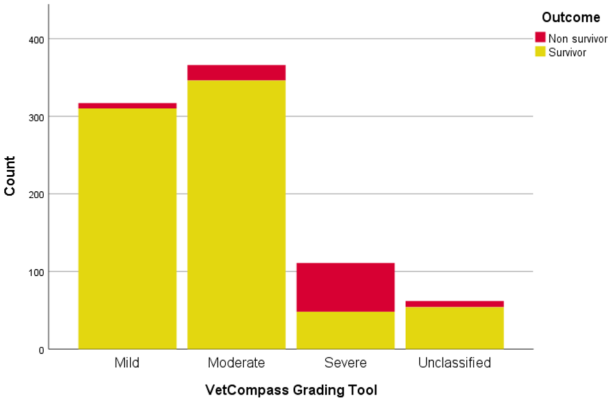


Figure 2. The event distribution and survival outcomes for HRI grades defined using the VetCompass Clinical Grading Tool for Heat-Related Illness in dogs presenting to primary-care veterinary practices in the UK between 2016 and 2018.

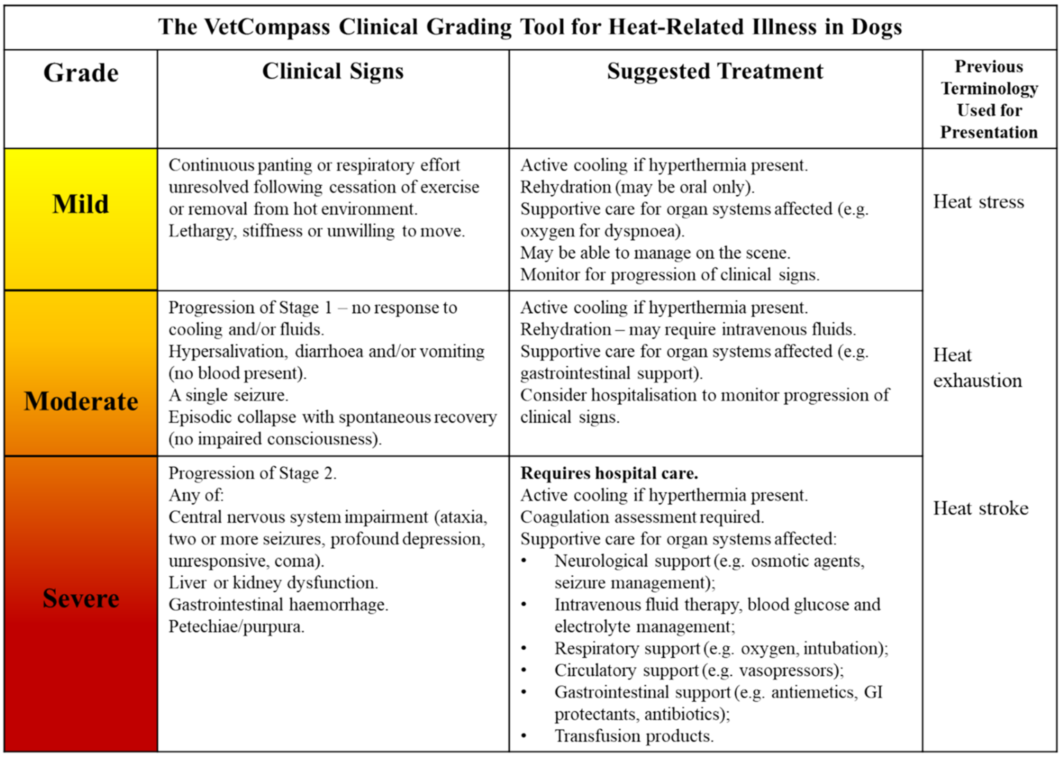
The utility of temperature thresholds was explored within the VetCompass HRI Grading Tool. The inclusion of temperature threshold ≥ 43 °C as a severe grade criterion within the VetCompass HRI Grading Tool would have changed the grading of three events: one originally graded mild would have changed to severe and two events originally graded moderate would have changed to severe. None of these events resulted in fatality, and only one of the three events resulted in hospitalisation beyond one day. This suggests limited additional value from adding a temperature threshold ≥ 43 °C as a severe grade criterion to the grading tool.

The inclusion of temperature threshold ≥ 41 °C as a severe grade criterion within the VetCompass HRI Grading Tool would have changed the grading of 83 (9.70%) of the 856 events; 40 (12.62%) of the 317 events originally graded mild would have changed to severe, and 43 (11.75%) of the 366 events originally graded moderate would have changed to severe. From the 40 events originally graded mild, there was one fatality, an elderly animal the owners elected to euthanise. From the 43 dogs originally graded moderate, there were four fatalities—three of which were unassisted deaths. Of these four dogs, one elderly dog was euthanised due to underlying laryngeal paralysis, one of the unassisted deaths was a dog that had experienced multiple HRI events that year and died under sedation, the remaining two dogs were brachycephalic one of which experienced a cardiac arrest and the other died following a tracheostomy. There were an additional 17 events that resulted in hospitalisation beyond one day, however all these events were discharged after one overnight stay.

This review suggests that the application of temperature thresholds add little additional value to the grading tool and therefore body temperature was omitted from the final VetCompass HRI Grading Tool definitions, in line with similar recommendations from Yamamoto et al.[14] for human HRI patients.

The distribution of HRI event severity using the novel VetCompass grading tool.

The distribution of HRI events using the VetCompass HRI Grading Tool is shown in Fig. 2. Overall, 39.92% of classified



The VetCompass Clinical Grading Tool for Heat-Related Illness in Dogs

Grade	Clinical Signs	Suggested Treatment	Previous Terminology Used for Presentation
Mild	Continuous panting or respiratory effort unresolved following cessation of exercise or removal from hot environment. Lethargy, stiffness or unwilling to move.	Active cooling if hyperthermia present. Rehydration (may be oral only). Supportive care for organ systems affected (e.g. oxygen for dyspnoea). May be able to manage on the scene. Monitor for progression of clinical signs.	Heat stress
Moderate	Progression of Stage 1 – no response to cooling and/or fluids. Hypersalivation, diarrhoea and/or vomiting (no blood present). A single seizure. Episodic collapse with spontaneous recovery (no impaired consciousness).	Active cooling if hyperthermia present. Rehydration – may require intravenous fluids. Supportive care for organ systems affected (e.g. gastrointestinal support). Consider hospitalisation to monitor progression of clinical signs.	Heat exhaustion
Severe	Progression of Stage 2. Any of: Central nervous system impairment (ataxia, two or more seizures, profound depression, unresponsive, coma). Liver or kidney dysfunction. Gastrointestinal haemorrhage. Petechiae/purpura.	**Requires hospital care.** Active cooling if hyperthermia present. Coagulation assessment required. Supportive care for organ systems affected: • Neurological support (e.g. osmotic agents, seizure management); • Intravenous fluid therapy, blood glucose and electrolyte management; • Respiratory support (e.g. oxygen, intubation); • Circulatory support (e.g. vasopressors); • Gastrointestinal support (e.g. antiemetics, GI protectants, antibiotics); • Transfusion products.	Heat stroke

Figure 3. The novel VetCompass clinical grading tool for heat-related illness in dogs.

HRI events were graded mild, 46.10% graded moderate and 13.98% graded severe. In comparison, the distribution of human HRI events presenting to 102 Japanese hospitals during the summer of 2012 classified by the JAAMHC in one paper was 48.86% stage I, 33.24% stage II and 17.90% stage III[15]. The distribution of canine HRI events between the grades of the VetCompass HRI Grading Tool closely reflected the distribution in human HRI patients reported by Yamamoto et al.[15].

Comparing the fatality rate distribution of canine versus human HRI events.

The fatality rate (death overall) for canine HRI events classified using the novel VetCompass HRI Grading Tool was 2.21% for mild events, 5.46% for moderate events and 56.76% for severe events. The unassisted death fatality rate increased from 0.32% in mild events, to 2.19% in moderate events, and 23.42% in severe events.

These fatality rates compare to the findings of a human study using the JAAMHC classification for human HRI events: stage I patients all survived, the fatality rate for stage II patients was 0.7%, increasing to 10.2% for stage III patients[15].

The final VetCompass HRI grading tool.

The final VetCompass Clinical Grading Tool for HRI in dogs (Fig. 3) incorporated clinical signs but excluded presenting body temperature as a defining criteria. Although a presenting body temperature ≥ 41 °C and ≥ 43 °C were both associated with a significantly increased relative risk of death compared to dogs presenting with lower body temperature, it is the duration of temperature elevation that results in clinical pathology, so a single temperature reading alone is poorly diagnostic of severe illness unless that temperature is above 45 °C[13]. Clinical management should aim to prevent worsening of the patient's condition through early temperature management, fluid therapy and supportive management of body systems affected[29,30].

Ethics approval.

Ethics approval was granted by the RVC Ethics and Welfare Committee (reference number SR2018-1652). This project used only data from a research repository, no actual dogs were involved in the project.

Discussion

This study reports that the most commonly recorded clinical signs in UK dogs with HRI presenting to primary-care veterinary practices were respiratory changes (excessive panting/dyspnoea) and lethargy. This is a key finding to assist dog owners, as early recognition of these milder clinical signs could allow them to take earlier action to prevent worsening of their pet's condition and prevent progression of the HRI. We also report that the clinical signs associated with the highest relative risk of death (both overall and unassisted) were abnormal mentation including unresponsive, coma, stupor and multiple seizures (including status epilepticus). The results from relative risk analysis were applied as an evidence base to support an adaptation of the JAAMHC classification for human HRI events to create the novel VetCompass Clinical Grading Tool for HRI in dogs.

Previous veterinary studies of HRI in dogs have tended to focus on the most severe subset of cases, using the Classical Heat Stroke Criteria heat stroke definition to determine case inclusion criteria[11,18,31]. These studies were generally restricted to dogs referred for specialist care, and so are poorly representative of the overall canine population. For this reason, we elected to compare the distribution of canine HRI events in the current study to the distribution of human HRI events reported in a study from Japan[15] rather than to previously reported studies in dogs. The progressive nature of HRI should theoretically result in the majority of HRI events being classed as stage I, with fewer events classed as stage II, and the minority of events progressing to stage III, especially as public awareness of HRI has increased the likelihood of early interventions such as cooling and removal from hot environments[32]. More canine HRI events were classified as moderate than mild compared to the human results, which may represent a variety of owner-related factors. Increased public awareness of HRI through national campaigns may have resulted in more owners managing milder cases at home rather than seeking active veterinary care. The impacts from financial costs of veterinary consultation may also play a role here: owners may preferentially present more severe cases for veterinary care because they perceive the clinical risk justifies the financial outlay whereas they may choose to monitor and manage milder cases on their own. This could drive a relative underreporting of milder HRI in UK dogs. It is also possible that some owners either did not recognise mild HRI events, or as suggested by Packer et al.[33], brachycephalic owners may in fact perceive mild HRI as "normal for their breed of dog".

The clinical signs included in the Grading Tool for severe HRI reflect the pathological findings reported in a study of 11 dogs that died (ten unassisted deaths and one euthanasia) as a result of HRI in one referral hospital[28], namely evidence of a coagulopathy, gastro-intestinal mucosal necrosis, renal damage, hepatopathy and brain damage. The presence of petechiae/purpura suggests a coagulopathy had developed, a consequence of endothelial damage from both thermal injury to cells and also secondary hypoperfusion, shock and systemic inflammatory response[1,28]. Disseminated intravascular coagulopathy (DIC) is a life threatening syndrome that occurs when widespread activation of the coagulation system is triggered alongside dysregulation of thrombin generation (e.g. a hypercoagulable to a hypocoagulable state)[34]. Heat-related illness can trigger DIC, as reported by Bruchim et al. where all of the dogs examined post mortem were found to have developed DIC as a result of their HRI[28]. A mortality rate of 62.5% has been reported for dogs with overt DIC (three or more coagulation variable abnormalities detected during clinical screening) triggered by a variety of inciting disorders including HRI[35]. It is therefore appropriate that the clinical signs of petechiae/purpura were included in the criteria for severe HRI in dogs, as it is for humans[14].

Histopathological examination of the brains and meninges of dogs that died as a result of HRI revealed mild to severe oedema and hyperaemia in all sections examined from all dogs in the previous study[28]. In another study of dogs presenting to a referral hospital with HRI, cases presenting with profoundly altered mentation (obtunded or comatose) had a fatality rate of 70%, and the dogs that presented with disorientation or stupor had a fatality rate of 41%[11]. In the present study, all clinical signs indicative of altered mentation had a significantly increased relative risk of both death overall and unassisted death, and are therefore included in the severe HRI criteria in the current grading tool.

Altered respiration was the most frequently recorded clinical sign for all dogs with HRI in the present study. Pulmonary oedema and hyperaemia were noted in all the deceased dogs examined at post mortem by Bruchim et al.[28], and tachypnoea was reported in around 80% of the dogs presented to the same referral hospital with heat stroke[11]. However, altered respiration including panting heavily or respiratory distress, was not associated with an increased relative risk of death or unassisted death in the present study. As panting is a key thermoregulatory mechanism in dogs for cooling, this clinical sign will be present in all conscious dogs with hyperthermia at some point during a HRI event and is therefore included in the criteria for mild HRI in the grading tool. Comatose dogs cease panting, which likely contributes to their reduced rate of cooling when immersed in cold water[36], and potentially contributes to the increased fatality rate in dogs that developed impaired mentation as a result of HRI.

The findings of the present study support the recommendations of recent human HRI studies[14,15] that body temperature should no longer be considered a reliable diagnostic criterion for staging HRI in dogs. Body temperature can fluctuate rapidly, especially when active cooling methods have been applied prior to clinical assessment[37]. There are also conflicting results on the associations between body temperatures per se and pathological changes in dogs. In a study of anaesthetised dogs, prolonged (90 min) whole body hyperthermia at 42.5 °C failed to induce histopathological or clinically significant neurological disturbance, when other physiological responses to hyperthermia (for example respiratory alkalosis or reduced blood pressure) were prevented[38]. Post exercise body temperatures of 42.5 °C have also been reported in dogs showing no clinical signs of HRI[39,40]. Experimental heat stroke studies carried out on dogs in the 1970s suggested that 43 °C is the critical temperature threshold for canine HRI[13]. In a series of inhumane experiments that involved exposing dogs to ambient temperatures of 50 °C both with and without physical exertion until they collapsed, a body temperature of 43 °C was reported as the critical limit for clinical effects. Dogs that did not exceed a body temperature of 43 °C had no clinical or clinicopathological signs of HRI, whilst dogs that developed a body temperature > 44 °C all died of heat stroke. The longer a dog had a body temperature > 43 °C, the greater the likelihood of death. The previously proposed critical body temperature threshold of > 41 °C for diagnosis of HRI can therefore no longer be considered appropriate. Any dog with a temperature approaching 41 °C should be actively cooled as a matter of urgency, but clinical signs should be used to then determine the severity of HRI present.

Hypothermia on presentation has previously been reported as being associated with an increased fatality rate[18]. However, Drobatz and Macintire[18] clarified that it was not possible to determine if hypothermia due to cooling contributed to the poor outcome, or if hypothermia was instead an effect of poor tissue perfusion caused by profound clinical disease. In the present study, hypothermia on presentation was not associated with an increased risk of death overall or unassisted death, reflecting the findings of Bruchim et al.[11]. Many veterinary texts caution against aggressive, rapid cooling of dogs with HRI due to a perceived hazard of hypothermia[41–43]. However, from the current study, it appears hypothermia does not increase the fatality risk for dogs. In humans with exertional HRI, cold water immersion is the gold standard treatment[44]. Rapid (within minutes of collapse) initiation of cooling using cold (10 °C) water immersion until the patient's body temperature dropped below 38.8 °C was associated with 100% survival rate in one study of over 200 HRI events[37]. In dogs, work to date has included the use of warm water (30 °C) immersion to effectively cool dogs with exertional hyperthermia but not HRI[45], and dogs with experimentally induced HRI cooled with a range of water temperatures[36]. The latter study reported that tap water (15–16 °C) achieved the fastest rate of cooling in conscious dogs with HRI, but found that comatose dogs cooled at a slower rate due to the cessation of panting[36]. As drowning is a risk to any HRI patient undergoing water immersion, especially patients with central nervous system impairment, constant monitoring is needed to ensure the head remains above the water level[29,44].

A novel severity scoring system has been proposed previously for dogs with HRI by Segev et al.[46]. However, that scoring system required comprehensive laboratory analysis including prothrombin and activated partial thromboplastin time, blood glucose, biochemistry, and haematology analysis, and required the use of a statistical model to determine the overall patient score. This reliance on laboratory tests requires the dog to be physically presented to the veterinary practice in order to take the samples, and the owners to be both willing and able to pay for the tests before the score can be determined. As noted in that study's limitations, the scoring system proposed by Segev et al. is aimed at assisting decision making for only the most severe of cases, and requires further testing before it can be deemed a reliable model[46].

In contrast, the novel VetCompass HRI Grading Tool proposed in the present study aimed to create a grading system that could be used by veterinary professionals to triage patients over the telephone or when presenting to the veterinary practice, and that can be used without the need for complex statistical modelling, potentially expensive laboratory testing or indeed any mathematical calculations. The tool could be displayed as a poster (see Fig. 3) in veterinary receptions, and be added to the emergency or treatment room as a quick reference guide to assist veterinary staff with decision making and provide advice to owners regarding a potential prognosis for dogs with HRI. It could be adapted as an educational tool to improve public awareness of the early signs of HRI in dogs, to be shared on social media to get to the attention of owners who are the key decision-makers in the early phases of most dogs with HRI. Delayed cooling has been associated with an increased fatality rate in dogs presenting to a referral hospital with HRI[11], thus improving owners' ability to recognise and promptly respond to signs of HRI in dogs should be considered a priority as global temperatures continue to rise.

This study had some limitations. As noted in previous studies, VetCompass clinical record data are not recorded for research purposes[3,20]. As a result, there are missing data within the dataset and descriptive data may be inaccurate or incomplete, because they are reliant upon the history recorded by the attending veterinary surgeon and so can be impacted by factors such as stress and workload, especially when recording clinical notes from emergency patient presentations. For events with an unassisted death, progressive changes in clinical signs may not have been accurately recorded within the electronic clinical history but may instead have been recorded on alternative documentation such as paper-based hospital records or cardiac arrest monitoring charts. Likewise, HRI cases that were euthanised may have limited clinical histories and clinical signs recorded if the owner requested euthanasia early during presentation. Some cases may also have been euthanised before additional clinical signs developed if there were financial constraints on treatment options, or if the dog was elderly or had other underlying health conditions that contributed to the decision to euthanise.

Future evaluation may help to refine the VetCompass HRI Grading Tool further by exploring the tool's predictive ability for other HRI factors such prolonged hospitalisation and dog conformations.

Conclusion

This study presents the novel VetCompass Clinical Grading Tool developed for dogs with heat-related illness, and aims to improve both owner and veterinary recognition of the progressive clinical signs associated with the disorder. Continued use of the previously available Classical Heat Stroke Criteria should be done with caution because those criteria were not designed for use with canine patients. There is a risk of underestimating the severity of the dog's condition due to a reliance on patient reported symptoms and presenting body temperature rather than observed clinical signs. Continued use of body temperature as a diagnostic criterion cannot be supported, in line with recent human medical advances. The VetCompass HRI Grading Tool offers a quick, practical and evidence-based tool for veterinary professionals to grade HRI cases and should assist in optimising clinical care and the clinical outcomes. As global temperatures continue to rise, uncomplicated triage tools such as the one proposed in this study can help to improve owner understanding and assist in decision making for effective early management when HRI occurs.

Data availability

Original data used for the current study is available: https://researchonline.rvc.ac.uk/id/eprint/13572/.

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Author contributions

E.J.H. was responsible for the conception and design of the study, E.J.H., A.J.C. and D.G.O. were responsible for acquisition and extraction of data. E.J.H. carried out the analysis and drafted the manuscript. E.J.H., A.J.C., J.B., D.B., and D.G.O were involved in interpreting the results, revising the manuscript and gave final approval of the version to be published. E.J.H., A.J.C., J.B., D.B., and D.G.O. agree to be accountable for all aspects of the accuracy or integrity of the work.

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Competing interests

The authors declare no competing interests.

Additional information

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