

Clinicopathological and prognostic significance of RECQL5 helicase expression in breast cancers

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ABSTRACT

RECQL5 is a member of the RecQ family of DNA helicases and has key roles in homologous recombination, base excision repair, replication and transcription. The clinicopathological significance of RECQL5 expression in breast cancer is unknown. In the current study we have evaluated *RECQL5* mRNA expression in 1977 breast cancers, and RECQL5 protein level in 1902 breast cancers [Nottingham Tenovus series (n=1650) and ER- cohort (n=252)]. Expression levels were correlated to aggressive phenotypes and survival outcomes. High *RECQL5* mRNA expression was significantly associated with high histological grade (p=0.007), HER2 overexpression (p=0.032), ER+/HER2-/high proliferation gene signature subtype, integrative molecular clusters (intClust 1 and 9) and poor breast cancer specific survival (BCSS) (ps<0.0001). In sub-group analysis, high *RECQL5* mRNA level remains significantly associated with poor BCSS in ER+ cohort (p<0.0001) but not in ER- cohort (p=0.116). At the protein level, in tumours with low RAD51, high RECQL5 level was significantly associated with high histological grade (p<0.0001), higher mitotic index (p=0.008), de-differentiation (p=0.025), pleomorphism (p=0.027) and poor BCSS (P=0.003). In sub-group analysis, high RECQL5/low RAD51 remains significantly associated with poor BCSS in ER+ cohort (p=0.010), but not in ER- cohort (p=0.628). In multivariate analysis, high *RECQL5* mRNA and high RECQL5/low RAD51 nuclear protein co-expression independently influenced BCSS (p=0.022) in whole cohort and in the ER+ sub-group. Pre-clinically, we show that exogenous expression of RECQL5 in MCF10A cells can drive proliferation supporting an oncogenic function for RECQL5 in breast cancer. We conclude that RECQL5 is a promising biomarker in breast cancer.

Summary: RECQL5 is a member of the RecQ family of DNA helicases and has key roles in homologous recombination, base excision repair, replication and transcription. We provide

the first clinical evidence that RECQL5 overexpression is associated with aggressive breast cancers.

Key words: RECQL5; breast cancer; biomarker; prognosis; ER positive breast cancer

INTRODUCTION

RecQ helicases are a highly conserved family of proteins with critical roles in the maintenance of genomic stability (1-4). RECQL5 is a key member of the mammalian RecQ helicase family (1). It is a 3'-5' helicase with weak Holiday junction unwinding activity (1). RECQL5 preferentially unwinds the lagging strand of DNA at replication fork structures and can promote strand exchange *in vitro* (5). Three isoforms of RECQL5 have been identified; RECQL5 α (410aa), RECQL5 β (435aa) and RECQL5 γ (991aa) (6). Whereas RECQL5 α and RECQL5 γ are cytoplasmic, RECQL5 β isoform has nuclear localisation (6). RECQL5 β (here in referred to as RECQL5) interacts with multiple DNA repair and metabolising proteins including RAD51, RAD50, PARP1, FEN1, RNA Polymerase II, WRN, BLM and Mre11, NBS1, PCNA, TopIIa and Top IIIa/b (1). RECQL5 has important roles in homologous recombination (HR), base excision repair (BER), DNA replication and transcription (1). Evidence for a role in HR includes findings that RECQL5 deficient cells have an increased rate of sister chromatid exchange (7), and that depleted cells accumulate γ H2Ax and RAD51 foci (8). Mechanistically RECQL5's function in HR can be proposed from *in vitro* studies showing that RECQL5 physically interacts with RAD51, causing an ATPase dependent disruption of RAD51 mediated presynaptic filament formation and hence has anti-recombinase activity (9) similar to Bloom syndrome helicase (BLM) (7). Further RECQL5 associates with the MRN complex and inhibits MRE11 exonuclease activity (10), which may also contribute to the HR function of RECQL5. Interestingly while the MRN complex is required to bring RECQL5 to sites of DSBs it's recruitment is independent of the helicase activity (11). RECQL5 may also have a role in base excision repair (BER). It's precise function in this pathway is not clear but RECQL5 interacts with the long patch BER proteins PCNA and FEN1, it's interaction stimulating FEN1 activity, and RECQL5 co-localises with FEN1 after oxidative damage of DNA (12). In addition the short patch BER protein XRCC1 is retained at sites of oxidative

damage in the absence of RECQL5 and expression of PARP1 and XRCC1 maybe regulated by RECQL5 (13). A role in protecting cells from DNA replication stress has also been shown for RECQL5. RECQL5 foci increase following replication stress and overexpressing RECQL5 can overcome thymidine induced replication stress (14). Likewise RECQL5 can prevent spontaneous replication fork collapse and RECQL5 depleted cells are hypersensitive the DNA replication inhibitor camptothecin, (15, 16). RECQL5 has also been implicated in regulation of transcription elongation and can suppress genomic instability associated with transcriptional stress (2, 17, 18).

Germline mutation of three of the RecQ helicases (BLM, WRN and RECQL4) leads to cancer predisposition syndromes namely Bloom syndrome, Werner syndrome and Rothmund-Thomson syndrome (3, 4). Although RECQL5 helicase has not been associated with any disease phenotype, in preclinical studies, RECQL5 deficient mice cells show increased levels of spontaneous double strand breaks, are susceptible to gross chromosomal rearrangements and are prone to develop lymphomas and various solid tumours including breast cancer (8) (19).

We hypothesised that RECQL5 may influence breast cancer pathogenesis. In the current study we have evaluated *RECQL5* mRNA expression in 1950 breast cancers, and RECQL5 protein level in 1902 breast cancers. We provide the first clinical evidence that RECQL5 may influence the development of aggressive breast cancer and have prognostic significance particularly in ER+ breast cancers. In addition we show that exogenous expression of RECQL5 in MCF10A cells can drive proliferation supporting a oncogenic function for RECQL5 in breast cancer.

MATERIALS AND METHODS

RECQL5 and mRNA expression: *RECQL5* mRNA expression was investigated in METABRIC (Molecular Taxonomy of Breast Cancer International Consortium) cohort. The METABRIC study protocol, detailing the molecular profiling methodology in a cohort of 1980 breast cancer samples is described by Curtis et al (20). Patient demographics are summarized in **supplementary Table S1** of supporting information. ER positive and/or lymph node negative patients did not receive adjuvant chemotherapy. ER negative and/or lymphnode positive patients received adjuvant chemotherapy. For this cohort, the mRNA expression was hybridized to Illumina HT-12 v3 platform (Bead Arrays), and the data were pre-processed and normalized as described previously (20). *RECQL5* expression was evaluated in this data set (*RECQL5* probe ID: ILMN_1697682). The probe was a perfect match and quality for its target, having a GC content of 58% , 0 SNPs and it does not possess a polyG tail at the end. Samples were classified into the intrinsic subtypes based on the PAM50 gene list. A description of the normalization, segmentation, and statistical analyses was previously described (20). Real time RT-qPCR was performed on the ABI Prism 7900HT sequence detection system (Applied Biosystems) using SYBR1 Green reporter. All the samples were analysed as triplicates. The Chi-square test was used for testing association between categorical variables, and a multivariate Cox model was fitted to the data using as endpoint breast cancer specific death. Xtile (Version 3.6.1) was used to identify a cut-off in gene expression values such that the resulting subgroups have significantly different survival courses. In addition, a corrected P-value was produced for each analysis by using Monte-Carlo Cross Validation (MCCV) simulations (50 random populations) in X-tile to avoid the problem of over fitting and finding aberrantly low p-value due to the analysis of multiple cut-points (Camp et al,2004) . The two- fold cross validation was used to randomly split the data in to two halves and find the optimal cut-point of

one half, and then divide the other half according to this cut-point. Then, the optimal cut-point of the second half was found and the first half was similarly divided. Finally, a survival analysis of the entire dataset was performed based on the average of the optimal cut-points obtained from the MCCV simulations (Camp et al., 2004).

RECQL5 protein expression in breast cancer: The study was performed in a consecutive series of 1650 patients with primary invasive breast carcinomas who were diagnosed between 1986 and 1999 and entered into the Nottingham Tenovus Primary Breast Carcinoma series. Patient demographics are summarised in **Supplementary Table S2**. This is a well-characterized series of patients with long-term follow-up that have been investigated in a wide range of biomarker studies (21-24). All patients were treated in a uniform way in a single institution with standard surgery (mastectomy or wide local excision), followed by Radiotherapy. Prior to 1989, patients did not receive systemic adjuvant treatment (AT). After 1989, AT was scheduled based on prognostic and predictive factor status, including Nottingham Prognostic Index (NPI), oestrogen receptor- α (ER- α) status, and menopausal status. Patients with NPI scores of <3.4 (low risk) did not receive AT. In pre-menopausal patients with NPI scores of ≥ 3.4 (high risk), classical Cyclophosphamide, Methotrexate, and 5-Fluorouracil (CMF) chemotherapy was given; patients with ER- α positive tumours were also offered endocrine therapy. Postmenopausal patients with NPI scores of ≥ 3.4 and ER- α positivity were offered endocrine therapy, while ER- α negative patients received classical CMF chemotherapy. Median follow up was 111 months (range 1 to 233 months). Survival data, including overall survival, disease-free survival (DFS), and development of loco-regional and distant metastases (DM), was maintained on a prospective basis. DFS was defined as the number of months from diagnosis to the occurrence of local recurrence, local lymph node (LN) relapse or DM relapse. Breast cancer specific survival (BCSS) was defined as the number of months from diagnosis to the occurrence of BC related-death. Local recurrence free survival

(LRS) was defined as the number of months from diagnosis to the occurrence of local recurrence. DM-free survival was defined as the number of months from diagnosis to the occurrence of DM relapse. Survival was censored if the patient was still alive at the time of analysis, lost to follow-up, or died from other causes.

We also evaluated an independent series of 252 ER- α negative invasive BCs diagnosed and managed at the Nottingham University Hospitals between 1999 and 2007. All patients were primarily treated with surgery, followed by Radiotherapy and anthracycline chemotherapy. The characteristics of this cohort are summarised in **supplementary Table S3**.

Tumor Marker Prognostic Studies (REMARK) criteria, recommended by McShane et al (25), were followed throughout this study. Ethical approval was obtained from the Nottingham Research Ethics Committee (C202313).

Tissue Microarrays (TMAs) and immunohistochemistry (IHC): Tumours were arrayed in tissue microarrays (TMAs) constructed with 2 replicate 0.6mm cores from the centre and periphery of the tumours. The TMAs were immunohistochemically profiled for RECQL5 and other biological antibodies (**Supplementary Table S4** of supporting information) as previously described (21-24). Immunohistochemical staining was performed using the Thermo Scientific Shandon Sequenza chamber system (REF: 72110017), in combination with the Novolink Max Polymer Detection System (RE7280-K: 1250 tests), and the Leica Bond Primary Antibody Diluent (AR9352), each used according to the manufacturer's instructions (Leica Microsystems). Leica Autostainer XL machine was used to dewax and rehydrate the slides. Pre-treatment antigen retrieval was performed on the TMA sections using sodium citrate buffer (pH 6.0) and heated for 20 minutes at 95⁰C in a microwave (Whirlpool JT359 Jet Chef 1000W). A set of slides were incubated for 60 minutes with the primary anti-RECQL5 antibody (HPA029971, Sigma-Aldrich, UK) and anti-RAD51 antibody (clone Ab88572, Abcam Ltd.,

Cambridge, UK), at a dilution of 1:100 and 1:70 respectively. Negative and positive (by omission of the primary antibody and IgG-matched serum) controls were included in each run. The negative control ensured that all the staining was produced from the specific interaction between antibody and antigen.

Evaluation of immune staining: The tumour cores were evaluated by two scorers (AA and TAF) and the concordance between the two scorers was excellent ($k = 0.79$). Whole field inspection of the core was scored and intensities of nuclear staining were grouped as follows: 0 = no staining, 1 = weak staining, 2 = moderate staining, 3 = strong staining. The percentage of each category was estimated (0-100%). H-score (range 0-300) was calculated by multiplying intensity of staining and percentage staining. RECQL5, RAD51 and TOPO2A expression was categorised based on the frequency histogram distributions. A median H score of ≥ 10 was taken as the cut-off for high RECQL5 and a median H score of ≥ 8 was taken as the cut-off for high RAD51 nuclear expression. For TOPO2A $>25\%$ staining cells were taken as high TOPO2A expression. Not all cores within the TMA were suitable for IHC analysis as some cores were missing or lacked tumour ($<15\%$ tumour).

Statistical analysis: Data analysis was performed using SPSS (SPSS, version 17 Chicago, IL). Where appropriate, Pearson's Chi-square, Fisher's exact, Student's t and ANOVA one way tests were used. Cumulative survival probabilities were estimated using the Kaplan–Meier method, and differences between survival rates were tested for significance using the log-rank test. Multivariate analysis for survival was performed using the Cox proportional hazard model. The proportional hazards assumption was tested using standard log-log plots. Hazard ratios (HR) and 95% confidence intervals (95% CI) were estimated for each variable. All tests were two-sided with a 95% CI and a p value <0.05 considered significant. For multiple comparisons, p values were adjusted according to Holm-Bonferroni correction method (26).

Breast cancer cell lines and culture: MCF-7 (ER+/PR+/HER2-, BRCA1 proficient), MDA-MB-231 (ER-/PR-/HER2-, BRCA1 proficient), MDA-MB-468 (ER-/PR-/HER2-, BRCA1 proficient) and MDA-MB-436 (ER-/PR-/HER2-, BRCA1 deficient) authenticated cell lines were purchased from ATCC and were grown in RPMI (MCF-7, MDA-MB-231) or DMEM (MDA-MB-468 and MDA-MB-436) medium with the addition of 10% foetal bovine serum and 1% penicillin/streptomycin. Cell lysates were prepared and Western blot analysis performed. Primary anti-RECQL5 antibody (HPA029971, Sigma-Aldrich, UK) was incubated over night at room temperature at a dilution of 1:2000. Primary anti- β actin antibody (1:10000 dilution [Abcam]) was used as a loading control. Infrared dye-labelled secondary antibodies (Li-Cor) [IRDye 800CW Mouse Anti-Rabbit IgG and IRDye 680CW Rabbit Anti-Mouse IgG] were incubated at a dilution of 1:10000 for 1 hour. Membranes were scanned with a Li-Cor Odyssey machine (700 and 800nm) to determine protein expression.

RECQL5 knockdown breast cancer cells using siRNAs: MCF7 cells were transfected with 50 nM RECQL5 siRNA (Dharmacon, Lafayette, CO) using *DharmaFECT* 1 reagent (Dharmacon, Lafayette, CO) and left for 48 hours. The cell lysates were prepared and western blotted for RECQL5 as above but immunoreactive protein was visualized using ECL reagents (Amersham Pharmacia) following manufacturer's instructions. The sequences used for Q5 β -1 and Q5 β -3 siRNA constructs were 5'-UGAAGAAGGUGGCCGAUUAU-3' and 5'-CUGCAA AUGUUGUGGUCAA-3' respectively.

RECQL5 overexpression in MCF10A cells and proliferation assay: 10,000 MCF10A cells were plated into replica wells of 6 well plate and transfected with pcDNA-RECQL5 β (a generous gift from Dr. Pavel Janscak - Institute of Molecular Cancer Research, University of Zurich) or empty vector control. Following trypsinisation to remove cells from the plate live

cells counted every 24 h post transfection using trypan blue exclusion. In parallel cell lysates were prepared and western blotted for RECQL5 as above but immunoreactive protein was visualized using ECL reagents (Amersham Pharmacia) following manufacturer's instructions.

Quantitative real time PCR: Total RNA was extracted from MCF-7, MDA-MB-231, MDA-MB-468 and MDA-MB-436 cells using RNeasy Mini kit (QIAGEN, UK). The quantification of the extracted RNA was done using a NanoDrop 2000c Spectrophotometer (Thermo Scientific, UK). The cDNA was synthesized from 0.5 µg of total RNA using RT² first strand kit (QIAGEN, UK). qPCR was performed using SYBR Green PCR Master mix (applied biosystems, Warrington, UK) with primer set (RECQL5 QuantiTect Prier Assay, Cat. No. QT00084973, QIAGEN) targeting RECQL5 gene. The glyceraldehyde-3-phosphate dehydrogenase housekeeper gene was used as an internal control (GAPDH QuantiTect Prier Assay, Cat. No. QT00079247, QIAGEN). The real-time PCR for each RNA sample was performed in triplicate. NTC (No Template Control) was used to rule out cross contamination of reagents and surfaces. NTC included all the RT-PCR reagents except the RNA template. Minus reverse transcriptase (- RT) control was used to rule out genomic DNA contamination.

RESULTS

High *RECQL5* mRNA levels associate with aggressive sporadic breast cancer: We initially profiled a panel of breast cancer cell lines. MDA-MB-436, MDA-MB-468 MCF-7 and MDA-MB 231 have robust expression of *RECQL5* mRNA (**Figure 1A**). We then proceeded to investigate *RECQL5* mRNA expression in the METABRIC cohort. 1306/1977 (6%) of breast tumours had low *RECQL5* mRNA expression and 34% (671/1977) of breast tumours had high *RECQL5* mRNA expression. High *RECQL5* mRNA expression was significantly associated with aggressive clinicopathological features including high histological grade, HER2 over expression, and triple negative phenotypes ($p < 0.05$) [**Table 1**]. High *RECQL4* mRNA expression was also found to be significantly correlated to previously described breast cancer molecular phenotypes; PAM50.Her2 ($p < 0.0001$) and Genufu subtype (ER+/Her2-/High proliferation) ($p < 0.01$) breast tumours [**Table 1**]. On the other hand, PAM50.LumA and Genufu subtypes (ER+/Her2-/low proliferation) were associated with low levels of *RECQL5* mRNA ($p < 0.05$) [**Table 1**]. Interestingly, PAM50.Basal was also more common in tumours with low levels of *RECQL5* mRNA ($p < 0.05$). Similarly, low *RECQL5* mRNA expression was associated with intClust.3 ($p < 0.00001$) and intClust.4 ($p < 0.001$) molecular phenotypes that have good prognosis (27). However, high *RECQL5* mRNA expression was significantly associated with intClust.1 ($p < 0.00001$), and intClust.9 ($p < 0.00001$) that have intermediate to poor clinical outcome (20).

We then proceeded to survival analysis in METABRIC cohort. High *RECQL5* mRNA expression was associated with poor breast cancer specific survival (BCSS) ($p < 0.0001$) in the whole cohort [**Figure 1B**]. In the ER+ sub-group, high *RECQL5* mRNA expression was found to be associated with poor BCSS ($p < 0.0001$) [**Figure 1C**]. In the ER+ sub-group that received

adjuvant endocrine therapy, high *RECQL5* mRNA expression remained associated with poor BCSS ($p < 0.001$) [Figure 1D]. However, in ER- sub-group, *RECQL5* mRNA expression did not significantly influence outcome in the ER- cohort, including ER- patients who received chemotherapy ($p = 0.116$ and $p = 0.213$ respectively) [Figure 1E, 1F].

In the multivariate Cox regression analysis, that included other validated prognostic factors, *RECQL5* mRNA expression was a powerful independent predictor for breast cancer specific survival in the whole cohort ($p = 0.038$), ER+ sub-group ($p = 0.046$) but not in the ER- sub-group ($p = 0.615$) (Table 2).

Together the data provides evidence that *RECQL5* mRNA level has clinicopathological significance and influence prognosis, particularly in ER+ breast cancers. We proceeded to evaluate *RECQL5* protein expression in breast cancers.

RECQL5 protein expression in sporadic breast cancer: We initially investigated *RECQL5* protein level in breast cancer cell lines and in MCF10A breast epithelial cells. As shown in Figure 2A, MDA-MB-436, MDA-MB-468 MCF-7 and MDA-MB 231 have robust expression of *RECQL5* protein. On the other hand, in MCF10A cells, *RECQL5* expression was low compared to MCF7 cells (Figure 2B). When *RECQL5* was overexpressed in MCF10A (Figure 2B) we observed increased proliferation in *RECQL5* overexpressing MCF10A cells compared to control MCF10A cells (Figure 2C). Taken together, the data suggest that *RECQL5* is a marker of proliferation and could have prognostic and/or predictive significance in human breast cancers. We proceeded to IHC investigation in human tumours. To provide evidence for the specificity of the anti-*RECQL5* antibody used for IHC studies, we generated *RECQL5* knockdown (KD) MCF7 cells using two siRNA constructs. As shown in Figure 2D, control

cells have robust RECQL5 expression seen as a single band while RECQL5 KD cells show almost complete loss of this band – demonstrating the specificity of the RECQL5 antibody.

We observed nuclear only localization of RECQL5 protein in breast cancers [**Figure 2D**]. There was no cytoplasmic staining in breast tumours. We initially investigated RECQL5 protein alone. 46.3% (556/1200) of tumours showed low nuclear RECQL5 expression and 53.7% (644/1200) of tumours revealed high nuclear RECQL5 expression. Tumours with low nuclear RECQL5 levels were significantly associated with high grade, high mitotic index, tubule formation, tumour type, HER2 overexpression, ER-, triple negative and basal type phenotype ($p < 0.05$) [**Supplementary Table 5**]. In addition, low RECQL5 expression was found to be associated with low levels of other DNA repair proteins such as BRCA1, XRCC1, FEN1, SMUG1, APE1, Pol β , ATM, ATR, Chk1, Chk2, TOP2A, Rad51, and DNA-PKc ($p < 0.01$) [**Supplementary Table 5**]. We then conducted the univariate survival analysis. At protein level, RECQL5 expression alone failed to show any statistically significant correlation with breast cancer specific survival in whole cohort [**Supplementary Figure S1A**]. We then proceeded to subgroup analysis and again found no statistically significant association with survival in ER+ [**Supplementary Figure S1B**] and ER- subgroups [**Supplementary Figure S1C**]. As RECQL5 alone, despite having clinicopathological associations with aggressive phenotype, did not have prognostic significance we hypothesised that RECQL5 may operate in the context of RAD51 or TOPO2A to influence clinical outcomes. We therefore proceeded to co-expression analysis.

RECQL5 co-expression with RAD51 or TOPO2A in sporadic breast cancer: RECQL5 physically interacts with RAD51 and disrupts RAD51 mediated presynaptic filament formation (1, 9). Tumours with high RECQL5-low RAD51 nuclear protein levels were significantly

associated with high grade, high mitosis and pleomorphism ($p < 0.05$) [**Table 3**]. Tumours with low RECQL5-low RAD51 nuclear protein levels were significantly associated with tubule formation, NPI >3.4 and ER/PR negativity ($p < 0.5$) [**Table 3**]. In univariate analysis, tumours with high RECQL5-low RAD51 nuclear protein levels were associated with poor breast cancer specific survival in the whole cohort ($p = 0.003$) [**Figure 2E**]. In sub-group analysis, ER+ tumours with high RECQL5-low RAD51 nuclear protein levels were associated with poor breast cancer specific survival ($p = 0.010$) [**Figure 2F**]. In ER- cohort, RECQL5-RAD51 co-expression did not influence survival ($p = 0.628$) [**Supplementary Figure S1D**]. We have previously shown a direct interaction between RECQL5 and Topoisomerase II α (TOP2A) where RECQL5 specifically stimulated the decatenation activity of TOP2A (28). Tumours with low RECQL5-high TOPO2A were significantly associated with high grade, high mitotic index, de-differentiation tumour type, high risk NPI and PR negativity (**Supplementary Table S6**). In univariate analysis, RECQL5-TOPO2A co-expression did not influence survival (**Supplementary Figures S1E, S1F, S1G**)

In multivariate analysis (**Table 4**), RECQL5-RAD51 co-expression remained statistically significant independent marker of prognosis ($p = 0.022$) in the whole cohort. NPI and HER-2 expression were other factors independently associated with breast cancer specific survival ($p = 0.001$ and 0.0001 respectively). In the ER+ sub-group, RECQL5-RAD51 co-expression was of borderline significance ($p = 0.07$), but not in the ER- sub-group ($p = 0.172$).

DISCUSSION

RECQL5 is a key member of the RecQ family of DNA helicases (1-4). RECQL5 is a multifunctional protein with roles in DNA replication, chromosomal segregation, DNA repair (including homologous recombination, single strand break repair and base excision repair) and transcription. Emerging pre-clinical evidence suggests that RECQL5 is a tumour suppressor. RECQL5 deficient mice are predisposed to lymphomas and solid tumours including breast tumours (1-4). In humans, polymorphisms within the *RECQL5* gene may predispose an individual to cancer including: osteosarcomas, laryngeal carcinomas and breast cancers (29-32). In a recent study in colorectal cancers, low RECQL5 expression was observed at the mRNA and protein levels (19). The authors concluded that RECQL5 deficiency may predispose to colorectal cancer. However, the study had several limitations, including a small cohort and lack of clear evidence of clinicopathological associations or survival outcomes (19).

The clinicopathological significance of RECQL5 in sporadic breast cancer is unknown. In the current study we have comprehensively evaluated RECQL5, and unravelled its complex role in breast cancers. At the mRNA level, we observed high expression in 34% of tumours. High *RECQL5* mRNA expression was significantly associated with aggressive phenotypes and adverse survival. The prognostic significance was particularly pronounced in ER+ sub-group, supporting the observation that high *RECQL5* mRNA expression was more likely in ER+/HER2 -/high proliferation Geneufu sub-type tumours. At the protein level, we observed high RECQL5 levels in 53.7% of breast cancers. In contrast to mRNA expression data, although low RECQL5 expression was associated with aggressive phenotype, RECQL5 protein alone did not influence survival outcomes in patients. The data suggest that RECQL5 may be subjected to complex post-transcriptional regulation. Another possibility is that the complex role of RECQL5 may operate in the context of RAD51. RECQL5 directly interacts

with RAD51 (9) and the anti-recombinogenic role of RECQL5 may be active through disruption of RAD51 mediated presynaptic filament formation during HR (33). Therefore, we conducted RECQL5-RAD51 co-expression studies and observed that tumours with high RECQL5/low RAD51 not only manifest aggressive phenotypes but were also associated with poor survival. In sub-group studies, similar to mRNA data, the prognostic significance was more pronounced in ER+ breast cancer but not in ER- tumours. Consistent with high RECQL5 being associated with aggressive phenotypes, over expression of RECQL5 in the normal breast cell line MCF10A increased proliferation. Interestingly RAD51 is reported as having relatively low expression in MCF10A cells (34) and the functional relationship between RECQL5, RAD51, proliferation, recombination and tumourigenesis will be the subject of future investigations. Taken together, the data provides the first clinical evidence that RECQL5 may influence breast cancer pathogenesis.

RECQL5 interacts with and is a general transcription elongation factor for RNA Pol II (2, 17, 18). Loss of RECQL5 leads to a genome-wide increase in the average rate of gene transcription, transcriptional stress and recombination (17) suggesting RECQL5 has a function in resolving such stress. RNA polymerases generate positive supercoiling ahead of the transcription apparatus, which in turn feeds back to reduce the processional rate of RNA polymerase. Topoisomerases are ubiquitous enzymes that remove supercoiling and therefore are required for normal transcription elongation. Specifically, type II topoisomerases generate transient protein-concealed double strand breaks while removing torsional stress from the DNA and collisions with the transcription apparatus can convert these protein-DNA complexes into permanent DNA strand breaks (35). Previously, we showed a direct interaction between RECQL5 and Topoisomerase II α (TOP2A) specifically stimulated the decatenation activity of TOP2A (28). TOP2A expression is a marker for proliferation and has been analyzed in a

number of breast cancer studies in part because it lies in close proximity to the HER2 gene on chromosome 17. Therefore, we were interested in evaluating if there were any expression correlations between RECQL5, which also resides on chromosome 17 (17q25.1), and TOP2A expression in our breast cancer cohorts. Interestingly, high grade tumours are more often scored as RECQL5- and TOP2A+, than any other expression pattern. This may reflect the fact that loss of RECQL5 promotes transcriptional stress. Additionally, while TOP2A is known as a marker for proliferation, loss of RECQL5 may make these cells more dependent on TOP2A to relieve transcriptional stress. Thus in this subgroup of patients, it would be interesting to evaluate the efficacy of topoisomerase targeted therapies, if in fact these tumours are more dependent on topoisomerase activities than other tumour types cells.

In conclusion, our data provides evidence that RECQL5 could be a promising biomarker in breast cancer and needs further investigation as a potential drug target.

Competing financial interests: The authors declare no competing financial interests

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Table 1: Association between *RecQL5* mRNA expression and clinico-pathologic variables in METABRIC cohort.

| VARIABLE | RECQL5 mRNA Expression | | P Values | |
|---------------------------------------|------------------------|-------------|----------------------------|---------------|
| | Low | High | Unadjusted | Adjusted |
| | N(%) | N (%) | | |
| A) Pathological Parameters | | | | |
| <u>Lymph node stage</u> | | | | |
| Negative | 684(52.6%) | 351(52.5%) | 0.990 | 25.74 |
| Positive (1-3) | 207(15.9%) | 107(15.9%) | | |
| Positive (>3) | 409(31.5%) | 213(31.7%) | | |
| <u>Grade</u> | | | | |
| G1 | 129(10.3%) | 40(6.2%) | 0.007 | 0.023 |
| G2 | 512(41.0%) | 258(40.2%) | | |
| G3 | 607(48.6%) | 343(53.5%) | | |
| <u>Tumour Size (cm)</u> | | | | |
| T 1a+b(1.0) | 61(4.7%) | 31(4.7%) | 0.097 | 0.157 |
| T 1c(>1.0-2.0) | 532(41.0%) | 234(35.6%) | | |
| T2 (>2.0-5) | 639(49.2%) | 362(55.0%) | | |
| T3 (>5) | 67(68.4%) | 31(31.6%) | | |
| <u>NPI</u> | | | | |
| ≤ 3.4 | 461(35.3%) | 219(32.6%) | 0.238 | 0.269 |
| >3.4 | 137(64.7%) | 1160(67.4%) | | |
| Her2 overexpression (No) | | | | |
| | 1159(88.7%) | 573(85.4%) | 0.032 | 0.075 |
| (Yes) | 147(11.3%) | 98(14.6%) | | |
| Triple negative (No) | | | | |
| | 1079(82.6) | 581 (88.6) | 0.023 | 0.066 |
| (Yes) | 227(17.4) | 90(13.4) | | |
| ER (Negative) | | | | |
| | 322(24.7%) | 148(22.1%) | 0.199 | 0.246 |
| (Positive) | 984(75.3%) | 523(77.9%) | | |
| PgR (Negative) | | | | |
| | 603(46.2%) | 333(49.6%) | 0.145 | 0.188 |
| (Positive) | 703(53.8%) | 338(50.4%) | | |
| <u>Genefu subtype</u> | | | | |
| ER-/Her-2 negative | 110(16.3%) | 40(12.6%) | 0.129 | 0.186 |
| ER+/Her-2 negative/high proliferation | 229(33.9%) | 137(43.1%) | 0.005 | 0.018 |
| ER+/Her-2 negative/low proliferation | 265(39.1%) | 103(32.4%) | 0.038 | 0.082 |
| Her-2 positive | 72(10.7%) | 38(11.9%) | 0.543 | 0.564 |
| <u>PAM50 subtype</u> | | | | |
| PAM50.Her2 | 130(11.2%) | 108(17.6%) | 1.5X10⁻⁴ | 0.0008 |
| PAM50.Basal | 233(20.1%) | 97(15.8%) | 0.029 | 0.075 |
| PAM50.LumA | 488(42.1%) | 227(37.1%) | 0.042 | 0.084 |
| PAM50.LumB | 309(26.6%) | 180(29.4%) | 0.214 | 0.252 |
| <u>IntClust subgroups</u> | | | | |

| | | | | |
|-------------|------------|-------------|-----------------------------|----------------|
| intClust.1 | 49(3.8%) | 88(13.1%) | 8.3X10⁻¹⁵ | 0.00001 |
| intClust.2 | 55(4.2%) | 17(2.5%) | 0.059 | 0.102 |
| intClust.3 | 221(16.9%) | 69(10.3%) | 7.8X10⁻⁵ | 0.0005 |
| intClust.4 | 267(20.4%) | 76(11.3%) | 3.9X10⁻⁷ | 0.00001 |
| intClust.5 | 120(63.5%) | 69(36.5%) | 0.433 | 0.469 |
| intClust.6 | 50(3.8%) | 36(5.4%) | 0.113 | 0.172 |
| intClust.7 | 113(8.7%) | 40.2(11.3%) | 0.056 | 0.104 |
| intClust.8 | 187(14.3) | 113(16.8%) | 0.139 | 0.191 |
| intClust.9 | 74(5.7%) | 72(10.7%) | 4.6X10⁻⁵ | 0.0004 |
| intClust.10 | 170(13.0%) | 55(8.2%) | 0.001 | 0.0043 |

Bold = Statistically significant;HER2: human epidermal growth factor receptor 2; ER: oestrogen receptor; PgR: progesterone receptor;Triple negative: ER-/PgR-/HER2- . Adjusted p values were calculated using Benjamini-Hochberg false discovery rate method to adjust for multiple testing.

Table 2. Multivariate analysis of RECQL5 mRNA expression in breast cancer

| | P-Value | Risk Ratio | 95% CI for Risk Ratio | |
|--|-----------------|------------|-----------------------|----------|
| | | | Lower | Upper |
| <u>Breast Cancer Specific Survival (Whole Cohort)</u> | | | | |
| Grade | 0.000004 | 1.447429 | 1.237421 | 1.693079 |
| Size (Cm) | 0.000001 | 1.121003 | 1.076755 | 1.167069 |
| LN Status | 0.000001 | 1.875371 | 1.666800 | 2.110040 |
| RECQL5 mRNA expression | 0.023530 | 1.223718 | 1.027549 | 1.457337 |
| <u>Breast Cancer Specific Survival (ER+ Cohort)</u> | | | | |
| Grade | 0.0002 | 1.411263 | 1.176981 | 1.692178 |
| Size (Cm) | 0.000001 | 1.180525 | 1.123389 | 1.240566 |
| LN Status | 0.000001 | 1.822326 | 1.578493 | 2.103825 |
| RECQL5 mRNA expression | 0.045 | 1.242008 | 1.004707 | 1.535359 |
| <u>Breast Cancer Specific Survival (ER- Cohort)</u> | | | | |
| Grade | 0.968564 | 1.008054 | 0.676448 | 1.502217 |
| Size (Cm) | 0.239188 | 1.046124 | 0.970452 | 1.127695 |
| LN Status | 0.000001 | 1.908038 | 1.539252 | 2.365181 |
| RECQL5 mRNA expression | 0.635591 | 1.078023 | 0.790092 | 1.470886 |

Bold: Statistically significant; HR: Hazard Ratio; CI: Confidence interval; LN: Lymph node

Table 3. RECQL5 – RAD51 protein co-expression and breast cancer

| VARIABLE | RECQL5 and RAD51 protein co-expression | | | | P- value (Unadjusted) | P -Value (Adjusted) |
|-----------------------------------|--|------------------------|------------------------|---------------------|----------------------------|---------------------|
| | RQ5n-/RAD51n- N (%) | RQ5n+/RAD51n- N (%) | RQ5n-/RAD51n+ N (%) | RQ5n+/RAD51n+ N% | | |
| A) Pathological Parameters | | | | | | |
| Tumour Size | | | | | | |
| ≤1cm | 12 (6.8) | 9 (5.8) | 10 (7.6) | 16 (8.6) | 0.031 | 0.045 |
| >1-2cm | 77 (43.8) | 65 (41.9) | 73 (55.7) | 107 (57.5) | | |
| >2-5cm | 84 (47.7) | 78 (50.3) | 45 (34.4) | 62 (33.3) | | |
| >5cm | 3 (1.7) | 3 (1.9) | 3 (2.3) | 1 (0.5) | | |
| Tumour Stage | | | | | | |
| 1 | 96 (54.5) | 83 (53.2) | 79 (60.3) | 112 (60.2) | 0.370 | 0.401 |
| 2 | 64 (36.4) | 57 (36.5) | 44 (33.6) | 52 (28.0) | | |
| 3 | 16 (9.1) | 16 (10.3) | 8 (6.1) | 22 (11.8) | | |
| Tumour Grade | | | | | | |
| G1 | 13 (7.4) | 18 (11.5) | 14 (10.7) | 37 (19.9) | 4.1x10⁻⁵ | 0.0005 |
| G2 | 59 (33.5) | 38 (24.4) | 53 (40.5) | 73 (39.2) | | |
| G3 | 104 (59.1) | 100 (64.1) | 64 (48.9) | 76 (40.9) | | |
| Mitotic Index | | | | | | |
| M1 (low; mitoses < 10) | 45 (26.0) | 34 (22.5) | 41 (31.5) | 72 (40.0) | 0.008 | 0.017 |
| M2 (medium; mitoses 10-18) | 38 (22.0) | 28 (18.5) | 24 (18.5) | 38 (21.1) | | |
| M3 (high; mitosis >18) | 90 (52.0) | 89 (58.9) | 65 (50.0) | 70 (38.9) | | |
| Tubule Formation | | | | | | |
| 1 (>75% definite tubule) | 5 (2.9) | 2 (1.3) | 7 (5.4) | 7 (3.9) | 0.025 | 0.046 |
| 2 (10%-75% definite tubule) | 45 (26.0) | 49 (32.5) | 43 (33.1) | 75 (41.7) | | |
| 3 (<10% definite tubule) | 123 (71.1) | 100 (66.2) | 80 (61.5) | 98 (54.4) | | |
| Pleomorphism | | | | | | |
| 1 (small-regular uniform) | 0 (0.0) | 1 (0.7) | 2 (1.6) | 2 (1.1) | 0.027 | 0.043 |
| 2 (Moderate variation) | 61 (35.5) | 42 (27.8) | 48 (37.2) | 82 (45.6) | | |
| 3 (Marked variation) | 111 (64.5) | 108 (71.5) | 79 (61.2) | 96 (53.3) | | |
| Tumour Type | | | | | | |
| IDC-NST | 121 (69.9) | 113 (72.4) | 75 (58.1) | 102 (55.1) | 0.002 | 0.005 |
| Tubular Carcinoma | 21 (12.1) | 22 (14.1) | 27 (20.9) | 50 (27.0) | | |
| Medullary Carcinoma | 7 (4.0) | 2 (1.3) | 3 (2.3) | 0 (0.0) | | |
| ILC | 14 (8.1) | 8 (5.1) | 13 (10.1) | 20 (10.8) | | |
| Others | 3 (1.7) | 1 (0.6) | 0 (0.0) | 1 (0.5) | | |
| Lymph Node Status | | | | | | |
| Negative | 81 (54.4) | 69 (51.1) | 72 (60.0) | 97 (58.4) | 0.353 | 0.417 |
| Positive (1-3) | 56 (37.6) | 54 (40.0) | 44 (36.7) | 53 (31.9) | | |
| Positive (>3) | 12 (8.1) | 12 (8.9) | 4 (3.3) | 16 (9.6) | | |

| <u>B) Aggressive Phenotype</u> | | | | | | |
|---------------------------------------|------------|------------|------------|------------|----------------------------|---------------|
| Her2 overexpression | | | | | | |
| No | 153 (87.4) | 123 (80.4) | 105 (81.4) | 159 (88.3) | 0.105 | 0.136 |
| Yes | 22 (12.6) | 30 (19.6) | 24 (18.6) | 21 (11.7) | | |
| Triple Negative Phenotype | | | | | | |
| No | 149 (84.7) | 130 (83.3) | 115 (87.8) | 151 (81.2) | 0.457 | 5.94 |
| Yes | 27 (15.3) | 26 (16.7) | 16 (12.2) | 35 (18.8) | | |
| NPI | | | | | | |
| ≤3.4 | 31 (18.3) | 31 (21.2) | 34 (27.4) | 68 (38.4) | 1.1x10⁻⁴ | 0.0005 |
| >3.4 | 138 (81.7) | 115 (78.8) | 90 (72.6) | 109 (61.6) | | |
| <u>C) Hormone Receptors</u> | | | | | | |
| ER | | | | | | |
| Negative | 60 (35.1) | 53 (34.9) | 32 (25.4) | 28 (15.7) | 7.6x10⁻⁵ | 0.0005 |
| Positive | 111 (64.9) | 99 (65.1) | 94 (74.6) | 150 (84.3) | | |
| PgR | | | | | | |
| Negative | 91 (54.5) | 77 (52.0) | 49 (39.5) | 63 (35.6) | 0.001 | 0.003 |
| Positive | 76 (45.5) | 71 (48.0) | 75 (60.5) | 114 (64.4) | | |

Bold = Statistically significant; HER2: human epidermal growth factor receptor 2; ER: oestrogen receptor; PgR: progesterone receptor; Triple negative: ER-/PgR-/HER2-. Adjusted p values were calculated using Benjamini-Hochberg false discovery rate method to adjust for multiple testing.

Table 4. Multivariate analysis of RECQL5-RAD51 protein co-expression in breast cancer

| | B | P value | Exp (B) | 95.0% CI for Exp (B) | |
|---|--------|---------------|---------|----------------------|--------|
| | | | | Lower | Upper |
| <u>Breast Cancer Specific Survival in the whole cohort</u> | | | | | |
| RECQL5-RAD51 co-expression | -0.069 | 0.022 | 0.934 | 0.880 | 0.990 |
| NPI | 0.769 | 0.001 | 2.158 | 1.378 | 3.379 |
| ER Status | 0.293 | 0.097 | 1.340 | .949 | 1.893 |
| HER2 Status | 0.728 | 0.0001 | 2.071 | 1.432 | 2.994 |
| <u>Breast Cancer Specific Survival in the ER+ cohort</u> | | | | | |
| RECQL5-RAD51 co-expression | -0.063 | 0.073 | 0.939 | 0.876 | 1.006 |
| NPI | 0.784 | 0.001 | 2.190 | 1.376 | 3.484 |
| HER2 Status | 0.848 | 0.001 | 2.335 | 1.448 | 3.767 |
| <u>Breast Cancer Specific Survival in the ER- cohort</u> | | | | | |
| RECQL5-RAD51 co-expression | -0.081 | 0.172 | 0.923 | 0.822 | 1.036 |
| NPI | 0.651 | 0.519 | 1.917 | 0.265 | 13.882 |
| HER2 Status | 0.551 | 0.057 | 1.735 | 0.984 | 3.062 |

Figure legends

Figure 1. **A.** *RECQL5* mRNA expression in breast cancer cell lines. **B.** Kaplan Meier curves showing BCSS (Breast cancer specific survival) based on *RECQL5* mRNA expression in the whole cohort **C.** Kaplan Meier curves showing BCSS (Breast cancer specific survival) based on *RECQL5* mRNA expression in ER+ cohort; **D.** Kaplan Meier curves showing BCSS (Breast cancer specific survival) based on *RECQL5* mRNA expression in ER+ cohort that had endocrine therapy; **E.** Kaplan Meier curves showing BCSS (Breast cancer specific survival) based on *RECQL5* mRNA expression in ER- cohort. **F.** Kaplan Meier curves showing BCSS (Breast cancer specific survival) based on *RECQL5* mRNA expression in ER- cohort that had chemotherapy.

Figure 2. **A1.** Western blot of *RECQL5* expression in breast cancer cell lines. **A2.** MCF10A breast cells were transfected with *RECQL5* or empty vector and. Extracts were made 48 h post transfection and western blotted for *RECQL5*. *RECQL5* level in MCF7 cells is shown for comparison. **B.** MCF10A breast cells were transfected with *RECQL5* or empty vector and cell number counted every 24 h. Mean and standard deviation are shown for 3 independent repeats. ** indicates a statistical significance of $P < 0.01$ at 72 h using Student's T-Test. **C.** Western blot of *RECQL5* expression in MCF-7 (*RECQL5* wild-type) and MCF-7 *RECQL5* knock down cell line. **D.** Microphotograph of *RECQL5* protein expression in breast tumours. **E.** Kaplan Meier curves showing BCSS based on *RECQL5*-RAD51 co-expression in the whole cohort. **F.** Kaplan Meier curves showing BCSS based on *RECQL5*-RAD51 co-expression in ER+ cohort.