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Dual Mode of Regulation of Cell Division Cycle 25 A Protein by TRB3

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We have recently demonstrated that TRB3, a novel stress-inducible protein, is an unstable protein regulated by the ubiquitin-proteasome system. The expression level of TRB3 protein is down-regulated by anaphase-promoting complex/cyclosome-cell division cycle 20 homolog 1 (APC/C^{Cdh1}) through its D-box motif. Here we demonstrate that TRB3 regulates the stability of cell division cycle 25 A (Cdc25A), an essential activator of cyclin dependent kinases (CDKs). The expression level of Cdc25A protein is suppressed by over-expression of TRB3, while knockdown of TRB3 enhances the endogenous Cdc25A expression level. On the other hand, Cdc25A degradation induced by DNA damage is significantly rescued by TRB3. When serine residues in the DSG motif, which is the critical sequences for the degradation of Cdc25A induced by DNA damage, is mutated to alanine (Cdc25A^{DSG2X}), both stimulatory and protective effects of TRB3 on the Cdc25A degradation is disappeared. TRB3 protein interacts with both wild Cdc25A and mutant Cdc25A^{DSG2X}. Expression level of the endogenous TRB3 protein is down-regulated in a genotoxic condition. These results suggest TRB3 is a regulator for adjusting the expression level of Cdc25A both in a normal and a genotoxic conditions.

Key words TRB3; cell division cycle 25 A; DNA damage; degradation; ubiquitin

Cell division cycle 25 A (Cdc25A) is one of the highly conserved dual specificity phosphatases that activate cyclin dependent kinase (Cdk) complexes to regulate the cell cycle progression.^{2,3)} Cdc25A activates Cdk2-cyclin E and Cdk2-cyclin A complexes during G₁/S transition,^{3,4)} and contributes the G₂/M transition by activating Cdk1-cyclin B complexes.⁵⁾ Cdc25A expression is precisely regulated by ubiquitin-mediated proteolysis in both a normal cell cycle and a genotoxic stress condition.⁶⁾ Cdc25A ubiquitination is mainly mediated by two ubiquitin ligase complexes; anaphase promoting complex/cyclosome-Cdh1 (APC/C^{Cdh1}) for its destruction during mitotic exit and early G₁,⁷⁾ and S-phase kinase-associated protein 1 (Skp1)-Cul1-Fbox-beta-transduction repeat-containing protein (β -TrCP) (SCF ^{β -TrCP}) for its proteolysis during G₁, S and G₂.⁸⁾ Binding of Cdc25A to APC/C^{Cdh1} is dependent on a KEN box without post-translational modifications,⁹⁾ while interaction with SCF ^{β -TrCP} requires the phosphorylation of serine residues within a so-called DSG motif.¹⁰⁾

Cdc25A plays a role in the checkpoint response to unrepliation or DNA damage.^{5,6,11)} Cdc25A is a phosphorylation target of checkpoint kinases (Chks) and is regulated by Chk kinases in response to DNA damage to degrade *via* the ubiquitin-proteasome pathway. Cells resistant to degradation of Cdc25A display defects in checkpoint arrest to lead the genomic instability.¹⁰⁾

In *Drosophila*, reinitiation of mitosis is controlled by regulated expression of Cdc25.¹²⁾ It has been reported that *tribbles*, an atypical member of the protein kinase superfamily, acts by specifically inducing degradation of *string*, one of the Cdc25A orthologs in *Drosophila*, *via* the proteasome pathway and delayed G₂/M transition.¹³⁾

We previously identified TRB3, as one of the human orthologs of *tribbles*, which induced by endoplasmic reticulum stress and contributed to cell growth inhibition.¹⁴⁾ *Trib-*

bles and TRB3 contain the classic substrate-binding domains of a protein kinase but not the ATP-binding and kinase-activating domains; therefore, they do not have a kinase activity.¹⁵⁾ Recently we have reported that TRB3 is an unstable protein regulated by the ubiquitin-proteasome system.¹⁶⁾ The expression level of TRB3 protein is down-regulated by anaphase-promoting complex/cyclosome Cdh1 (APC/C^{Cdh1}) which is a key ubiquitin ligase complex, which regulates the progression of the cell cycle.

In this study, we found that TRB3 interacts with Cdc25A to destabilize its protein in a normal condition, however prevented its degradation in response to DNA damage.

MATERIALS AND METHODS

Reagents Dulbecco's modified Eagle's medium, anti- β -actin monoclonal antibody (AC-15), and anti-FLAG monoclonal antibody (M2) were purchased from Sigma. Fetal bovine serum was from HyClone (Logan, UT, U.S.A.). MG132 was obtained from Peptide Institute (Osaka, Japan). Anti-Cdc25A polyclonal antibody (M-191) was from Santa Cruz (Santa Cruz, CA, U.S.A.). Anti-Myc monoclonal antibody (9E10) and anti-HA monoclonal antibody (12CA5) were from Roche (Indianapolis, IN, U.S.A.). Anti-green fluorescent protein (GFP) monoclonal antibody (JL8) was from Clontech (Mountain View, CA, U.S.A.). Anti-p21 monoclonal antibody (05-345) was from Upstate (Lake Placid, NY, U.S.A.). The antiserum against human TRB3 was prepared as described previously.¹⁵⁾

Cell Culture The embryonic kidney cell line 293, the human cervical carcinoma cell line HeLa and human melanoma cell line A375 were cultured as described previously.¹⁷⁾

Construction of Expression Plasmids The plasmids

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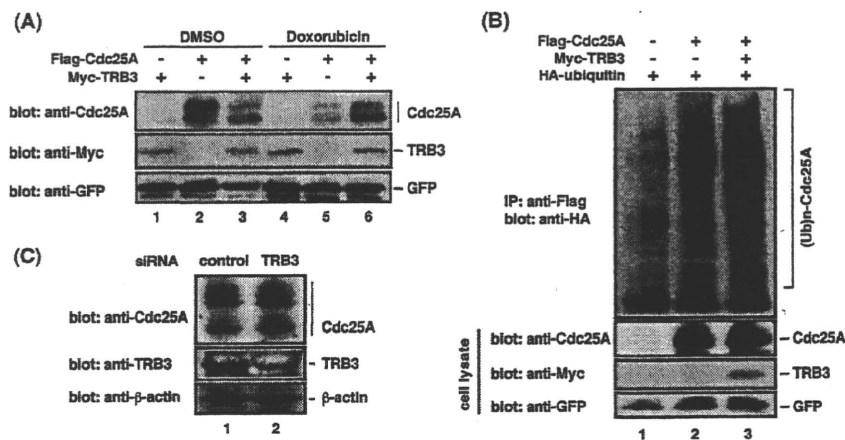


Fig. 1. TRB3 Positively and Negatively Regulates the Cdc25A Protein Stability

(A) HeLa cells were transiently transfected with indicated constructs. After 24 h, cells were treated with or without 0.5 μ M doxorubicin for 24 h. The cell lysates were analyzed by immunoblotting using indicated antibodies. The pEGFP-C1 expression plasmid was included in each transfection as a transfection efficiency control. (B) 293 cells were transiently transfected with indicated constructs. After 24 h, cells were treated with 10 μ M MG132 for 12 h. The cell lysates were immunoprecipitated (IP) with anti-Flag antibody and multi-ubiquitinated Cdc25A was detected by immunoblotting with anti-HA antibody. The expression level of each protein was assessed by immunoblotting using anti-Cdc25A, anti-Myc and anti-GFP antibodies. (C) HeLa cells were transiently transfected with control (scramble) siRNA or TRB3 siRNA twice every 24 h. The cell lysates were harvested and analyzed by immunoblotting using anti-Cdc25A, anti-TRB3 and anti- β -actin antibodies.

pCMV5-Flag-TRB3 was constructed as described previously.¹⁴ The plasmids pCMV5B-Flag-Cdc25A, pCMV5B-Myc-Cdc25A, pCMV5B-Flag-Cdc25A(1-260) lacking amino acids (aa) 261-525, pCMV5B-Flag-Cdc25A(261-525) lacking aa1-260, pCMV5B-Flag-Cdc25A(261-330) lacking aa1-260 and 331-525, pCMV5B-Flag-Cdc25A(331-460) lacking aa1-330 and 461-525, pCMV5B-Flag-Cdc25A(461-525) lacking aa1-460 or pCMV5B-Flag-Cdc25A(331-525) lacking aa1-330, pCMV5B-Flag-Cdc25A^{DSG2X}, replacing Ser⁸² and Ser⁸⁸ with Ala, pCMV5B-Flag-Cdc25A^{KEN2mt}, replacing Lys¹⁴¹, Glu¹⁴² and Asn¹⁴³ with Ala were generated by polymerase chain reaction (PCR). pMT-123 (HA-Ub)¹⁸ was kindly provided by Dr. D. Bohmann (University of Rochester Medical Center). All constructs were verified by sequencing.

Immunoprecipitation and Western Blot Analysis

Cells were transiently transfected and treated as described in the Figure Legends. The cells were lysed in RIPA buffer (50 mM Tris-HCl, pH 8.0, 150 mM NaCl, 0.1% sodium dodecyl sulfate (SDS), 0.5% deoxycholate, and 1% Triton X-100) supplemented with protease inhibitors. The lysates were subjected to immunoprecipitation, and 1–2% of the lysate or co-immunoprecipitates was subjected to SDS-polyacrylamide gel electrophoresis (PAGE) (5–12.5%), transferred onto a polyvinylidene difluoride (PVDF) membrane and probed with the antibodies indicated in the Figure Legends. The immunoreactive proteins were visualized using ECL (Amersham Bioscience) or Immobilon (Millipore) Western blotting detection reagents, and light emission was quantified with a LAS1000 lumino image analyzer (FUJI, Japan).

RNA Interference Double stranded RNA duplexes corresponding to human TRB3 was obtained from Dharmacon Inc. (Chicago, IL, U.S.A.).

Transfection 293 and HeLa cells were transfected using the Chen-Okayama method as described previously.¹⁷ For RNA interference, HeLa cells were transfected using a lipofection method with Lipofectamine 2000 (Invitrogen).

RESULTS

TRB3 Negatively and Positively Regulates the Stability of Cdc25A Protein

To determine the TRB3 effect on the Cdc25A stability, we first examined the co-transfection experiment in HeLa cells. Over-expression of TRB3 resulted in decreased Cdc25A steady-state protein levels (Fig. 1A, lane 3), which accompanied by accumulation of polyubiquitin-reactive signals in the Cdc25A immune-complexes (Fig. 1B). We also investigated whether TRB3 depletion affects the Cdc25A protein stability. As shown in Fig. 1C, endogenous TRB3 silencing by small interfering RNA (siRNA) in HeLa cells resulted in increased endogenous Cdc25A steady-state levels. Similar result has been observed when endogenous TRB3 was knock-downed in HepG2 cells.¹⁶

Cdc25A is one of the well-known targets of the DNA damage to induce cell cycle arrest.¹⁰ The expression level of Cdc25A protein is remarkably decreased, when cells are treated with doxorubicin, an anticancer drug that leads to DNA double-strand breaks (Fig. 1A, lane 5). Strikingly, TRB3 rescues the breakdown of Cdc25A protein induced in response to DNA damage (lane 6). These results indicate that TRB3 regulates the Cdc25A stability negatively in a normal condition and positively under the genotoxic stress.

Cdc25A Physically Interacts with TRB3 As TRB3 is considered to be a regulator of Cdc25A, we next examined whether TRB3 can interact with Cdc25A. Cell extract was prepared from 293 cells co-expressed with Myc-TRB3 and Flag-Cdc25A, followed by immunoprecipitation-Western blot analysis. As shown in Fig. 2A, TRB3 was found to interact with Cdc25A. We next assayed the interaction of various Cdc25A deletion mutants to map the region responsible for TRB3 binding. The deletion mutant with C-terminal half of Cdc25A (aa 261-525) is relatively stable and shown to be interacted with TRB3 (Fig. 2B). Further experiments demonstrated that the region aa 331-460 is crucial in TRB3 binding (Fig. 2C). On the other hand, the N-terminal half region of Cdc25A (aa 1-260) is not detected even in the presence of a

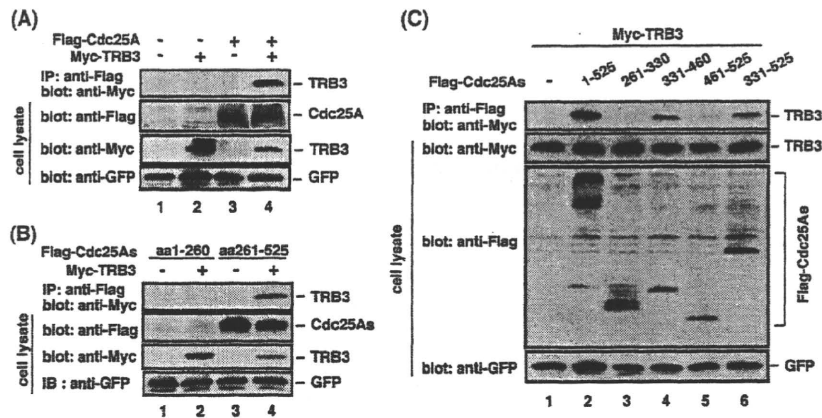


Fig. 2. TRB3 Physically Interacts with Cdc25A

(A, B) 293 cells were transiently transfected with indicated constructs. After 24 h, the cells were treated with $10 \mu\text{M}$ MG132 for 12 h. The cell lysates were immunoprecipitated (IP) with anti-Flag antibody, and immunoblotting of cell lysates was performed with anti-Flag or anti-Myc antibodies. (C) 293 cells were transiently transfected with the expression plasmid for Myc-TRB3 in the presence of the expression plasmids for full length Flag-Cdc25A (1-525) or its deletion mutants. After 24 h, cells were treated with $10 \mu\text{M}$ MG132 for 12 h. The cell lysates were immunoprecipitated (IP) with anti-Flag antibody and immunoblotted with anti-Myc antibody. The expression level of each protein was assessed by immunoblotting of cell lysates with anti-Flag, anti-Myc or anti-GFP antibodies.

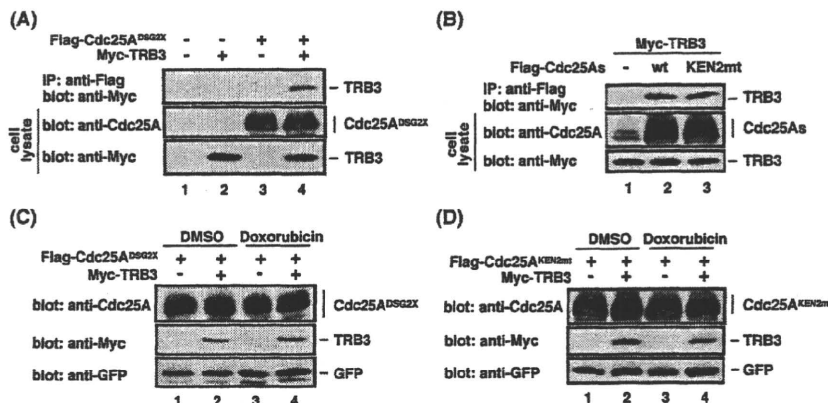


Fig. 3. DSG Motif and KEN Box in Cdc25A Are Not Necessary to Interact with TRB3, but Responsible for Its Unstabilizing Effect

(A, B) 293 cells were transiently transfected with the expression plasmids of Flag-Cdc25A^{DSG2X} (replacement of both Ser82 and Ser88 to Ala in Cdc25A) (A) or Flag-tagged wild-type Cdc25A or Flag-Cdc25A^{KEN2mt} (replacement of KEN (141-143) to AAA in Cdc25A) (B) in the presence of the expression plasmid Myc-TRB3. After 24 h, the cells were treated with $10 \mu\text{M}$ MG132 for 12 h. The cell lysates were immunoprecipitated (IP) with anti-Flag antibody, and immunoblotted by anti-Myc antibody. The expression level of each protein was assessed by the immunoblotting of the cell lysates with anti-Cdc25A or anti-Myc antibodies. (C, D) HeLa cells were transiently transfected with the expression plasmids of Flag-Cdc25A^{DSG2X} (C) or Flag-Cdc25A^{KEN2mt} (D) in the presence of the expression plasmid Myc-TRB3. After 24 h, cells were treated with $0.5 \mu\text{M}$ doxorubicin for another 24 h. The cell lysates were analyzed by immunoblotting using anti-Cdc25A or anti-Myc antibodies. The pEGFP-C1 expression vector was included in each transfection as a transfection efficiency control, and its level was detected with anti-GFP antibody.

proteasome inhibitor, MG132, so it is hard to consider whether N-terminal region is necessary for TRB3 association from this experiment.

Role of DSG Motif and KEN Box of Cdc25A in Its Down-Regulation by TRB3 Cdc25A is constantly tuned over in cycling cells. Two different ubiquitin ligases (SCF ^{β -TrCP} and APC/C^{Cdh1} complex) are known to be involved in Cdc25A turnover, and interaction with these complexes requires specific recognition motifs in Cdc25A. One is DSG motif for SCF ^{β -TrCP} binding,¹⁰ and the other is KEN box for APC/C^{Cdh1}.⁹ To examine the possible involvement of these regions in the unstabilizing effect of TRB3, we determined the effect of mutation of these motifs (Cdc25A^{DSG2X} and Cdc25A^{KEN2mt}). These mutants are quite stable and still interact with TRB3 in 293 cells (Figs. 3A, B). When Myc-TRB3 is co-expressed with Flag-Cdc25A^{DSG2X}, its expression level remained unaffected compared to that of single transfection

(Fig. 3C). Likewise, over-expressed TRB3 did not change the expression level of KEN2 mutated Cdc25A either (Fig. 3D). These results suggest that DSG and KEN motifs in Cdc25A are involved in the TRB3 effect of its unstabilizing.

The expression levels of these mutants are not different even after doxorubicin treatment (Fig. 3C, D, lane 3), indicating that both mutants are resistant to the proteolytic degradation induced in response to DNA damage (Figs. 3C, D, lane 3). When these mutants were used, the regulatory effect of TRB3 on Cdc25A expression was not observed (Figs. 3C, D, lane 4).

TRB3 Is Down-Regulated by Genotoxic Stress We have already shown that TRB3 is markedly induced by endoplasmic reticulum (ER) stress *via* induction of stress-related transcription factors, activating transcription factor (ATF) and CCAAT/enhancer-binding protein (C/EBP) homologous protein (CHOP).¹⁴ To determine whether the expression

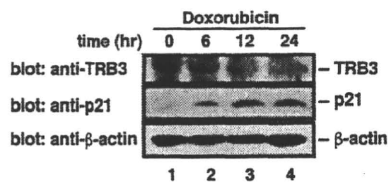


Fig. 4. TRB3 Is Down-Regulated in Response to DNA Damage

p53 wild-type human melanoma cell line, A375 cells were treated with 0.5 μ M doxorubicin for indicated periods of time. The cell lysates were analyzed by immunoblotting using anti-TRB3, anti-p21 and anti- β -actin antibodies.

level of TRB3 protein is also regulated by DNA damage stress, A375 cells, which are human melanoma cell lines with wild type p53, were treated with doxorubicin. As shown in Fig. 4, doxorubicin time-dependently down-regulates the expression of endogenous TRB3 protein. We also observed the obvious induction of endogenous p21 protein, which is a well-established downstream target of p53, by doxorubicin treatment.

DISCUSSION

As Cdc25A is an essential activator of cyclin-dependent kinase during normal cell-cycle progression, it is strictly regulated at the protein level, being periodically synthesized and degraded *via* ubiquitin-proteasome pathway.^{4,8,19} Cdc25A is also thought to be one of the proto-oncogenes because of its transformation ability²⁰ and its over-expression in many cancers, both at mRNA and protein levels.²¹ This deregulated expression may be due to anomalous E2F1/c-Myc transcriptional activity or alternatively to a reduced rate of protein degradation. Our results demonstrated that TRB3 down-regulates the Cdc25A expression level in a normal condition and recovers its degradation induced in response to DNA damage, suggesting that TRB3 could be a crucial regulator of Cdc25A for fine-tuning of its abundance.

In *Drosophila*, reinitiation of mitosis is regulated by Cdc25 expression level.¹² One of the Cdc25 orthologs in *Drosophila*, *string* is expressed zygotically in the embryo. It has been reported that *tribbles*, an atypical member of the protein kinase superfamily, acts by specifically inducing degradation of *string* *via* the proteasome pathway and delayed G₂/M transition.¹³ Our observation also demonstrates the Cdc25A unstabilizing effect of TRB3, one of the *tribbles* orthologs at the steady state. The TRB3 action to Cdc25A could be also shown and involved in the oocyte maturation.

We have previously showed that TRB3 is markedly induced by various ER stresses.¹⁴ However, genotoxic stress was reported to down-regulate TRB3 mRNA expression.²² Consistent with this, we demonstrate that the protein level of Cdc25A is also decreased in response to DNA damage induced by an anticancer drug, doxorubicin. This result indicates that under the genotoxic condition, the suppressive effect of TRB3 on the Cdc25A proteolysis is usually down-regulated due to the reduction of TRB3 expression itself. On the contrary, these finding support the idea that under the various stressful conditions (ER stress, hypoxia, amino acid deprivation, oxidative stress, *etc.*) to induce the TRB3 expression, Cdc25A protein would be stabilized even under the genotoxic conditions by up-regulated TRB3 and the

checkpoint function will be lost, thus resulting in genomic instability and cancer predisposition. Multiple primary human lung, colon, and breast tumors express high levels of TRB3 transcript.^{23,24} It is possible that the accumulation of Cdc25A protein by TRB3 over-expressed in multiple human tumors and tumor-derived cell lines is involved in the tumorigenesis and malignant alteration of cancer. Further study is necessary to clarify whether over-expressed TRB3 is contributed to tumorigenesis.

We show that TRB3 interacts with the region aa 331-460 of Cdc25A. This region is the part of catalytic domain of Cdc25A, which raises the possibility that TRB3 regulates the phosphatase activity of Cdc25A and its binding ability to CDK/cyclin complexes as well. TRB3 can also associate with KEN or DSG mutants of Cdc25A, indicating that TRB3 might not compete with β -TrCP or Cdh1 for binding to Cdc25A *via* these motifs. However, the unstabilizing activity of TRB3 to these two Cdc25A mutants are not observed at all, suggesting that these motifs are crucial to facilitate the unstabilizing of Cdc25A protein by TRB3 and that β -TrCP and/or Cdh1 are involved in this effect.

We have previously demonstrated that TRB3 is a short-lived protein and its steady-state level is balanced through proteasome-dependent degradation, which is facilitated by APC/C^{Cdh1}.¹⁶ APC/C is a key ubiquitin ligase complex, which regulates the progression of the cell cycle by control the ubiquitination and subsequent degradation of a number of core cell-cycle regulators. As previously mentioned, APC/C^{Cdh1} also regulates the Cdc25A stability in a normal condition at mitotic exit and in early G₁. Taken together, it is possible that the expression of TRB3 is periodically regulated in cell cycle, resulting the Cdc25A stability is also time-dependently modified.

Important question still remain unsolved. Why TRB3 regulates differently the Cdc25A stability in the cell conditions? A possibility is that the modification mode of Cdc25A protein is different from in a normal condition and under the genotoxic stress. Cdc25A is a well-characterized target of Chk1/Chk2 and other kinase(s) in response to DNA damage.¹² Phosphorylation could alter the interaction or response of TRB3 to Cdc25A, resulting in the different action of TRB3 to Cdc25A stability. A second possibility is that TRB3 may differently influence the function of Cdc25A kinase(s) and Cdh1. Steady state level of Cdc25A is mainly controlled by APC/C^{Cdh1} through its KEN box. In contrast, in the case of the genotoxic condition, SCF ^{β -TrCP} is mainly responsible for the breakdown of Cdc25A phosphorylated by Chk1 and a recently discovered kinase NEK11.^{10,25} We have previously demonstrated that TRB3 silencing caused the accumulation of Cdc25A and Cdc20, another well-known target of APC/C^{Cdh1}, in HepG2 cells without any change of Cdh1 expression level, suggesting that TRB3 has some influence on the Cdh1 dependent degradation.¹⁵ TRB3 is considered as a pseudokinase, which contains the typical substrate-binding domains, but lack the ATP binding and kinase-activation domains.¹⁵ It is possible that some kinase(s) or other modifying enzyme(s) cannot recruit to Cdc25A or upstream kinase(s) when they interact with TRB3, and that TRB3 could be an endogenous kinase inhibitor, acting as a decoy kinase-like protein for upstream kinase(s) for Cdc25A phosphorylation.

In summary, this study provides that the cell-cycle activator, Cdc25A is positively and negatively regulated by stress inducible pseudokinase TRB3 at the protein level. Important roles of TRB3 in Cdc25A implicate the additional function of TRB3 in cell cycle regulation besides the recently described roles in the stress response. These results allowed us to investigate the precise role of TRB3 in cell cycle to understand whether TRB3 contributes to deregulation of DNA damage checkpoints and tumorigenesis.

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RESEARCH COMMUNICATION

Essential role of Tip60-dependent recruitment of ribonucleotide reductase at DNA damage sites in DNA repair during G1 phase

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A balanced deoxyribonucleotide (dNTP) supply is essential for DNA repair. Here, we found that ribonucleotide reductase (RNR) subunits RRM1 and RRM2 accumulated very rapidly at damage sites. RRM1 bound physically to Tip60. Chromatin immunoprecipitation analyses of cells with an I-SceI cassette revealed that RRM1 bound to a damage site in a Tip60-dependent manner. Active RRM1 mutants lacking Tip60 binding failed to rescue an impaired DNA repair in RRM1-depleted G1-phase cells. Inhibition of RNR recruitment by an RRM1 C-terminal fragment sensitized cells to DNA damage. We propose that Tip60-dependent recruitment of RNR plays an essential role in dNTP supply for DNA repair.

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Maintenance of the optimal intracellular concentrations of deoxyribonucleotides (dNTPs) is critical not only for faithful DNA synthesis during DNA replication and repair, but also for the survival of all organisms. Ribonucleotide reductase (RNR), composed of a tetrameric complex of two large catalytic (RRM1) subunits and two small subunits (RRM2 or 53R2), catalyzes de novo synthesis of dNTPs from the corresponding ribonucleotides (Reichard 1993). This reaction is the rate-limiting process in DNA precursor synthesis and is regulated by multiple complex mechanisms, including transcriptional and subcellular localization regulation of RNR (Nordlund and Reichard 2006). In order to duplicate their chromosomal DNA,

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mammalian S-phase cells possess 15–20 times more dNTP pools than resting quiescent cells, whereas whole dNTP pools were almost unchanged after DNA damage, suggesting the presence of a unique mechanism that supplies a sufficient quantity of dNTPs at repair sites (Hakansson et al. 2006). DNA synthesis must function properly in both repair and replication (dNTP concentrations in fibroblasts were estimated to be as follows: ~0.5 μ M in G0/G1-phase cells, and ~10 μ M in S-phase cells, given that the average volume of a fibroblast is 3.4 pL) (Imaizumi et al. 1996). Although the amount of dNTPs required for DNA repair is small, their concentration during DNA synthesis is critical because DNA polymerase involved in DNA repair (Kraynov et al. 2000; Johnson et al. 2003) has similar kinetic affinities for dNTPs (~10 μ M) to those involved in DNA replication (~10 μ M) (Dong and Wang 1995). Therefore, the dNTPs might be compartmentalized close to the damage sites during the DNA repair process. In this study, we show that, in mammals, both RRM1 and RRM2 rapidly accumulated at double-strand break (DSB) sites in a Tip60-binding-dependent manner.

Results and Discussion

In order to understand the mechanisms by which dNTPs are sufficiently supplied at DNA damage sites in mammals, we first examined changes in the subcellular localization of RRM1 and RRM2 subunits after ionizing irradiation (IR) irradiation. Although both RRM1 and RRM2 predominantly localized in the cytoplasm as reported previously (Pontarin et al. 2008), we also detected trace, but significant, signals of both proteins in chromatin fraction (see Fig. 1C; Supplemental Fig. S4A–D). After removing soluble RNR proteins by detergent extraction, we found that RRM1 and RRM2 proteins formed nuclear foci that colocalized with γ H2AX (Fig. 1A). RRM1 nuclear foci were not evident without DNA damage (Supplemental Fig. S1A) or after RRM1 depletion by siRNA (Supplemental Fig. S1B). Ultraviolet A (UVA) microirradiation resulted in the accumulation of RRM1 and RRM2 along microirradiated lines as early as 5 min after treatment (Fig. 1B). These accumulations were also observed when cells were not subjected to detergent extraction or preincubation with BrdU (Supplemental Fig. S2A,B), but were significantly compromised when R1 expression was knockdown by siRNA (Supplemental Figs. S2C, S4B), excluding the possibility that accumulated signals at DSB sites were artifacts during cell-staining processes. These results indicated that RNR, at least in part, was rapidly recruited to DSB sites.

In order to determine the molecular basis underlying RNR recruitment at the sites of DSBs, we performed yeast two-hybrid screening using RRM1 as a bait. Of a total of 5×10^6 transformants from a HeLa cell cDNA library, 45 positive colonies were confirmed to be lacZ-positive. They contained overlapping cDNAs derived from three genes: RRM2 and 53R2 (both encoding a small subunit of RNR), and another encoding Tip60 histone acetyltransferase (Tip60). Small C-terminal RRM1 deletion mutants (Δ 761-C and Δ 781-C) failed to bind Tip60, but retained the ability to bind to RRM2 (Supplemental Fig. S3A). In contrast, the N-terminal truncation mutant of Tip60

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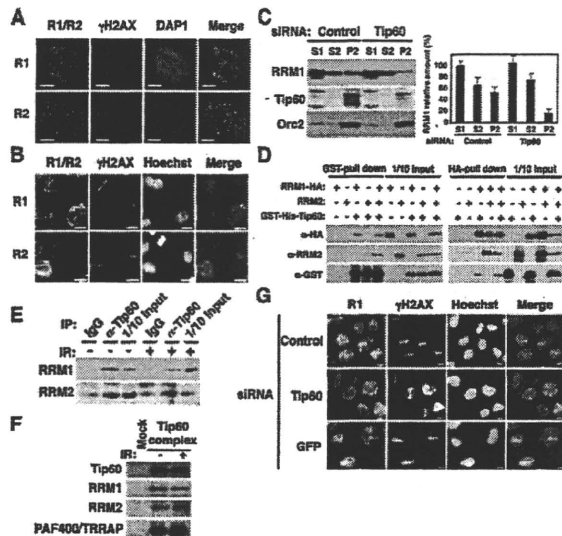


Figure 1. Tip60-dependent recruitment of RNR at DSB sites. **(A)** HeLa cells were exposed to IR at 1 Gy, subjected to in situ detergent extraction after 5 min, and immunostained with the indicated antibodies. Bars, 5 μ m. **(B)** GMO2063 cells were subjected to UVA microirradiation and immunostained with the indicated antibodies after 5 min. RRM1 or RRM2 and γ H2AX signals are shown in green and red, respectively, in merged images. Bars, 10 μ m. **(C)** IR-irradiated HeLa cell lysates treated with the indicated siRNAs were fractionated as described in the Materials and Methods. **(Left panels)** The fractions were subjected to immunoblotting using the indicated antibodies. **(Right panel)** The RRM1 bands were quantitated, and the results are presented as percentages of S1 fraction. Data are mean \pm standard deviation ($n = 3$). **(D)** S69 lysates expressing RRM1-HA, RRM2, or GST-His-Tip60 were subjected to GST pull-down or HA pull-down assays using the indicated antibodies. **(E)** Chromatin fractions from IR- or mock-treated HeLa cells (after 5 min) were solubilized with micrococcal nuclease. The solubilized extracts were immunoprecipitated with anti-Tip60 antibodies or control IgG. The resulting precipitates and a 10% input (1/10 Input) were immunoblotted with the indicated antibodies. **(F)** The affinity-purified Tip60 complexes, as described in the Materials and Methods, were subjected to immunoblotting using the indicated antibodies. **(G)** GMO2063 cells were treated with control, Tip60, or GFP siRNAs and then subjected to UVA microirradiation as in **B**.

(TC2) could interact with RRM1, but no mutant with any additional truncation of TC2 was able to do so (Supplemental Fig. S3B). Full-length Tip60 failed to bind full-length RRM2 (Supplemental Fig. S3C). We generated the C-terminal fragment of RRM1 (amino acids 701–792) with a SV40 nuclear localization signal (NLS-RC1-HA) and examined its ability to bind Tip60 in vivo and in vitro. NLS-RC1-HA, but not a control NL-GFP-HA fragment, was detected in the anti-Myc immunoprecipitates when transiently coexpressed with Tip60-Myc (Supplemental Fig. S3D). Purified MBP-fused RC1 produced in *Escherichia coli* was capable of binding to GST-Tip60 expressed in insect cells (Supplemental Fig. S3E). Both Δ 761-C and Δ 781-C failed to bind chromatin, further confirming that the binding of RRM1 to chromatin required its interaction with Tip60 (Supplemental Fig. S3F).

Similarly to Chk1 (Niida et al. 2007; Shimada et al. 2008), endogenous RRM1 was present in cytosolic (S1), nucleoplasmic (S2), and chromatin-bound (P2) fractions (Supplemental Fig. S4A). Tip60 existed predominantly in

the chromatin-bound fraction (P2). Both RRM1 and Tip60 proteins in this fraction were partly solubilized by treatment with micrococcal nuclease (Mnase), suggesting that they associated with chromatin. RRM1 knockdown showed a significant decrease of RRM1 protein levels in both soluble and chromatin-bound fractions (Supplemental Fig. S4B). IKK α and Orc2 were detected predominantly in soluble and chromatin fractions, respectively, indicating that cell fractionation was done successfully. Ectopic RRM1-HA present in the chromatin fraction was increased when Tip60-Myc-His was coexpressed, although a low level of RRM1-HA was detected in the absence of Tip60-Myc-His, presumably due to the presence of endogenous Tip60 (Supplemental Fig. S4C). The amounts of RRM1 and Tip60 bound to the chromatin were not affected by DNA damage (Supplemental Fig. S4D). However, depletion of RRM1 resulted in a reduction in the amount of RRM1 on chromatin (Fig. 1C). Taken together, chromatin binding of RRM1 appeared to be Tip60-dependent. RRM1-HA, but not the RRM2 subunit alone, formed a complex with GST-His-Tip60 in insect cells (Fig. 1D, left panels). RRM2 also formed a complex with GST-His-Tip60 in a manner dependent on the presence of RRM1-HA. Consistently, accumulation of RRM2 at DSB sites was compromised when RRM1 was depleted (Supplemental Fig. S2D). Immunoprecipitations using anti-HA antibodies demonstrated that RRM1-HA bound to both RRM2 and GST-His-Tip60 (Fig. 1D, right panels). RRM1 and RRM2 were detected in the precipitates of anti-Tip60 antibodies from the solubilized chromatin, even in the absence of DNA damage (Fig. 1E). To further confirm the interaction between RNR and Tip60, we purified the Tip60 complex from HeLa cell nuclear extracts expressing Flag-HA Tip60 as reported previously (Ikura et al. 2000, 2007). RRM1 and RRM2, as well as PAF400/TRRAP as a positive control (Murr et al. 2006), were detected in Tip60 complex from extracts with or without DNA damage (Fig. 1F). Tip60 knockdown by siRNA or shRNA abrogated accumulation of RRM1 along with microirradiated lines (Fig. 1G; Supplemental Fig. S2E). These results suggested that RRM1 recruitment at DSB sites was Tip60-dependent.

To determine precisely whether RRM1 was recruited at the site of DNA damage, we generated *Ku*-deficient mouse embryonic fibroblasts (MEFs) in which a single DSB was introduced after infection with adenoviruses expressing I-SceI. This DSB was not rapidly repaired by nonhomologous end-joining, making it easy to detect proteins accumulating at this DSB site by chromatin immunoprecipitation (ChIP) analysis (*STEFKu70*^{-/-} *phprt-DR-GFP*) (Fig. 2A; Pierce et al. 2001). Introduction of the DSB was confirmed by Southern blotting (Supplemental Fig. S5). ChIP analyses revealed a substantial increase in the binding of RRM1 as well as Rad51 and Tip60 to a DNA break site. An increase in acetylation of histone H4 was also observed at the damage site (Fig. 2B). These were not seen on infection with control LacZ. Tip60 depletion by two independent siRNAs resulted in a loss of RRM1 binding to a DSB site, as well as a reduction in acetylation of histone H4 (Fig. 2C). A mutant Tip60 lacking histone-acetylating activity could recruit RRM1 to the DSB site similarly to wild-type RRM1 (Supplemental Fig. S6A). Inhibition of ATM, ATR, and DNA-PK by caffeine did not affect RRM1 recruitment (Supplemental Fig. S6B). These results further supported the notion that complex

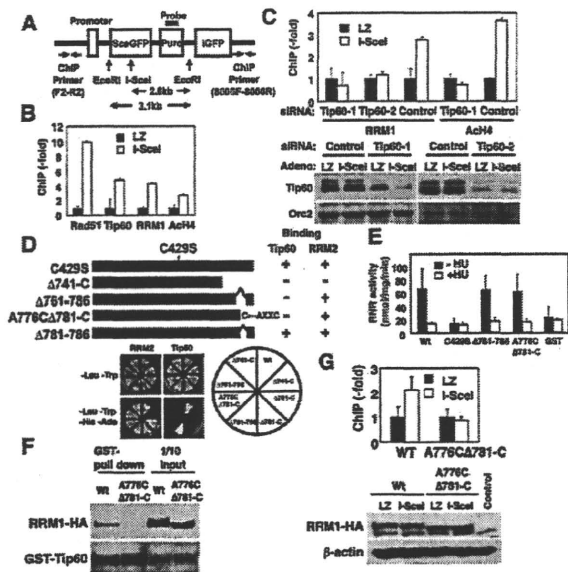


Figure 2. RRM1 is recruited at DSB sites in a Tip60-dependent manner. (A) Map of the I-SceI cassette construct containing the I-SceI site, the probe for Southern blotting, and a set of primers for the ChIP assay. (B) *STEFKu70^{-/-}phprt-DR-GFP* cells infected with I-SceI adenoviruses were subjected to ChIP analysis using the indicated antibodies as described in the supporting Materials and Methods. Data are shown as percentages of increases in PCR products from cells expressing I-SceI (I-SceI) relative to those from cells expressing Lac Z (LZ). Data are mean \pm standard deviation ($n = 3$). (C) *STEFKu70^{-/-}phprt-DR-GFP* cells were transfected with two independent Tip60 siRNAs (Tip60-1 and Tip60-2) or control siRNA. ChIP analysis was performed as in B. (Bottom panels) Aliquots of cell lysates were subjected to immunoblotting using anti-Tip60 antibodies. (D) The constructs used are schematically represented, and the specific interaction between RRM1 mutants and Tip60 was assayed using yeast two-hybrid screening. (E) An in vitro RNR assay of complexes containing wild-type or various RRM1 mutants was performed as described in the Materials and Methods. (Black bars) -HU; (white bars) +HU (10 mM). Data are mean \pm standard deviation ($n = 3$). (F) Sf9 lysates expressing GST-His-Tip60 and the indicated RRM1-HA were subjected to GST pull-down assay using the indicated antibodies. (G) Knockout-knock-in *STEFKu70^{-/-}phprt-DR-GFP* cells expressing wild-type or A776CA781-C RRM1-HA were generated by transfection with vectors for either wild-type or A776CA781-C RRM1 and then with RRM1 siRNA. Expression vectors of wild type and A776CA781-C contain mutations in a specific sequence targeted by siRNA. (Top panel) Cells were subjected to ChIP analysis using anti-HA antibodies as in B. (Bottom panels) Aliquots of cell lysates were subjected to immunoblotting using the indicated antibodies.

formation between RNR and Tip60 is required for recruitment of RNR to sites of DNA damage.

We then examined if RNR recruitment at damage sites was required for effective DNA repair. We first generated RRM1 mutants that lack the ability to bind Tip60 but retain RNR activity. Given that the C-terminal CXXC motif of RRM1 is important for RNR function (Zhang et al. 2007), we constructed RRM1 mutants containing the CXXC motif but lacking Tip60-binding ability ($\Delta 761-786$ and A776CA781-C) (Fig. 2D). Wild-type RRM1 or its mutants were coexpressed with RRM2 in insect cells, and the resultant complexes were subjected to an in vitro RNR assay (Fukushima et al. 2001). RNR complexes containing wild-type, $\Delta 761-786$, and A776CA781-C RRM1

retained hydroxyurea [HU]-sensitive RNR activity (HU is a specific RNR inhibitor), whereas an inactive C429S mutant or GST protein as a negative control did not show RNR activity (Fig. 2E). The specific activity of RNR containing wild-type, $\Delta 761-787$, and A776CA781-C RRM1 (~ 50 nmol/mg per minute) was similar to that reported previously (Guittet et al. 2001), confirming the reliability of our results. The A776CA781-C mutant failed to form a complex with GST-Tip60 (Fig. 2F). ChIP analysis using RRM1 knockout-knock-in *STEFKu70^{-/-}phprt-DR-GFP* cells revealed that the A776CA781-C mutant failed to accumulate at the DSB site (Fig. 2G). These results indicated that direct interaction of RRM1 to Tip60 is required for triggering its accumulation at the DSB site.

A comet assay revealed that DNA damage in cells was repaired efficiently within 1 h in the absence of HU. However, treatment with HU, and RRM1 or RRM2 depletion, resulted in an impairment of DNA repair (Fig. 3A,B). RNR activity was thus essential for effective repair. Ectopic expression of wild-type RRM1 with mutations in a specific sequence targeted by siRNA effectively rescued the impaired DNA repair in cells depleted of endogenous RRM1 (Fig. 3C). In contrast, ectopic expression of C429S, $\Delta 761-786$, and A776CA781-C RRM1 failed

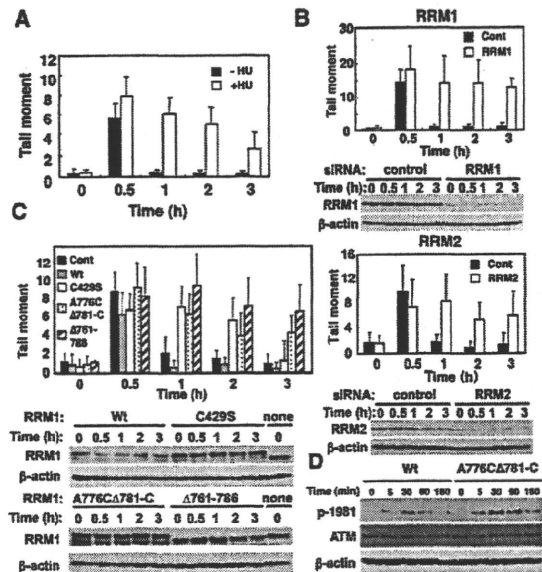


Figure 3. Recruitment of active RNR at DNA damage sites is a prerequisite for effective DNA repair. (A) HeLa cells were treated with (open bars) or without (filled bars) 2.5 mM HU, exposed to IR (4 Gy), and subjected to a comet assay as described in the Materials and Methods. The results were obtained by counting at least 50 cells per sample in three independent experiments. (B) HeLa cells were transfected with a control (filled bars) or RRM1 or RRM2 siRNA (open bars), and DNA repair was evaluated as in A. Cell lysates were subjected to immunoblotting using the indicated antibodies. (C) HeLa cells were transfected with or without (filled bars) either wild-type (gray bars), C429S (open bars), A776CA781-C (dotted), or $\Delta 761-786$ (hatched) RRM1. RRM1-transfected cells were then transfected with RRM1 siRNA. Expression vectors of wild type and various RRM1 mutants contain mutations in a specific sequence targeted by siRNA. DNA repair activity and expression of RRM1 were examined as in B. (D) Knockout-knock-in HeLa cells expressing wild type or A776CA781-C RRM1-HA were exposed to IR, and cell lysates were subjected to immunoblotting as in C.

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to do so. ATM was activated independently of Tip60 binding to RNR, but this activation was enhanced and prolonged in cells expressing A776CA781-C, presumably due to impaired DNA repair (Fig. 3D). It is therefore conceivable that recruitment of active RNR at DNA damage sites is a prerequisite for effective DSB repair, but not for activation of checkpoint signaling. Tip60 is also known to participate in transcriptional regulation of several genes. Neither RRM1 nor RRM2 proteins were affected by Tip60 depletion or overexpression (Supplemental Fig. S7), indicating that the effect of Tip60 did not result from changes in RRM1 and RRM2 expression.

ChIP analyses revealed that NLS-RC1-HA specifically inhibited RRM1 binding, but did not affect Rad51 or Tip60 binding, or increase H4 acetylation at the DSB site in *STEFKu70^{-/-}phprt-DR-GFP* cells (Fig. 4A). Expression of NLS-RC1-HA suppressed accumulation of endogenous RRM1 at DNA damage sites (Supplemental Fig. S8A,B), but did not affect the foci formation of 53BP1 at DSB sites (Fig. 4B), or complex formation and activity (Supplemental Fig. S9A,B) of endogenous RNR. However, cells expressing NLS-RC1-HA, but not NLS-GFP-HA, had

unrepaired DNA in the tail at 2 h (Fig. 4C). A quantitative colony formation assay was used to examine the DNA damage sensitivity of cells expressing NLS-RC1-HA. Induction of NLS-RC1-HA sensitized cells to IR (Fig. 4D).

Given that levels of dNTP pools are higher during S phase than during G1 phase (Hakansson et al. 2006), recruitment of RNR at damage sites may function at a specific phase of the cell cycle where dNTP pools are low. To address this issue, we synchronized cells at S phase or G1 phase by arrest and release of thymidine or nocodazole, respectively. Recruitment of wild-type RRM1 at a DSB site was observed at both G1 and S phase (Supplemental Fig. S10). However, a comet assay revealed that A776CA781-C failed to rescue the impaired DNA repair in RRM1-depleted cells at G1 phase, but not at S phase (Fig. 4E). Consistently, RRM1 mutation of Tip60 binding slightly sensitizes cells to Zeocin (Supplemental Fig. S11A), which causes DNA strand breaks, but not to MMC (Supplemental Fig. S11B), which can cause interstrand cross-linking repaired mainly at S-G2 phase. Intriguingly, this G1-phase-specific impairment of DNA repair was restored when excess amounts of dADP, dGDP, dCDP, and dUMP (250 μ M) were supplied in the culture medium (Supplemental Fig. S12). These results suggested that recruitment of RNR was required specifically for effective DNA repair in cells with low levels of dNTPs.

The present study suggests that the RNR recruitment to DSB sites likely provides mechanistic insights into the regulatory events that ensure a balanced supply of dNTPs during mammalian DNA repair. RNR appears to form a complex with Tip60 independently of DNA damage. Thus, it is possible that the RNR–Tip60 complex might have an alternative function, such as regulation of transcription. In response to DNA damage, regulation of the RNR subunit by Wtm1 and Dif1 in budding yeast is radically different in terms of cellular localization (Lee and Elledge 2006; Lee et al. 2008) from that observed in the present study, however, important changes in the subcellular localization of RNR might be conserved. Given that Tip60 is a key regulator of DNA damage responses, the concomitant recruitment of RNR at damage sites suggests the presence of a synthetic regulatory mechanism for DNA repair in mammals.

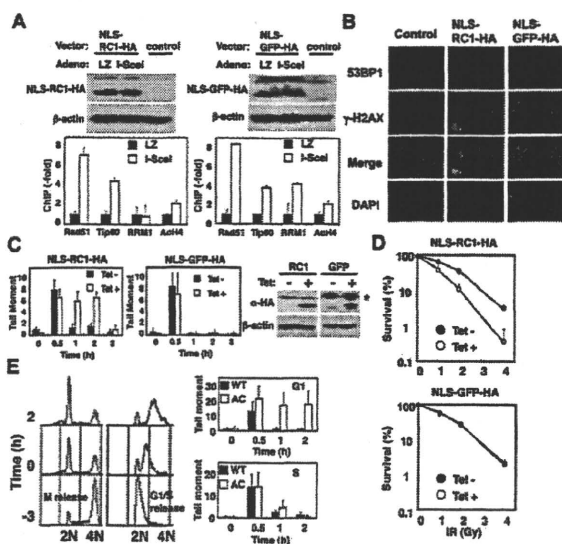


Figure 4. Inhibition of recruitment of RNR at DSB sites by ectopic expression of NLS-RC1-HA abrogates DNA repair and sensitizes cells to DNA damage. (A) *STEFKu70^{-/-}phprt-DR-GFP* cells expressing NLS-RC1-HA (SV40 NLS-RC1 fragment, 701–792 amino acids) or NLS-GFP-HA (GFP fragment, 1–93 amino acids) were subjected to ChIP analysis as in Figure 2B. (Top panels) Cell lysates were subjected to immunoblotting using the indicated antibodies. (B, left panels) Tet-on HeLa cells expressing NLS-RC1-HA or NLS-GFP-HA were treated with or without tetracycline (1 μ g/mL), exposed to IR (4 Gy), and subjected to immunostaining with the indicated antibodies and a comet assay as in Figure 3A. (Right panels) IR-untreated lysates were subjected to immunoblotting using the indicated antibodies. (C) Asterisk (*) represents nonspecific bands. (D) These cells were exposed to the indicated dose of IR, and a quantitative colony formation assay was performed 8 d after treatment. Data are mean \pm standard deviation ($n = 3$). (E) Knockout–knock-in HeLa cells expressing either wild-type (filled bars) or A776CA781-C (open bars) RRM1-HA were synchronized as described in the Materials and Methods. Synchronized cells were then released into G1 phase or S phase (time -3) and exposed to IR (4 Gy) 3 h after release (time 0). (Right panels) DNA repair was evaluated as in A. (Left panels) Cell cycle distributions are presented.

Materials and methods

Antibodies

Antibodies used were as follows: α -Rad51 (Ab-1, Oncogene Research Products), α -RRM1 (sc-11733 and sc-11731, Santa Cruz Biotechnologies), α -HA (11 666 606 001, Roche Applied Sciences, and PM002, MBL), α -Myc (sc-40 and sc-789, Santa Cruz Biotechnologies), α -RRM2 (sc-10844, Santa Cruz Biotechnologies), α -GST (sc-459, Santa Cruz Biotechnologies), α -Chk1 (sc-8408, Santa Cruz Biotechnologies), α -IKK α (sc-7182, Santa Cruz Biotechnologies), α -Orc2 (sc-13238, Santa Cruz Biotechnologies), α -ATM (sc-23921, Santa Cruz Biotechnologies), α -ATMp1981 (no. 4526, Cell Signaling), α -acetylated histone H4 (no. 06-866, Upstate Biotechnologies), and α -phospho-histone H2AX [411-pc-020, TREVIGEN], and 05-636, Upstate Biotechnologies). Anti-Tip60 rabbit polyclonal antibodies were generated by immunization with recombinant GST-His-Tip60 produced in insect cells, and the serum obtained was affinity-purified using a GST-His-Tip60 column.

Two-hybrid interaction assays

The *pGBKT7-RRM1* plasmid was generated by insertion of the full-length human RRM1-encoding sequence. *pGBKT7-RRM1* was transformed into

the yeast strain AH101 and mated with yeast Y187 pretransformed with a HeLa cell cDNA library (BD Biosciences). The deletion mutants of RRM1 and Tip60 were amplified by PCR using specific sets of primers. Primer sequences are supplied in the Supplemental Material.

Affinity purification of Tip60 complex

Affinity purification of Tip60 complex was performed as described previously (Ikura et al. 2000, 2007). For the induction of DNA damage, cells were γ -irradiated (12 Gy) after centrifugation.

In situ detergent extraction and immunofluorescence analysis

Immunofluorescence on paraformaldehyde-fixed cells was performed according to a previous report (Green and Almouzni 2003), using the indicated antibodies.

Microirradiation

Microirradiation was performed as described previously (Ikura et al. 2007). In brief, GM02063 cells were maintained on the microscope stage in a ChamSlide TC live-cell chamber system (Live Cell Instrument) at 37°C. Microirradiation was performed using an LSM510 confocal microscope (Carl Zeiss). Sensitization of cells was performed by incubating the cells for 20 h in medium containing 2.5 μ M deoxyribosylthymine and 0.3 μ M bromodeoxyuridine (Sigma), and then staining with 2 μ g/mL Hoechst 33258 (Sigma) for 10 min before UVA microirradiation. The 364-nm line of the UVA laser was used for microirradiation (three pulses at 30 μ W). Samples were examined with a Zeiss Axioplan 2 equipped with a charge-coupled device camera AxioCam MRm controlled by Axiovision software (Zeiss).

Knockdown experiments

HeLa cells or STEFKu70^{-/-} *phprt-DR-GFP* cells were transfected with either control siRNA (Silencer Negative Control #1, Ambion 4611), siRNAs for human Tip60 (sc-37966, Santa Cruz Biotechnologies), mouse Tip60-1 (sc-37967, Santa Cruz Biotechnologies), mouse Tip60-2 (D-057795-02-0010, Dharmacon), or RRM1 (GGAUCGCGUCUCUAA CUUtt) using Lipofectamine 2000 reagent (Invitrogen).

Subcellular fractionation and Mnase treatment

Subcellular fractionation was performed according to a previous report (Mendez and Stillman 2000). The isolated chromatin fraction (1×10^6 cells) was treated with Mnase (15 U) for 30 min at 37°C.

Establishment of STEFKu70^{-/-} cells containing a *phprt-DR-GFP* cassette

The *phprt-DR-GFP* vector (10 μ g) was linearized with PvuI and transfected into STEFKu70^{-/-} cells. Cells were selected with 1.25 μ g/mL puromycin for 12 d, and single colonies were screened by Southern blotting using puromycin cDNA as a probe. Clones having only one copy of the *phprt-DR-GFP* cassette were used for experiments.

Establishment of Tet-on HeLa cells expressing NLS-RC1

pcDNA4/TO-NLS-RC1 (10 μ g) was linearized with XhoI and transfected into HeLa T-Rex cells (Invitrogen). Positive clones were selected with Zeocin (250 μ g/mL) and Blastcidin (5 μ g/mL) for 12 d and screened by immunoblotting using anti-HA antibodies for the detection of NLS-RC1 induction in the presence of tetracycline (1 μ g/mL).

Generation of adenoviruses expressing I-SceI endonuclease

The full-length *I-SceI* fragment harboring the CAG promoter and poly A signal was subcloned into *pAd/PL-DEST* (Invitrogen). Adenoviruses expressing *I-SceI* were generated according to the manufacturer's protocol (Invitrogen).

ChIP assay

A population of STEFKu70^{-/-} cells (1×10^7) containing *phprt-DR-GFP* cells infected with adenoviruses expressing *I-SceI* was cross-linked with 1% formaldehyde for 10 min at 37°C. ChIP assays were performed essentially as described (Shimada et al. 2008). Precipitated DNA was resuspended in 50 μ L of water and analyzed by quantitative real-time PCR with the ABI PRISM7000 system using Power SYBR Green PCR Master Mix (Applied Biosystems) as described (Katsuno et al. 2009). Primers used for detection of the *I-SceI* break site were indicated in Figure 2A. As an internal control for normalization of the specific fragments amplified, mouse GAPDH locus was amplified using whole genomic DNAs with mGAPDH-F and mGAPDH-R. Primer sequences are supplied in the Supplemental Material.

Comet assay

Alkaline comet assays were performed using a Trevigen's Comet Assay kit (4250-050-k) according to the manufacturer's instructions. DNA was stained with SYBR Green, and slides were photographed digitally (Nikon Eclipse E800 lens and Fuji CCD camera). Tail moments were analyzed as reported previously (Park et al. 2006) using TriTek Comet Score Freeware.

Measurement of DNA damage sensitivity

Tet-on HeLa cells expressing NLS-RC1-HA or NLS-GFP-HA were irradiated with varying doses of IR in the presence or absence of doxycycline (1 μ g/mL), and then washed with PBS. Eight days after an additional incubation, surviving colonies were counted, and their relative numbers were expressed as percentages of the untreated cells ($n = 3$).

RNR assay

Insect cells were coinfecting with baculoviruses expressing wild-type RRM1 or its mutants, and with those expressing wild-type RRM2. RNR complexes were immunopurified, and their activities were determined according to a method reported previously (Fukushima et al. 2001). Amounts of wild-type RRM1 protein or its mutant proteins were determined by SDS-PAGE and used for calculating specific activities.

Cell cycle synchronization

For synchronization of cells at S phase, knockout-knock-in HeLa cells expressing wild-type or A776CA781-C RRM1-HA were first synchronized at the G1/S boundary by exposure to 2.5 mM thymidine for 16 h, and then released into S phase by wash-out of thymidine with PBS and the addition of 20% FBS containing DMEM. Cells were then exposed to IR 3 h after release. For synchronization of cells at G1 phase, knockout-knock-in HeLa cells were synchronized at M phase by exposure to 100 ng/mL nocodazole for 16 h and released into G1 phase by wash-out of nocodazole with PBS and addition of 20% FBS containing DMEM. Cells were then exposed to IR 3 h after release.

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