Investigating the role of Rts1 in DNA replication initiation

Ana B.A. Wallis ID, Conrad A. Nieduszynski ID

Sir William Dunn School of Pathology, University of Oxford, Oxford, Oxfordshire, OX1 3RE, UK

Abstract

Background: Understanding DNA replication initiation is essential to understand the mis-regulation of replication seen in cancer and other human disorders. DNA replication initiates from DNA replication origins. In eukaryotes, replication is dependent on cell cycle kinases which function during S phase. Dbf4-dependent kinase (DDK) and cyclin-dependent kinase (CDK) act to phosphorylate the DNA helicase (composed of mini chromosome maintenance proteins: Mcm2-7) and firing factors to activate replication origins. It has recently been found that Rif1 can oppose DDK phosphorylation. Rif1 can recruit protein phosphatase 1 (PP1) to dephosphorylate MCM and restricts origin firing. In this study, we investigate a potential role for another phosphatase, protein phosphatase 2A (PP2A), in regulating DNA replication initiation. The PP2A regulatory subunit Rts1 was previously identified in a large-scale genomic screen to have a genetic interaction with ORC2 (a DNA replication licensing factor). Deletion of RTS1 synthetically rescued the temperature-sensitive (ts-) phenotype of ORC2 mutants.

Methods: We deleted RTS1 in multiple ts-replication factor Saccharomyces cerevisiae strains, including ORC2. Dilution series assays were carried out to compare qualitatively the growth of double mutant Δrts1 ts-replication factor strains relative to the respective single mutant strains.

Results: No synthetic rescue of temperature-sensitivity was observed. Instead we found an additive phenotype, indicating gene products function in separate biological processes. These findings are in agreement with a recent genomic screen which found that RTS1 deletion in several ts-replication factor strains led to increased temperature-sensitivity.

Conclusions: We find no evidence that Rts1 is involved in the dephosphorylation of DNA replication initiation factors.
Introduction

Errors during DNA replication can lead to aneuploidy and DNA damage (Passerini et al., 2016). An insufficient concentration of replication factors can also lead to genomic instability (Orr et al., 2010). Therefore, it is important that cells ensure that a single round of DNA replication occurs in each cell cycle. DNA replication initiates from DNA replication origins (origins). In *Saccharomyces cerevisiae* origins are formed of an autonomously replicating sequence (ARS) which contains an 11bp ARS consensus sequence (ACS). Origins recruit the origin recognition complex (ORC) via the ACS, which in turn facilitates origin licensing. Origin licensing factors (Cdc6 and Cdt1) bind at the origin and allow the mini-chromosome maintenance (MCM) proteins to also bind. Post-licensing, firing factors (Cdc45, Sld2, Sld3, Dpb11) recruit the loading complex which contains GINS (a four-subunit complex), Cdc45 and the replicative polymerases (Polɛ, Polδ and Polτ) (Yeeles et al., 2015). Cdc45, MCM and GINS collectively form the CMG (Yeeles et al., 2015). The CMG melts DNA, unwinding the DNA double helix to allow loading of the polymerases, to begin DNA replication. To prevent re-replication, origin licensing in eukaryotes is limited to G1 phase of the cell cycle, and origin firing is restricted to S phase (Blow & Dutta, 2005). In *S. cerevisiae*, loss of DNA re-replication control leads to genome instability including gene amplification (Green et al., 2010).

The activities of licensing and firing factors are influenced by cell cycle kinases. For example, origin firing is dependent upon two kinases: the Dpb4-dependent kinase (DDK) and the cyclin-dependent kinase (CDK). DDK phosphorylates multiple chromatin-bound MCM subunits, including Mcm4 and Mcm6. Phosphorylation facilitates Sld3, Sld7 and Cdc45 binding. Subsequently, CDK phosphorylates Sld3 and Sld2, which then recruits the loading complex (Zegerman, 2015), which leads to origin firing.

However, the kinase-driven view of replication initiation outlined above is now known to be incomplete (Dağ et al., 2014). A role for dephosphorylation in controlling DNA replication initiation was established recently (Dağ et al., 2014; Hiraga et al., 2014; Mattarocci et al., 2014; Poh et al., 2014). The Rap1-interacting factor (Rif1) is able to recruit protein phosphatase 1 (PP1) to MCM subunits and dephosphorylate them (Dağ et al., 2014; Hiraga et al., 2014; Mattarocci et al., 2014; Poh et al., 2014). A greater DDK concentration is therefore required to promote origin firing, since the MCM phosphorylation rate must exceed its dephosphorylation rate. Conversely, DDK can bind directly to Rif1 and inhibit its interaction with PP1 (Hiraga et al., 2014). Therefore, as DDK levels increase during S phase, MCM phosphorylation is promoted and dephosphorylation is inhibited. The resulting feedback loop allows for a rapid switch from low MCM phosphorylation in G1 to high MCM phosphorylation in S phase.

Rif1-PP1 involvement in DNA replication control appears to be conserved throughout eukaryotes, both *Xenopus* egg extract and HeLa cell studies support the findings in yeast (Poh et al., 2014; Yamazaki et al., 2012). Additionally, there is evidence that Rif1-PP1 controls further aspects of DNA replication initiation. For example, in yeast, Rif1-PP1 may antagonise CDK phosphorylation (Stark et al., 2015). In *RIF1* null yeast strains phosphorylation of Sld3, but not Sld2, is increased (Mattarocci et al., 2014). Deletion of *RIF1* can partially rescue the phenotype of temperature-sensitive (ts-) origin firing factor alleles including Dpb11, Cdc45 and Sld3 (Mattarocci et al., 2014). In human cells, Rif1-PP1 is active during mitotic exit. Dephosphorylation of Orc2, an ORC subunit, allows the process of origin licensing to start again. Human Rif1-PP1 not only antagonises MCM phosphorylation, but also positively promotes DNA replication origin licensing (Hiraga et al., 2017).

Before a role for Rif1-PP1 in DNA replication was described, Rif1 was known to be a telomere-associated protein, contributing to the late replication of telomeric regions (Lian et al., 2011). Rif1 has also been implicated in a PP1-independent role in DNA replication at the whole genome level. The conserved replication timing of some genomic domains is altered in *RIF1* mutant cells due to disordered chromatin organisation. These observations led to a role for Rif1 in physically grouping similarly timed replication domains being described (Foti et al., 2016).

The importance of Rif1-PP1 dephosphorylation raises the question of whether other phosphatases are implicated in DNA replication control. A large genomic screen for genetic interactions previously identified a potential synthetic rescue of mutant ORC2 by additional *RTS1* deletion (Costanzo et al., 2010). Rts1 is a regulatory subunit for the PP2A phosphatase, which has been previously implicated in DNA replication. PP2A antagonises the DNA damage checkpoint protein Chk1 (Petersen et al., 2006), and its function is required for Cdc45 loading onto chromatin (Chou et al., 2002; Peplowska et al., 2014). Whether this interaction is direct, occurs via dephosphorylation of Sld3 (Guo et al., 2015), or uses another protein complex (Chowdhury et al., 2010) is as yet unclear. It has also been proposed that another regulatory subunit of PP2A, PR-48, allows it to bind to and dephosphorylate the licensing factor Cdc6 during mitotic exit, promoting origin licensing during G1 (Yan et al., 2000). Unlike PP1, which in humans is regulated by more than 90 different subunits, PP2A has only 13 regulatory subunits in humans, and 3 in yeast (Stark et al., 2015).

Whilst Rif1 is associated with telomeres and late-replicating regions of DNA, Rts1 is associated with the protection of centromeres, which are known to replicate early (Mccarroll & Fangman, 1988). Rts1-PP2A is enriched at centromeres pre-anaphase promoting cell cycle progression after appropriate microtubule binding, and correct chromosome segregation (Peplowska et al., 2014).

This study investigates a putative role for Rts1-PP2A, akin to Rif1-PP1, in controlling DNA replication licensing and firing. We use a panel of ts-replication factor mutants to screen for synthetic rescue by *RTS1* deletion. We find that *RTS1* deletion using classical genetics does not alleviate the lethality caused by inactivating origin initiation factors. Whilst the published synthetic rescue given by *rff1Δ* is confirmed in these strains, we
find an additive effect for rts1Δ. This indicates that two separate pathways are compromised. Although these data contradict the original genetic interactions screen (Costanzo et al., 2010) they are in accordance with a more recent screen (Costanzo et al., 2016), suggesting that RTS1 deletion results in an enhanced (rather than alleviated) phenotype in some replication factor mutants.

**Methods**

**Yeast strains and methods**

Yeast strains were cultured both in liquid and on solid YPAD media (CCM1010 and CM0510 respectively; Formedium, Hunstanton, UK), and manipulated according to established practices (Treco & Winston, 2008). Most yeast strains used had a W303 background. However, strains from the *S. cerevisiae* genome deletion project (Giaever et al., 2002) had an S288c background. All strains used are listed in Table 1.

In order to delete *S. cerevisiae* genes, the appropriate KanMX deletion cassettes from the SGDP were incorporated into a recipient strain by transformation. Deletion was confirmed by PCR spanning the deletion site. Oligonucleotide sequences are listed in Table 2. Ts-initiation factor mutant strains were confirmed by a lack of growth on solid YPAD plates at restrictive temperatures. Ts-initiation factor mutations with respective permissive and restrictive temperatures are listed in Table 3. Double mutant (ts-mutant / gene deletion) strains were confirmed by temperature-sensitivity and G418 resistance (400 µg/ml G418 disulfate salt; A1720-5G, Sigma-Aldrich, St Louis, MO, USA), relative to wild-type sister colonies.

### Table 1. List of yeast strains

<table>
<thead>
<tr>
<th>STRAIN</th>
<th>GENOTYPE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7107</td>
<td>MATa: RAD5, BUD4, leu2, ura3, trp1, ade2, his3</td>
<td>T. Tanaka lab</td>
</tr>
<tr>
<td>45-1</td>
<td>MATa: leu2-3, 112 ura3-52 ade2-1 lys2-801 cdc45-1</td>
<td>C. Nieduszynski lab</td>
</tr>
<tr>
<td>CNY167</td>
<td>MATa: ade2-1 his3-11,15 leu2-3,112 trp1-1 ura3-1 can1-100 Gal+ orc5-1</td>
<td>C. Nieduszynski lab</td>
</tr>
<tr>
<td>AUY080</td>
<td>MATa: ade2-1 trp1-1 can1-100 leu2-3,112 his3-11,15 ura3 GAL+ ssd1,d2 RAD5 orc2-1</td>
<td>C. Nieduszynski lab</td>
</tr>
<tr>
<td>K2539</td>
<td>MATa: cdc9-1 Backcrossed three times to K69/K700</td>
<td>T. Tanaka lab</td>
</tr>
<tr>
<td>dbf4-1</td>
<td>MATa: ade2-1 his3-11,15 leu2-3,112 trp1-1 ura3-1 can1-100 ssd1,d2 Gal+ dbf4-1</td>
<td>Tanaka &amp; Nasmyth, 1996</td>
</tr>
<tr>
<td>YKB2</td>
<td>MATa: leu2-3,112 trp1-1 can1-100 ura3-1 ade2-1 his3-11,15, cdc7-4</td>
<td>Mattarocci et al., 2014</td>
</tr>
<tr>
<td>YYK32</td>
<td>MATa: leu2-3,112 trp1-1 can1-100 ura3-1 ade2-1 his3-11,15, cdc45-27, bar1Δ::hisG</td>
<td>Mattarocci et al., 2014</td>
</tr>
<tr>
<td>YYK14</td>
<td>MATa: leu2-3,112 trp1-1 can1-100 ura3-1 ade2-1 his3-11,15, sld3-4, bar1Δ::hisG</td>
<td>Mattarocci et al., 2014</td>
</tr>
<tr>
<td>YNIG63(2)</td>
<td>MATa: leu2-3,112 trp1-1 can1-100 ura3-1 ade2-1 his3-11,15, dpb11-24, bar1Δ::hisG</td>
<td>Mattarocci et al., 2014</td>
</tr>
<tr>
<td>YCH175</td>
<td>MATα: ho, ade2, trp1, can1, leu2, his3, GAL, psi + W303-1; cdc6-1</td>
<td>Mattarocci et al., 2014</td>
</tr>
<tr>
<td>YOR014W</td>
<td>rts1Δ::KanMX S288c</td>
<td>Giaever et al., 2002</td>
</tr>
<tr>
<td>YBR275C</td>
<td>rif1Δ::KanMX S288c</td>
<td>Giaever et al., 2002</td>
</tr>
<tr>
<td>YDR007W</td>
<td>trp1Δ::KanMX S288c</td>
<td>Giaever et al., 2002</td>
</tr>
<tr>
<td>ACY001</td>
<td>W303 MATα rts1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY004</td>
<td>W303 MATα rts1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY007</td>
<td>W303 MATα rif1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY010</td>
<td>W303 MATα rif1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY013</td>
<td>W303 MATα trp1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY016</td>
<td>W303 MATα trp1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY036</td>
<td>W303 Diploid orc2-1 rts1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY113</td>
<td>W303 MATα orc2-1 rts1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY044</td>
<td>W303 Diploid orc2-1 rif1Δ::kanMX</td>
<td>This Study</td>
</tr>
<tr>
<td>ACY100</td>
<td>W303 MATα orc2-1 rif1Δ::kanMX</td>
<td>This Study</td>
</tr>
</tbody>
</table>
Dilution series assay
Strains were inoculated into YPAD liquid medium and cultured for 12–16 hours. Haploid cell concentration was inferred from attenuation measured at 600 nm (using a BioMate3 spectrophotometer; Thermofisher, Waltham, MA, USA). Cells were diluted initially to 10^7 cells/ml, before serial 10-fold dilutions were prepared. Dilution spots of 5 µl were pipetted onto YPAD agar plates and incubated at stated temperatures. Control strains were included on each plate. After two days, plates were photographed and images were analysed qualitatively by observation of relative growth of yeast strains.

Results
RTS1 deletion does not synthetically rescue orc2-1
The combination of two mutations, which individually decrease cell fitness, can restore fitness if the genes have opposing effects (Synthetic Rescue, Figure 1). In the presence of a replication factor mutant, such as orc2-1, even at the permissive temperature origin firing can be reduced by as much as 30% (Shimada et al., 2002), leading to growth deficiency. We first examined RTS1 deletion in an orc2-1 strain (Figure 2A), since a synthetic rescue phenotype has been reported (Costanzo et al., 2010). A dilution series viability assay was used to assess synthetic rescue. We found that an orc2-1 rts1Δ strain had a more severe ts-phenotype than either the orc2-1 or rts1Δ strains (Figure 2A). This additive effect indicates that the two genes are not acting within the same pathway. Conversely, a small synthetic rescue was observed in the orc2-1 rif1Δ strain (Figure 2A). It has previously been shown that RIF1 deletion leads to slight synthetic rescue in orc5-1 strains, consistent with this result (Matarrocci et al., 2014).

The origin licensing factor Cdc6 is not opposed by RTS1
Since Rif1 recruits PP1 to oppose DDK phosphorylation, RIF1 deletion provides limited or no rescue to the temperature sensitivity of pre-Replication Complex (pre-RC) factors mutants, which
Table 2. List of oligonucleotides. A list of oligonucleotides used in this study.

<table>
<thead>
<tr>
<th>PRIMER 1</th>
<th>PRIMER 2</th>
<th>PRODUCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC0003</td>
<td>AC0004</td>
<td>rif1Δ::kanMX</td>
</tr>
<tr>
<td>TTTTCAGTTCTTTGTGTTTTTCC</td>
<td>GATCCCTTTAGAATGGAGAATTG</td>
<td></td>
</tr>
<tr>
<td>AC0005</td>
<td>AC0006</td>
<td>tsf1Δ::kanMX</td>
</tr>
<tr>
<td>TAAACCATCGTCGCCGTAAGA</td>
<td>GGAAGAGGGAAGCGAAAAGA</td>
<td></td>
</tr>
<tr>
<td>CA1118</td>
<td>CA0010</td>
<td>Confirms 5' insertion of rif1Δ::kanMX</td>
</tr>
<tr>
<td>CCATTACGCTGCTATCAAGA</td>
<td>AAGAAACAAGAAGTCAACAGAAG</td>
<td></td>
</tr>
<tr>
<td>CA1117</td>
<td>CA0009</td>
<td>Confirms 3' insertion of rif1Δ::kanMX</td>
</tr>
<tr>
<td>GATAATGTCGGGCAATCAGG</td>
<td>GCGGTAGCATTTCCATCATAA</td>
<td></td>
</tr>
<tr>
<td>CA1118</td>
<td>CA0011</td>
<td>Confirms 5' insertion of rts1Δ::kanMX</td>
</tr>
<tr>
<td>CCATTACGCTGCTATCAAGA</td>
<td>GGCATGTCAATACGTCTCGTT</td>
<td></td>
</tr>
<tr>
<td>CA1117</td>
<td>CA0012</td>
<td>Confirms 3' insertion of rts1Δ::kanMX</td>
</tr>
<tr>
<td>GATAATGTCGGGCAATCAGG</td>
<td>GGCAAGGTTTGACGAAAAGA</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Temperature-sensitive mutation strains used in this study. Mutant forms of replication initiation factors, temperatures at which we observed phenotypes, and the study that originally reported each strain.

<table>
<thead>
<tr>
<th>TS-REPLICATION FACTOR MUTATION</th>
<th>TEMPERATURE AT WHICH PHENOTYPE OBSERVED</th>
<th>TEMPERATURE AT WHICH NO PHENOTYPE OBSERVED</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>orc2-1</td>
<td>30</td>
<td>23</td>
<td>Foss et al., 1993</td>
</tr>
<tr>
<td>cdc6-1</td>
<td>33</td>
<td>30</td>
<td>Hartwell et al., 1973</td>
</tr>
<tr>
<td>cdc7-4</td>
<td>30</td>
<td>23</td>
<td>Hartwell et al., 1973</td>
</tr>
<tr>
<td>dbf4-1</td>
<td>32</td>
<td>30</td>
<td>Johnston &amp; Thomas, 1982</td>
</tr>
<tr>
<td>cdc45-27</td>
<td>32</td>
<td>30</td>
<td>Kamimura et al., 2001</td>
</tr>
<tr>
<td>cdc45-1</td>
<td>23</td>
<td>30</td>
<td>Moir et al., 1982</td>
</tr>
<tr>
<td>cdc9-1</td>
<td>30</td>
<td>23</td>
<td>Hartwell et al., 1973</td>
</tr>
<tr>
<td>dpb11-24</td>
<td>37</td>
<td>32</td>
<td>Tanaka et al., 2007</td>
</tr>
</tbody>
</table>

function prior to DDK (Mattarocci et al., 2014). Given that this study aimed to investigate a role for Rts1 in opposing the action of Orc2, we next looked for a genetic interaction between RTS1 and another origin licensing factor: CDC6, which loads MCM. Deleting RTS1 in the context of cdc6-1 showed no rescue relative to the original ts-strain (Figure 2B). Similarly, deletion of RIF1 gave no synthetic rescue, consistent with published data (Mattarocci et al., 2014). It has previously been shown that rts1Δ yeast strains are ts at 37°C (Auesukaree et al., 2009; Shu & Hallberg, 1995), while rif1Δ strains are not (Mattarocci et al., 2014). Our study confirmed both these phenotypes (Figure 2B).

Rts1 does not antagonise DDK phosphorylation
A potential role for Rts1-PP2A phosphatase in DNA replication initiation could be to oppose the action of a kinase. The established role for Rif1-PP1 in opposing DDK activity indicates that regulation of phosphorylation is key during this step of replication initiation. Therefore, RTS1 was deleted in combination with ts-forms of both subunits of DDK (Cdc7 and Dbf4). However, rts1Δ had a slightly additive effect on temperature-sensitivity in both cdc7-4 (Figure 3A) and dbf4-1 (Figure 3B) strains. This was in stark contrast to the strong restoration of cell growth at elevated temperatures in cdc7-4 rif1Δ (Figure 3A) and dbf4-1 rif1Δ (Figure 3B) strains. This suggests that Rif1 and Rts1 do not have analogous roles in control of DNA replication initiation, and that Rts1-PP2A does not antagonise DDK activity.

Replication firing factors are not opposed by Rts1
MCM phosphorylation by DDK recruits the firing factor, Cdc45. The sequential recruitment of further firing factors (e.g. Dpb11) relies on phosphorylation by CDK. Therefore, Rts1-PP2A activity could be important following DDK activity, to limit CDK-induced origin firing. In order to test this hypothesis, RTS1 was deleted in the context of ts- cdc45-1 and dpb11-24 firing factors. Unlike rif1Δ,
**Figure 1. A summary of genetic interactions.** Two genes, A and B, show genetic interactions as a result of the interacting functions of their products: A and B. When A and B function in different cellular processes, the relative fitness of an \(AB\) double mutant is a product of the relative fitness of the two single mutants (no genetic interaction). If the double mutant strain has a lower than expected viability, it is described as synthetic lethality, indicating redundant functions for the two gene products in one cellular process. In contrast, a greater than expected viability (synthetic rescue) indicates that the gene products have opposing roles in a cellular process.

**rts1Δ** did not rescue **cdc45-27** or **dpb11-24** temperature-sensitivity (Figure 4AI, 4B). Conversely, **rts1Δ** led to an increased lethality in these strains, suggesting either an additive or synthetic lethality effect (Figure 1).

However, the cold-sensitive **cdc45-1** strain (restricted at 15°C) had no phenotypic rescue by either **rif1Δ** or **rts1Δ** (Figure 4AII). Instead, an additive effect was observed for both gene deletions, which was stronger in the case of **RTS1**. This additive effect of **rif1Δ** in cold-sensitive **cdc45-1** contradicts the known rescue of **ts-cdc45-27** by **rif1Δ** (Mataracce et al., 2014), a finding repeated in this study. Therefore, the significance of an additive effect of **rts1Δ** with **cdc45-1** is unclear.

**Synthetic lethality of RTS1 and CDC9 ligase**

Since the detrimental effect of **RTS1** deletion alongside ts-DNA replication initiation factors appeared to be most severe in factors which function later in the firing process, we hypothesised that Rts1 could play a role in DNA replication post-firing. Therefore, **RTS1** was deleted alongside a ts-**CDC9** ligase allele (**cdc9-1**). Cdc9 ligates lagging strand Okazaki fragments, aiding in DNA replication during elongation. **RTS1** deletion in a **cdc9-1** strain led to the greatest synthetic lethality, relative to **RTS1** deletion in the other ts-strains examined. No effect of **rif1Δ** was seen in **cdc9-1** cells. This was anticipated, since Rif1 is known to function during replication initiation. These data show that, if Rts1 plays a role in DNA replication, it is not akin to that...
Discussion

In this study, \textit{RTS1}, which encodes a regulatory subunit for the PP2A phosphatase, was deleted in the context of a range of ts-replication factor mutants. At no stage of DNA replication initiation (licensing, DDK-phosphorylation, and origin firing) did deletion of \textit{RTS1} lead to synthetic rescue of ts-phenotypes. In contrast, deletion of \textit{RIF1} was able to rescue ts-mutants of replication firing factors, and some replication licensing factors. Rif1 recruits PP1 phosphatase to DNA replication origins where it counteracts MCM phosphorylation by DDK. When replication origin firing is limited by mutant replication factors, removing this negative regulation allows more replication origins to fire, giving synthetic rescue. In contrast, \textit{rts1Δ} leads to increased temperature-sensitivity when combined with \textit{orc2-1}, \textit{cdc7-4}, \textit{cdc61S-1}, and \textit{dpb11-24} mutant replication factors. The lack of synthetic rescue given by \textit{rts1Δ} in these strains indicates that there is no evidence for a role for Rts1 in limiting origin firing, analogous to that played by Rif1.

Without a genetic interaction, combining mutations in genes involved in separate pathways will give an additive effect.
However, alone, \( rts1 \Delta \) has no growth inhibition at temperatures below 34°C. Therefore, the extent of reduced cell viability seen in some double mutant strains, such as \( dpb11-24 \ rts1 \Delta \) at 32°C (Figure 4), suggests synthetic lethality. This may be the result of non-specific protein instability after heat stress, in \( rts1 \Delta \) strains. Over-expression of \( RTS1 \) can partially rescue lethality of a ts-\( HPS60 \) allele (Shu & Hallberg, 1995). Hps60 is a mitochondrial protein that aids in protein refolding after heat stress (Shu & Hallberg, 1995). A reduced capability to maintain protein structure in heat stress conditions could explain the increased temperature sensitivity of unstable replication factor forms in \( rts1 \Delta \) cells. This could be analogous to the partial rescue of the ts-phenotype of \( orc2-1 \) by mutations in the ubiquitin ligase \( UBA1 \) (Shimada et al., 2002). Therefore, investigation of heat stress in \( rts1 \Delta \) strains would be needed to elucidate the molecular mechanism.

The extent of the additional lethality given by \( rts1 \Delta \) alongside mutant ts-replication factors is inconsistent. If added lethality of \( rts1 \Delta \) depends on the function of the ts-factor, this could indicate a functional genetic interaction between that replication factor and \( RTS1 \). In DDK and pre-RC factor mutants (\( cdc7-4 \), \( dbf4-1 \), \( cdc6-1 \)) there is either mildly increased temperature-sensitivity or no effect given by \( rts1 \Delta \) (Figure 2B, Figure 3). However, in post-DDK acting firing factors \( cdc45-1 \) and \( dpb11-24 \), the observed increase in the ts-phenotype is larger (Figure 4). We cannot exclude the possibility that this effect is due to greater heat-instability of the \( cdc45-1 \) and \( dpb11-24 \) mutant replication factors. However, these

![Figure 4. RTS1 causes synthetic lethality with DNA replication firing factors and a DNA replication progression factor.](image_url)

Budding yeast strains with ts-mutants of replication factors, together with either wild type, \( rts1 \Delta \) or \( rif1 \Delta \) were characterised by dilution viability assays. Wild type strains, without ts-replication factors, are shown at the top of each panel, as a control. (A) Ts- (I) and cold- sensitive (II) forms of Cdc45, (B) the replication firing factor Dbp11, which functions post-DDK, and (C) Cdc9 ligase, are assayed.
data may suggest a role for Rts1 late in DNA replication initiation, demonstrating a genuine negative genetic interaction between RTS1 and post-DDK replication firing factors.

Interestingly, the greatest synthetic lethality is seen between RTS1 and a replication elongation factor: CDC9. Cdc9 is important for DNA replication progression and elongation rather than initiation. Accordingly, we find no synthetic rescue by rif1Δ in the cdc9-1 strain (Figure 4). The observed synthetic lethality of RTS1 deletion in a cdc9-1 strain may provide evidence for a complementary role for Rts1 function in allowing replication fork progression. In cdc9-1 strains, increased DNA damage is seen due to the collapse of replication forks. This results in double strand breaks (DSBs), and the DNA damage response (DDR) being activated. One of the ways to repair DSBs is via break-induced replication (BIR), which is activated in cdc9-1 cells (Vasianovich et al., 2014). A role for Rts1 in recruiting PP2A phosphatase to control phosphorylation steps in the DDR, potentially in BIR, could be hypothesised. In this instance, rts1Δ in a cdc9-1 background would give increased lethality, since there would also be an impaired capacity for cells to repair cdc9-1 dependent DSBs.

Evidence in support of the synthetic lethality of RTS1 and DNA replication factors can be found on BioGRID, a summary of published genetic interactions in budding yeast. A combination of high and low throughput genetic interaction screens show that RTS1 exhibits negative genetic interactions (a term reserved for genetic screens which show a more lethal phenotype in strains where two mutations are combined than in the respective single mutant strains) with DBF4, CDC6 and ORC6 and DPB11 (Archambault et al., 2005; Collins et al., 2007; Costanzo et al., 2016). However, we show here, for the first time, negative genetic interactions of RTS1 with CDC45 and CDC9.

Conclusions

Given the wealth of recent literature outlining the importance of Rif1 in opposing the actions of DDK kinase, it is clear that phosphatases play an important role in controlling DNA replication origin firing. However, we do not find evidence for an analogous role for PP2A, specifically via its regulatory subunit Rts1. Deletion of RTS1 in combination with mutations in origin licensing factor genes, ORC and CDC6, showed little or no genetic interaction, providing no genetic evidence for Rts1-PP2A controlling DNA replication origin licensing. Further, we found no role for Rts1 in opposing DDK phosphorylation. However, we observed some level of increased temperature-sensitivity phenotype when RTS1 was deleted in many of the replication initiation factor mutant strains, alluding to a potential synthetic lethality phenotype. Increased temperature-sensitivity was most pronounced in late-acting DNA replication firing factors Cdc45 and Dpb11. Additionally, an increased requirement for RTS1 in a cdc9-1 background was found. We speculate that a functional overlap between Rts1-PP2A and Cdc9 may exist via replication fork progression mechanisms. Rts1 may recruit PP2A during BIR, or the DDR, in response to DSBs. Over-expression of RTS1 could potentially compensate for the increased replication fork collapse seen in cdc9-1 mutants, giving synthetic rescue of temperature-sensitivity. Further studies would be needed to confirm this hypothesis.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

Competing interests

No competing interests were disclosed.

Grant information

Wellcome Trust [110064] grant to CN.

Biotechnology and Biological Sciences Research Council [BB/M011224/1] grant funded AW.

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgements

We are grateful to Tomoyuki Tanaka and David Shore for sending us yeast strains, detailed in Table 1. We are also grateful to Carolin A. Müller, Dzmitry G. Batrakou, Rosemary H.C. Wilson and Emma D. Heron who gave feedback on the manuscript.

References


time is mediated by telomere length but is independent of histone tail
Published Abstract | Publisher Full Text | Free Full Text

On SJ, Gaymee T, Ladon D, et al.: Reducing MCM levels in human primary T
cells during the G→S transition causes genomic instability during the first
PubMed Abstract | Publisher Full Text | Free Full Text

and ATR in a Cdk2- and Cdc7-independent DNA damage checkpoint. Mol Cell
PubMed Abstract | Publisher Full Text | Free Full Text

Peplowska K, Walek AU, Storchova Z: Sgo1 regulates both condensin and
e1004411.
PubMed Abstract | Publisher Full Text | Free Full Text

Passey SJ, Rosenbach E, de Pagter MG, et al.: The presence of extrachromosomes
PubMed Abstract | Publisher Full Text | Free Full Text

Page 11 of 13
Wellcome Open Research 2018, 3:23 Last updated: 28 MAR 2018

Shimada K, Passero P, Gasser SM: ORC and the intra-S-phase checkpoint: A
3236–3252.
PubMed Abstract | Publisher Full Text | Free Full Text

Shyu AY, Hallberg RL: SCS1, a multicopy suppressor of hsps60-ts mutant alleles,
5618–5626.
PubMed Abstract | Publisher Full Text | Free Full Text

Tanaka S, Umemori T, Hira K, et al.: CDK-dependent phosphorylation of Sld2
and Sld3 initiates DNA replication in budding yeast. Nature. 2007; 449(7255):
532–332.
PubMed Abstract | Publisher Full Text | Free Full Text

Vasianovich Y, Harrington LA, Makovets S: Break-induced replication requires
DNA damage-induced phosphorylation of Pif1 and leads to telomere
PubMed Abstract | Publisher Full Text | Free Full Text

Yamazaki S, Ishii A, Kanoh Y, et al.: Rif1 regulates the replication timing
PubMed Abstract | Publisher Full Text | Free Full Text

Yan Z, Fedorov SA, Murmy MC, et al.: PR48, a novel regulatory subunit of
protein phosphatase 2A, interacts with Cdc6 and modulates DNA replication
PubMed Abstract | Publisher Full Text | Free Full Text

Yeeles JT, Deegan TD, Janska A, et al.: Regulated eukaryotic DNA replication
PubMed Abstract | Publisher Full Text | Free Full Text

Zegerman P: Evolutionary conservation of the CDK targets in eukaryotic DNA
PubMed Abstract | Publisher Full Text
The hypothesis that underlies this work is that RTS1, the regulatory unit of the PP2A phosphatase, could counteract the initiation of DNA replication through dephosphorylating initiation factors, in a way similar to the action of Rif1-PP1 on MCM. However, this hypothesis is very fragile as it solely relies on a positive interaction between rts1-delta with a ts-orc2 mutant, which was previously reported in a large-scale genomic screen for genetic interactions (Constanzo et al., 2010). Firstly, the score actually reported in the CellMap website (thecellmap.org) for this positive interaction is very low (0.07), below the default confidence threshold set for this study (0.08). Secondly, such large-scale genomic screens are often populated with a large number of weakly supported false positives. Therefore, it is not very surprising that a careful examination of an originally weakly supported interaction could lead to a different result. Thirdly, the authors also mention that more a recent screen reported opposite observations (enhanced phenotype in some replication mutants). Finally, the authors also indicate in the introduction that Rts1 is required for Cdc45 loading onto chromatin, which is not very compatible with their initial hypothesis that Rts1 could counteract replication initiation. Altogether these elements show that the initial hypothesis onto which the manuscript is constructed is not really reliable. I would suggest reformulating the manuscript and presenting equitably to two alternative hypotheses in the introduction, namely Rts1 is promoting or opposing replication initiation. I would also clearly state that Rif1 is used as a control to discriminate between the 2 hypotheses because as it is now presented, the reason why a parallel is made between the role of Rif1 and that of Rts1 is not really evident.

I have few other minor concerns. I found the title to be a bit misleading because this work does not directly assess the role of RTS1 in DNA replication initiation per se but rather at the genetic interactions between this gene and other initiation factors.

I had a hard time trying to understand the logic of Fig 1. I think the legend could be more explicit to guide the reader through the different cases.

I would also suggest to replace throughout the text ‘synthetic lethality’ by ‘negative interaction’ because synthetic lethality is generally considered as an extreme case of a negative interaction where two mutations, each causing limited fitness defect on their own, result in an inviable phenotype. I would also replace ‘synthetic rescue’ by ‘positive interaction’ for the same reason. This would allow avoiding turn of phrases such as ‘greater synthetic lethality’.
In the first paragraph of the result section, the authors mention that an orc2-1 mutant was reported to show growth deficiency even at permissive temperature. However, the spotting assay in Fig. 2A does not show any growth defect at restrictive temperature for the single orc2-1 mutant.

In its entirety, this study confirms a number of phenotypes previously described, including the opposing actions of Rif1 and DDK on replication initiation, which confirms that the experiments are carefully performed. It also highlights some new observations such as a small positive interaction between orc2-1 and rif1. The controls are adequate (comparison of WT and all single and double mutants) and the described data are convincing. The introduction section is really well written and give a very good overview of the interplay between the various actors involved in replication initiation. All in all, the study is a valuable additional contribution to the field of DNA replication.

Is the work clearly and accurately presented and does it cite the current literature? 
Yes

Is the study design appropriate and is the work technically sound? 
Yes

Are sufficient details of methods and analysis provided to allow replication by others? 
Yes

If applicable, is the statistical analysis and its interpretation appropriate? 
Not applicable

Are all the source data underlying the results available to ensure full reproducibility? 
No source data required

Are the conclusions drawn adequately supported by the results? 
Yes

Competing Interests: No competing interests were disclosed.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.