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RESEARCH ARTICLE

Spd2 assists Spd1 in the modulation of ribonucleotide reductase architecture but does not regulate deoxynucleotide pools

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ABSTRACT

In yeasts, small intrinsically disordered proteins (IDPs) modulate ribonucleotide reductase (RNR) activity to ensure an optimal supply of dNTPs for DNA synthesis. The *Schizosaccharomyces pombe* Spd1 protein can directly inhibit the large RNR subunit (R1), import the small subunit (R2) into the nucleus and induce an architectural change in the R1–R2 holocomplex. Here, we report the characterization of Spd2, a protein with sequence similarity to Spd1. We show that Spd2 is a $CRL4^{Cdt2}$-controlled IDP that functions together with Spd1 in the DNA damage response and in modulation of RNR architecture. However, Spd2 does not regulate dNTP pools and R2 nuclear import. Furthermore, deletion of *spd2* only weakly suppresses the $Rad3^{ATR}$ checkpoint dependency of $CRL4^{Cdt2}$ mutants. However, when we raised intracellular dNTP pools by inactivation of RNR feedback inhibition, deletion of *spd2* could suppress the checkpoint dependency of $CRL4^{Cdt2}$ mutant cells to the same extent as deletion of *spd1*. Collectively, these observations suggest that Spd1 on its own regulates dNTP pools, whereas in combination with Spd2 it modulates RNR architecture and sensitizes cells to DNA damage.

KEY WORDS: Genome stability, Ribonucleotide reductase, $CRL4^{Cdt2}$ ubiquitin ligase, Intrinsically disordered proteins, *S. pombe*, Cancer model

INTRODUCTION

Correct regulation of the levels of the building blocks of DNA is emerging as a pre-requisite for the maintenance of genome integrity. Cancer development is presumed to be initiated by oncogenic mutations that cause replication stress, thereby increasing the risk of replication fork collapse and the subsequent formation of DNA lesions (Halazonetis et al., 2008). This type of oncogenic replication stress has been reported to be accompanied by a significant reduction in cellular deoxynucleoside triphosphate (dNTP) pools, possibly due to an imbalance between nucleotide synthesis and DNA replication activity (Beck et al., 2012; Bester et al., 2011). Furthermore, such oncogenic S phase problems, including shorter inter-origin distances and slower fork migration, can be reversed by an exogenous supply of nucleosides, suggesting that insufficient levels of the building blocks of DNA might play an important causal role in the early stages of tumor development.

The rate-limiting step in dNTP production is catalyzed by the essential and highly conserved enzyme ribonucleotide reductase (RNR), which reduces ribonucleoside diphosphates to their corresponding deoxy forms. Eukaryotic cells use class Ia RNR, a heteromeric enzyme consisting of up to three copies of two different dimeric subunits, R1 and R2. The catalytic activity resides in the large R1 subunit, whereas the smaller R2 subunit donates reducing power to the reaction from a diferric tyrosyl radical (Nordlund and Reichard, 2006).

Consistent with deoxynucleotide pools being important for the maintenance of genome integrity, cellular RNR function is tightly regulated at several levels. Expression of both subunits is induced under conditions in which DNA synthesis is required (i.e. in S phase or after DNA damage) (Elledge et al., 1993). Furthermore, the activity of RNR is regulated by two intricate feedback-control mechanisms (Reichard, 2010). The R1 subunit contains two allosteric effector-binding sites, the specificity site and the activity site. The specificity site ensures a balanced supply of the four DNA building blocks, by binding dNDP species that are present in excess, thereby remodeling the catalytic site towards other base substrates. The activity site represents a molecular switch that regulates the overall activity of the enzyme by monitoring the cellular dATP:ATP ratio; RNR is inactive when dATP is bound, and it becomes activated when dATP is replaced by ATP. Recent structural studies suggest that the inactive form of the enzyme is a hexameric ring consisting of three R1 dimers with an R2 dimer embedded in the middle (Fairman et al., 2011). Less is known about the structure of the active ATP-bound form, but the molecular interaction between the R1 and R2 subunits appears to be altered relative to that of the dATP-bound complex, and the ATP-bound form might contain additional R2 dimers (Hofer et al., 2012). RNR can be locked genetically in its active configuration by replacing Asp57 in the activity site with Asn. Mammalian cell lines harboring this D57N-mutated version of R1 have highly increased dNTP pools, indicating that a large proportion of RNR complexes is normally in the inhibited form *in vivo* (Weinberg et al., 1981).

In yeasts, RNR activity is additionally regulated by a group of small intrinsically disordered proteins (IDPs). In fission yeast, the Spd1 protein can inhibit RNR by two different mechanisms. It can sequester the R2 subunit in the nucleus, away from the R1 subunit, which is mainly cytosolic (Liu et al., 2003), and it can also directly bind to and inhibit the R1 subunit (Håkansson et al., 2006). We reported recently that Spd1 can modulate the RNR complex in a third fashion; if the R1 and R2 subunits are tagged with different fluorescent proteins, a fluorescence resonance

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energy transfer (FRET) reaction can be observed between them, and this signal is absent in *Δspd1* cells (Nestoras et al., 2010). It is unclear how the underlying Spd1-mediated change in the molecular interactions between R1 and R2 affects RNR function. Interestingly, these three molecular functions of Spd1 can be separated genetically, suggesting that the protein mediates them by different molecular mechanisms (Nestoras et al., 2010).

The limited sequence conservation of RNR-inhibitory IDPs has, thus far, precluded resolution of the issue of whether mammalian counterparts exist. However, in the distantly related budding yeast *Saccharomyces cerevisiae*, two Spd1-related IDPs, Dif1 and Sml1, sequester R2 in the nucleus or inhibit R1, respectively. Interestingly, synteny analysis suggests that these two genes arose through genome duplication of a common ancestor with both functions, similar to *S. pombe* Spd1 (Lee et al., 2008). A third potential Spd1-related protein, Hug1, is also predicted in the budding yeast genome, but no function has yet been assigned to this protein (Basrai et al., 1999).

When fission yeast cells undergo DNA replication or repair, the Spd1 protein becomes degraded by $CRL4^{Cdt2}$-mediated ubiquitylation (Holmberg et al., 2005; Liu et al., 2003), a process that occurs on chromatin-associated PCNA (Salguero et al., 2012). Spd1 degradation also requires the Csn1 and Csn2 subunits of the COP9 signalosome (Liu et al., 2003). The $CRL4^{Cdt2}$ E3 ubiquitin ligase is activated by transcriptional induction of the Cdt2 substrate adaptor, which becomes expressed in unperturbed S phase by the *Mlu*I cell-cycle box (MCB) transcription complex. Following DNA damage, Cdt2 is induced by a $Rad3^{ATR}$-dependent pathway (Liu et al., 2005; Moss et al., 2010).

$CRL4^{Cdt2}$-defective cells undergo DNA replication in the presence of Spd1, and this gives rise to severe S phase stress; replication proceeds slowly, with concomitant activation of the $Rad3^{ATR}$ checkpoint, which becomes essential for cell survival under these conditions. Furthermore, such cells are hypersensitive to DNA damaging agents, are defective in double-strand break (DSB) repair by homologous recombination, display >20-fold increase in spontaneous mutation rates, and are also completely unable to undergo pre-meiotic S phase (Holmberg et al., 2005; Liu et al., 2005; Liu et al., 2003; Moss et al., 2010). The requirement for a functional $Rad3^{ATR}$ pathway and the defects in recombination and pre-meiotic S phase are all fully reversed by deletion of the *spd1* gene or by overexpression of fission yeast R2 ($Suc22^{R2}$), suggesting that these phenotypes are caused by Spd1-mediated RNR inhibition. By contrast, the increased mutation rates and sensitivity to DNA damage are only partially suppressed by Spd1 loss, indicating that deregulation of other $CRL4^{Cdt2}$-controlled processes also contributes to these phenotypes.

The systematic genetic analysis of *spd1* has shown that certain mutants that are defective in nuclear import of the RNR R2 subunit or in the FRET reaction between R1 and R2 still require the $Rad3^{ATR}$ pathway for survival when the Spd1 degradation pathway is inactivated (Nestoras et al., 2010). These observations are consistent with a model where Spd1 causes checkpoint activation by inhibiting dNTP formation by direct binding to RNR. However, we recently reported that Spd1 accumulation can cause checkpoint activation even in cells that have highly elevated dNTP pools, owing to inactivation of RNR feedback inhibition (Fleck et al., 2013). Hence, Spd1 might also cause checkpoint activation independently of deoxynucleotide synthesis.

In the present study, we have characterized Spd2, an Spd1-related putative RNR inhibitor that was identified in a comparative genome sequencing study (Rhind et al., 2011). We show that Spd2, similar to Spd1, is an IDP that becomes degraded by $CRL4^{Cdt2}$ ubiquitylation following inhibition of RNR by hydroxyurea. Similar to *Δspd1*, deletion of *spd2* can rescue the damage sensitivity of $CRL4^{Cdt2}$ mutants, and Spd2, like Spd1, is required for the FRET signal between R1 and R2. However, Spd2 does not share the ability of Spd1 to sequester the R2 subunit in the nucleus, and, surprisingly, it does not seem to affect cellular dNTP pools. These observations support a model where Spd2 can assist Spd1 in an S phase inhibitory pathway that functions independently of dNTP formation.

RESULTS

Spd2 – a new RNR inhibitor homolog

The genomes of four *Schizosaccharomyces* species have recently been sequenced (Rhind et al., 2011). The availability of the sequences of three additional fission yeast species allowed the identification of >100 new conserved open reading frames in the *S. pombe* genome. One of these proteins, Spd2, shows limited similarity to Spd1 (19% overall sequence identity) and other RNR inhibitors (Fig. 1).

In general, the homology among RNR inhibitors is limited to a number of short motifs. The Spd1 and Spd2 orthologs also appear to have diverged considerably, but are very well conserved within the Spd1 and Spd2 subgroups (Fig. 1A). The Spd1 and Spd2 families share a small domain near their C-terminal ends, which is absent from the other known RNR inhibitors. We will refer to this as the Spd domain (Fig. 1B).

The Spd1 and Spd2 orthologs of the four fission yeast species all contain a Hug domain (Fig. 1A), which is also present in the *S. cerevisiae* Hug1 and Dif1 proteins and in *Ashbya gossypii* Aer122c, but is absent from budding yeast Sml1 (Fig. 1B). The Hug domain of Dif1 is required for nuclear import of the small RNR subunit (Lee et al., 2008; Wu and Huang, 2008), and genetic analysis suggests that the Hug domain of Spd1 might have a similar function (Nestoras et al., 2010). The N-terminal part of the Hug domain in Spd1 was recently shown to constitute a PCNA-interacting protein (PIP) degron, mediating binding to PCNA, which is a prerequisite for $CRL4^{Cdt2}$-dependent ubiquitylation and subsequent degradation of Spd1 (Salguero et al., 2012). This motif is present in Spd2 (Fig. 1), suggesting that the protein is degraded by a similar mechanism (see below).

The $CRL4^{Cdt2}$ degradation pathway is absent from budding yeast. Instead, degradation of Sml1 and Dif1 during S phase or in response to DNA damage is triggered by Dun1-mediated phosphorylation of a phospho-degron referred to as the Sml1 domain (Lee et al., 2008; Uchiki et al., 2004; Wu and Huang, 2008; Zhao and Rothstein, 2002). Consistent with a different degradation mechanism in fission yeast, this Sml1 degron is absent in both Spd1 and Spd2 (Fig. 1B).

Finally, Sml1 can bind to and inhibit the large RNR subunit through its Rnr1 domain (Zhao et al., 2000). Although it has been shown that *S. pombe* Spd1 also can bind to the large RNR subunit (Håkansson et al., 2006), conservation of the Rnr1 domain in Spd1 is limited to a short stretch of amino acid residues. In Spd2, the conservation of the Rnr1 domain is even more limited, if not absent (Fig. 1B).

Spd2 is an IDP

Similar to Spd1 and Sml1 (Danielsson et al., 2008; Nestoras et al., 2010), the sequence of Spd2 has the typical characteristics of an IDP – a high content of charged residues (29%) and a low aliphatic index (67.94; for reference, myoglobin=95.1). These

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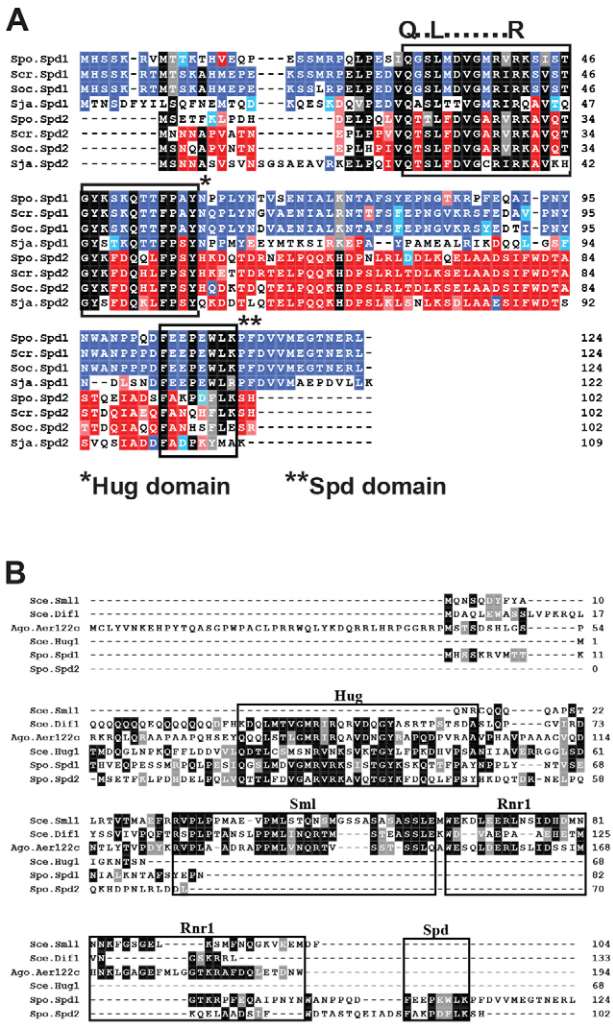

Fig. 1. Spd2 is homologous to Spd1 and other known RNR inhibitors. (A) Comparison of amino acid sequences of Spd1 and Spd2 orthologs of the four *Schizosaccharomyces* species *S. pombe* (Spo), *S. cryophilus* (Scr), *S. octosporus* (Soc) and *S. japonicus* (Sja). Residues are highlighted in black and grey when they are identical and similar, respectively, between Spd1 and Spd2 orthologs. Amino acid residues in dark and light blue indicate conservation predominantly in Spd1 orthologs, and in dark and light red predominantly in Spd2 orthologs. The Hug domain (*) and the Spd domain (**) are boxed. Amino acids defining the Spd1 PIP degron (Q-x-x-L-x-x-x-x-x-x-x-R) (Salguero et al., 2012) are marked above the aligned sequences. (B) Alignment of Spd2 with other fungal RNR inhibitors. Identical and similar amino acid residues are highlighted in, respectively, black and gray. Hug, Sml and Rnr1 domains, as defined previously (Lee et al., 2008), are boxed. Spd1 and Spd2 share a unique domain close to the C-terminus, which we termed the Spd domain.

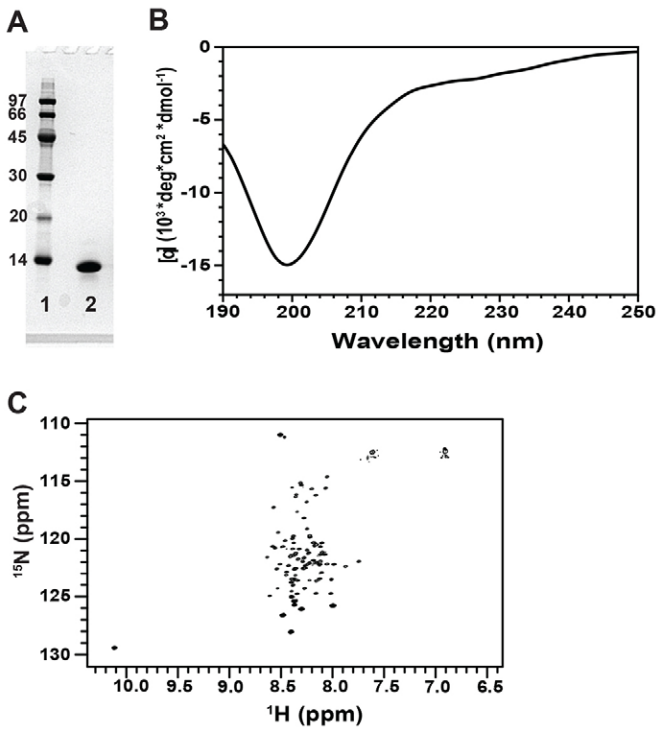

Fig. 2. Structural properties of Spd2. (A) Spd2 was purified to homogeneity, and the mobility was investigated by electrophoresis. Lane 1, marker; lane 2, purified Spd2. (B) A far-UV circular dichroism spectrum of purified Spd2, showing a large negative ellipticity with a maximum at 199 nm, suggesting a disordered protein with little or no secondary structure. (C) An NMR spectrum of purified Spd2 showing that only a small dispersion of signals was observed in the ^{1}H- dimension, further suggesting that the protein is disordered with no globular fold.

proteins lack well-structured three-dimensional folds and are distinctive in having regions that form lowly populated, transient structures and/or contain conserved sequence motifs (Tompa, 2002). Importantly, these local features are central to target recognition, and the flexibility of the IDPs is essential for binding to more than one partner. To investigate the disorder characteristics of Spd2 by spectroscopy, recombinant Spd2 was produced in *Escherichia coli* and purified to >98% homogeneity (Fig. 2A). A far-UV circular dichroism spectrum of Spd2 showed no signs of pronounced secondary structure elements, with little negative ellipticity in the 210–220 nm range (Fig. 2B). Instead, a large negative ellipticity with a maximum at 199 nm suggested a disordered protein with little or no secondary structure. In support of this, a ^{15}N,^{1}H-heteronuclear single quantum coherence (HSQC) nuclear magnetic resonance (NMR) spectrum of ^{15}N-labeled Spd2, recorded at 10°C, showed a narrow dispersion of signals in the ^{1}H dimension, further suggesting that the protein is disordered with no globular fold (Fig. 2C). Unlike Spd1, the peaks of the NMR spectrum of Spd2 were of almost equal intensity, revealing the higher solubility of this protein compared with Spd1 (Nestoras et al., 2010; data not shown). Thus, Spd2 possesses hallmarks of an IDP (Tompa, 2002), with low-complexity sequence, a lack of secondary structure elements in a far-UV circular dichroism spectrum and a collapsed NMR spectrum.

Spd1 and Spd2 both inhibit S phase

We next constructed a strain deleted for the *spd2* gene. Similarly to *Δspd1* cells, this *Δspd2* strain showed no obvious phenotypic differences to wild-type cells with regard to cell shape and growth rate (data not shown). Spd1 was originally identified as a protein that inhibited S phase progression when overexpressed, thereby causing cell elongation (Woollard et al., 1996). We found that overexpression of Spd2 similarly caused cell elongation (Fig. 3A). The elongation of cells by overexpression of Spd2 did not require functional Spd1 and vice versa.

Next, we used flow cytometry (FACS) to monitor the cell-cycle distribution in cells overexpressing Spd1 or Spd2. The

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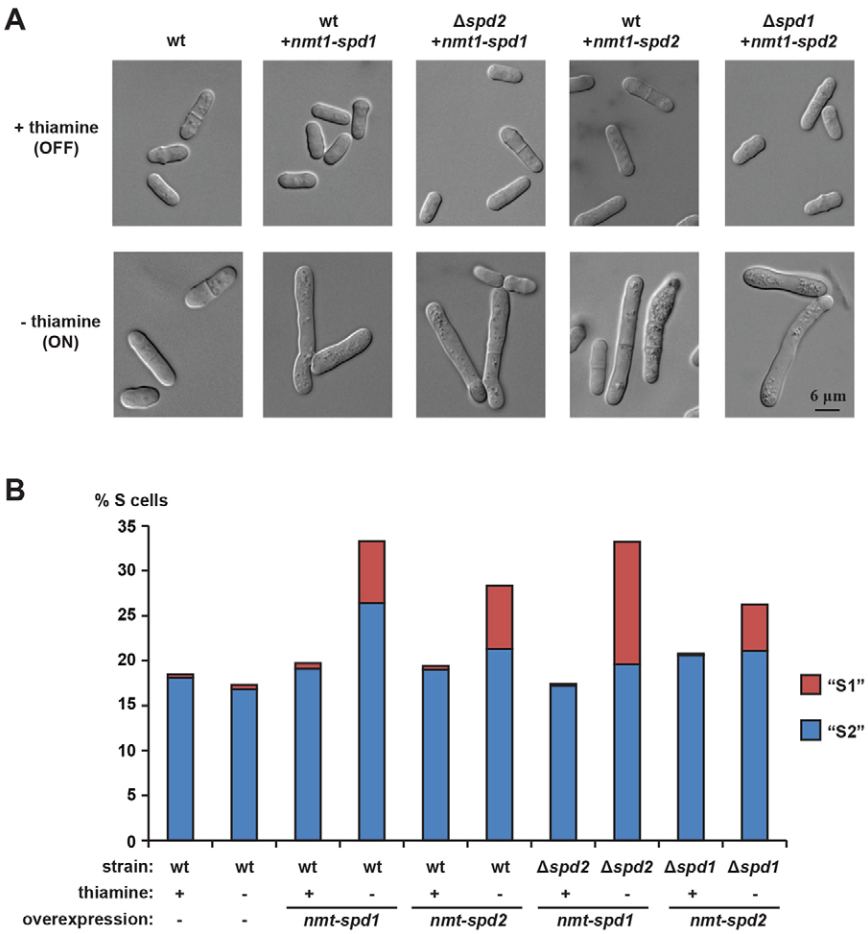

Fig. 3. Overexpression of Spd2 inhibits S phase. (A) Overexpressing either Spd1 or Spd2 leads to the accumulation of a subset of cells with elongated and aberrant cell shapes. The effect of Spd2 overexpression is not dependent on a functional *spd1*$^{+}$ gene and vice versa. Cells were grown to mid-log phase in minimal medium with or without thiamine for 24 hours before pictures were taken. wt, wild type. Scale bar: 6 μm. (B) Quantification of FACS analysis of cells overexpressing Spd1 or Spd2. Cell-cycle distribution was analyzed as reported previously (Knutsen et al., 2011). S1, the fraction of S phase cells with one nucleus; S2, binucleate cells (as defined by the width of the DNA signal) undergoing replication. When overexpressing either Spd1 or Spd2, the proportion of S phase cells increased, in particular S1 cells. Representative examples of this quantification method are given in supplementary material Fig. S1.

interpretation of FACS data in fission yeast is complicated by the fact that G1 and S phase cells are still attached to their sisters, thus giving rise to a 2C signal. However, by measuring the DNA signal width, it is possible to discriminate G1 and S cells from G2 cells (Knutsen et al., 2011), thus giving a more precise estimate of the S phase population. By using this method, we found that overexpression of Spd2 caused a strong increase in the number of cells undergoing S phase, suggesting that the protein – similarly to Spd1 – delays DNA replication (Fig. 3B; supplementary material Fig. S1). Again, Spd1 and Spd2 could cause this phenotype independently of one another.

Spd2 is a CRL4^{Cdt2} target

Spd1 is a target of the CRL4^{Cdt2} E3 ubiquitin ligase (Holmberg et al., 2005; Liu et al., 2005; Liu et al., 2003), and we next investigated whether this was also the case for Spd2. Because we found that epitope tagging of Spd1 adversely affected its functionality (data not shown), we raised antibodies against recombinant Spd1 and Spd2 proteins. Similar to Spd1, Spd2 was degraded in response to treatment with hydroxyurea, and this response was completely abolished in CRL4^{Cdt2}-defective *Δddb1* cells, where the steady-state level of Spd2 was also higher than that observed in wild-type cells (Fig. 4A). Furthermore, deletion of *spd2* suppressed the elongated-cell phenotype and improved the growth rate of CRL4^{Cdt2}-defective *Δddb1* cells to approximately the same extent as did *spd1* deletion (data not shown). Hence, consistent with the presence of a PIP degron in the protein (Fig. 1A), we conclude that Spd2, like Spd1, is a target for CRL4^{Cdt2}-mediated ubiquitylation.

The degradation of Spd2 appeared to be independent of Spd1 and vice versa (Fig. 4A,C). Deletion of *spd2* apparently caused a modestly elevated level of Spd1 in asynchronously growing cells (Fig. 4C). Consistent with this, we found that *spd1* mRNA levels were 1.5-fold increased in exponentially growing *Δspd2* cells compared with wild-type cells (supplementary material Fig. S2).

Spd1 becomes degraded as cells enter S phase, because the CRL4 substrate adaptor Cdt2 is controlled by the S-phase-specific transcription complex MCB (Liu et al., 2005). We synchronized wild-type cells by centrifugal elutriation and monitored the levels of Spd1 and Spd2 as cells progressed through S phase (Fig. 4B). As observed previously (Liu et al., 2003), Spd1 became downregulated as cells entered S phase, but for Spd2, we could not detect a similar robust reduction.

Spd2 functions in the DNA damage response

CRL4^{Cdt2}-defective cells are sensitive to the RNR inhibitor hydroxyurea and the DNA alkylating agent methyl methane sulphonate (MMS) (Holmberg et al., 2005; Zolezzi et al., 2002), and this phenotype can be partially suppressed by concomitantly deleting the *spd1* gene, suggesting that the accumulation of excess Spd1 protein contributes to the observed drug sensitivity. We therefore investigated whether deletion of the *spd2* gene could also affect the damage sensitivity of CRL4^{Cdt2}-defective *Δddb1* cells. Rescue of the MMS sensitivity of *Δddb1* occurred to a similar modest extent in both *Δddb1 Δspd1* and *Δddb1 Δspd2* double mutants, and there was no further suppression of the phenotype in the *Δddb1 Δspd1 Δspd2* triple mutant. However, the

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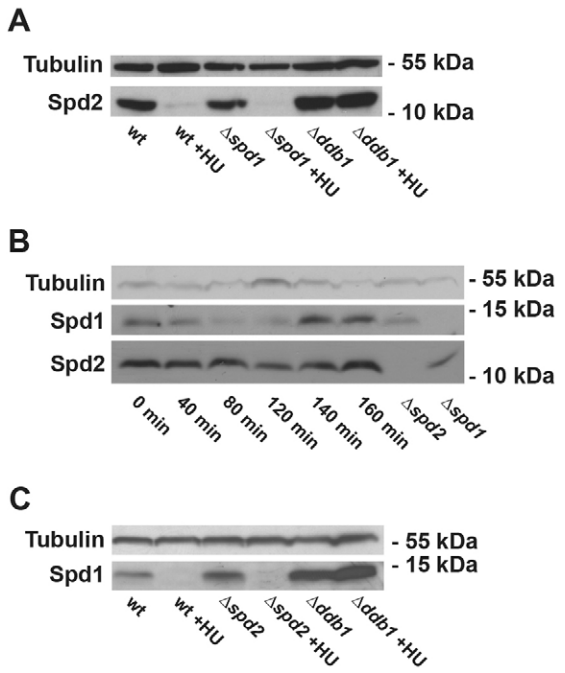

Fig. 4. Spd2 is degraded by CRL4^{Cdt2} during replication stress. (A) Samples from the indicated strains were harvested before and after 4 hours of growth in the presence of hydroxyurea (HU) and the Spd2 levels were monitored by western blotting. Spd2 was degraded upon hydroxyurea-induced replication stress in wild-type (wt) and *Δspd1* cells, but not in CRL4^{Cdt2}-defective *Δddb1* cells. (B) Wild-type cells were synchronized in G2 by centrifugal elutriation and samples were harvested at the indicated time-points. Spd1 and Spd2 levels were monitored by western blotting. The fraction of S phase cells (Knutsen et al., 2011) peaked at 50% between 80 and 120 minutes. Unlike Spd1, Spd2 was not strongly downregulated at S phase. (C) Samples from the indicated strains were harvested before and after 4 hours of growth in the presence of hydroxyurea, and Spd1 levels were monitored by western blotting. Spd1 was degraded upon hydroxyurea-induced replication stress in wild-type and *Δspd2* cells, but not in *Δddb1* cells. A slightly elevated abundance of Spd1 was observed in *Δspd2* cells. Tubulin was used as loading control in all three panels. A molecular mass marker was run alongside samples, and the marker bands are given by size (kDa).

observed suppression was too weak to draw firm conclusions on the epistatic relationship between *spd1* and *spd2* (Fig. 5A). We also tested for sensitivity to the DSB-inducing agent zeocin. Similar to *spd1*, deletion of *spd2* could rescue the sensitivity of *Δddb1* cells to zeocin. However, deletion of *spd1* on its own conferred almost complete suppression, again making it difficult to evaluate epistasis (Fig. 5A).

When deleting *spd2*, the hydroxyurea sensitivity of Δ*ddb1* cells could be suppressed to almost the same extent as when deleting *spd1*, and when both genes were deleted, we saw increased rescue (Fig. 5B). Thus, *spd1* and *spd2* have both overlapping and separate functions in the DNA damage sensitivity conferred by CRL4^{Cdt2} inactivation.

Spd2 is required for Cdc22^{R1}–Suc22^{R2} FRET

When the small and large RNR subunits are tagged with two different fluorescent proteins, a FRET signal can be observed in wild-type cells (Nestoras et al., 2010). The underlying molecular mechanism for this signal is not clear, but because it is absent from cells not expressing Spd1, it presumably represents an Spd1-dependent remodeling of RNR complex architecture that brings the two fluorescent proteins into closer proximity. We analyzed whether FRET was also dependent on Spd2 and found that this was indeed the case; in both the nucleus and cytoplasm, the FRET signal was lost in a *Δspd2* strain (Fig. 6A,B). Thus, both Spd1 and Spd2 promote the architectural change in RNR structure that is manifested by the FRET signal between Cdc22^{R1} and Suc22^{R2}.

Spd2 is not required for Suc22^{R2} nuclear import

Spd1 regulates the nuclear import of the small RNR subunit Suc22^{R2} (Liu et al., 2003). In wild-type cells, Suc22^{R2} accumulates in the nucleus, whereas it becomes largely cytosolic in *Δspd1* mutant cells, and upon hydroxyurea-induced degradation of Spd1, Suc22^{R2} redistributes to the cytosol (Liu et al., 2003; Nestoras et al., 2010). Because the Cdc22^{R1} subunit is mainly cytosolic, this nuclear export of Suc22^{R2} has been proposed to cause the formation of an increased number of active RNR complexes (Liu et al., 2003; Nielsen, 2003). We found that Suc22^{R2} nuclear localization was lost in Δ*spd1* cells but unchanged in Δ*spd2* cells (Fig. 6C). Thus, nuclear import of Suc22^{R2} clearly constitutes an Spd1-dependent function that is not shared by Spd2.

Spd2 accumulation partially inhibits meiosis

Cells defective in the CRL4^{Cdt2} E3 ubiquitin ligase are unable to undergo meiosis, and this defect can be suppressed by concomitantly deleting the *spd1* gene (Holmberg et al., 2005; Nestoras et al., 2010; Yoshida et al., 2003). We therefore tested the effect of deleting *spd2* on meiotic competence of the CRL4^{Cdt2} mutants *Δddb1*, *Δcsn1* and *Δcdt2* (Fig. 7A). The majority of zygotes of all three homothallic CRL4^{Cdt2} mutants could not develop spores (~80–90%; Fig. 7A), consistent with previous data, and these defects were suppressed to almost wild-type levels by deletion of *spd1* (~85–90% asci with four spores versus 97% in wild type). By contrast, deleting *spd2* in these CRL4^{Cdt2} mutant backgrounds only partially rescued meiosis. Besides empty zygotes (~50%), asci with two spores (~30%) were predominantly formed (Fig. 7A,B). A *Δddb1 Δspd2 Δspd1* triple mutant underwent meiosis as efficiently as a *Δddb1 Δspd1* double mutant (~90% four-spored asci for both strains). Hence, Spd2 has an inhibitory function during meiosis. However, in contrast to Spd1, meiosis of the CRL4^{Cdt2} mutants was still partially inhibited in the absence of Spd2.

Spd2 accumulation plays a role in checkpoint activation but does not affect dNTP levels

CRL4^{Cdt2}-defective cells rely on activation of the Rad3^{ATR} checkpoint for viability, and this phenotype is suppressed by deletion of the *spd1* gene (Holmberg et al., 2005; Liu et al., 2003; Nestoras et al., 2010), suggesting that Spd1 accumulation is the major cause of checkpoint activation. We confirmed that CRL4^{Cdt2}-defective *Δddb1* and *Δcsn1* cells carrying a temperature-sensitive *rad3* allele died at the restrictive temperature, and that their viability was largely restored by elimination of the *spd1* gene (Fig. 7C). When deleting *spd2* in *rad3-TS Δddb1* or *rad3-TS Δcsn1* backgrounds, we also observed rescue of viability, albeit only partially (Fig. 7C). Simultaneous deletion of *spd1* and *spd2* fully restored viability to a level above that observed following *spd1* deletion, suggesting that the two accumulated proteins can cause checkpoint activation independently of one another (Fig. 7C). Thus, Spd1 is the major CRL4^{Cdt2} target causing Rad3^{ATR} dependency, whereas the contribution from Spd2 appears to be modest.

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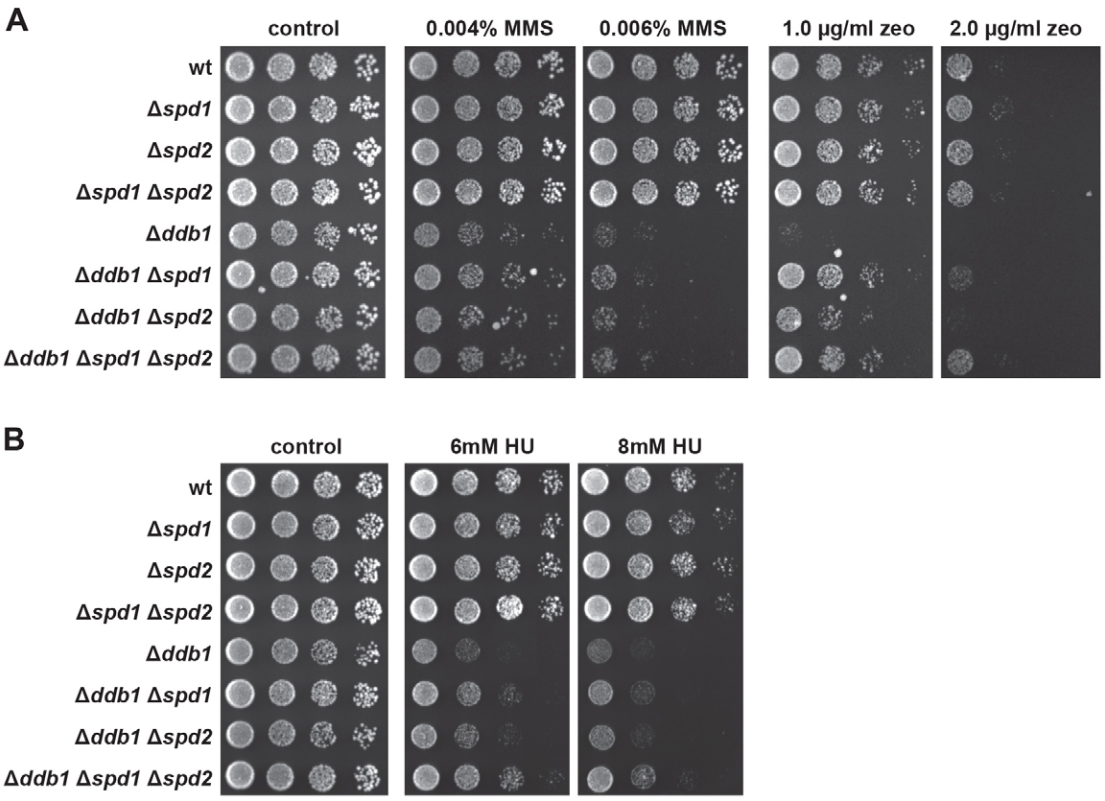

Fig. 5. Spd2 has a function similar to Spd1 in the damage response. (A) Fivefold serial dilutions of the indicated strains were spotted onto control plates or plates containing the indicated concentrations of MMS or zeocin (zeo, a bleomycin related drug). Although the sensitivity of *Δddb1* to MMS is rescued to the same extent in *Δspd1*, *Δspd2* and *Δspd1 Δspd2* mutant cells, zeocin sensitivity is rescued better by *Δspd1* than by *Δspd2*. wt, wild type. (B) Spot test on plates containing 6 or 8 mM hydroxyurea. Here, *Δspd1 Δspd2* double-mutant cells show better rescue of *Δddb1* than either single mutant.

Presumably, checkpoint activation triggered by Spd1 accumulation is signaled by replication stress, involving the formation of single-stranded DNA caused by RNR inhibition and possibly also by interference with PCNA, the other known interaction partner of Spd1 (Holmberg and Nielsen, 2012; Moss et al., 2010; Salguero et al., 2012; Fleck et al., 2013). We found that *Δspd2* cells – unlike *Δspd1* cells – did not have elevated dNTP pools (Fig. 7D). Hence, the modest checkpoint dependency caused by Spd2 accumulation appears to be unrelated to repression of dNTP pools.

Elevated dNTP pools enhance *Δspd2*-dependent suppression of CRL4^{Cdt2} defects

The results reported thus far in this paper demonstrate that Spd2 shares some, but not all, functions with Spd1. In particular, overall cellular dNTP pools appear to be repressed by Spd1 but not by Spd2, and we speculated that this difference might explain why – for certain phenotypes – we observed a weaker rescue of CRL4^{Cdt2}-defective cells when deleting *spd2* as opposed to *spd1*. In other words, Spd1-mediated repression of deoxynucleotide pools might still obscure the effect of deleting *spd2*. To test this hypothesis, we monitored the effect of deleting *spd2* in CRL4^{Cdt2}-defective cells that had their dNTP pools upregulated independently of Spd1. In order to do this, we utilized the *cdc22^{D57N}* mutant, which displays elevated dNTP pools because the dATP feedback inhibition of RNR is abolished (Chabes et al., 2003; Fleck et al., 2013). Importantly, CRL4^{Cdt2}-compromised *Δddb1 cdc22^{D57N}* cells have higher dNTP levels than wild-type cells (Fleck et al., 2013). Interestingly, homothallic *Δddb1 Δspd2 cdc22^{D57N}* triple-mutant cells sporulated at a level comparable to *Δddb1 Δspd1* cells and much better than the corresponding *Δddb1 Δspd2* and *Δddb1 cdc22^{D57N}* double-mutant cells (Fig. 8A). Similarly, the combination of *Δspd2* and *cdc22^{D57N}* allowed growth of *rad3-TS Δddb1* at the restrictive temperature to the same extent as Δ*spd1*, and much better than either *Δspd2* or *cdc22^{D57N}* alone (Fig. 8B). These results confirm that Spd2 shares certain functions with Spd1, and they are consistent with a model where these shared functions do not include Spd1-mediated control over dNTP levels.

DISCUSSION

The fission yeast Spd1 protein has attracted considerable interest because of its impact on genome integrity, but its biological function remains enigmatic. Strikingly, most of our knowledge of Spd1 function comes from studies of cells that artificially over-accumulate Spd1 – either through ectopic expression of the gene or by inactivation of its CRL4^{Cdt2} degradation pathway. In general, the phenotypes associated with loss of Spd1 function seem quite harmless to the cell. In fact, elimination of Spd1 often improves growth or survival under conditions that challenge genome integrity. Spd1 inhibits S phase and becomes degraded when cells embark on DNA synthesis. Its function includes a negative effect on deoxynucleotide formation when DNA replication is not ongoing, but perhaps the protein also plays more dynamic roles in preventing damage to the genome (Holmberg and Nielsen, 2012; Fleck et al., 2013).

In this report we have characterized the Spd1-related protein Spd2. We have shown that Spd2 – similar to Spd1 – is a CRL4^{Cdt2}-targeted IDP that inhibits DNA replication and modulates RNR structure. Curiously, Spd2 appears to participate only in a subset of Spd1-controlled processes. It seems to be required neither for nuclear import of RNR R2 nor for repression of deoxynucleotide pool levels. Furthermore, the relationship between Spd1 and Spd2 is complex. Both proteins can inhibit S phase independently of one another when over-accumulated, but for the architectural remodeling of RNR (as

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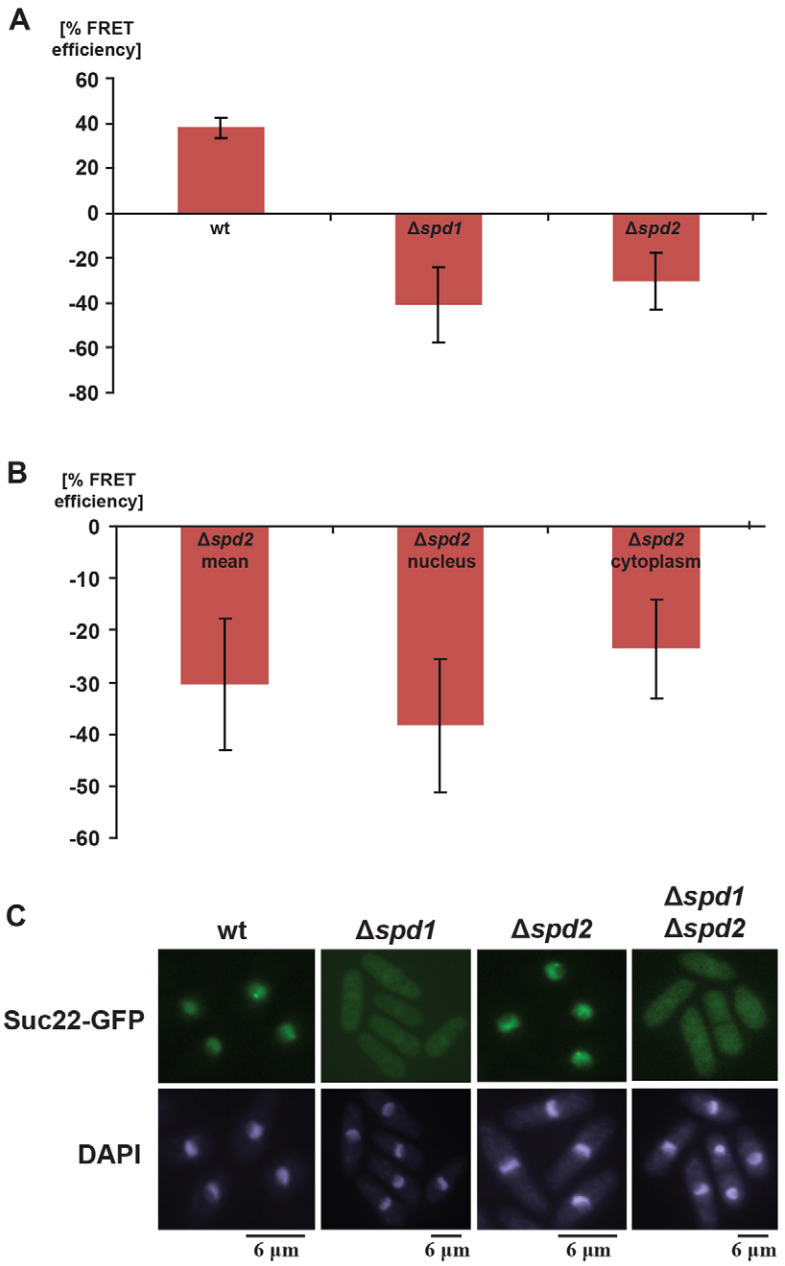

Fig. 6. Deleting *spd2* abolishes RNR FRET, but does not affect Suc22 localization. (A) In wild-type (wt) cells, CFP-tagged Suc22^{R2} and YFP-tagged Cdc22^{R1} give rise to a FRET signal, which is lost when either *spd1* or *spd2* is deleted. (B) The FRET signal is lost in both the nucleus and the cytoplasm of *Δspd2* cells. Data show the mean±s.d.; n=8–10 cells. (C) Suc22–GFP accumulates in the nucleus in wild-type cells. The nuclear localization was intact in *Δspd2* cells, but was abolished in *Δspd1* and *Δspd1Δspd2* cells. Scale bars: 6 µm.

manifested by the FRET assay) they seem to cooperate. According to a recent quantitative expression study, Spd1 and Spd2 are present at similar levels in the cell (respectively, ~14,000 and ~16,000 molecules/cell, Marguerat et al., 2012), so their different behavior seems to be caused by different functions rather than different concentrations.

CRL4^{Cdt2}-defective cells constitutively activate their Rad3^{ATR} checkpoint, presumably because Spd1 reduces dNTP pools and interferes with other thus-far-uncharacterized functions that are important for genome integrity (see below). Thus, in accordance with previous reports (Holmberg et al., 2005; Liu et al., 2003; Nestoras et al., 2010), we found that the viability of CRL4^{Cdt2}-defective *rad3-TS* cells was restored by deleting the *spd1* gene (Fig. 7C). However, deletion of *spd2* only caused an intermediate suppression of viability in this assay. Hence, accumulation of Spd2 appears to make cells much less dependent on the Rad3^{ATR} checkpoint pathway for survival than does Spd1 accumulation. Furthermore, because simultaneous deletion of *spd1* and *spd2* caused enhanced suppression (Fig. 7C), the two proteins appear to activate the checkpoint independently of one another.

Unlike Spd1, Spd2 is not required for nuclear import of Suc22^{R2}. Analogous to the *S. cerevisiae* Dif1 protein, genetic analysis suggests that the Hug domain of Spd1 is required for nuclear import of Suc22^{R2} (Nestoras et al., 2010). The Hug domain is well conserved in Spd2 (Fig. 1), so the fact that Spd2 is dispensable for Suc22^{R2} nuclear import suggests that other regions in Spd1 are also needed. Consistent with this, mutant *spd1-m2* (replacing amino acids K5, R6 and V7 with alanines) was reported also to be defective in Suc22^{R2} nuclear import (Nestoras et al., 2010). This region is absent in Spd2 (Fig. 1A). The biological relevance of Spd1-mediated nuclear Suc22^{R2} import is not yet known, but genetically this function can be separated from checkpoint activation (Nestoras et al., 2010).

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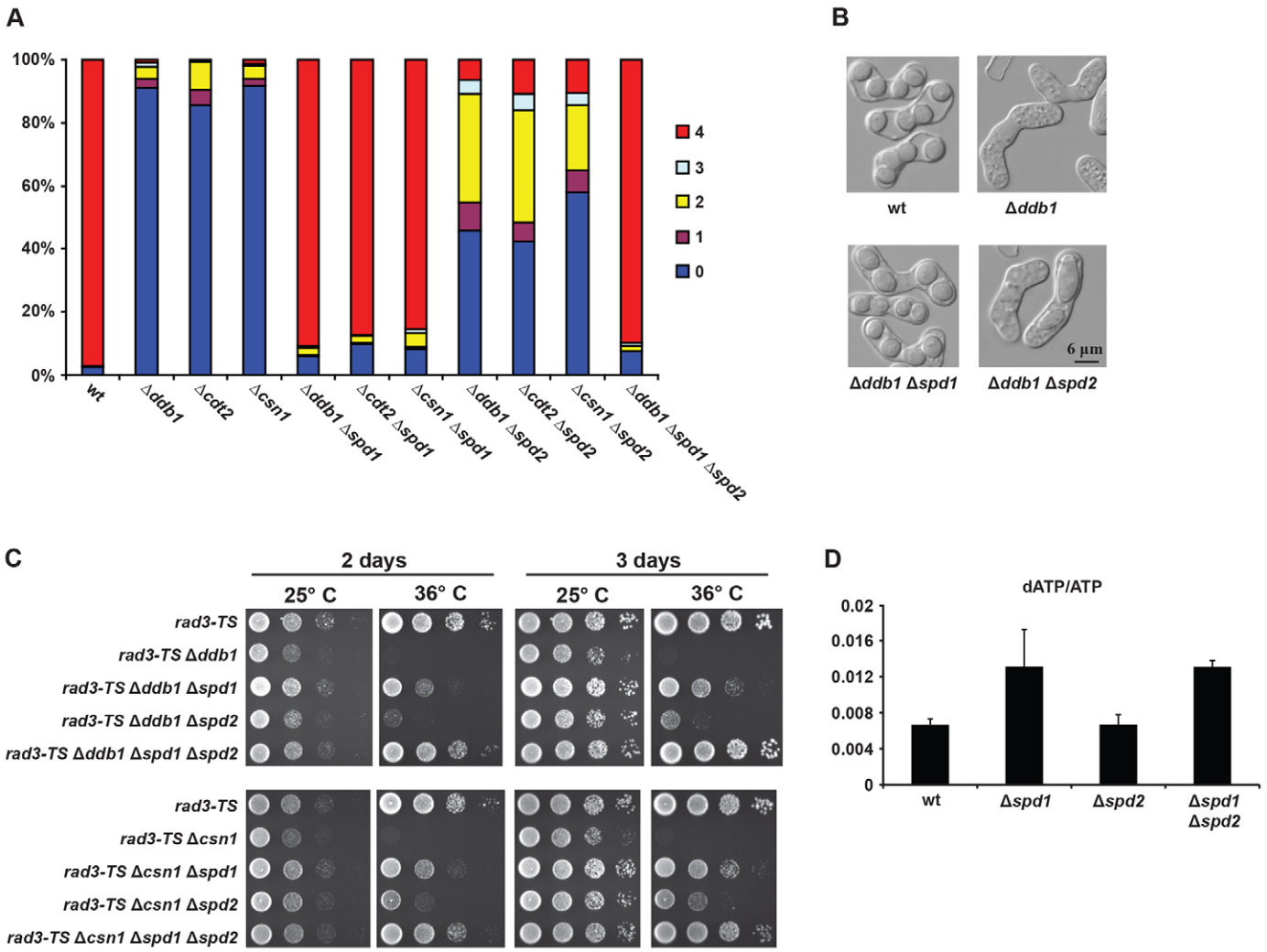

Fig. 7. Deleting *spd2* partially rescues the meiotic defect and checkpoint dependency of CRL4^{Cdt2}-defective cells. (A) Homothallic h^{90} cells starved for a nitrogen source go through meiosis, resulting in the formation of four-spored asci. Shown are the percentages of zygotes or asci with 0–4 spores of the various homothallic strains as indicated. In wild-type (wt) cells, close to 100% of asci are four-spored. When components of the CRL4^{Cdt2} pathway were absent (*Δddb1*, *Δcdt2* or *Δcsn1*), meiosis became defective, resulting almost exclusively in asci without spores. When deleting *spd1* in CRL4^{Cdt2}-defective cells, the sporulation efficiency was reverted to almost wild-type levels. When *spd2* was deleted in CRL4^{Cdt2}-defective cells, the sporulation efficiency was only partially rescued. However, most spore-containing asci had fewer than four spores. (B) Representative images of zygotes or asci of wild-type and mutant strains as indicated. Whereas *Δspd1* restored the sporulation efficiency of *Δddb1* cells to almost the wild-type level, *Δddb1 Δspd2* mainly produced empty zygotes and asci with two spores. Scale bar: 6 µm. (C) Cells lacking a functional CRL4^{Cdt2} pathway require a functional checkpoint for viability. Tenfold serial dilutions of the indicated strains were spotted onto YEA and incubated for the indicated number of days. *rad3-TS Δddb1* and *rad3-TS Δcsn1* cells were unable to grow at the restrictive temperature. Deletion of *spd1* largely rescued viability, consistent with previous results (Holmberg et al., 2005). Deletion of *spd2* caused a partial rescue of viability in *rad3-TS Δddb1* and *rad3-TS Δcsn1* backgrounds. Simultaneous deletion of *spd1* and *spd2* caused full rescue, suggesting that accumulated Spd1 and Spd2 can contribute to checkpoint activation independently of one another. (D) Cellular dATP and ATP concentrations were measured by a primer extension assay as a measure of regulation of overall dNTP pools. Strains lacking *spd1* had elevated dNTP pools due to deregulation of RNR. However, deleting *spd2* did not cause elevated dATP pools. $P<0.05$ for wild type versus *Δspd1* and wild type versus *Δspd1 Δspd2*.

Both Spd1 and Spd2 become degraded in a CRL4^{Cdt2}-dependent reaction when RNR is inhibited by hydroxyurea (Fig. 4A,C). Ubiquitylation of CRL4^{Cdt2} target proteins requires binding to DNA-associated PCNA, so, in principle, Spd1 and Spd2 should also both be downregulated when Cdt2 is induced at S phase. However, unlike the situation for Spd1, we did not observe a robust downregulation of Spd2 during unperturbed S phase (Fig. 4B).

Although Spd1 on its own appears to control deoxynucleotide pools and Suc22^{R2} nuclear import, it mediates the conformational change in RNR complexes (reflected by the FRET signal) together with Spd2. In our assays for checkpoint dependency and meiotic competence, we found that some inhibitory function remained in the *Δspd2* CRL4^{Cdt2} mutant backgrounds (Fig. 7A,C). We reasoned that this might be due to inhibition of dNTP formation by accumulated Spd1 protein. Hence, we introduced the *cdc22*^{D57N} mutation into these backgrounds. This mutation abolishes the allosteric feedback inhibition of RNR and elevates the dNTP pools to a level well above that obtained by deleting *spd1* (Fleck et al., 2013). Interestingly, on their own, both the *cdc22*^{D57N} mutation and *Δspd2* could partially rescue the checkpoint requirement and meiotic defect of CRL4^{Cdt2}-mutated cells. However, when combined, we saw a better suppression in both assays, similar to the effect obtained by

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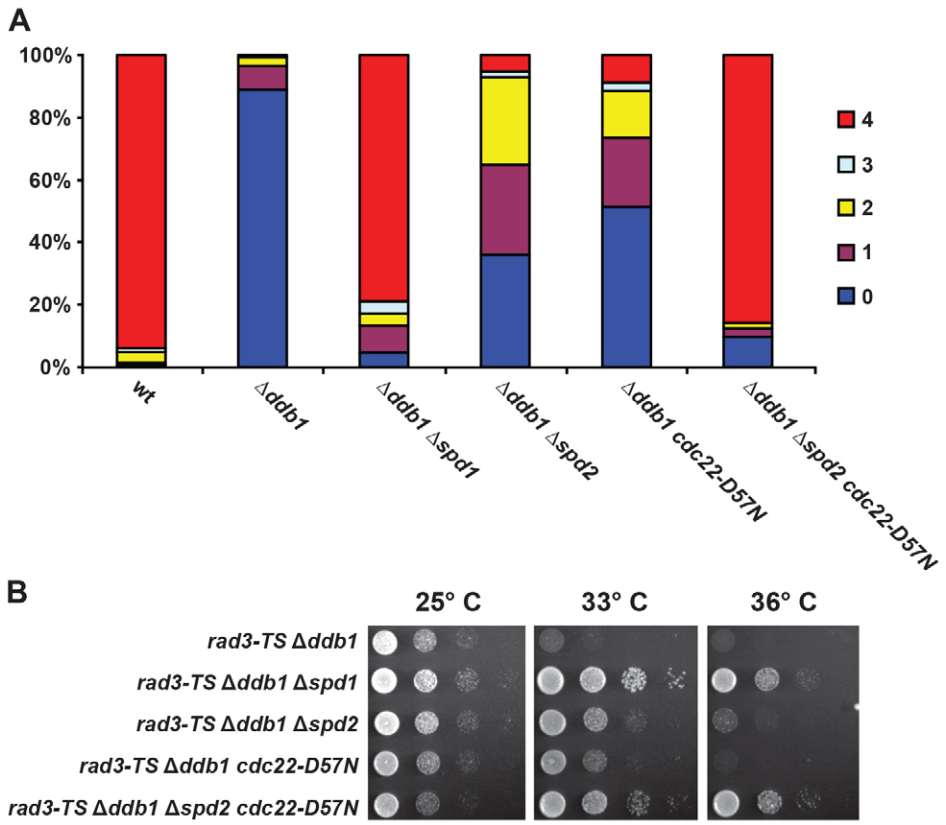

Fig. 8. Combining *Δspd2* with the *cdc22^{D57N}* mutation rescues *Δddb1* deficiencies to the same extent as deleting *spd1*. (A) Consistent with Fig. 7A, *Δspd1* rescued the sporulation deficiency of an *h^{90} Δddb1* strain almost fully. Both *Δspd2* and *cdc22^{D57N}* rescued the deficiency partially, but when combining *Δspd2* and *cdc22^{D57N}*, the sporulation levels were rescued almost fully. wt, wild type. (B) Both *Δspd2* and *cdc22^{D57N}* rescued the viability of a *rad3-TS Δddb1* strain partially, but when combined, viability was rescued to a similar extent as by *Δspd1*.

deleting *spd1* (Fig. 8). Therefore, an important conclusion of the present study is that excess Spd1 can cause checkpoint activation by both deoxynucleoside-dependent and -independent mechanisms, and only the latter seems to require Spd2. In accordance with this, we recently reported that Spd1 accumulation can cause checkpoint activation even in cells that have elevated dNTP pools due to the *cdc22-D57N* mutation (Fleck et al., 2013).

A key unanswered question is how Spd1 and Spd2 can cause checkpoint activation independently of deoxynucleotide regulation. Currently, the only known mutual function of Spd1 and Spd2 is the conformational change in RNR architecture manifested by the FRET assay. Hence, a molecular characterization of the RNR FRET phenomenon is highly important for understanding how small IDP proteins like Spd1 and Spd2 regulate genome integrity. Equally important, particularly from a cancer perspective, is the issue of whether this complex yet fascinating group of proteins also exists in human cells.

MATERIALS AND METHODS

Strains and media

Strain construction and growth media were applied according to standard genetic techniques for *S. pombe* (Moreno et al., 1991). A list of strains used in this study is included as supplementary material Table S1. Δ*spd2* was constructed as follows. A PCR reaction was performed with the pFA6a-kanMX plasmid (Bähler et al., 1998) as template and the primer set ONP687 and ONP688 (5′-GATACTTTTAATTGTTTTACTTATC-CAGGCGCCAGCTGAAGCTTCGTAC-3′ and 5′-TCGAAAGCTTTA-TCTTGCTCATTTATTCATGGCCACTAGTGGATCTGATA-3′), two additional PCR reactions were performed with purified genomic *S. pombe* DNA and the primer sets ONP689 and ONP690 (5′-ATGAATA-AATGAGCAAGATAAAGCTTTCGA-3′ and 5′-AGTAACTTTCGAC-ACATTCAAATGGTGT-3′) and ONP691 and ONP692 (5′-CCTGGAT-AAGTAAAACAATTAAAAAGTATC-3′ and 5′-ACGACTTGAAGCT-TACTCGCTTCTAAAAGG-3′). The three PCR products were used for a fusion PCR with ONP690 and ONP692, and the resulting amplicon was used for transformation of Eg432. G418-resistant clones were selected, positive clones were checked for correct recombination of the PCR product and a resulting strain was designated Eg2806 and used for subsequent studies. Plasmids for overexpression of Spd1 (pON736) or Spd2 (pON1126) from the thiamine-repressible *nmt1* promoter were obtained by cloning the ORFs into pREP3 (Maundrell, 1990).

FACS

Cells were fixed as described previously (Kjaerulff et al., 2005), and stained with Sytox Green (Molecular Probes) as recommended by the manufacturer. Quantification of S phase cells with the aid of the DNA signal width was performed as described previously (Knutsen et al., 2011). For each sample, a total of 30,000 cells were counted, and after gating at least 75% were still present.

Sensitivity assays

Fivefold dilution series of the indicated strains were spotted onto YEA plates containing the indicated drugs. Plates were cast 2 days prior to use and kept at room temperature. Pictures were taken after 3 days of incubation at 33℃ (or indicated temperature).

Structural analysis

The Spd2 ORF was ligated into a pET11a plasmid and expressed in BL21(DE3) cells grown in 1 litre of LB medium to an OD_{600} of 0.7–0.8 and induced with 0.01 mM IPTG for 3 hours at 37℃. Purification of Spd1 and Spd2, and structural analyses of Spd2 were performed essentially as described previously (Nestoras et al., 2010). The far-UV circular dichroism spectrum of Spd2 was recorded from 250 to 190 nm on 10 µM Spd2 and 10 mM NaH_2PO_4, pH 7.4, subtracting the corresponding buffer spectrum. The ^{15}N, ^{1}H-HSQC NMR spectrum was recorded on 277 µM ^{15}N-Spd2, 100 mM NaCl and 10 mM NaH_2PO_4, pH 7.4, at 10℃.

Western blotting

Cultures were grown to mid-log phase at 30℃ in YE and 5×10^7 cells were harvested. All samples were trichloroacetic acid (TCA) extracted,

run on 15% SDS-PAGE gels and wet blotted (300 mA) for 1.5 hours at 4℃. After blocking, membranes were incubated overnight at 4℃ with the indicated primary antibodies. To study protein levels in response to hydroxyurea treatment, cultures were grown to mid-log phase and 5×10^7 cells were harvested, 20 mM hydroxyurea was added to the remainder of the cultures and, after 4 hours, 5×10^7 cells were harvested. To analyze synchronous populations, 6 litres of culture was grown to mid-log phase and cells were size-sorted by elutriation. The smallest-sized cells were collected at a concentration of $\sim2\times10^6$ cells/ml and incubated at 30℃. 1×10^8 cells were harvested at each of the indicated time-points. Polyclonal rabbit anti-Spd1 and anti-Spd2 antibodies were raised against *E. coli* purified proteins by Yorkshire Bioscience.

Cell biology

Suc22–GFP localization assay and FRET analysis of the Cdc22 and Suc22 FRET-pair were performed as described previously (Nestoras et al., 2010). For meiotic analysis, h^{90} strains of the indicated genotypes were spotted onto solid sporulation medium at 25℃ and after 3 days the number of spores (0–4) in $\geq$100 individual zygotes or asci were counted.

dNTP pools

dNTP measurement were performed as described previously (Beck et al., 2012), and the levels were normalized to those of ATP. For normalization, the dNTP:ATP ratio was set to 1 in the wild type.

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Competing interests

The authors declare no competing interests.

Author contributions

O.F. performed experiments presented in Figs 1 and 7A; S.S.B. and B.B.K performed those presented in Fig. 2; U.F. performed those presented in Fig. 3; A.-S.S. performed those presented in Fig. 6A,B; K.L. performed those presented in Fig. 6C; C.H. performed those presented in Figs 7D and 8A. R.V.-H. performed all other experiments. A.M.C., C.H., O.F., R.V.-H. and O.N. contributed to conceptual development of the project and interpretation of the results. R.V.-H. and O.N. wrote the paper together.

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Supplementary material

Supplementary material available online at
http://jcs.biologists.org/lookup/suppl/doi:10.1242/jcs.139816/-/DC1

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