

# BNIP3 is essential for mediating 6-thioguanine- and 5-fluorouracil-induced autophagy following DNA mismatch repair processing

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DNA mismatch repair (MMR) processes the chemically induced mispairs following treatment with clinically important nucleoside analogs such as 6-thioguanine (6-TG) and 5-fluorouracil (5-FU). MMR processing of these drugs has been implicated in activation of a prolonged G2/M cell cycle arrest for repair and later induction of apoptosis and/or autophagy for irreparable DNA damage. In this study, we investigated the role of Bcl2 and adenovirus E1B Nineteen-kilodalton Interacting Protein (BNIP3) in the activation of autophagy, and the temporal relationship between a G2/M cell cycle arrest and the activation of BNIP3-mediated autophagy following MMR processing of 6-TG and 5-FU. We found that BNIP3 protein levels are upregulated in a MLH1 (MMR<sup>+</sup>)-dependent manner following 6-TG and 5-FU treatment. Subsequent small-interfering RNA (siRNA)-mediated BNIP3 knockdown abrogates 6-TG-induced autophagy. We also found that p53 knockdown or inhibition of mTOR activity by rapamycin cotreatment impairs 6-TG- and 5-FU-induced upregulation of BNIP3 protein levels and autophagy. Furthermore, suppression of Checkpoint kinase 1 (Chk1) expression with a subsequent reduction in 6-TG-induced G2/M cell cycle arrest by Chk1 siRNA promotes the extent of 6-TG-induced autophagy. These findings suggest that BNIP3 mediates 6-TG- and 5-FU-induced autophagy in a p53- and mTOR-dependent manner. Additionally, the duration of Chk1-activated G2/M cell cycle arrest determines the level of autophagy following MMR processing of these nucleoside analogs.

**Keywords:** BNIP3, p53, mTOR, autophagy, nucleoside analogs

*Cell Research* (2010) 20:665-675. doi:10.1038/cr.2010.40; published online 6 April 2010

## Introduction

DNA mismatch repair (MMR) is one of the several DNA repair processes that are vital for maintaining genome stability [1]. It corrects not only mismatches but also insertion-deletion loops (IDLs) that may occur during replication and recombination of DNA. DNA mismatches or IDLs are recognized and initially bound by either MutS $\alpha$ , a heterodimer of MSH2 and MSH6, or MutS $\beta$ , a heterodimer of MSH2 and MSH3, respectively.

Following binding to DNA mispairs or IDLs and undergoing ATP-hydrolysis-dependent conformational transitions, the MutS $\alpha$  or MutS $\beta$  complexes further recruit another heterodimeric complex of MLH1 and PMS2 (MutL $\alpha$ ) to activate subsequent MMR steps such as the excision of the mispairs or IDLs and the resynthesis of the DNA strand [1, 2]. MMR deficiency is associated with human hereditary nonpolyposis colorectal cancer and a modest percentage (up to 15%) of several common sporadic solid tumors, indicating that MMR functions as an important tumor suppression mechanism [3].

MMR also plays an important role in the cytotoxic effects of several classes of clinically active chemotherapy drugs, including methylating agents such as temozolomide; platinum analogs such as cisplatin and carboplatin; and nucleoside analogs such as 6-thioguanine (6-TG) and 5-fluorouracil (5-FU) [2, 3]. In response to these DNA-damaging agents, MMR has been implicated

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Received 9 October 2009; revised 18 January 2010; accepted 9 February 2010; published online 6 April 2010

in initially activating a G2/M cell cycle arrest followed by the activation of programmed cell death pathways, including both apoptosis [2, 3] and autophagy [4, 5].

Since these DNA-damaging agents are clinically used in cancer therapy, there is considerable interest in understanding the molecular mechanisms controlling the cognate cellular processes. To this end, 6-TG has been used as a model drug to investigate the molecular events following MMR processing of chemotherapy drugs, because its intracellular processing has been well studied. After 6-TG is taken up by cells, it is metabolically modified by hypoxanthine-guanine phosphoribosyl transferase (HPRT) to yield 6-thioguanosine monophosphate. Following subsequent phosphorylations, 6-thioguanosine triphosphate can then be incorporated into genomic DNA [6]. In the DNA, the incorporated 6-TG is further chemically methylated by S-adenosylmethionine to form S6-methylthioguanine [7]. During subsequent DNA replication, S6-methylthioguanine can pair with thymine as well as its normal partner, cytosine. The resultant S6-methylthioguanine-thymine mispairs are identified and processed by MMR as replication errors [7]. MMR processing of 6-TG-induced mispairs occurs over several cell cycles and results in DNA single-strand breaks [8] that may then activate a G2/M cell cycle arrest followed by the induction of apoptosis and autophagy [4, 5, 8].

Macroautophagy (hereafter referred to as autophagy) is a catabolic process involving the degradation of a cell's own components through the lysosomal machinery [9]. During this process, part of the cytoplasm, including organelles such as mitochondria and long-lived proteins, are sequestered in a double-membrane vesicle called an autophagosome. Then, the autophagosome delivers its contents to a lysosome for degradation by lysosomal enzymes [9, 10]. Degradation and recycling of the contents of the vesicle enable the cell to continue to carry out essential processes for cell survival under stress conditions [11, 12]. However, prolonged autophagy results in type II (autophagic) programmed cell death [11].

Bcl2 and adenovirus E1B Nineteen-kilodalton Interacting Protein (BNIP3) is a Bcl-2 homology domain-only protein of the Bcl-2 family [13]. BNIP3 mRNA and protein levels are upregulated through hypoxia-inducing factor-1 (HIF-1)-dependent and -independent mechanisms under stress conditions such as hypoxia [13, 14]. BNIP3 upregulation has been implicated in activation of apoptosis, autophagy and necrosis, depending on the cell type and nature of the stimulus [13-15].

Checkpoints are present in all phases of the cell cycle and function to maintain the integrity of the genome [16]. Many clinically important chemotherapy drugs including 6-TG and 5-FU, which are used in this study, impart

damage to the genome and activate cell cycle checkpoints [16-18]. Checkpoint kinase 1 (Chk1) is a key element in the DNA damage response pathway and plays a crucial role in the S-G(2)-phase checkpoints. The G2/M checkpoint prevents the cell from entering mitosis (M phase) if the genome is damaged [17, 18].

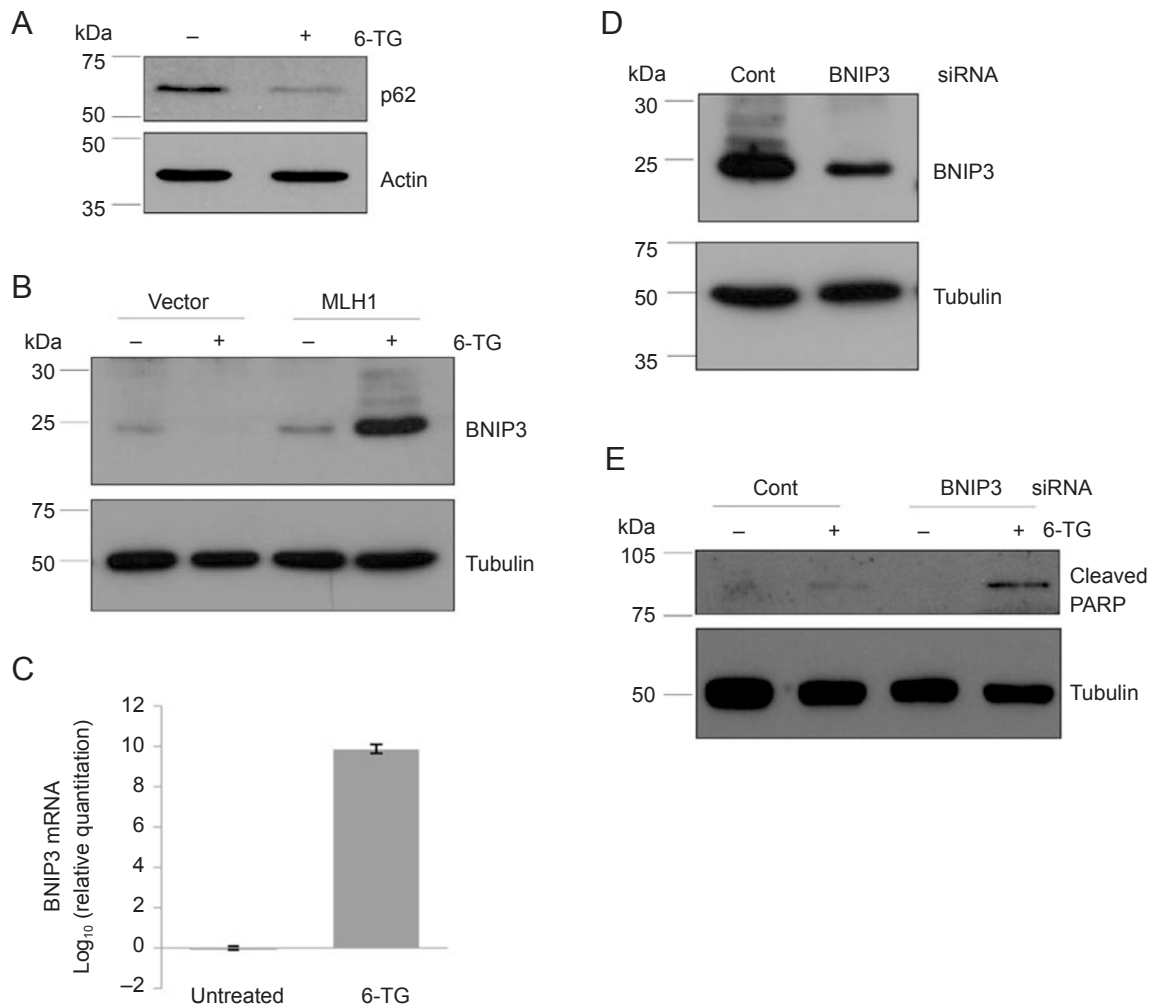
In our earlier reports, we showed that MMR machinery, including MLH1 and MSH2, initiates 6-TG-induced autophagy in a p53- and mTOR-dependent manner [4, 5, 19]. In this study, we investigated the role of BNIP3 in mediating 6-TG- and 5-FU-induced autophagy and the relationship between a G2/M cell cycle arrest and the activation of autophagy following MMR processing of these nucleoside analogs. We found that BNIP3 mediates induction of autophagy following p53 and mTOR activation as a result of MMR processing of both drugs. Our results also indicate that the activation of a G2/M cell cycle arrest produces an inhibitory effect on the extent of autophagy after MMR-mediated drug processing.

## Results

### *BNIP3 is required for induction of autophagy after DNA MMR processing of 6-TG and 5-FU*

In our previous reports [4, 5], we used acridine orange staining, GFP-LC3 punctate dots and LC3 immunoblot analysis to demonstrate that 6-TG induces a MMR-dependent autophagic response. To further confirm 6-TG-induced autophagy flux, we took advantage of a recently identified marker, p62/SQSTM1, for autophagic flux [20, 21]. After autophagy induction, p62/SQSTM1 binds directly to LC3 via a specific sequence motif and is itself degraded by autolysosomes after fusion of autophagosomes with lysosomes [20, 21]. Since p62 accumulates when autophagy degradation is blocked and gets degraded when autophagy flux is induced, p62/SQSTM1 has been widely used as a marker to study autophagic flux [21]. As shown in Figure 1A, 6-TG treatment induces a dramatic decrease in p62/SQSTM1 levels in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells, indicating that autophagic flux is induced instead of being blocked after 6-TG treatment.

To better understand the molecular mechanisms underlying MMR-initiated autophagy following 6-TG treatment as we reported earlier [4, 5, 19], we measured the protein levels of BNIP3 using immunoblot analysis with anti-BNIP3 antibodies. At 3 days after a 24 h 6-TG treatment (when 6-TG-induced autophagy peaks as shown below), we observed that BNIP3 protein levels are upregulated in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells but not in HCT116 (MLH1<sup>-</sup>, MMR<sup>-</sup>) cells (Figure 1B). Consistently, BNIP3 mRNA dramatically increases after 6-TG treatment in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells



**Figure 1** BNIP3 protein levels are upregulated in a MMR-dependent manner in response to 6-TG. **(A)** HCT116 cells stably transfected with MLH1 cDNA (MLH1<sup>+</sup>, MMR<sup>+</sup>) were treated with 3 μM 6-TG for 24 h, harvested and subjected to immunoblot analysis with antibodies against p62/SQSTM1 at day 3 after 6-TG treatment. **(B)** HCT116 cells stably transfected with an empty vector (MLH1<sup>-</sup>, MMR<sup>-</sup>) or with MLH1 cDNA (MLH1<sup>+</sup>, MMR<sup>+</sup>) were treated with 3 μM 6-TG for 24 h, harvested and subjected to immunoblot analysis with antibodies against BNIP3 at day 3 after 6-TG treatment. **(C)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3 μM 6-TG for 24 h. Total RNA was isolated at day 3 after 6-TG treatment. Quantitative real-time PCR was then performed as described in the Materials and Methods. The expression levels of BNIP3 mRNA were normalized to those of the endogenous control 18S rRNA and the mean ΔCt obtained in untreated cells for BNIP3 mRNA was used as calibrator. The relative quantitation values from triplicate reactions were plotted on a log<sub>10</sub> scale as mean ± standard error. **(D)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were transfected with control luciferase (cont) or BNIP3 siRNA oligos, as described in the Materials and Methods. At 2 days after the siRNA transfection, the cells were harvested and analyzed by immunoblot analysis with antibodies against BNIP3. **(E)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3 μM 6-TG for 24 h, harvested and subjected to immunoblot analysis with antibodies against cleaved PARP at day 3 after 6-TG treatment.

(Figure 1C). These data suggest that MMR mediates the upregulation of BNIP3 following 6-TG treatment. Since multiple bands from immunoblot analysis with anti-BNIP3 antibodies were detected around 25 kDa, we next performed small-interfering RNA (siRNA)-mediated silencing of BNIP3 expression to determine the specificity of the antibodies against BNIP3. As shown in Figure 1D,

BNIP3 knockdown dramatically reduces signals from the multiple bands around 25 kDa, indicating that the antibodies against BNIP3 are specific. Since BNIP3 is implicated in promoting apoptosis [13-15], we then investigated whether or not a 6-TG-induced increase in BNIP3 expression affects induction of apoptosis. We found that siRNA-mediated silencing of BNIP3 expression does

not impair 6-TG-induced poly(ADP-ribose) polymerase (PARP) cleavage, a marker of apoptosis [22], in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells (Figure 1E).

We next questioned whether BNIP3 plays an essential role in MMR-initiated autophagy. As shown by the immunoblot in Figure 2A, siRNA-mediated suppression of BNIP3 expression (upper panel) markedly reduces a 6-TG-induced increase in the expression of LC3-II (lower panel), a specific marker of autophagy [23, 24], compared to control siRNA-transfected cells. To confirm this result, we used another clinically active anti-cancer drug, 5-FU, which is also recognized and processed by MMR [25, 26]. As expected, BNIP3 knockdown (Figure 2B, upper panel) also dramatically inhibits the induction of autophagy following a 48 h exposure to 5-FU (5 μM), as measured by LC3-II expression (Figure 2B, lower panel). Together, these data suggest that BNIP3 is essential for activation of autophagy after MMR processing of nucleoside analogs such as 6-TG and 5-FU.

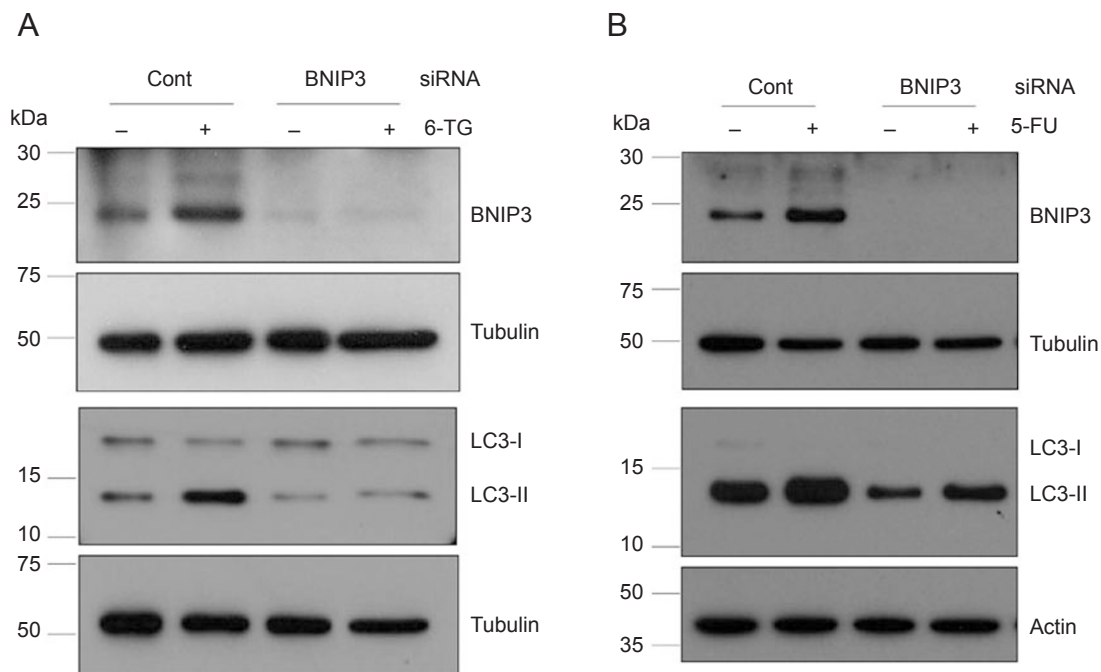
*Suppression of p53 expression impairs BNIP3 upregulation following MMR processing of 6-TG and 5-FU*

In our previous report [4], we showed that p53 me-

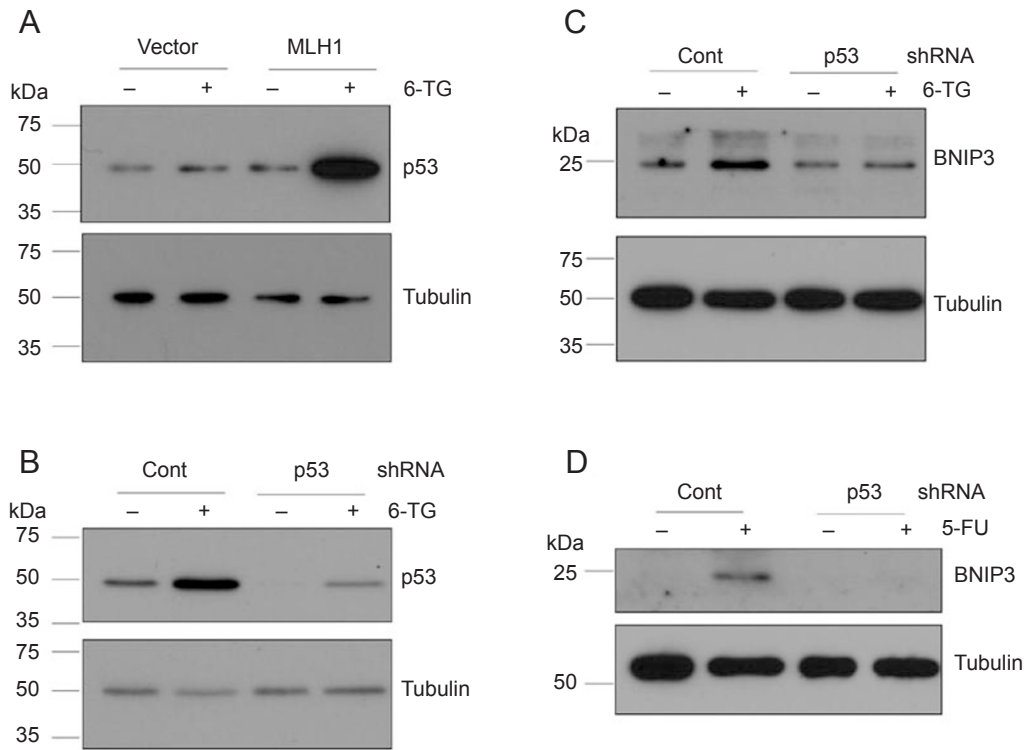
diates induction of autophagy after MMR processing of 6-TG. Here, we questioned whether p53 is required for the upregulation of BNIP3 protein levels following MMR processing of 6-TG and 5-FU. In agreement with the 6-TG-induced upregulation of BNIP3 protein levels, as shown in Figure 1B, p53 is stabilized and activated in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells but not in HCT116 (MLH1<sup>-</sup>, MMR<sup>-</sup>) cells following 6-TG treatment (Figure 3A). Furthermore, Small hairpin RNA (shRNA)-mediated silencing of p53 expression (Figure 3B) abrogates 6-TG-induced upregulation of BNIP3 protein levels in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells (Figure 3C). In agreement, p53 knockdown also impairs 5-FU-induced increase in BNIP3 protein levels (Figure 3D). These data suggest that p53 is required for the upregulation of BNIP3 protein levels following MMR processing of both 6-TG and 5-FU.

*Rapamycin inhibition of mammalian target of rapamycin (mTOR) suppresses upregulation of BNIP3 protein levels following MMR processing of 6-TG and 5-FU*

Previously, we have also shown that mTOR positively regulates 6-TG-induced autophagy [19]. Here, we ques-



**Figure 2** siRNA-mediated silencing of BNIP3 expression impairs 6-TG and 5-FU-induced autophagy. **(A)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3 μM 6-TG for 24 h. Control luciferase (cont) or BNIP3 siRNA oligos were then transfected into the cells, as described in the Materials and Methods. At day 3 after exposure to 6-TG, the cells were harvested and analyzed by immunoblot analysis with antibodies against BNIP3 (upper panel) and LC3 (lower panel). **(B)** Control luciferase (cont) or BNIP3 siRNA oligos were transfected into HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells, as described above. The cells were then incubated with 5 μM 5-FU for 48 h, harvested and subjected to SDS-PAGE and immunoblot analysis with anti-BNIP3 (upper panel) and anti-LC3 (lower panel).



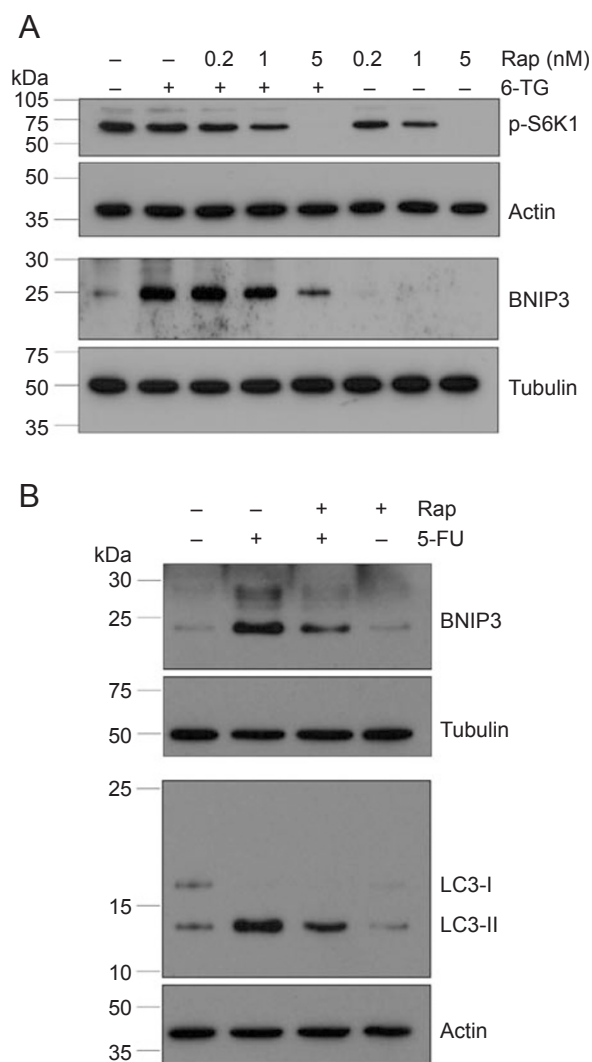
**Figure 3** shRNA-mediated suppression of p53 expression abrogates 6-TG and 5-FU-induced upregulation of BNIP3 protein levels. **(A)** HCT116 cells stably transfected with an empty vector (MLH1<sup>-</sup>, MMR<sup>-</sup>) or with MLH1 cDNA (MLH1<sup>+</sup>, MMR<sup>+</sup>) were treated with 3  $\mu$ M 6-TG for 24 h, harvested and subjected to immunoblot analysis with antibodies against p53 at day 3 after 6-TG treatment. **(B)** Small hairpin RNA-mediated stable silencing of p53 expression was performed, as described in the Materials and Methods. p53 expression was tested by immunoblot analysis with anti-p53. Control and p53-knockdown HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were then treated with 3  $\mu$ M 6-TG for 24 h **(C)** or 5  $\mu$ M 5-FU for 48 h **(D)**. At 72 h after 6-TG exposure or 48 h after 5-FU addition, the cells were harvested and subjected to SDS-PAGE and immunoblot analysis with anti-BNIP3.

tioned whether mTOR affects the upregulation of BNIP3 protein levels following MMR processing of 6-TG and/or 5-FU. As shown in Figure 4A, rapamycin cotreatment inhibits mTOR activity (upper panel) and subsequently reduces the 6-TG-induced increase in BNIP3 protein levels in a dose-dependent manner (lower panel), as measured by immunoblot analysis with anti-phospho-p70S6K (S6K1) (Thr<sup>389</sup>), a downstream target of activated mTOR [27, 28], and anti-BNIP3. Consistent with these results, rapamycin cotreatment also largely inhibits the 5-FU-induced increase in BNIP3 protein levels (Figure 4B, upper panel) and suppresses 5-FU-induced autophagy, as indicated by the decrease in the amount of LC3-II protein expression (Figure 4B, lower panel). Thus, these results suggest that mTOR modulates the upregulation of BNIP3 protein levels following MMR processing of both 6-TG and 5-FU.

*Suppression of Chk1 expression promotes 6-TG-induced autophagy*

To better understand the temporal relationship be-

tween the G2/M cell cycle arrest and BNIP3-mediated autophagy after MMR processing of 6-TG, we measured the dynamic changes of these cellular responses. We treated HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells with 6-TG (3  $\mu$ M) for 24 h and then monitored the temporal changes in the onset of G2/M cell cycle arrest and apoptosis using propidium iodide staining and flow cytometry, as well as of autophagy using GFP-LC3 staining, daily over a period of 5 days. Our results show that the G2/M cell cycle arrest reached a peak at day 1 (Figure 5A). In agreement, our immunoblot analysis using anti-phospho-Chk1 (Ser<sup>345</sup>) showed that Chk1 activation also peaked at day 1 (Figure 5B), consistent with its role as an essential regulator of MMR-initiated G2/M cell cycle arrest [29, 30]. In contrast, autophagy (Figure 5C) and apoptosis (Figure 5D) exhibited relatively late peak responses at day 3 after the 24-h exposure to 6-TG in MMR<sup>+</sup> cells. MMR<sup>-</sup> cells did not show any changes in the G2/M population or in the extent of autophagy or apoptosis with 6-TG treatment, compared to untreated MMR<sup>+</sup> and MMR<sup>-</sup> cells (data not shown).



**Figure 4** Inhibition of mTOR by rapamycin impairs 6-TG and 5-FU-induced upregulation of BNIP3 protein levels. **(A)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3  $\mu$ M 6-TG for 24 h. Then, 0, 0.2, 1 or 5 nM rapamycin was added for another 3 days to inhibit mTOR activity. At day 3 after exposure to 6-TG, cells were harvested and analyzed by immunoblot analysis with antibodies against phospho-p70S6K (S6K1) (Thr<sup>389</sup>) (upper panel) and BNIP3 (lower panel). **(B)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were cotreated with 5  $\mu$ M 5-FU and 5 nM rapamycin for 48 h. The treated cells were harvested and analyzed by immunoblot analysis with anti-BNIP3 (upper panel) and anti-LC3 (lower panel).

To further determine whether the G2/M cell cycle arrest affects the activation of 6-TG-induced autophagy in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells, we performed siRNA-mediated silencing of Chk1 expression (Figure 6A) to inhibit the 6-TG-induced G2/M cell cycle arrest. As shown in Figure 6B, suppression of Chk1 expression by Chk1 siRNA dramatically reduces the 6-TG-induced G2/M cell

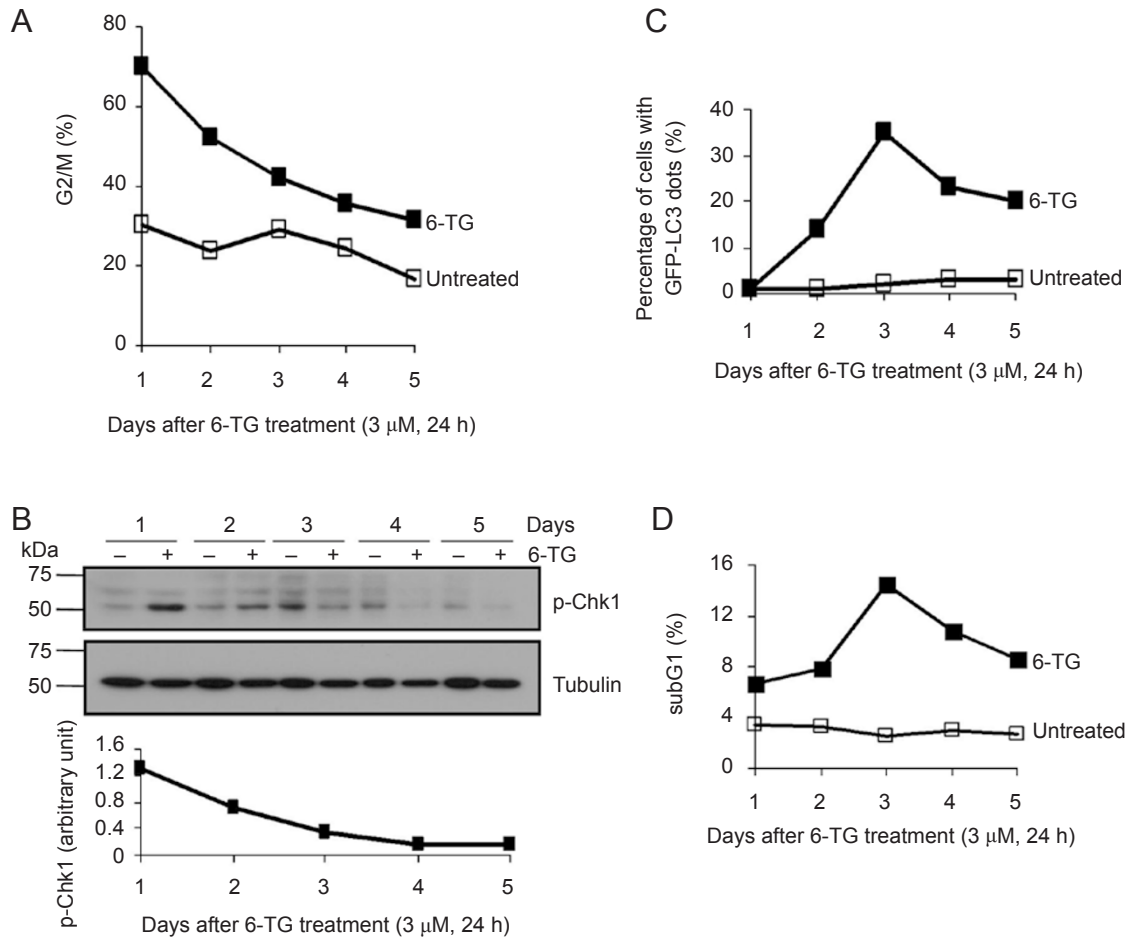
cycle arrest. Interestingly, Chk1 knockdown promotes 6-TG-induced autophagy by three-fold compared to control siRNA-transfected cells (Figure 6C), indicating that the Chk1-mediated G2/M cell cycle arrest produces an inhibitory effect on autophagy following MMR processing of 6-TG.

## Discussion

DNA MMR is principally involved in correcting mismatches of the normal bases in the daughter strand that occurs during scheduled and unscheduled DNA synthesis [1]. In addition, MMR mediates cytotoxicity of several classes of clinically active chemotherapy drugs, including the nucleoside analogs, 6-TG and 5-FU [1-3]. We previously reported that MMR initiates an autophagic response following 6-TG damage processing [4, 5], besides its well-known role in induction of apoptosis [1-3]. In this report, we continue to investigate the underlying molecular mechanisms leading to the activation of autophagy following MMR processing of 6-TG as well as 5-FU. We report that BNIP3 mediates MMR-initiated autophagy in a p53- and mTOR-dependent manner. We also show that the duration of a Chk1-activated G2/M cell cycle arrest determines the level of autophagy following MMR processing of 6-TG.

Increased expression of BNIP3 has been implicated in apoptosis, autophagy and necrosis [13-15]. Surprisingly, our results show that siRNA knockdown of BNIP3 enhances 6-TG-induced cleavage of PARP (Figure 1E), a marker of apoptosis. However, we also found that BNIP3 plays an essential role in mediating 6-TG- and 5-FU-induced autophagy (Figure 2). These data suggest that the induction of BNIP3 and then autophagy inhibits apoptosis after MMR processing of 6-TG. The underlying mechanism may be that 6-TG-induced autophagy degrades damaged mitochondria with loss of membrane potential and, thus, eliminates the triggers of apoptosis [31].

The expression of BNIP3 is reported to be tightly regulated, as its overexpression induces cell death [13, 14]. Under hypoxic conditions, the HIF-1 is stabilized and accumulates to function as a transcription factor to induce expression of multiple genes, including BNIP3 [13, 14]. In response to hypoxia, stabilization of p53 also ensues, but BNIP3 upregulation under hypoxia was found to be independent of p53 [14]. However, in our study, the upregulation of BNIP3 protein levels depends on p53 activation as a consequence of MMR processing of 6-TG and 5-FU (Figure 3). Since p53 usually functions as a transcription factor and BNIP3L, a BNIP3 homolog, is regulated by p53 at the transcriptional level [32], we are

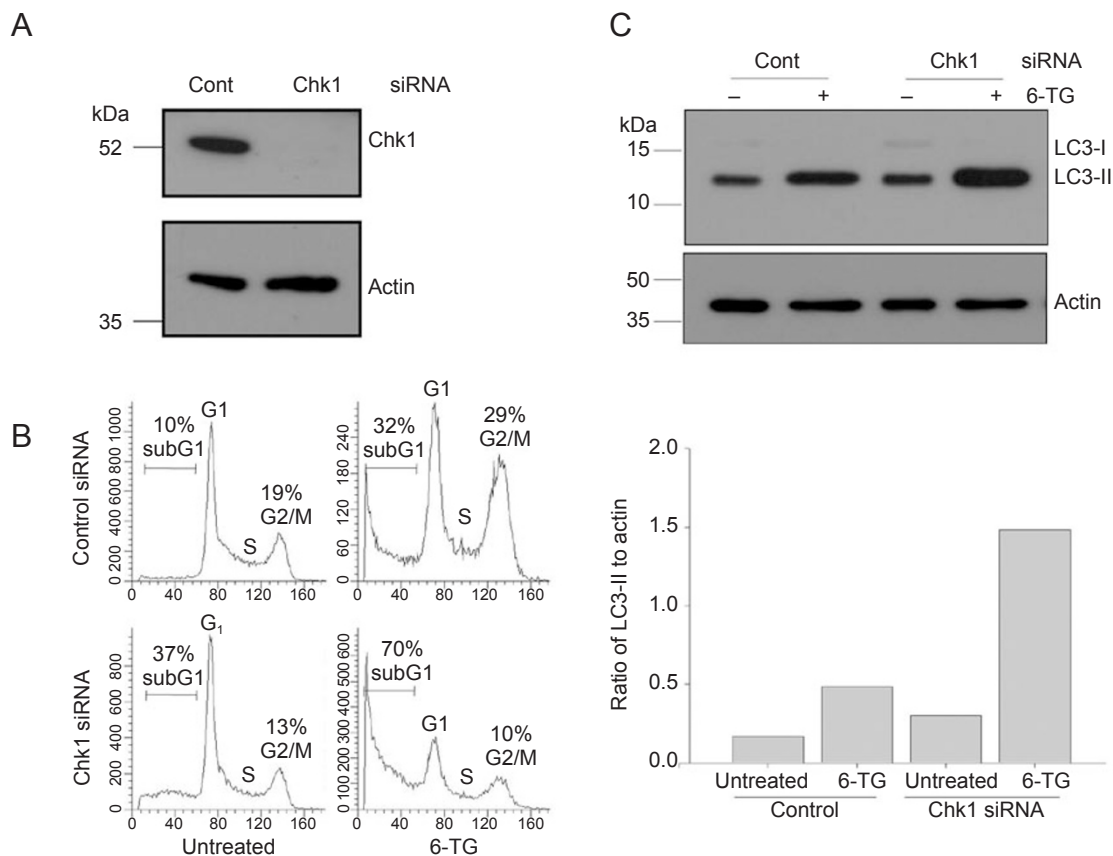


**Figure 5** 6-TG induces a G2/M cell cycle arrest peaking at day 1, while activation of autophagy and apoptosis exhibits a peak response at day 3 in MMR<sup>+</sup> cells. HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3 μM 6-TG for 24 h. The cells were then harvested and stained with propidium iodide for cell cycle analysis (A), as described in the Materials and Methods, or subjected to immunoblot analysis with anti-phospho-Chk1 (Ser<sup>345</sup>) (B) daily for up to 5 days after 6-TG treatment. The amount of phospho-Chk1 (Ser<sup>345</sup>) and tubulin was quantified using NIH Image J and the ratio of phospho-Chk1 (Ser<sup>345</sup>) to tubulin following 6-TG treatment was graphed in the lower panel. (C) HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were stably transfected with pGFP-LC3, as described in the Materials and Methods. The GFP-LC3-expressing cells were treated with 3 μM 6-TG for 24 h. The cells were examined under fluorescence microscopy and the percentage of GFP-LC3-positive cells with GFP-LC3 punctate dots was determined for up to 5 days after 6-TG treatment. A minimum of 250 cells per sample was counted. (D) HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3 μM 6-TG for 24 h. The cells were then harvested, stained with propidium iodide and then subjected to flow cytometry for DNA content analysis as described above. The percentage of cells in subG1 was then graphed. *Open square*, untreated; *closed square*, 6-TG treated.

currently attempting to determine whether p53 increases BNIP3 expression through regulating BNIP3 promoter activity.

Extensive studies have described that rapamycin inhibits mTOR, a negative regulator of autophagy, and then activates autophagy in mammalian cells [33, 34]. Recent reports further suggest that under nutrient-rich conditions, mTOR inhibits autophagy, probably through its association with the protein complex, ULK1-mAtg13-FIP200, and phosphorylation of ULK1 and mAtg13 on sites that inhibit their activity [35, 36]. Under starvation

conditions, mTOR dissociates from the ULK1-mAtg13-FIP200 complex, inducing ULK1 to become active and phosphorylate mAtg13 and FIP200, thus promoting the translocation of the protein complex to sites of autophagosome formation [35, 36]. However, some recent studies have shown that autophagy can also be induced in an mTOR-independent manner [37, 38]. Previously, we have reported that mTOR inhibition by rapamycin and siRNA knockdown of S6K1, one of mTOR downstream effector, inhibit 6-TG-induced autophagy [19]. We further found that mTOR inhibition by rapamycin activates



**Figure 6** siRNA-mediated silencing of Chk1 expression promotes 6-TG-induced autophagy. **(A)** Control luciferase (cont) or Chk1 siRNA were transfected into HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells, as described in the Materials and Methods. Chk1 protein levels were determined by immunoblot analysis with anti-Chk1. **(B)** HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 3  $\mu$ M 6-TG for 24 h. Control luciferase (cont) or Chk1 siRNA oligos were then transfected to the cells as described above. At day 3 after exposure to 6-TG, the cells were harvested, stained with propidium iodide for cell cycle analysis **(B)** as described in the Materials and Methods or subjected to SDS-PAGE and immunoblot analysis with anti-LC3 **(C)**. The amount of LC3-II and actin was quantified using NIH Image J and the ratio of LC3-II to actin was graphed in the lower panel.

Akt, probably through relieving the negative feedback inhibition by mTOR-S6K1 [19]. Activated Akt resulting from mTOR inhibition by rapamycin may phosphorylate and inactivate its substrates such as Foxo, which has recently been found to be involved in autophagy in *Drosophila* [39] and mouse skeletal muscle [40]. Here, we also show that mTOR modulates the upregulation of BNIP3 protein levels following MMR processing of 6-TG and 5-FU (Figure 4). Although the precise mechanism is still not well understood, activated S6K1 by mTOR has been reported to participate in protein synthesis [41, 42]. Therefore, our data, as presented in Figure 4, suggest that mTOR-S6K1 may also control BNIP3 protein translation and play a positive role in regulating 6-TG-induced autophagy. After MMR processing of 6-TG or 5-FU, the effect of BNIP3 on mediating induction of autophagy may be dominant over the negative regulatory effect of

mTOR, as discussed above. This may also explain why mTOR inhibition by rapamycin inhibits 6-TG- or 5-FU-induced autophagy instead of activating autophagy.

When BNIP3 expression is induced by certain stress stimuli, it localizes to the mitochondria through its transmembrane domain. This domain integrates into the outer membrane of the mitochondria, thereby resulting in opening of the permeability transition pore, loss of mitochondrial membrane potential ( $\Delta\psi_m$ ) and increase in production of reactive oxygen species (ROS) [13-15]. ROS have been implicated as a critical trigger of activation of autophagy [14, 43]. Therefore, we speculate that following initiation of MMR processing of chemotherapy drugs such as 6-TG and 5-FU, p53 is activated and functions as a transcription factor to upregulate BNIP3 transcription, while the mTOR-S6K1 axis modulates BNIP3 protein translation. The upregulated BNIP3 disturbs mi-



tochondrial function, subsequently increases production of ROS and then mediates the activation of autophagy as a consequence of MMR processing of 6-TG and 5-FU. Experiments are planned to test these hypotheses.

In this study, we also show that a Chk1-activated G2/M cell cycle arrest produces an inhibitory effect on 6-TG-induced autophagy following MMR processing (Figure 6). These data suggest that if chemical inhibitors are developed and used to inhibit Chk1 activity (e.g., UCN-01), synergistic cytotoxic effects of MMR processing of nucleoside analogs such as 5-FU and 6-TG combined with Chk1 inhibitors may result [44].

In conclusion, we show that BNIP3 plays an essential role in mediating the induction of autophagy in a p53- and mTOR-dependent manner following MMR processing of 6-TG and 5-FU. Our results also indicate that the Chk1-activated G2/M cell cycle arrest produces an inhibitory effect on the extent of autophagy following MMR processing of 6-TG.

## Materials and Methods

### Cell culture

Human colorectal cancer (HCT116) cells are MMR-deficient (MLH1<sup>-</sup>, MMR<sup>-</sup>) because the *hMLH1* gene in these cells contains a base substitution that results in a termination signal at codon 252 (TCA→TAA) [45]. HCT116 cells with stable transfection of human MLH1 cDNA to restore MMR activity (MLH1<sup>+</sup>, MMR<sup>+</sup>) in the HCT116 cells as well as the empty vector control HCT116 cells (MLH1<sup>-</sup>, MMR<sup>-</sup>) were kindly provided by Dr Françoise Praz (Centre National de la Recherche Scientifique, Villejuif, France) [46]. The cells were maintained in Dulbecco's modification of Eagle's Medium (DMEM) (Mediatech Inc, Herndon, VA, USA) and supplemented with 10% FBS (Hyclone, Logan, UT, USA), penicillin (100 µg/ml), streptomycin (100 U/ml), L-glutamine (2 mM) and nonessential amino acids (0.1 mM) (Invitrogen, Carlsbad, CA, USA).

### Drug treatment

Cells were seeded at 30 000 cells per 60-mm dish and allowed to attach and grow for ~17-18 h prior to drug treatments. On the basis of preliminary experiments and prior published data [3-5, 9, 25, 26], cells were exposed to 3 µM 6-TG for 24 h or 5 µM 5-FU for 48 h (Sigma-Aldrich, St. Louis, MO, USA), after which cells were incubated in drug-free medium for up to 5 days. To assess the effects of inhibition of mTOR on 6-TG MMR processing, HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were treated with 6-TG (3 µM × 24 h) and then treated with various concentrations of rapamycin (EMD Chemicals Inc, Gibbstown, NJ, USA) (0, 0.2, 1.0 or 5.0 nM) for 3 days prior to analysis. To assess the effect of inhibition of mTOR on 5-FU MMR processing, HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells were cotreated with 5 µM 5-FU and 5 nM rapamycin for 48 h prior to analyses.

### Stable transfection of GFP-LC3 in HCT116 cells

HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells with stable expression of GFP-

LC3 were generated, as we have described previously [4]. pGFP-LC3 plasmids were kindly provided by Dr Tamotsu Yoshimori (National Institute of Genetics, Shizuoka-ken, Japan) [23].

### RNA interference-mediated gene silencing of BNIP3, Chk1 and p53 expression

Small-interfering RNA (siRNA) oligos were chemically synthesized by Dharmacon Inc (Lafayette, CO, USA). The siRNA sequence specific for luciferase (cont: 5'-CGU ACG CGG AAU ACU UCG AdTdT-3') was used as a control. The sense siRNA sequences for knocking down BNIP3 and Chk1 are: 5'-AAG GAA CAC GAG CGU CAU GAA dTdT-3' (BNIP3) and 5'-GCG UGC CGU AGA CUG UCC AdTdT-3' (Chk1). siRNAs were transfected using LipofectAMINE 2000 (Invitrogen), according to the manufacturer's protocol. shRNA-mediated stable silencing of p53 in HCT116 (MLH1<sup>+</sup>, MMR<sup>+</sup>) cells was performed, as we described previously [4].

### Quantitative real-time polymerase chain reaction

Total RNA was isolated using the RNeasy Mini Kit (Qiagen, Valencia, CA, USA). Quantitative real-time polymerase chain reactions were performed in triplicate for each sample on a 7500 Real-Time PCR System (Applied Biosystems, Foster City, CA, USA). The thermocycling conditions were: initial 10 min incubation at 95 °C followed by 40 cycles of denaturation for 15 s at 95 °C and extension/annealing for 1 min at 60 °C. PCR data were collected and analyzed using Sequence Detection System software. PCR primers used for BNIP3 gene are: 5'-GCC CAC CTC GCT CGC AGA CAC-3' (forward) and 5'-CAA TCC GAT GGC CAG CAA ATG AGA-3' (reverse). Relative quantitation of BNIP3 mRNAs was performed by the comparative  $\Delta\Delta C_t$  method [47]. The expression levels of BNIP3 mRNA are normalized to those of the endogenous control 18S rRNA, and the mean  $\Delta C_t$  obtained in untreated cells for BNIP3 mRNA was used as calibrator. The relative quantitation values were plotted on a log<sub>10</sub> scale.

### Propidium iodide staining for analysis of cell cycle and apoptosis

Cells were fixed with 90% ethanol at -20 °C for 15 min, incubated with RNase, stained with propidium iodide (Sigma-Aldrich) and then subjected to flow cytometry (Epics XL-MCL, Beckman Coulter Inc). Flow cytometric data were analyzed with Modfit 3.0 (Verity Software, Topsham, ME, USA).

### Western blotting

SDS-PAGE and immunoblot analyses were carried out, as described previously [4]. The primary antibodies used for immunoblot analyses included rabbit polyclonal antibodies against LC3 kindly provided by Dr Tamotsu Yoshimori (National Institute of Genetics, Shizuoka-ken, Japan) [23] or purchased from Abcam Inc (Cambridge, MA, USA); rabbit polyclonal antibodies against cleaved PARP (Promega, Madison, WI, USA); rabbit monoclonal antibodies against phospho-Chk1 (Ser<sup>345</sup>) and mouse monoclonal antibodies against phospho-S6K1 (Thr<sup>389</sup>) (Cell Signaling Technology Inc, Danvers, MA, USA); mouse polyclonal antibodies against p62/SQSTM1 (Abnova, Taipei, Taiwan) and mouse monoclonal antibodies against  $\beta$ -actin and  $\alpha$ -tubulin (Sigma-Aldrich), p53 (Santa Cruz Biotechnology Inc, Santa Cruz, CA, USA) and BNIP3 (Abcam Inc).

## Acknowledgments

We thank Dr Francoise Praz for providing the cell systems used in this study, Dr Tamotsu Yoshimori for providing the antibody against LC3 and pEGFP-LC3 plasmids and all members of the Kinsella laboratory for their helpful discussions. The study was supported by NIH grant U56 CA112963, the DBJ Foundation, the Richard A Green Foundation and the University Radiation Medicine Foundation.

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