Slippage of Mitotic Arrest and Enhanced Tumor Development in Mice with BubR1 Haploinsufficiency

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Abstract

A compromised spindle checkpoint is thought to play a key role in genetic instability that predisposes cells to malignant transformation. Loss of function mutations of BubR1, an important component of the spindle checkpoint, have been detected in human cancers. Here we show that BubR1+/− mice embryonic fibroblasts are defective in spindle checkpoint activation, contain a significantly reduced amount of securin and Cdc20, and exhibit a greater level of micronuclei than do wild-type cells. RNA interference-mediated down-regulation of BubR1 also greatly reduced securin levels. Moreover, compared with wild-type littermates, BubR1+/− mice rapidly develop lung as well as intestinal adenocarcinomas in response to challenge with carcinogen. BubR1 is thus essential for spindle checkpoint activation and tumor suppression.

Introduction

The spindle checkpoint functions to block the anaphase entry until each of every condensed chromosome has successfully attached to the spindle microtubules. Vertebrate BubR1 plays a key role in spindle microtubule binding, during which it is extensively phosphorylated (1). Hyperphosphorylated BubR1 and other components of the checkpoint machinery, including Bub1, Bub3, Mad1, Mad2, and CENP-E, are associated with unattached kinetochores (2, 3). Although it appears that BubR1 and Mad2 may function in a single pathway after spindle checkpoint activation (4), BubR1 is a much more potent inhibitor of the anaphase-promoting complex (APC) than is Mad2 (5). A recent study shows that spindle checkpoint activation or silencing is mediated through CENP-E-dependent activation or inactivation of BubR1 kinase (6). A loss of spindle checkpoint function is thought to contribute to the development of cancer because of its role in maintaining genomic stability (7). Indeed, aneuploidy is prevalent in many types of cancer. Although the physiological and molecular basis of this abnormality remains unclear, recent studies indicate that chromosomal instability is closely associated with the loss of a functional spindle checkpoint (7). Mutations in BubR1 have been detected in colon cancer (8), and in addition, a recent study has shown that BubR1 is epigenetically down-regulated in a substantial fraction of human cancers (9). To determine the physiological function of BubR1, we have generated BubR1 mutant mice. Mouse embryonic fibroblasts (MEFs) from BubR1+/− animals were found to contain lower levels of securin and Cdc20 as well as BubR1 than MEFs from wild-type embryos. BubR1 deficiency resulted in mitotic slippage and formation of micronuclei at an enhanced rate. Moreover, BubR1+/− animals were prone to rapid development of tumors in multiple organs after exposure to a carcinogen.

Materials and Methods

Immunoblot Analysis. MEFs or HeLa cells were suspended in a lysis buffer (1), and the cell lysates were centrifuged at 12,000 × g for 10 min at 4°C. Equal amounts of proteins were then subjected to SDS-PAGE and immunoblot analysis with antibodies to BubR1, securin (Novocastra), Mad2, Cdc20, Plk3, or α-tubulin (Sigma). Immune complexes were detected with an appropriate secondary antibody conjugated with horseradish peroxidase (Sigma) and enhanced chemiluminescence reagents (Amersham Pharmacia Biotech).

Fluorescence Microscopy and Immunohistochemistry. Cells fixed in methanol were treated with 0.1% Triton X-100 on ice and then washed three times with ice-cold PBS. After blocking with 2% BSA in PBS for 15 min on ice, cells were incubated for 1 h with antibodies to BubR1, α-tubulin, or CREST; washed with PBS; and then incubated with appropriate secondary antibodies conjugated with Rodamine-Red-X or FITC (Jackson Immunoresearch). Cells were finally stained with 4',6-diamidino-2-phenylindole (1 μg/ml; Fluka). Fluorescence microscopy was performed on a Nikon microscope, and images were captured using a digital camera (Optromics). Immunohistochemistry was performed using a kit purchased from Vector Laboratory according to the instructions provided by the supplier.

RNA Interference. Double-stranded RNAs of 21 nucleotides in length were synthesized by Dharmacon Research. The targeting sequence was 5'-AAGGGAGGCGCCGUCUGUACG-3', corresponding to the coding region of 1281–1301 in human BubR1 (accession number AF065670 GenBank) and 1259–1279 in mouse BubR1 (accession number NM009773 GenBank) relative to the first nucleotide of ATG start codon. The control small interfering RNA (siRNA) targets luciferase mRNA (accession number X65324) of the firefly (Photorus pyralis), and the targeting sequence was 5'-UUUACTACCGTGAATCTCTCGA-3' (GL-3; Dharmacon Research). Double nucleotides (dTdT) were added at the 3' end of each strand. RNA duplexes were transfected into HeLa cells via the Oligofectamine approach (Invitrogen).

Mouse Carcinogenesis Assay. At 6 weeks of age, female mice (10 wild-type and 10 BubR1+/−) were fed semipurified AIN-76A diets. One week after initiation of diets, both groups of mice were given s.c. azoxymethane (AOM; 4 mg/kg body weight) two times weekly for 4 weeks. All animals were weighed once every 2 weeks until termination of the study. Eight or 12 weeks after carcinogen treatment, mice were sacrificed by CO2 euthanasia, and their organs were removed and flushed with Krebs Ringer solution. The dissected organs were opened and fixed flat between two pieces of filter paper in 10% buffered formalin for microadenoma analysis. After a minimum of 24 h in buffered formalin, the organs were cut into segments and placed in a Petri dish containing 0.2% methylene blue in Krebs Ringer solution. They were then placed mucosal side up on a microscope slide and observed through a light microscope. The colon microadenomas present were scored according to standard procedures that are being used routinely in our laboratory (10). Colons showing adenoma-like masses were fixed and subjected to histological analysis after H&E staining.

Results

To study the consequence of loss of BubR1 function on genetic instability and tumor formation, we have generated BubR1 mutant...
mice (11). BubR1 deficiency results in early embryonic death (11). To confirm that BubR1+/− cells actually contained a reduced level of BubR1, we examined the abundance of BubR1 in MEFs derived from embryonic day 14.5 embryos produced from intercrosses of BubR1+/– mice. The genotype of each MEF line was determined by nested PCR (11). Immunoblot analysis revealed that the amount of BubR1 in BubR1+/− MEFs was less than that in wild-type MEFs (Fig. 1A). Interestingly, the average level of BubR1 in BubR1+/− MEFs was about 25% (rather than the expected 50%) of that in wild-type MEFs (data not shown). This greatly reduced level of BubR1 apparently failed to accumulate at kinetochores during early mitosis (Fig. 1B), suggesting that BubR1 in BubR1+/− MEFs may not be efficiently activated. Indeed, exposure to the spindle checkpoint activator nocodazole for 16 h resulted in an apparent upshift of BubR1 due to phosphorylation1 in wild-type MEFs but not in BubR1+/− MEFs (Fig. 1A). Thus, ablation of one BubR1 allele apparently reduced the expression of the other allele, and the reduced level of BubR1 also compromised its activation after microtubule disruption.

BubR1 functions as a potent inhibitor of APC during activation of the spindle checkpoint (5). Metaphase and anaphase transition requires the destruction of securin in an APC-dependent manner. Cells with a compromised spindle checkpoint would be expected to exhibit increased APC activity and a consequent reduced abundance of securin. Indeed, immunoblot analysis revealed that the amount of securin in cycling BubR1+/− MEFs was reduced compared with that in wild-type cells. Although nucodazole induced a slight accumulation of securin in BubR1+/− MEFs, the steady-state level of this protein was much lower in these cells than in wild-type MEFs treated with nocodazole for the same time (Fig. 1C). Consistent with the notion that BubR1+/– cells are defective in spindle checkpoint control, in addition, the abundance of Cdc20 was low in cycling BubR1+/− MEFs. On nocodazole treatment, Cdc20 was greatly increased in these cells. The kinetics of Cdc20 increase in BubR1+/− MEFs was similar to that observed in wild-type MEFs until about 18 h posttreatment; Cdc20 in these cells then returned to a level lower than that in wild-type MEFs (Fig. 1C, 18 h and beyond). Moreover, a significant fraction of BubR1 in wild-type MEFs, but not in BubR1+/− MEFs, was phosphorylated on nocodazole treatment, and the phosphorylation peaked between 14 and 18 h posttreatment. On the other hand, Mad2 levels in BubR1+/− MEFs were not significantly modulated in the presence or absence of nocodazole.

To confirm that BubR1 deficiency directly caused a reduction of securin, we examined securin levels in HeLa cells transfected with siRNAs targeting human BubR1 or luciferase (as a negative control). BubR1 siRNA, but not control one, effectively down-regulated BubR1 expression 3 days after transfection (Fig. 1D). Consistently, the securin level was also significantly reduced. By day 5, securin had almost completely disappeared from HeLa cells transfected with siRNA targeting BubR1.

To determine whether mitosis was affected in BubR1+/− MEFs, we examined the percentage of cells positive for phosphorylated histone H3, a mitotic marker tightly associated with chromosome condensation (Fig. 2A). Fluorescence microscopy revealed that there existed significantly fewer phosphorylated histone H3-positive cells in BubR1+/− MEFs than in wild-type MEFs (Fig. 2B). About 3.8% of BubR1+/− MEFs were in mitotic stages as revealed by phosphorylated histone H3 staining, whereas 9.2% of cells were mitotic in wild-type MEFs (Fig. 2C). Chromosome mis-segregation and micronuclei formation are hallmarks of a compromised spindle checkpoint (7). A greatly increased number of BubR1+/− MEF cells contained spontaneously formed micronuclei compared with the wild-type MEFs (Fig. 2, D and E). Irregular nuclear shape and nuclear blebbing were also observed in BubR1+/− MEFs (data not shown).

Because mutations of the BubR1 gene were first identified in human colon cancer cells (8) and because BubR1 is epigenetically down-regulated in a substantial fraction of human cancers (9), we investigated whether BubR1+/− mice were more susceptible to carcinogenesis after treatment with AOM, a colon carcinogen. Wild-type mice typically develop a low incidence of colonic tumors 6–8 months after initiation of AOM treatment (12). About 2 months after the completion of AOM treatment, BubR1+/− mice had already exhibited abnormal and dilated crypts (data not shown). These mice subsequently developed a significant number of microadenomas and adenoma-like masses (Fig. 3B; Table 1). Polyps were scarcely detected in colons of wild-type C57BL/6 mice at this stage of treatment (Table 1), however. Histological studies revealed that when compared with the

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1 Wei Dai and Tongyi Liu, unpublished data.
normal structure of colon, these polyps were indeed neoplastic (Table 1; Fig. 3, C and D). Colonic tubular adenomas were lined with mild dysplastic epithelium, and glands exhibited partial loss of polarity with a mild architecture distortion (Fig. 3C). Based on common pathological criteria (e.g., gland architecture, nuclear/cytoplasmic ratio, nuclear location, and amount of interglandular stroma), many large tumors from BubR1−/− animals were classified as well to moderately differentiated adenocarcinomas with complex and highly packed glands (Fig. 3D).

We next examined several other major organs (e.g., spleen, liver, and lung) for any sign of tumor formation. No neoplastic growths were detected in either BubR1−/− or wild-type spleens. To our surprise, BubR1−/− mice, but not the wild-type mice, developed many lung adenocarcinomas (Fig. 4A) as well as neoplasms in liver (data not shown). Tumor masses were typically well circumscribed, but not encapsulated, and situated at the periphery of the lung. They exhibited hyperchromatic and pleomorphic nuclei with abundant eosinophilic cytoplasm. Consistent with pulmonary adenocarcinoma, some tumor cells apparently formed glands with a lumen, whereas others formed trabecular patterns (Fig. 4A). Immunohistochemical studies revealed that lung adenocarcinomas were strongly stained with proliferative cell nuclear antigen (Fig. 4B), indicating that these tumor cells were

![Fig. 2. Mitotic slippage associated with abnormal nuclear morphology in BubR1−/− deficient cells. A, wild-type mouse embryonic fibroblasts (MEFs) fixed and stained with antibodies to phosphorylated histone H3 (H3-P; green) or kinetochoore antigen CREST (red) were examined by fluorescence microscopy. DNA was stained with 4',6-diamidino-2-phenylindole. A typical prophase cell strongly stained with phosphorylated histone H3 is shown. Bar, 10 μm. B, BubR1−/− and wild-type MEFs fixed and stained with an antibody to phosphorylated histone H3 (green, top panels) and 4',6-diamidino-2-phenylindole (blue, bottom panels). Bar, 50 μm. C, both BubR1−/− and wild-type MEFs positive for phosphorylated histone H3 were scored from 500 cells, and the percentage of the positive cells is shown. D, BubR1−/− and wild-type MEFs stained with antibody to α-tubulin and 4',6-diamidino-2-phenylindole were examined by fluorescence microscopy. Arrows denote micronuclei. Bar, 5 μm. E, micronuclei formed in both BubR1−/− and wild-type MEFs were scored from 500 cells; the percentage of cells with micronuclei is shown.](https://cancerres.aacrjournals.org)
highly proliferative. The susceptibility of $BubR1^{+/−}$ mice to lung tumor formation after challenge with the colon carcinogen AOM is unexpected because C57/BL6 mice are very resistant to the development of tumors, even when the lung-specific carcinogens such as 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone are used. It is intriguing to note that lung appears prone to development of cancer when the spindle checkpoint is compromised because Mad2 or Bub3 haploinsufficiency also results in enhanced development of lung cancer (13, 14).

**Discussion**

Extensive biochemical and molecular analyses have shown that $BubR1$ plays a central role in spindle checkpoint activation (5, 15, 16). It both coordinates the interaction of Bub3, Mad1, Mad2, and CENP-E with kinetochores and contributes to inhibition of APC activity during activation of this checkpoint. The APC is an E3 ubiquitin ligase that mediates the polyubiquitination of securin, thereby targeting it for degradation by the proteosome (16). Securin binds to and inhibits the proteolytic activity of separase, which destroys the link between sister chromatids by cleaving the chromatid cohesin factor Scc1. Degradation of securin is required for the separation of sister chromatids during mitosis. Reduced levels of securin in $BubR1^{+/−}$ MEFs are closely correlated with $BubR1$ deficiency as well as with its activation status (Fig. 1C). Moreover, down-regulation of $BubR1$ via RNA interference resulted in almost complete disappearance of securin (Fig. 1D), strongly suggesting that $BubR1$ plays a pivotal role in the inhibition of APC during spindle checkpoint activation. In fact, enhanced genetic instability (e.g., polyploidy and micronuclei formation) in $BubR1^{+/−}$ MEF cells correlates very well with the observation that securin$^{−/−}$ cells lose chromosomes with a high frequency (17).

It is believed that one of the consequences of the loss of spindle checkpoint is genetic instability of the resulting daughter cells, which predisposes these cells to malignant transformation. Some evidence indicates that structural alterations or a loss of functional spindle checkpoint components may trigger certain cancers because mutations have been detected in $Bub1$ and $BubR1$ (8, 18). Although we have not...
Fig. 4. *BubR1*+/− mice, but not wild-type mice, develop lung adenomas after exposure to azoxymethane. A, lung sections from *BubR1*+/+ and *BubR1*+/− mice treated with azoxymethane for 12 weeks were stained with H&E (magnifications, ×100 and ×400, respectively). Arrow indicates a solitary tumor mass in *BubR1*+/− lung; the region is subjected to high-power magnification. B, neighboring sections of the same lung tissue from *BubR1*+/− mice were subjected to immunohistochemical studies after staining with either control immunoglobulin (IgG) or proliferative cell nuclear antigen IgG (magnifications, ×100). Arrows indicate a solitary tumor; the same region is subjected to high-power magnification (×400).
observed a significant increase in spontaneous tumors in \textit{BubR1}\textsuperscript{+/−} mice, our recent studies have demonstrated that these mice are prone to the development of neoplastic lesions of colon and lung within 2 months after they have been challenged with the carcinogen. In contrast, neither lesion is detected in wild-type mice at the same treatment stage, suggesting that \textit{BubR1} is a tumor susceptibility gene. Consistently, recent \textit{in vitro} studies show that adenomatous polyposis coli protein plays an important role in chromosomal segregation by interacting with BubR1 and that defects in adenomatous polyposis coli lead to increased chromosomal instability (19), underscoring the importance of further exploration of the role of \textit{BubR1} in colon cancer using this animal model. Intriguingly, it is expected that a significantly compromised spindle checkpoint observed with \textit{BubR1}\textsuperscript{+/−} MEF cells would conceivably lead to widespread aneuploidy and rapid development of spontaneous tumors in the transgenic animals. Our explanations are as follows: (a) the spindle checkpoint in \textit{BubR1}\textsuperscript{+/−} cells is compromised, but not completely failed; and (b) animals are capable of elimination of most cells with severe chromosomal instabilities through apoptosis. This mechanism would prevent the early onset of tumors until a second insult occurs during aging or under a carcinogen stress. This view is supported by the facts that haploinsufficiency of \textit{Mad2} and \textit{Bub3/Rae1} results in a significantly enhanced lung cancer incidence in aging (beyond 18 months; Ref. 13) and carcinogen-challenged (20) mice, respectively.

In this study, we have addressed an \textit{in vivo} role of \textit{BubR1} by using a mouse gene knockout approach. \textit{BubR1} haploinsufficiency results in a compromised spindle checkpoint, leading to slippage of mitotic arrest. A recent study shows that CENP-E functions as an activator of the essential checkpoint kinase BubR1; inactivation of BubR1 kinase activity silences the signaling of the spindle checkpoint (6). Thus, the availability of \textit{BubR1}\textsuperscript{+/−} mice should now greatly facilitate characterization of the functional interactions between BubR1 and various spindle checkpoint components, including CENP-E, Mad2, and other spindle checkpoint gene products.

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