SURVEY AND SUMMARY

RTEL1: an essential helicase for telomere maintenance and the regulation of homologous recombination

Evert-Jan Uringa1, Jillian L. Youds2, Kathleen Lisaingo1, Peter M. Lansdorp1,3,* and Simon J. Boulton2,*

1Terry Fox Laboratory, BC Cancer Agency, Avenue, Vancouver, BC, V5Z 1L3, Canada, 2DNA Damage Response Laboratory, Cancer Research UK, London Research Institute, Clare Hall, Blanche Lane, South Mimms EN6 3LD, UK and 3Department of Medicine, University of British Columbia, Vancouver, BC, V5Z 4E3, Canada

Received August 11, 2010; Revised October 8, 2010; Accepted October 12, 2010

ABSTRACT

Telomere maintenance and DNA repair are crucial processes that protect the genome against instability. RTEL1, an essential iron–sulfur cluster-containing helicase, is a dominant factor that controls telomere length in mice and is required for telomere integrity. In addition, RTEL1 promotes synthesis-dependent strand annealing to direct DNA double-strand breaks into non-crossover outcomes during mitotic repair and in meiosis. Here, we review the role of RTEL1 in telomere maintenance and homologous recombination and discuss models linking RTEL1’s enzymatic activity to its function in telomere maintenance and DNA repair.

INTRODUCTION

Telomeres are protective structures at the end of chromosomes, the maintenance of which is essential for genomic stability (1). In vertebrates, telomeres are composed of repetitive TTAGGG DNA (2) and associated proteins, which form a core complex known as the Shelterin complex (3). Telomeres protect chromosomes by distinguishing chromosomal ends from DNA double-strand breaks (DSBs), a function that is essential in avoiding chromosome end-to-end fusions and inappropriate recombination events (4).

Telomeres can form a protective lariat-like structure, referred to as the telomeric-loop, or T-loop (5). T-loops are created through strand invasion by the 3′ single-stranded overhang of telomeric DNA into duplex telomere repeats. This strand invasion displaces the identical sequence strand of the duplex telomeric DNA and so forms a displacement-loop (D-loop) at the base of the T-loop. The D-loop is also an intermediate in the DNA repair pathway via homologous recombination (HR) (6). This repair pathway is the main method for repairing DSBs when sister chromatid templates are available and is also required for meiotic recombination. How the T-loop is resolved during replication or how the invaded strand in the D-loop structure is displaced to promote repair to a non-crossover (NCO) outcome is still largely unknown.

In addition to the T-loop configuration, the guanine (G)-rich nature of the telomere may also pose a challenge for telomere maintenance. In vitro, single-stranded G-rich telomeric sequences are capable of forming stable structures called G-quadruplex (or G4) DNA (7). In vivo, G4 DNA might form at telomeres during replication, repair and transcription. The resolution of T-loops and telomeric G4 DNA could be important for telomere maintenance, and therefore, genomic stability.

Rtel1 (for Regulator of Telomere Length 1) is an essential helicase that plays a crucial role in telomere maintenance and DNA repair (8,9). Rtel1 was originally discovered as the dominant factor in setting telomere
length in mice (9). In the absence of Rtel1, telomeres are not maintained and chromosome fusions are observed. In addition, RTEL1 was found to be a key protein in the repair of DSBs (8,10). It disrupts D-loops in vitro and promotes synthesis-dependent strand annealing (SDSA) in vivo. Notably, RTEL1 activity is not limited to mitotic cells, as RTEL-1 is required to regulate meiotic recombination in Caenorhabditis elegans. Here, we review the emerging role of RTEL1 at telomeres and in DNA repair and introduce a model linking the anti-recombinase activity of RTEL1 to its functions in telomere maintenance and DNA repair.

RTEL1 AND TELOMERE LENGTH REGULATION IN THE MOUSE

Telomeres shorten with each round of DNA replication (11). Typical and sporadic losses of telomeric DNA are compensated for by the enzyme telomerase. In yeast (12), maize (13) and Arabidopsis (14), the telomere length set point seems to be determined by multiple genes. In mice, telomere length is controlled by genetic (9) as well as epigenetic factors (15). Rtel1 was identified as a dominant genetic factor setting telomere length in mice (9,16). Most laboratory mice including Mus musculus have long telomeres, with lengths between 25 and 150 kb (17), but a related mouse species, Mus spretus, has telomeres between 5 and 15 kb (18), similar to the telomere length in human cells (19–21). Hodes and co-workers (16) found that telomeres of Mus spretus-derived chromosomes in the offspring of crosses between M. spretus with M. musculus were significantly longer than in the M. spretus parent, suggesting that a dominant genetic mechanism was elongating M. spretus telomeres during development. Genotype mapping pointed to a locus on distal chromosome 2 containing a dominant factor(s) determining telomere length setting in mice. This factor was shown to be Rtel1 based on the finding that Rtel1 expression from the M. musculus parent was required to elongate the telomeres of M. spretus-derived chromosomes (9). Mice lacking Rtel1 die around Day 10–11 with defects in multiple organs. The average telomere length of Rtel1-deficient embryonic stem cells is around 68% of that in wild-type cells (9). It is unknown how Rtel1 determines this telomere length equilibrium and how the difference between M. musculus and M. spretus Rtel1 determines a long or short telomere phenotype in these mice. However, differences between M. musculus and M. spretus Rtel1 are found in the promoter region, in the last four exons of the gene, and in mRNA splice variants (9). In addition, it is unknown if RTEL1 also determines telomere length in humans. However, no association was found between telomere length and single-nucleotide polymorphisms (SNPs) in RTEL1 (22).

RTEL1 AND OTHER FeS CLUSTER-CONTAINING HELICASES

RTEL1 belongs within the DEAH subfamily of the Superfamily 2 (SF2) helicases and is classified as a RAD3-related helicase with 5’ to 3’ directionality (23,24). An iron–sulfur (FeS) domain classifies RTEL1 within a very small subclass of FeS cluster-containing DNA helicases (25). Xeroderma pigmentosum group D (XPD) is the founding member of this subclass, which also contains ChlR1 and FANCJ, in addition to RTEL1 (26). Mutations in XPD, FANCJ and ChlR1 are responsible for the genetic disorders xeroderma pigmentosum (XP) (27), Fanconi anemia (FA) (28–31) and Warsaw breakage syndrome (32). Thus far, heritable mutations in RTEL1 have not been linked to specific human genetic syndromes. However, two independent studies identified intronic SNPs in RTEL1 associated with glioma susceptibility (33,34). Furthermore, RTEL1 is located in a gene-rich cluster (20q13.3) that is amplified in several human cancers (35–38). It is unclear if RTEL1 is directly implicated in these malignancies, since this cluster also contains other tumor susceptibility genes (38–40). The key characteristic of the XPD family of helicases is the conservation of four cysteine residues, which bind iron ions to form an FeS cluster (25). Removal of the archael XPD FeS domain abolishes its helicase activity and can destabilize its tertiary structure (25,41). The crystal structures of archael XPDs are consistent with a role of the FeS domain in separating the two strands of the DNA duplex (41–43). This is supported by the findings that the FeS-cluster-containing domain of archael XPD recognizes the single-stranded DNA (ssDNA) and double-stranded DNA (dsDNA) junction and that the DNA duplex is opened near the FeS domain (44). Based on the sequence similarity of the helicase core domain, it is likely that other FeS cluster-containing helicases, including RTEL1, also recognize the ssDNA–dsDNA junction. Disruption of the FeS cluster in RAD3 (yeast XPD) causes defective excision repair resulting in ultraviolet (UV) sensitivity in vivo (25). Clinically relevant mutations giving rise to syndromes in XPD and FANCJ patients cause the destabilization of the FeS cluster in archael XPD (25,41,42).

The severity of FA, XP and Warsaw breakage syndrome emphasize the important roles of the helicases containing FeS clusters in the maintenance of genome stability. Changes in the availability of iron and in the biogenesis of FeS clusters will likely influence RTEL1, XPD, FANCJ and ChlR1 protein levels. Interference with the packaging of FeS clusters into proteins was recently found to contribute to genomic instability (45). It is likely that compromised levels of FeS containing helicases are responsible for this phenotype.

In addition to its helicase motifs and FeS domain, a conserved eight amino acid PIP [proliferating cell nuclear antigen (PCNA)-interacting protein (46)] box is present at the C-terminus of the RTEL1 protein. PCNA is a highly conserved eukaryotic protein that functions in DNA replication as a sliding clamp encircling the DNA and acts as a cofactor for DNA polymerases. Currently, the RTEL1–PCNA interaction is speculative, but the RTEL1 PIP box could be necessary to properly orient the protein relative to DNA.
RTEL1 ANTAGONIZES HOMOLOGOUS RECOMBINATION IN VITRO

Although RTEL1 was originally predicted to be a helicase involved in recombination and repair, a biochemical function had remained elusive. Recent studies have now shown that RTEL1 antagonizes homologous recombination events upon DSB formation (8,10). After a DSB is sensed, the two duplex ends are resected to give 3’ ssDNA that is subsequently bound by Replication Protein A (RPA). RPA is then displaced by RAD51 recombinase to form a nucleoprotein filament, which searches for and invades the intact homologous dsDNA template (47), resulting in the formation of a D-loop structure (48). The invaded 3’ end is extended by a DNA synthesis reaction, copying the information on the homologous DNA template. Subsequently, the strand is displaced and annealed to the other processed DNA end, and the repair reaction is completed by additional DNA synthesis and ligation. A DSB repaired via this SDSA pathway yields a NCO repair product (49,50). Alternatively, if the other processed DNA strand is also captured in the D-loop, a double Holliday junction intermediate will be formed. Resolution of a double Holliday junction can give rise to crossover (CO) repair products (51).

Human RTEL1 possesses biochemical properties consistent with a role in antagonizing HR by promoting SDSA (8,10,52). In vitro, purified RTEL1 inhibits the formation of D-loops in an ATP-dependent manner (Figure 1) (8). In addition, RTEL1 was found to actively reverse HR by disrupting preformed D-loops in the presence of calcium (8), which activates and stabilizes the nucleoprotein filament, making it capable of performing the strand exchange reaction (53). In contrast to RTEL1, BLM, the helicase defective in human Bloom’s syndrome, and FANCJ are unable to dissociate preformed D-loops in the presence of calcium (8,54,55), but can catalyze the disruption of a RAD51 nucleoprotein filament in an unstable state (54,55). RTEL1 has no detectable disruption activity toward single-stranded RAD51 nucleoprotein filaments (8), indicating a unique anti-recombinase mechanism of RTEL1. Thus, the biochemical activity of RTEL1 is distinct from other known anti-recombinases, including yeast Srs2 and mammalian FBH1, BLM, FANCJ and RECQL5, all of which can disrupt single-stranded RAD51 nucleoprotein filaments (54–59). In the presence of RPA, RTEL1 was shown to preferentially disrupt a 3’ ssDNA invasion D-loop with a 5’ overhang but had almost no activity on a D-loop with a 5’ ssDNA invasion and a 3’ overhang, or a substrate with no overhang (10). The biochemical activity of RTEL1 is perhaps most similar to the yeast helicase Mph1, which is also able to disrupt D-loops; however, Mph1 was shown to have similar affinity for D-loops with a 5’ ssDNA invasion and 3’ overhang, with a 3’ ssDNA invasion and 5’ overhang and with no overhang (60). While Mph1 promotes NCO repair of mitotic DSBs (60), it is thus far unclear whether Mph1 might function to regulate meiotic recombination. The fact that RTEL1 can unwind a 3’ end invaded D-loop supports the hypothesis that RTEL1 stimulates SDSA-mediated DSB repair, during which such enzymatic activity is required to disassemble the D-loop intermediate and thereby promote NCO repair products (52). Detailed analysis of the phenotypes of C. elegans rtel-1 mutants and human Rtel1-deficient cells is consistent with the hypothesis that the biochemical activity of RTEL1 in disrupting D-loops is responsible for both mitotic repair and regulating meiotic recombination.

TELOMERE LOSS IN RTEL1-DEFICIENT CELLS

Chromosome ends with low or undetectable telomere repeats are abundant in Rtel1 null ES cells (9), suggesting significant telomere loss. One possible explanation for this telomere phenotype might be that Rtel1 is required to open the D-loop structure within the T-loop (Figure 2a). Importantly, the telomeric D-loop resembles the preferred RTEL1 substrate: a 3’ ssDNA invaded D-loop with a 5’ overhang. Potentially, telomeric D-loops could be inappropriately processed by the HR pathway since this structure resembles a strand-invasion intermediate in HR. This was observed in mammalian cells expressing a truncated form of TRF2 (telomere repeat-binding factor 2) in which HR dependent large T-loop-sized circular telomeric DNAs were generated (61). In the absence of RTEL1, T-loops might be less efficiently resolved. Failing to open the T-loop for replication and/or transcription could lead to large telomeric deletions causing the telomere phenotype seen in Rtel1-deficient cells. In addition, Rtel1 could be required to prevent the 3’ single-stranded telomere end from invading the telomeres of other chromosomes (Figure 2b). This activity might prevent telomere recombination events, chromosome entanglements and subsequent breakage when attached chromosomes attempt to separate during mitosis. Two other helicases important for telomere maintenance are the human RecQ family members Werner syndrome protein (WRN) and BLM. Both helicases interact biochemically and functionally with TRF1, TRF2, and POT1 (protection of telomeres 1) (62–65). In vitro, WRN and BLM have been implicated in unwinding the telomeric D-loop (63,64,66). Future experiments will determine if RTEL1 similarly unwinds telomeric D-loop structures and if this activity is required in vivo.

An alternative explanation for the short telomere phenotype of Rtel1 null cells could be that RTEL1, which shares sequence similarity with the helicase FANCJ, may also be required to resolve G-quadruplex structures (67,68). G4 DNA could naturally be present at the telomere or arise during lagging strand replication of G-rich telomeric DNA, as was proposed (9). In addition, hybrid G4 DNA/RNA structures might form following transcription of telomeric DNA (69–71). FANCJ patient cells present genomic deletions corresponding to a G4 DNA signature motif (67) and are hypersensitive to telomestatin (68), a compound which specifically binds G4 DNA (72,73). In dog-1 (C. elegans FANCJ) mutants, large G-tract deletions throughout the genome and mild telomeric instability was observed (74–76). By contrast, in rtel-1 mutants genomic G-tract
Model for RTEL1 promoting synthesis-dependent strand annealing (SDSA). (a) After a DSB is sensed, the two duplex ends are resected to give 3′-ssDNA that is subsequently bound by RPA (orange). RPA is replaced by RAD51 recombinase (blue) to form a nucleoprotein filament that searches and invades the homologous dsDNA, forming a D-loop. The invaded strand serves as a primer for DNA synthesis, which copies the information on the homologous DNA strand. RTEL1 (green) promotes SDSA by the displacement of a 3′-end invaded D-loop. Although the mechanism by which RTEL1 promotes strand displacement is unknown, RTEL1 is proposed to recognize the ssDNA–dsDNA junction via its FeS domain, and act as a 5′-to-3′ helicase. The displaced strand can now anneal to the other processed DNA end and the repair reaction will be completed by DNA synthesis and ligation, resulting in a non-crossover outcome. Note that RTEL1 may displace invading strands from both of the processed DNA ends, however, only one invading strand is shown for clarity. Alternative models of RTEL1 action include: (b) RTEL1 translocation in a 5′-to-3′ direction along template strand, as opposed to the invading strand. (c) Although it is thought that SDSA occurs earlier than double Holliday junction formation, it is also possible, though less likely, that RTEL1 may act on the other processed DNA end. This activity might prevent the other processed DNA end from becoming part of the repair reaction, known as second end capture, and so prevent the formation of a double Holliday junction, which could be resolved as a crossover product.
deletions were not detected and a telomere phenotype was not reported \((8,74)\). It is interesting to note that \textit{C. elegans} \textit{rtel-1 dog-1} double mutant animals display a synthetic lethal phenotype in which sterility results from replication-associated problems in the germline prior to meiosis \((8\); Youds and Boulton, unpublished data\). Thus, some overlapping function for \textit{rtel-1} and \textit{dog-1} during replication is likely, at least in \textit{C. elegans}. Experiments to conditionally knock out both \textit{Rtel1} and \textit{FancJ} might reveal partially overlapping roles with regard to G4 DNA maintenance, particularly at telomeres. In addition to \textit{FANCJ}, the \(3'\) to \(5'\) helicases \textit{WRN} and \textit{BLM} are able to unwind G4 DNA \textit{in vitro} \((77–79)\). Table 1 compares the existing data on \textit{RTEL1} and \textit{FANCJ}.

A recent study revealed that mammalian telomeres are difficult regions to replicate and resemble fragile sites \((80,81)\). In the absence of \textit{Trf1}, the replication fork has a greater tendency to stall when encountering telomeric DNA. It was proposed that \textit{Trf1} might act by recruiting or activating helicases like \textit{Rtel1} and \textit{Blm} to telomeres \((80)\). \textit{Rtel1}-deficient \textit{ES} cells and single \textit{Rtel1} and \textit{Blm} knockdown mouse embryonic fibroblasts (MEFs) both show a mild fragile-telomere phenotype, which in MEFs is epistatic to the deletion of \textit{Trf1} \((80)\). These results indicate that \textit{Rtel1} and \textit{Trf1} act in the same pathway to suppress telomere fragility. Additional functional studies of the biochemical and cellular activities of \textit{RTEL1}, \textit{FANCJ}, \textit{WRN} and \textit{BLM} may reveal more specific and redundant roles of these proteins in the regulation of the telomeric D-loop, G-quadruplexes, and other biological structures.

**RTEL1 REGULATES MITOTIC AND MEIOTIC RECOMBINATION IN VIVO**

Besides the requirement of \textit{Rtel1} for telomere maintenance, a role in DNA repair was envisioned upon studying differentiating \textit{Rtel1}-deficient \textit{ES} cells \((9)\). Interestingly, within hours of the induction of differentiation, \textit{Rtel1}-deficient \textit{ES} cells showed a variety of chromosomal abnormalities, including broken chromosomes and chromatid gaps, pointing to a more general role of \textit{Rtel1} in maintaining genomic stability. Subsequently, a role for \textit{RTEL-1}/\textit{RTEL1} in regulating HR was elucidated from work in \textit{C. elegans} and human cell lines \((8)\). In the budding yeast \textit{Saccharomyces cerevisiae}, the DNA helicase \textit{Srs2} is an anti-recombinase that regulates

---

**Table 1. Summary of the relationship of \textit{RTEL1} and \textit{FANCJ}**

|                      | \textit{dog-1}/\textit{FancJ}/\textit{FANCJ} | \textit{rtel-1}/\textit{Rtel1}/\textit{RTEL1} | \textit{dog-1}/\textit{FancJ}/\textit{FANCJ} |
|----------------------|---------------------------------------------|-----------------------------------------------|---------------------------------------------|
| Best BLAST hit       | \textit{rtel-1}/\textit{Rtel1}/\textit{RTEL1} | Helicase domains including DEXDc, HELICx2, DEAD_2 and DinG, BRCA1-interaction site, Fe-S motif | \textit{dog-1}/\textit{FancJ}/\textit{FANCJ} |
| Synthetic lethal in \textit{C. elegans} when combined with mutation in DNA damage sensitivity? | \textit{rtel-1} | Yes: ICL-inducing agents, \textit{dog-1}: mild instability | \textit{dog-1}, \textit{mus-81}, \textit{him-6}/\textit{BLM}, \textit{recq-5}/\textit{RECQ5} |
| Elevated recombination? | G4 DNA, forked duplex DNA, D-loop | Inhibits RAD51 strand exchange | Yes: ICL-inducing agents, \textit{Rtel1}/\textit{RTEL1}: dramatic loss |
| Activity on \textit{in vitro} biochemical substrate | Inhibits RAD51 strand exchange | Yes | Yes: \textit{D-loop} recombination intermediate |
| Activity with respect to recombination | Yes: Fanconi anemia subgroup J | None identified | \textit{D-loop} recombination intermediate |
| Human patients identified? | None identified | | \textit{Disassembles \textit{D-loop} intermediate} |

---
HR (56,57). Yeast SRS2 is synthetic lethal with SGS1, the sole S. cerevisiae RecQ helicase that bears homology to five human RecQ helicases, particularly to human BLM (82). This synthetic lethality is due to an accumulation of toxic recombination intermediates (82). No sequence homologs of SRS2 exist in higher organisms, but the SGS1 homolog in C. elegans is him-6/BLM (83). Therefore, based on the synthetic lethality of SRS2 and SGS1 in yeast, a screen to find a candidate for a C. elegans gene with an Srs2-like function was conducted by searching for genes that showed synthetic lethality when knocked-down in a him-6/BLM mutant strain. rtel-1 was identified as being synthetic lethal with him-6/BLM, making it a candidate for the SRS2 analog in C. elegans. Furthermore, rtel-1 showed synthetic lethal phenotypes when combined with mutations in mus-81, dog-1 and rec-5 (8). The synthetic lethality in these strains correlated with an accumulation of RAD-51 foci in the germline, a marker of persistent HR intermediates. Furthermore, rtel-1 mutation causes synthetic sick phenotypes when combined with deletions in either rfs-1 or helq-1, two genes that encode proteins functioning late in HR to disassemble RAD-51 from double-stranded DNA filaments (84).

Caenorhabditis elegans rtel-1 and dog-1 mutants and human cells deficient for RTE1L and FANCI are sensitive to DNA interstrand crosslinks (ICLs) (8,28–31,75). Based on epistasis experiments in C. elegans, dog-1 acts in the fcd-2/FANCD2 pathway, while rtel-1 appears to act in a separate pathway for ICL repair. rtel-1 mutants are also sensitive to camptothecin (8). Surprisingly, C. elegans rtel-1 mutants and RTE1L depleted cells are not sensitive to ionizing radiation (IR). However, it is possible that in the absence of RTE1L, all DSBs are efficiently repaired with a CO outcome. In accordance with a role of RTE1L in antagonizing recombination, recombination frequencies were increased in RTE1L-depleted HeLa cells (8).

In addition to mitotic DNA repair, RTE1L is also required to promote NCO repair during meiosis (10). Meiotic DSBs are not randomly distributed along chromosomes, but tend to occur in specific regions (85). Through homologous recombination, DSBs can be repaired by either a CO or a NCO event (86). The number of DSBs created exceeds the number of final CO events, in some organisms by more than ten times (87,88). How specific DSBs are selected to become COs is unknown, but the mechanism behind this ensures that each pair of homologs gets at least one CO (known as the obligate CO). In addition, a mechanism called CO interference regulates the distribution of COs along the chromosome in such a way that COs tend to occur further apart from each other than expected by chance (89). When the number of meiotic DSBs is reduced, the number of COs is maintained at the expense of NCOs; this is called CO homeostasis (90).

Recently, C. elegans RTE1L was shown to enforce both meiotic CO interference and homeostasis (10). Wild-type C. elegans only ever have a single CO per chromosome (91,92). rtel-1 mutants showed up to three COs per chromosome that were randomly distributed, suggesting a lack of CO interference. Furthermore, the CO increase was not due to increased formation of meiotic DSBs per chromosome in wild-type meiosis is 2.1, while just one of these is resolved into a CO. How RTE1L is recruited and regulated in a way that just half of the DSBs induced during wild-type meiosis result in a CO is an intriguing question. Designated COs may be protected from RTE1L activity by certain proteins; alternatively, RTE1L activity may be carefully regulated such that RTE1L only becomes active after the obligate COs have been completed.

It will be of interest to determine if RTE1L is also required for CO interference and homeostasis in mammals. Human RTE1L could have similar functions in meiosis since it was shown to disassemble D-loop recombination intermediates in vitro (8,10). In mice, the highest Rtel1 expression is detected in spermatogonia and meiotic spermatocytes within the testes (9). Although full knockout of Rtel1 function is lethal, the requirement of mouse Rtel1 in meiosis could potentially be studied if a (pre)meiotic-Cre transgenic line were available, since mice with conditional knock-out alleles have been established (97).

CONCLUDING REMARKS

RTE1L is an essential helicase, a dominant factor in setting telomere length in mice and is required for telomere and genome maintenance. Furthermore, RTE1L is a key protein in mitotic and meiotic DSB
repair and promotes NCO repair outcomes through SDSA. As it is currently unknown how RTEL1 is recruited and regulated during DSB repair, in both mitotic and meiotic cells, determining its post-translational modifications and interacting proteins may shed light on these questions. Live-cell imaging of fluorescent-tagged RTEL1 and co-localization studies with other DNA repair proteins will enhance our understanding of the biological function and dynamics of RTEL1.

The data available on RTEL1 so far do not exclude the possibility that RTEL1 is preferentially recruited to, or has higher enzymatic activity at G-rich regions in the genome. In humans, 25,618 meiotic recombination hot spots have been identified (98). Interestingly, potential G4 DNA-forming sequences were found to be significantly enriched within recombination hot spots (99). Also, G4 DNA was predicted to be formed within a 50-bp window around all of the top seven previously reported short-recombination enriched sequences (98,99). It is possible that RTEL1 is recruited to meiotic DSBs by G4 DNA structures at recombination hot spots to prevent COs from occurring. Possible recruitment to G4 DNA could be direct or indirect via binding to other G4 DNA-binding proteins. In yeast, Mre11 and the meiosis-specific protein Hop1 bind G4 DNA, and Hop1 itself promotes G4 DNA formation (100,101); thus, homologs and binding partners of these proteins are potential recruiters of RTEL1 to G4 DNA.

Finally, given that RTEL1 has already been shown to play multiple roles in maintaining genome stability, both at telomeres and more generally at sites of mitotic DNA damage, as well as regulating meiotic recombination, RTEL1 could be classified as having a tumor suppressive function. Certainly, Rtel1-deficient cells will undergo uncontrolled HR and that may result in telomere loss and/or gain and chromosomal rearrangements and translocations, all of which are characteristic of cancer cells. Conversely, upregulated RTEL1 function might prevent HR when it is needed as a legitimate means of repair. RTEL1 mutation has already been associated with resetting of the telomere set-point (33,34), and RTEL1 was shown to be overexpressed in gastrointestinal tract tumors (35). A challenge ahead will be to determine whether RTEL1 dysfunction plays a causative role in these and other cancers.

ACKNOWLEDGEMENTS
The authors thank Ester Falconer for helpful comments and critically reading this article.

FUNDING
The Canadian Institutes of Health Research (MOP38075, GMH79042 to P.M.L.); Terry Fox Foundation (018006 to P.M.L.); Cancer Research UK (to S.J.B.). S.J.B. is a Royal Society Wolfson Research Merit Award holder. Funding for open access charge: Canadian Cancer Society Research Institute and the Terry Fox Foundation.

Conflict of interest statement. None declared.

REFERENCES
1. Blackburn,E.H. (2001) Switching and signaling at the telomere. Cell, 106, 661–673.
2. Moyzis,R.K., Buckingham,J.M., Cram,L.S., Dani,M., Deaven,L.L., Jones,M.D., Meyne,J., Ratliff,R.L. and Wu,J.R. (1988) A highly conserved repetitive DNA sequence, (TTAGGG)n, present at the telomeres of human chromosomes. Proc. Natl Acad. Sci. USA, 85, 6622–6626.
3. de Lange,T. (2005) Shelterin: the protein complex that shapes and safeguards human telomeres. Genes Dev., 19, 2100–2110.
4. de Lange,T. (2009) How telomeres solve the end-protection problem. Science, 326, 948–952.
5. Griffith,J.D., Comeau,L., Rosenfield,S., Stansel,R.M., Bianchi,A., Moss,H. and de Lange,T. (1999) Monomeric telomeres end in a large duplex loop. Cell, 97, 503–514.
6. de Lange,T. (2004) T-loops and the origin of telomeres. Nat. Rev. Mol. Cell. Biol., 5, 323–329.
7. Sen,D. and Gilbert,W. (1992) Guanine quartet structures. Methods Enzymol., 211, 191–199.
8. Barber,L.J., Yous,J.L., Ward,J.D., Mcllwraith,M.J., O’Neil,N.J., Petakorin,M.I., Martin,J.S., Collis,J.S., Cantor,S.B., Auclair,M. et al. (2008) RTEL1 maintains genomic stability by suppressing homologous recombination. Cell, 135, 261–271.
9. Ding,H., Schertzer,M., Wu,X., Gertsenstein,M., Selig,S., Kammar,M., Pourvai,R., Poon,S., Vulto,I., Chavez,E. et al. (2004) Regulation of murine telomere length by Rtel: an essential gene encoding a helicase-like protein. Cell, 117, 873–886.
10. Yous,J.L., Met,D.G., Mcllwraith,M.J., Martin,J.S., Ward,J.D., O’Neil,N.J., Rose,A.M., West,S.C., Meyer,B.J. and Boulton,S.J. (2010) RTEL1 enforces meiotic crossover interference and homeostasis. Science, 327, 1254–1258.
11. Lansdorp,P.M. (2005) Major cutbacks at chromosome ends. Trends Biochem. Sci., 30, 388–395.
12. Walmsley,R.M. and Petes,T.D. (1985) Genetic control of chromosome length in yeast. Proc. Natl Acad. Sci. USA, 82, 506–510.
13. Burr,B., Burr,F.A., Matz,E.C. and Romero-Severson,J. (1992) Pinning down loose ends: mapping telomeres and factors affecting their length. Plant Cell, 4, 953–960.
14. Shakirov,E.V. and Shippden,D.E. (2004) Length regulation and dynamics of individual telomere tracts in wild-type Arabidopsis. Plant Cell, 16, 1959–1967.
15. Chiang,Y.J., Calado,R.T., Hathcock,K.S., Lansdorp,P.M., Young,N.S. and Hodes,R.J. (2010) Telomere length is inherited with resetting of the telomere set-point. Proc. Natl Acad. Sci. USA, 107, 10148–10153.
16. Zhu,L., Hathcock,K.S., Hande,P., Lansdorp,P.M., Seldin,M.F. and Hodes,R.J. (1998) Telomere length regulation in mice is linked to a novel chromosome locus. Proc. Natl Acad. Sci. USA, 95, 8648–8653.
17. Kipling,D. and Cooke,H.J. (1990) Hypervariable ultra-long telomeres in mice. Nature, 347, 400–402.
18. Starling,J.A., Maule,J., Hastic,N.D. and Allshire,R.C. (1999) Extensive telomere repeat arrays in mouse are hypervariable. Nucleic Acids Res., 18, 6881–6888.
19. Cross,S.H., Allshire,R.C., McKay,S.J., McGill,N.I. and Cooke,H.J. (1989) Cloning of human telomeres by complementation in yeast. Nature, 338, 771–774.
20. Allshire,R.C., Gosden,J.R., Cross,S.H., Cranston,G., Rout,D., Sugawara,N., Szostak,J.W., Fantes,P.A. and Hastic,N.D. (1988) Telomeric repeat from T. thermophila cross hybridizes with human telomeres. Nature, 332, 656–659.
21. de Lange,T., Shiu,L., Myers,R.M., Cox,D.R., Naylor,S.L., Killery,A.M. and Varums,H.E. (1990) Structure and variability of human chromosome ends. Mol. Cell Biol., 10, 518–527.
22. Mirabello,L., Yu,K., Kraf,P., De Vivo,I., Hunter,D.J., Prescott,J., Wong,J.Y., Chatterjee,N., Hayes,R.B. and Savage,S.A. (2010) The association of telomere length and genetic variation in telomere biology genes. Hum. Mutat., 31, 1050–1058.
23. Fairman-Williams,M.E., Guenther,U.P. and Jankowsky,E. (2010) SF1 and SF2 helicases: family matters. Curr. Opin. Struct. Biol., 20, 313–324.
37. Shinomiya, T., Mori, T., Ariyama, Y., Sakabe, T., Fukuda, Y., van der Lelij, P., Chrzanowska, K.H., Godthelp, B.C., Wrensch, M., Jenkins, R.B., Chang, J.S., Yeh, R.F., Xiao, Y., Levran, O., Attwooll, C., Henry, R.T., Milton, K.L., Neveling, K., Litman, R., Peng, M., Jin, Z., Zhang, F., Zhang, J., Powell, S., Levitus, M., Waisfisz, Q., Godthelp, B.C., de Vries, Y., Hussain, S., Andressoo, J.O. and Hoeijmakers, J.H. (2005)

39. Ozon, S., Byk, T. and Sobel, A. (1998) SCLIP: a novel SCG10-like staining regions.

Genes Chromosomes Cancer

38. Pitti, R.M., Marsters, S.A., Lawrence, D.A., Roy, M., Kischkel, F.C., Dowd, P., Huang, A., Donahue, C.J., Sherwood, S.W., Baldwin, D.T. et al. (1998) Genomic amplification of a decay receptor for Fas ligand in lung and colon cancer. Nature

36. Schurmann, A., Assmann, S. and Joost, H.G. (1995) ARP is a plasma membrane-associated Ras-related GTPase with remote similarity to the family of ADP-ribosylation factors. J. Biol. Chem., 270, 30657–30662.

40. FANTI, J., Fuss, J.O., Cheng, Q.J., Arvai, A.S., Hammel, M., Roberts, V.A., Cooper, P.K. and Tainer, J.A. (2008) XPD helicase structures and activities: insights into the cancer and aging phenotypes from XPD mutations. Cell, 133, 789–800.

42. Liu, H., Rudolf, J., Johnson, K.A., McMahon, S.A., Oke, M., Carter, L., McRobbie, A.M., Brown, S.E., Naismith, J.H. and White, M.F. (2008) Structure of the DNA repair helicase XPD. Cell, 133, 801–812.

44. Pugh, R.A., Honda, M., Leesley, H., Thomas, A., Lin, Y., Nilges, M.J., Cann, I.K. and Spies, M. (2008) The iron-containing domain is essential in Rad3 helicases for coupling of ATP hydrolysis to DNA translocation and for targeting the helicase to the single-stranded DNA-double-stranded DNA junction. J. Biol. Chem., 283, 1732–1743.

45. Veatch, J.R., McMurray, M.A., Nelson, Z.W. and Gottschling, D.E. (2009) Mitochondrial dysfunction leads to nuclear genome instability via an iron–sulfur cluster defect. Cell, 137, 1247–1258.

46. Warbrick, E. (1998) PCNA binding through a conserved motif. Bioessays, 20, 195–199.

47. Sung, P., Krejci, L., Van Komen, S. and Schorn, M.G. (2003) Rad51 recombinase and recombination mediators. J. Biol. Chem., 278, 42792–42732.

48. Kasamatsu, H., Robberson, D.L. and Vinograd, J. (1971) A novel closed-circular mitochondrial DNA with properties of a replicating intermediate. Proc. Natl Acad. Sci. USA, 68, 2252–2257.

49. Allers, T. and Lichten, M. (2001) Differential timing and control of noncrossover and crossover recombination during meiosis. Cell, 106, 47–57.

50. Cromie, G.A., Hyppa, R.W., Taylor, A.F., Zakharievich, K., Hunter, N. and Smith, G.R. (2006) Single Holliday junctions are intermediates of meiotic recombination. Cell, 127, 1167–1178.

51. Schwacha, A. and Kleckner, N. (1995) Identification of double Holliday junctions as intermediates in meiotic recombination. Cell, 83, 783–791.

52. Adelman, C.A. and Boulton, S.J. (2010) Metabolism of postsynaptic recombination intermediates. FEBS Lett., 584, 3709–3716.

53. Bugrev, D.V. and Mazin, A.V. (2004) Ca2+ activates human homologous recombination protein Rad51 by modulating its ATPase activity. Proc. Natl Acad. Sci. USA, 101, 9988–9993.

54. Bugrev, D.V., Yu, X., Egelman, E.H. and Mazin, A.V. (2007) Novel pro- and anti-recombination activities of the Bloom’s syndrome helicase. Genes Dev., 21, 3085–3094.

55. Sommers, J.A., Rawtani, N., Gupta, R., Bugrev, D.V., Mazin, A.V., Cantor, S.B. and Brosh, R.M. Jr (2009) FANCJ uses its motor ATPase to destabilize protein-DNA complexes, unwind triplexes, and inhibit RAD51 strand exchange. J. Biol. Chem., 284, 7505–7517.

56. Krejci, L., Van Komen, S., Li, Y., Vilmalj, J., Reddy, M.S., Klein, H., Ellenberger, T. and Sung, P. (2003) DNA helicase Srs2 disrupts the Rad51 presynaptic filament. Nature, 423, 305–309.

57. Veauze, X., Jeasset, J., Soustelle, C., Kowalezkowski, S.C., Le Cam, E. and Fabre, F. (2003) The Srs2 helicase prevents recombination by disrupting Rad51 nucleoprotein filaments. Nature, 423, 399–399.

58. Hu, Y., Raynard, S., Sehorn, M.G., Lu, X., Bussen, W., Zheng, L., Stark, J.M., Barnes, E.L., Chi, P., Janssak, P. et al. (2007) RECQ15/Recq15 helicase regulates homologous recombination and suppresses tumors formation via disruption of Rad51 presynaptic filaments. Genes Dev., 21, 3073–3084.

59. Fugger, K., Mistrik, M., Danielsen, J.R., Dinant, C., Falk, J., Bartk, J., Lukas, J. and Mailand, N. (2009) Human Fh1 helicase contributes to genome maintenance via pro- and anti-recombination activities. J. Cell. Biol., 186, 655–663.

60. Prakash, R., Satory, D., Dray, E., Papusha, A., Scheller, J., Kramer, W., Krejci, L., Klein, H., Haber, J.E., Sung, P. et al. (2009) Yeast Mph1 helicace dynamin-like associates Rad51-mude D-loops: implications for crossover control in mitotic recombination. Genes Dev., 23, 67–79.
61. Wang,R.C., Smogorzewska.A. and de Lange,T. (2004) Homologous recombination generates T-loop-sized deletions at human telomeres. Cell, 119, 355–368.

62. Lillard-Wetherell,K., Machwe,A., Langland,G.T., Combs,K.A., Behbehani,G.K., Schenberg,S.A., German,J., Turchi,J.J., Orren,D.K. and Groden,J. (2004) Association and regulation of the BLM helicase by the telomeres proteins TRF1 and TRF2. Hum. Mol. Genet., 13, 1919–1932.

63. Opresko,P.L., Mason,P.A., Pedell,E.R., Loi,M., Hickson,I.D., Cech,T.R. and Bohr,V.A. (2005) POT1 stimulates ReqG helicases WRN and BLM to unwind telomeric DNA substrates. J. Biol. Chem., 280, 32069–32080.

64. Opresko,P.L., Otterlei,M., Graakjaer,J., Bruheim,P., Dawut,L., Kolvraa,S., May,A., Seidman,M.M. and Bohr,V.A. (2004) The Werner syndrome helicase and exonuclease cooperate to resolve telomeric D loops in a manner regulated by TRF1 and TRF2. Mol. Cell., 14, 763–774.

65. Opresko,P.L., von Kobbe,C., Laine,J.P., Harrigan,J., Hickson,I.D. and Bohr,V.A. (2002) Telomere-binding protein TRF2 binds to and stimulates the Werner and Bloom syndrome helicases. J. Biol. Chem., 277, 41100–41119.

66. Ghosh,A., Rossi,M.L., Auldts,J., Croteau,D. and Bohr,V.A. (2009) Telomeric D-loops containing 8-oxo-2'-deoxyguanosine are preferred substrates for Werner and Bloom syndrome helicases and are bound by POT1. J. Biol. Chem., 284, 31074–31084.

67. London,T.B., Barber,L.J., Mosedale,G., Kelly,G.P., Opresko,P.L., von Kobbe,C., Laine,J.P., Harrigan,J., Hickson,I.D. and Balasubramanian,S., Hickson,I.D., Boulton,S.J. and Hiom,K. (2008) FANCJ is a structure-specific DNA helicase associated for the identification of G-quadruplex structures: discovery of a DNA–RNA G-quadruplex. Angew. Chem. Int. Ed. Engl., 47, 5136–5139.

68. Wu,Y., Shin-ya,K. and Brosh,R.M. Jr (2008) FANCJ helicase are DNA structure-specific helicases. EMBO J., 27, 9–15.

69. Anderson,L.K., Reeves,A., Webb,L.M. and Ashley,T. (1999) Distribution of crossing over on mouse synaptonemal complexes using immunofluorescent localization of MLH1 protein. Genetics, 151, 1569–1579.

70. Yang,H.H. and Spyropoulos,B. (1997) Rad51 immunocytology and stained cross-link repair. J. Biol. Chem., 272, 13615–13619.

71. Yu,Y., Suzuki,Y. and Komiyama,M. (2009) Click chemistry upstream of guanine-rich DNA. Disruption of dog-1 in Caenorhabditis elegans triggers deletions in Spectrum of mutational events in the absence of DOG-1/FANCJ defective in Fanconi anemia and breast cancer unwinds defective in C elegans. J. Biol. Chem., 283, 2098–2110.

72. Xu,Y., Suzuki,Y. and Komiyama,M. (2010) Telomeric D-loops containing 8-oxo-2'-deoxyguanosine are DNA structure-specific helicases. J. Biol. Chem., 283, 32069–32080.

73. Xu,Y., Suzuki,Y. and Komiyama,M. (2009) Telomeric D-loops containing 8-oxo-2'-deoxyguanosine are preferred substrates for Werner and Bloom syndrome helicases and are bound by POT1. J. Biol. Chem., 284, 31074–31084.

74. London,T.B., Barber,L.J., Mosedale,G., Kelly,G.P., Opresko,P.L., von Kobbe,C., Laine,J.P., Harrigan,J., Hickson,I.D. and Balasubramanian,S., Hickson,I.D., Boulton,S.J. and Hiom,K. (2008) FANCJ is a structure-specific DNA helicase associated for the identification of G-quadruplex structures: discovery of a DNA–RNA G-quadruplex. Angew. Chem. Int. Ed. Engl., 47, 5136–5139.

75. Wu,Y., Shin-ya,K. and Brosh,R.M. Jr (2008) FANCJ helicase are DNA structure-specific helicases. EMBO J., 27, 9–15.

76. Anderson,L.K., Reeves,A., Webb,L.M. and Ashley,T. (1999) Distribution of crossing over on mouse synaptonemal complexes using immunofluorescent localization of MLH1 protein. Genetics, 151, 1569–1579.

77. Yang,H.H. and Spyropoulos,B. (1997) Rad51 immunocytology and stained cross-link repair. J. Biol. Chem., 272, 13615–13619.

78. Wu,Y., Shin-ya,K. and Brosh,R.M. Jr (2008) FANCJ helicase are DNA structure-specific helicases. EMBO J., 27, 9–15.

79. Sun,H., Karow,J.K., Hickson,I.D. and Maizels,N. (1998) The Bloom's syndrome helicase and exonuclease cooperate to resolve telomeric D loops in a manner regulated by TRF1 and TRF2. Mol. Cell., 14, 763–774.

80. Sfeir,A., Kosiyatrakul,S.T., Hockemeyer,D., MacRae,S.L., Karlseder,J., Schildkraut,C.L. and de Lange,T. (2004) Saccharomyces cerevisiae Mre11 is a high-affinity G4 DNA-binding protein and a G-rich DNA-specific endonuclease: implications for replication of telomeric DNA. Nucleic Acids Res., 33, 4692–4703.

81. Muniyappa,K., Anuradha,S. and Byers,B. (2008) Yeast meiosis-specific protein Hop1 binds to G4 DNA and promotes its formation. Mol. Cell. Biol., 20, 1361–1369.