USP1 deubiquitinase maintains phosphorylated CHK1 by limiting its DDB1-dependent degradation

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The maintenance of genetic stability depends on the fine-tuned initiation and termination of pathways involved in cell cycle checkpoints and DNA repair. Here, we describe a new pathway that regulates checkpoint kinase 1 (CHK1) activity, a key element controlling both checkpoints and DNA repair. We show that the ubiquitin-specific peptidase 1 (USP1) deubiquitinase participates in the maintenance of both total and phosphorylated levels of CHK1 in response to genotoxic stress. We establish that USP1 depletion stimulates the damage-specific DNA-binding protein 1-dependent degradation of phosphorylated CHK1 in both a monoubiquitylated Fanconi anaemia, complementation group D2 (FANCD2)-dependent and -independent manner. Our data support the existence of a circuit in which CHK1 activates checkpoints, DNA repair and proliferating cell nuclear antigen and FANCD2 monoubiquitinylation. The latter two events, in turn, switch off activated CHK1 by negative feedback inhibition, which contributes to the downregulation of the DNA damage response. This pathway, which is compromised in the cancer-prone disease Fanconi anaemia (FA), likely contributes to the hypersensitivity of cells from FA patients to DNA damage and to the clinical phenotype of the syndrome; it may also represent a pharmacological target to improve patient care and develop new cancer therapies.

INTRODUCTION

Genetic stability in response to DNA damage and stalled replication forks depends on the relatively well-described interconnected action of cell cycle checkpoints and DNA repair mechanisms (1,2). A crucial role in the maintenance of the genomic stability is played by the signalling pathway initiated by replication protein A (RPA)-coated single-strand DNA stretches that are generated during replication fork stalling or via the resection of double-strand breaks that activate S and G2/M checkpoints through the ataxia telangiectasia and RAD3 related (ATR)-mediated phosphorylation of checkpoint kinase 1 (CHK1). This phosphorylation triggers CHK1 activation and downstream CHK1-mediated events that regulate cell cycle arrest and DNA repair (2,3). In addition to its role in cell cycle regulation, CHK1 is functionally or directly involved in proliferating cell nuclear antigen (PCNA) and Fanconi anemia, complementation group D2 (FANCD2) monoubiquitylation (4–7) and in the full activation of the homologous recombination (HR) protein RAD51 (8). Consequently, it is likely that CHK1 activity requires a fine-tuned regulation to optimize the cellular response to DNA damage. Indeed, studies in yeast reported that shortening or delaying CHK1 activation results in cellular hypersensitivity to DNA damage despite an opposite effect on mitotic entry (9). Recent studies demonstrated that CHK1 is part of both checkpoint initiation and termination. CHK1 phosphorylation may both participate in CHK1 activation and downstream CHK1-mediated events that regulate cell cycle arrest and DNA repair (2,3). In addition to its role in cell cycle regulation, CHK1 is functionally or directly involved in proliferating cell nuclear antigen (PCNA) and Fanconi

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phosphorylation by ATR, is ubiquitinylated by the E3 ligase complex associating the Skp1-Cul1-F-box proteins to the beta-transducin repeat containing protein (SCFβTrcp), a process impeded by the deubiquitinase ubiquitin specific peptidase 7 (USP7) (12). Indeed, CLASPIN degradation contributes to checkpoint termination, preventing ATR-mediated CHK1 phosphorylation. Consequently, full checkpoint termination is the result of the coordinated action of all these distinct pathways. Because CHK1 expression has been associated with anticancer therapy resistance (13–16), a better understanding of the different mechanisms involved in CHK1 signalling may reveal new predictive biomarkers of tumour responsiveness and has major implications for cancer therapy choices.

Rare genetic diseases, such as Fanconi anaemia (FA) syndrome (17), which are caused by inherited recessive mutations in DNA damage response (DDR) genes, represent fundamental models to approach how cells cope with DNA lesions and replicative stress (18). FA patients present with aplastic anaemia, developmental defects and a predisposition to cancer (19). No fewer than 15 FANC proteins are required for cellular and chromosomal resistance to interstrand DNA crosslinks (ICLs) (19–25). At least eight FANC proteins (FANCA/B/C/E/F/G/L/M) are assembled into the FANC core complex that catalyses the monoubiquitinylation of FANC D2 (mono-Ub-FANC D2) and FANCI (mono-Ub-FANCI) during S phase or in response to DNA damage, promoting their chromatin localization, assembly in subnuclear foci and interaction with the FANC D2/FANCI-associated nuclelease 1 protein (24,26–28). The other FANC proteins, FANCJ/BRIP 1, FANC D1/BRC A2 and FANCN/PALB2, act in parallel or downstream of FANC D2, completing the so-called FANC pathway. The FANC pathway participates in the regulation of HR (26–28) and is required for ICL resistance by direct or functional interactions with partners, such as ATR, BReast CaNcer predisposition gene/protein 1 (BRCA1), bloom syndrome-mutated protein and the meiotic recombination 11 homolog (MRE11)-RAD50–Nibrin (NBN or NBS1) complex (29–37). Recently, RAD51C mutations have been reported in one family of patients with an FA-like phenotype, supporting the link between FA, HR resistance by direct or functional interactions with partners, such as ATR, BReast CaNcer predisposition gene/protein 1 (BRCA1), bloom syndrome-mutated protein and the meiotic recombination 11 homolog (MRE11)-RAD50–Nibrin (NBN or NBS1) complex (29–37).

Results

USP1 depletion impacts the stability and phosphorylation of CHK1 in both a monoUbiquitinylated FANC D2-dependent and -independent manner

FANC pathway deficiency is associated with DNA damage-induced CHK1 hyperphosphorylation (5), suggesting that FANC D2 monoUbiquitinylation could restrain checkpoint signalling. Thus, we hypothesized that a higher constitutional level of mono-Ub-FANC D2 should result in the opposite, i.e. a lower level of phosphorylated CHK1 (p-CHK1). In order to increase FANC D2 monoUbiquitinylation and address the involvement of the FANC pathway in CHK1 regulation, we depleted the USP1 deubiquitinase using siRNA in U2OS and HeLa cells. As expected (42,44), USP1 downregulation induced higher levels of both mono-Ub-FANC D2 and mono-Ub-PCNA in the absence of genotoxic stress (Fig. 1A and D). In U2OS cells, USP1 depletion was consistently associated with a clear reduction in the steady-state level of the CHK1 protein (Fig. 1A and B). In HeLa cells, the observed effects of USP1 depletion on the steady-state level of CHK1 were more variable (Fig. 1C and D). Nevertheless, quantitative analysis of seven independent experiments indicated that the CHK1 levels in USP1-deficient HeLa cells were significantly lower than in USP1-proficient HeLa cells (Fig. 1E, $P < 0.05$). Using U2OS cells transiently transfected with a CHK1–FLAG construct (Supplementary Material, Fig. S1A), we corroborated the observation that the decrease in CHK1 steady-state levels was caused by USP1 downregulation. The CHK1 steady-state decrease was also observed with an unphosphorylatable 2S/A mutant CHK1–FLAG protein (Supplementary Material, Fig. S1A); for this mutant, p-CHK1 is not a prerequisite for its own downregulation. Co-depletion of USP1, together with the FANC core complex proteins FANCC or FANC D2, rescued the steady-state level of FA cells in late S/G2 could also represent a defect in recovering from the ATR/CHK1 checkpoint in response to ICL-inducing agents. To test this hypothesis and gain insight into the mechanisms involved in CHK1 regulation, we analysed the activation of CHK1 in cells expressing a constitutively ‘activated’ FANC pathway by knocking down the deubiquitinase ubiquitin-specific peptidase 1 (USP1), which restrained the monoUbiquitinylation of FANC D2/FANCI (42,43). Following this approach, we discovered USP1-regulated and damage-specific DNA-binding protein 1 (DDB1)-dependent mechanisms that are involved in the downregulation of activated CHK1 in human cells in both a FANC pathway-dependent and -independent manner.

Figure 1. USP1 depletion specifically downregulates p-CHK1 and protein levels. (A) Untreated U2OS cells were lysed 72 h after transfection with the indicated siRNAs. The lysates were analysed by western blot using the indicated antibodies. (B) U2OS cells transfected with the indicated siRNA were treated with 2 μg/ml/1 h of MMC and lysed 20 h after treatment. The lysates were analysed by western blot using the indicated antibodies. (C) Two days after transfection with the indicated siRNAs, HeLa cells were treated for 1 h with the reported dose of MMC and washed before the addition of pre-warmed complete medium. Cells were lysed 20 h later, and the analysed by western blot using the indicated antibodies. (D) HeLa cells were treated with 5 μg/ml/1 h of MMC 2 days after siRNA transfection, and proteins were extracted 20 h after treatment to examine the activation of several DDR proteins by immunoblotting. (E) Quantification of the ratio of CHK1 to actin, p345CHK1 to CHK1 and p345CHK1 to actin in HeLa cells treated with 5 μg/ml/1 h of MMC and lysed 20 h later. Values represent the mean and SD of three (MMC treatment) to seven experiments (untreated). Student’s t-test was used: $*P < 0.05$, $**P < 0.01$. (F) 293T cells stably expressing a chicken FANC D2-KR-ubiquitin fusion (clone Ub2) or FANC D2-KR-monoUbiquitin fusion (clone mUb3) were treated with 10 μg/ml/1 h of MMC and lysed at the end of the treatment (2 mM for 30 min) or UV (5J) and lysed 1 h after irradiation, and the phosphorylation of CHK1 and H2AX was analysed by immunoblotting.
of CHK1 (Fig. 1A). Consequently, monoubiquitination of FANCD2 could be a major event involved in USP1-dependent regulation of CHK1 steady-state levels.

Subsequently, we exposed the cells to the DNA cross-linking agent mitomycin C (MMC) or to ultra violet C (UVC) to analyse the behaviour of DNA damage-induced p-CHK1 in USP1-depleted cells. USP1 depletion was associated with a consistent and significant reduction in the level of phosphorylated S345-CHK1 in both U2OS and HeLa cells (Fig. 1B–E and Supplementary Material, Fig. S1B). More importantly, the reduced phosphorylation of CHK1 observed in USP1-depleted cells appeared to be highly specific. Indeed, both the DNA damage-induced phosphorylation and the expression of other ATR/ataxia telangiectasia-mutated protein (ATM) targets, including NBN, RPA32, RAD17 and structural maintenance chromosome 1 (SMC1), were not modified by USP1 depletion (Fig. 1C and D). Moreover, depletion of the FANCCore complex component FANCA, which is necessary for FANCD2 monoubiquitinylation, rescued p-CHK1 in USP1-depleted cells exposed to MMC or UVC (Fig. 1D and Supplementary Material, Fig. S1B). Thus, FANC pathway proficiency and FANCD2 monoubiquitinylation may be required for the observed effects of USP1 depletion on p-CHK1.

To directly observe an active role for monoubiquitinylated FANCD2 in CHK1 downregulation, we stably expressed a constitutively monoubiquitinylated chicken form of FANC D2 (45) in HEK293T cells (Fig. 1F). Ectopic expression of mono-Ub-FANCD2 slightly increased p-CHK1 and phosphorylated histone 2 AX (γH2AX) levels, revealing that cells that constitutively express monoubiquitinylated FANCD2 undergo DNA stress and activate a DDR response. Nevertheless, in contrast to USP1-depleted cells (Fig. 1B–E), the reduction of phosphorylation of CHK1 observed in USP1-depleted cells exposed to MMC or UVC (Fig. 1D and Supplementary Material, Fig. S1B). Thus, FANC pathway proficiency and FANCD2 monoubiquitinylation may be required for the observed effects of USP1 depletion on p-CHK1.

To support the finding that mono-Ub-FANCD2 is a key element controlling CHK1 level/phosphorylation, we analysed the behaviour of a CHK1–FLAG construct stably expressed in MRC5 fibroblasts following deprivation of either USP1 or FANC D2 (Fig. 2A). Again, USP1 depletion was associated with increased FANCD2 monoubiquitinylation and downregulation of CHK1. Notably, in contrast to USP1 depletion, FANCD2 downregulation induced a higher level of CHK1–FLAG, and a fraction of this protein appeared to be phosphorylated (Fig. 2A). Moreover, we analysed CHK1 behaviour following MMC exposure in the chicken DT40 parental cell line, FANCD2 knock-out (KO) DT40 cells, FANCD2 KO DT40 cells ectopically corrected with a wild-type FANC D2 and FANC D2 KO DT40 cells expressing the FANCD2 non-monoubiquitinylable lys (K) 563 arg (R) (KR) form (Fig. 2B). FANCD2-deficient DT40 cells showed a clear hyperphosphorylation of CHK1, which was rescued by the expression of the wild-type FANC D2 gene but not by the expression of the FANC D2-KR form. Notably, in ‘corrected’ DT40 cells, the level of CHK1 was also clearly reduced when compared with that of the KO counterpart. Altogether, these observations validate the negative role of the activated FANC pathway in both CHK1 stabilization and phosphorylation.

Finally, to ascertain if elements other than mono-Ub-FANCD2 participate in USP1-mediated CHK1 downregulation, we depleted USP1 in FA-C, FA-G and FA-D2 fibroblasts (Fig. 2C). Depletion of USP1 in cells derived from FA patients resulted in decreased CHK1 levels and phosphorylation, suggesting that mono-Ub-FANCD2 is not the only USP1 target involved in CHK1 regulation and that the germ-line-derived inactivation of the FANC pathway in FA patient-derived cells uncovered or selected other pathways to compensate for their intrinsic deficiency and assure cell survival.

In conclusion, using several approaches and cellular models, USP1 depletion specifically affects the steady-state levels and the phosphorylation of CHK1 without perturbing ATR signalling following both FANC pathway-dependent and -independent mechanisms.

**USP1 depletion impacts CHK1 independently of both the cell cycle and DNA repair**

Because CHK1 is a cell cycle regulated and DNA damage checkpoint protein, we asked whether (a) the downregulation of CHK1 in USP1-depleted cells is an experimental artefact resulting from modifications of the cell cycle and/or altered DNA repair capabilities caused by USP1 depletion and (b) USP1 depletion modifies the G2 checkpoint in response to DNA damage.

We first examined the cell cycle distribution in USP1-depleted cells. In accordance with published data on Usp1 knockout (KO) mouse embryonic fibroblasts (MEFs) (46), USP1 depletion had no major effects on the cell cycle progression in unchallenged cells (Fig. 3A and B). Consequently, the lower level of CHK1 in USP1-depleted cells is not merely a consequence of cell accumulation in G1.

Then we monitored cell cycle recovery in response to MMC in both U2OS and HeLa cells. As reported in Figure 3A, USP1-depleted U2OS cells re-enter the cell cycle more rapidly than USP1-proficient cells, suggesting that USP1 depletion could accelerate recovery from the G2 checkpoint. In contrast, as predicted from studies with Usp1 knockout (KO) MEFs (46), USP1-depleted HeLa cells showed an increased MMC-induced G2/M content compared with USP1-proficient cells (Fig. 3B). Because U2OS and HeLa cells differ in their p53 status, we repeated experiments in the presence of the p53 inhibitor pifithrin-α, and we observed no difference in the response (data not shown). Consequently, the differences between U2OS and HeLa cells seem to be independent of their p53 status. Western blot analysis of the two downstream core cellular checkpoint kinases CHK1 and CHK2 revealed major differences between the HeLa and U2OS cells (Fig. 3C). HeLa cells showed a higher level of phosphorylated CHK1 and CHK2; this result could support the prolonged G2/M checkpoint when CHK1 signalling decreases as a result of USP1 depletion. The observed differences in CHK2 phosphorylation between HeLa and U2OS cells appeared to be linked to higher basal levels of CHK2, which appeared slightly phosphorylated as a consequence of USP1 depletion (Supplementary Material, Fig. S1C). Moreover, data from
Usp1−/− MEFs support our observations that p-CHK2 increases significantly in USP1-depleted HeLa cells following MMC (46). Notably, although the authors did not stress this point in their article, the p-CHK1 level is lowered in response to MMC in Usp1−/− MEFs, as we report here. Thus, CHK1 downregulation in USP1-depleted cells is not a consequence of cell cycle modifications and cannot be generally implicated in the exit or recovery from the S or G2/M checkpoints.

Next, we asked whether CHK1 dephosphorylation and/or degradation in USP1-depleted cells are the consequences of increased DNA repair capabilities. To determine whether USP1 depletion modifies the intrinsic DNA repair capabilities of DNA-damaged cells, we analysed by dot blot the repair kinetics of 6–4 pyrimidine–pyrimidone (6-4 PP) lesions induced by UVC exposure. As presented in Figure 4A, 6-4 PP were eliminated with equal kinetics in both USP1-proficient and -deficient cells, meaning that the DNA repair pathways involved in the elimination of this lesion work normally in the absence of USP1.

FANCD2 and PCNA monoubiquitinylation, as well as FANCD2 redistribution in sub-nuclear foci, is considered mandatory for cellular resistance to stalled replication forks. Consequently, the reduction in p-CHK1 and/or stability following DNA damage could be the normal behaviour of cells in which USP1 depletion results in enhanced FANCD2 or PCNA activity as a consequence of higher levels of their monoubiquitinylated forms (42). However, more recent data in avian DT40 cells (47) and mice (46) demonstrated a cellular hypersensitivity to MMC in the absence of USP1. In accordance with these results, we observed a defect in FANCD2 foci formation in USP1-depleted human cells (Fig. 4B and C). Importantly, defective FANCD2 relocalization was not the consequence of an impaired formation of γH2AX foci, which are required for FANCD2 assembling in subnuclear foci (48) (Fig. 4B). Hence, as predicted by data obtained in chicken and mice (46,47), this result suggests that FANCD2 undergoes a finely regulated ubiquitinylation/deubiquitinylation cycle to perform its physiological role and be recruited to and accumulate in nuclear foci. Consequently, this challenges the idea that enhanced DNA repair activity by mono-Ub-FANCD2 is responsible for the weaker CHK1 activation observed in USP1-depleted cells.

The most obvious conclusion of our data (Figs 1 and 4) is that CHK1 dephosphorylation and/or degradation in USP1-depleted cells is not caused by increased DNA repair capabilities in USP1-deficient cells but is directly linked to USP1 downregulation.

USP1 limits DDB1-dependent degradation of CHK1

Multiple pathways and proteins are involved in CHK1 regulation (49). Among these players, the adaptor protein CLASPIN appears to be a master regulator of CHK1 activity (50). We observed that the siRNA-mediated depletion of CLASPIN strongly reduced UVC-induced p-CHK1 but not CHK1 protein levels (Fig. 5A). Compared with CLASPIN depletion, USP1 depletion affected both the CHK1 steady-state level and phosphorylation without discernible effects on

Figure 2. USP1 depletion and FANCD2 monoubiquitinylation have implications in CHK1 downregulation. (A) MRC5 fibroblasts stably expressing CHK1–FLAG were transfected with the indicated siRNAs and lysed 72 h later. CHK1–FLAG was then immunoprecipitated, and its phosphorylation was analysed by western blot. (B) p-CHK1 and levels as observed in untreated and MMC-exposed DT40 cells. Fancd2ko indicates the cells carrying knockout Fancd2 alleles; +FANCD2 indicates previous cells (Fancd2ko) transfected with a wt Fancd2 (i.e. Fancd2 corrected); and +KR indicates Fancd2ko cells expressing a Fancd2 KR mutant form. Proteins were isolated 6 h after treatment with 100 ng/ml of MMC and analysed by western blot with the indicated antibodies. (C) FA-D2, FA-G and FA-C human fibroblasts were transfected with USP1-siRNA. MMC was added 48 h later at 2 μg/ml for 1 h and cells were lysed 24 h later. The lysates were analysed by western blot with the indicated antibodies.
Interestingly, co-depletion of USP1 and CLASPIN had an additive effect on both UVC-induced p-CHK1 and CHK1 protein levels. Altogether, these results suggest that CLASPIN is not an intermediary player downstream of USP1 in the regulation of CHK1. On the contrary, our data suggest that CLASPIN-dependent and USP1-regulated events work on convergent pathways to turn on and restrain CHK1 activation.

Genotoxic stresses may promote the degradation of phosphorylated CHK1 in a Cul1- and/or Cul4A-dependent manner (51). During replication, a fraction of CHK1 is indeed polyubiquitylated by a CUL4A/DDB1-containing E3 ligase and is subsequently degraded by the proteasome (10). Hence, we directly tested the role of DDB1 in CHK1 stability by silencing it alone or in addition to USP1. Curiously, for unknown reasons, DDB1 depletion reduced USP1 steady-state levels (Fig. 5B). Nevertheless, the reduced level of USP1 in DDB1-depleted cells appeared sufficient to deubiquitylate FANCD2 and maintain a normal ratio of FANCD2-L to FANCD2-S. Co-depletion of DDB1 with USP1 nearly abrogated the reduced stability and phosphorylation of CHK1 observed following the simple depletion of USP1 in MMC- and UVC-treated cells (Fig. 5B). Moreover, FANCD2 monoubiquitylation in USP1-depleted cells was not modified by the depletion of DDB1, suggesting that downregulation of CHK1 in USP1-depleted cells requires DDB1 downstream of FANCD2. In agreement with the hypothesis that phosphorylated CHK1 is ubiquitylated and subsequently degraded in the absence of USP1, treatment with the proteasome inhibitor MG-132 could increase the level of CHK1 in USP1-depleted cells but not in control cells (Fig. 5C). However, because MG-132 could strongly reduce mono-Ub-FANCD2 ([52] and data not shown), the restoration of CHK1 levels could be the consequence of its blocked degradation, the loss of FANCD2 monoubiquitylation or both. Nevertheless, this result demonstrates that CHK1 downregulation is the consequence of a rapidly reversible mechanism, likely proteasomal degradation.

Importantly, the already described interaction between
endogenous CHK1 and DDB1 (10) was enhanced in USP1-depleted HEK293T cells (Fig. 5D), which was consistent with the idea that CHK1 degradation is linked to DDB1. Similar results were obtained with exogenous CHK1–FLAG (data not shown). It is important to note that USP1 depletion neither reduced the steady-state level of another known DDB1 target, chromatin licensing and DNA replication factor 1 (CDT1) (53), nor enhanced its DNA damage-induced degradation, suggesting that the DDB1/CUL4A machinery is not simply overactive in USP1-depleted cells (Fig. 5E and F). Altogether, our results suggest that USP1 depletion specifically promotes the degradation of phosphorylated CHK1 in a DDB1-dependent manner.

DISCUSSION

We present evidence that the USP1 deubiquitinase controls a feedback loop that limits CHK1 activity to rescue DNA-damaged cells. A fully proficient DDR cell activates a response to overcome the difficulties imposed by spontaneously arising and genotoxin-induced delayed or stalled DNA replication forks. CHK1 participates in this response by both delaying cell cycle progression and participating in DNA repair. CHK1 is indeed required for the monoubiquitylation of PCNA and FANC2, which is involved in the resolution of replicative stress. ATR-mediated phosphorylation of CHK1 may start a sequence of events that simultaneously initiates and limits checkpoints through the targeted degradation of phosphorylated CHK1 (11,51). Similarly, the full activation of both FANC2 and PCNA, in addition to the resolution of DNA replication difficulties, could also participate in cell recovery from cell cycle checkpoints. We propose that the stimulation of CHK1 degradation by mono-Ub-FANC2 represents a feedback mechanism that contributes to the recovery of DNA-damaged cells (Fig. 5G). This feedback could participate in the extinction of FANC2 and RAD51, which is under the control of p-CHK1 (4–6,8), limiting HR events that could be toxic for the cells. In this regard, the compromised HR efficiency of USP1-depleted cells could be the consequence of FANC2 dysfunction (46), weaker CHK1 activity (8) or both. Our data suggest that DDB1-dependent degradation of phosphorylated CHK1 could be one of the mechanisms explaining these findings.

The regulation of the DDB1/CUL4A-based E3 ligases is a complex process that requires the presence of DDB1 and CUL4-associated factors (DCAFs) for the specific targeting of various substrates of this ubiquitin ligase (54). USP1 depletion specifically affects CHK1. Consequently, it is tempting to speculate that mono-Ub-FANC2 promotes the association of the yet unidentified CHK1-specific DCAF with DDB1 and/or CHK1, thereby enhancing CHK1 degradation and inactivation.

It is difficult to determine whether CHK1 regulation depends on FANC2, FANC1 or monoubiquitylated FANC2/FANC1 dimer, and we cannot exclude a role for PCNA or other presently unknown targets of USP1 in the CHK1 control. A PCNA/FANC2 interaction has been recently identified, and this interaction may be required for proficient FANC2 monoubiquitylation (55,56). Thus, PCNA could participate in the control of p-CHK1 via its action on FANC2. However, without excluding this possibility, the observation that USP1 depletion in FA cells has an effect on phosphorylation/stability of CHK1 indicates that mono-Ub-PCNA could influence CHK1 levels independently from its role in FANC2 monoubiquitylation.

We propose that the accumulation of 4N DNA content following ICL-inducing agents in FA cells (57) is a consequence of both defective DNA repair and a failure in recovering from checkpoint arrest through the inhibition of CHK1. Our data predict that FA cells, which cannot monoubiquitylate FANC2, display overactive CHK1. Indeed, Gautier and colleagues (58) observed more p-CHK1 at the basal level in FANCA-deficient cells compared with FANC-proficient cells, a phenotype that is expected to result from compromised DDB1-dependent degradation of phosphorylated CHK1. In agreement with this, transient depletion of FANC2 strongly
increased p-CHK1 in untreated cells (Fig. 1E). This CHK1 overactivation may be detrimental for FA patients; recently, an ‘FA-M’ patient was identified who did not display classical symptoms of FA and presented with bi-allelic mutations in both $FANCA$ and $FANCM$ (59). The brother of this patient carried only bi-allelic mutations in $FANCA$ and developed ‘typical’ FA. It is tempting to speculate that the mild phenotype of the ‘FA-M/FA-A’ patient is due to the compensatory
effect of the mutations in FANCM. Because FANCM is required for efficient ATR/CHK1 activation independently of the FANC complex (60), we propose that an overactivation of CHK1, triggered by FANCA mutations, is compensated for by FANCM deficiency, leading to normal CHK1 activity and a mild FA phenotype. The same hypothesis could be evoked for all FA patients presenting with a mild clinical phenotype or who develop bone marrow failure later in life, as proposed in a recently published study (61). Thus, bi-allelic FANC mutations could be associated with a partial impairment of CHK1 activation or activity resulting in a better outcome for these patients.

MATERIALS AND METHODS

Cell culture and drugs
HeLa cells, U2OS, HEK293T, FA cells (PD20, PD331 and PD352) and wild-type SV40-immortalised MRC5 fibroblasts were routinely grown in DMEM (Gibco) supplemented with 10% fetal calf serum (Dutchel), 2 mM glutamine, 1 mM sodium pyruvate, 100 U/ml penicillin and 100 µg/ml streptomycin (all from Gibco) at 37°C in 5% CO₂, MRC5 stably expressing CHK1–FLAG cells were selected and maintained in G418-containing medium (400 µg/ml). HEK293T cells were transfected with the chicken FANC D2 constructs previously described (45), and clones were selected using Zeocin. DT40 cells were grown in the same medium described above but supplemented with 1% chicken serum and 50 µM β2-mercaptoethanol (45). Genotoxic treatments were performed as previously described (5).

Transfections
Single siRNAs were purchased from Eurogentec. The following sequences were used: Ctrl (CGUCGACGGAUACUUCGATT), FANCA (GGGUCAAGGGGAAAAAUATT), and USP1a (CGACACGUAUGGAAUUUUTT) and USP1b (GAGAAGGACUUUCUGAATTT) used as a mix. Luciferase (used as a control in a few experiments), FANCD2 and CLASPIN siRNAs were previously described (5). DDB1 and FANCC smartpool siRNAs were obtained from Dharmacol. Transfection of siRNA (usually at 100 nM) was performed with Oligofectamine (Invitrogen), and experiments were carried out 48–72 h later. In the case of double transfection, the same total amount of siRNA was used by adding control siRNA to the single siRNA of interest. The CHK1 construct was transfected in U2OS cells with Lipofectamine LTX (Invitrogen), and experiments were performed as previously described (5).

Cell extracts and antibodies
Cells were washed in ice-cold PBS and disrupted in lysis buffer [50 mM Tris pH 7.9, 150 mM NaCl, 1 mM EDTA and 0.5% NP-40, supplemented with protease and phosphatase inhibitors (Roche)]. After 20 min of incubation on ice, lysates were combined with 4X Laemmli buffer containing β2-mercaptoethanol, sonicated, denaturated by boiling and separated by SDS–PAGE. The antibodies used were directed against FANC D2, RAD17, CHK1, actin, NBS1 and PCNA (Santa Cruz Biotechnology); FANC D2, RPA32, SM C1, p966SMC1 and vinculin (Abcam); p645RAD17, p345CHK1 and p343NBS1 (Cell Signalling); p68CHK2 and RPA32 (Calbiochem); CLASPIN, FANCI, DDB1 and CDT1 (Bethyl); and γH2AX (Upstate). Antibodies that had been produced and kindly provided by the Fanconi Anemia Research Fund were also used against USP1 (D3598) and FANCA (D5300 and D6512). Signals were detected by the Gene-Gnome apparatus, and their intensities were quantified using the Genetools (Syngene Bio Imaging) software or Image J.

Immunofluorescence
Cells grown on glass cover slips were fixed in 4% paraformaldehyde for 15 min before permeabilization in 0.5% Triton for 5 min. After blocking in 5% BSA, cells were stained with antibodies against FANC D2 (Abcam ab2187; 1/1000) and γH2AX (Upstate; 1/2000) for 1 h in IF buffer (0.5% Tween 20, 12% BSA, 0.036% NaN₃ in PBS). Primary antibody detection was achieved by incubation with donkey anti-rabbit Alexafluor 594 and donkey anti-mouse Alexafluor 488 secondary antibodies (Molecular Probes; 1/1000) for 1 h at room temperature. Slides were mounted in Vectashield containing DAPI (Vector Laboratories) and examined at a magnification of ×100 using a fluorescence microscope (Olympus). Only nuclei showing more than five discrete FANC D2 foci were considered as FANC D2 foci-positive.

Co-immunoprecipitation
HEK293T cells were seeded in 100 mm Petri dishes and transfected with the indicated siRNAs. Three days later, cells were treated for 4 h with HU (5 mM) and were disrupted in lysis buffer. Lysates were clarified with protein G/agarose and normal mouse IgG (Santa Cruz Biotechnology). Immunoprecipitation was performed on 1–2 mg of cell lysates using 2 µg of monoclonal anti-CHK1 (G4) antibody captured with protein G/agarose. Immunoprecipitates were washed four times in lysis buffer before eluting the beads in Laemmli buffer. To avoid cross-reactions with the IgG heavy chains, a secondary antibody that does not recognize denatured IgG (TrueBlot™; eBioscience) was used to detect CHK1. Anti-FLAG beads (Sigma) were also used to immunoprecipitate exogenous FLAG-tagged CHK1.

Repair of UV-induced DNA lesions
Genomic DNA was extracted using the NucleoSpin Tissue kit (Macherey-Nagel) before denaturation for 5 min at 95°C. Dot blotting on Nylon membranes was performed with 200 ng of DNA for detection of 6-4 PP. Membranes were incubated in 0.4 N NaOH for 20 min at room temperature before blocking in 5% non-fat dried milk in PBS-T. An antibody recognizing 6-4 PP was used at 1/2000 (Cosmo Bio), and anti-single-stranded DNA was used as a loading control (Chemicon).
SUPPLEMENTARY MATERIAL

Supplementary Material is available at HMG online.

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Conflict of Interest statement. None declared.

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