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IL-18 Production Downstream of the Nlrp3 Inflammasome Confers Protection against Colorectal Tumor Formation

Mohammad Hasan Zaki,* Peter Vogel,† Mathilde Body-Malapel,‡ Mohamed Lamkanfi,§,¶ and Thirumala-Devi Kanneganti*  

Colorectal cancer is a leading cause of cancer-related deaths worldwide. Chronic inflammation is recognized as a predisposing factor for the development of colon cancer, but the molecular mechanisms linking inflammation and tumorigenesis have remained elusive. Recent studies revealed a crucial role for the NOD-like receptor protein Nlrp3 in regulating inflammation through the assembly of proinflammatory protein complexes termed inflammasomes. However, its role in colorectal tumor formation remains unclear. In this study, we showed that mice deficient for Nlrp3 or the inflammasome effector caspase-1 were highly susceptible to azoxymethane/dextran sodium sulfate-induced inflammation and suffered from dramatically increased tumor burdens in the colon. This was a consequence of markedly reduced IL-18 levels in mice lacking components of the Nlrp3 inflammasome, which led to impaired production and activation of the tumor suppressors IFN-γ and STAT1, respectively. Thus, IL-18 production downstream of the Nlrp3 inflammasome is critically involved in protection against colorectal tumorigenesis. The Journal of Immunology, 2010, 185: 4912–4920.

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Abbreviations used in this paper: AOM, azoxymethane; ASC, apoptosis-associated speck-like protein containing CARD; COX, cyclooxygenase; DSS, dextran sodium sulfate; IBD, inflammatory bowel disease; NLR, NOD-like receptor; WT, wild-type.

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Nlrp3 inflammasome was recently shown to confer protection against experimental colitis in mice (27–29). In this regard, mice lacking the inflammasome components Nlrp3, ASC, or caspase-1 all presented with more severe clinical manifestations of colitis and suffered from increased epithelial injury, bacterial invasion, and death rates (27–29). The increased susceptibility to colitis was correlated with defective IL-18 production in inflammasome-deficient mice (27, 29). Despite the role of the Nlrp3 inflammasome in controlling colitis-associated inflammation, its role in controlling colitis-associated tumorigenesis and the relevant inflammasome effector pathways in this process have remained unclear.

To resolve these issues, we determined the rate of colorectal tumor formation in Nlrp3−/− and Casp1−/− mice in the commonly used azoxymethane (AOM)/dextran sodium sulfate (DSS) model. IL-18 production downstream of the Nlrp3 inflammasome was found to exert a protective role against colorectal tumor formation. IL-18-mediated activation and induction of the respective tumor suppressors STAT1 and IFN-γ may represent a potentially critical mechanism for Nlrp3-mediated resistance against colitis-associated tumorigenesis.

Materials and Methods

Mice

Nlrp3−/−, ASC−/−, and Casp1−/− mice backcrossed to a C57BL/6 background for at least 10 generations have been described before (30). IL-18−/− mice were donated by Dr. Paul G. Thomas (St. Jude Children’s Research Hospital). All mice were 8- to 10-wk-old males and were maintained in a pathogen-free facility, and the animal studies were conducted under protocols approved by the St. Jude Children’s Research Hospital Committee on the Use and Care of Animals.

Induction of colorectal cancer

Mice were injected i.p. with 10 mg/kg AOM (Sigma-Aldrich, St. Louis, MO). After 5 d, 3% DSS (molecular mass, 36–40 kDa; MP Biologicals, Solon, OH) was given in drinking water over 5 d followed by regular drinking water for 2 wk. This cycle was repeated twice and mice were sacrificed 4 wk after the last DSS cycle.

Histopathological analysis

Formalin-processed sections of cecum and colon (proximal, middle, and distal) were processed and embedded in paraffin by standard techniques. Longitudinal sections of 5 µm thick were stained with H&E and examined by a pathologist blinded to the experimental groups. Colitis scores of each segment were assigned based on the extent and severity of inflammation, ulceration, and hyperplasia of the mucosa. Severity scores for inflammation were as follows: 0, normal (within normal limits); 1, mild (small, focal, or widely separated, limited to lamina propria); 2, moderate (multifocal or locally extensive, extending to submucosa); 3, severe (transmural inflammation with ulcers covering >20 crypts). Scores for ulceration were as follows: 0, normal (no ulcers); 1, mild (one to two ulcers involving up to a total of 20 crypts); 2, moderate (one to four ulcers involving a total of 20–40 crypts); 3, severe (more than four ulcers or >40 crypts). Mucosal hyperplasia scores were assigned as follows: 0, normal (within normal limits); 1, mild (crypts two to three times normal thickness, normal epithelium); 2, moderate (crypts two to three times normal thickness, hyperplastic epithelium, reduced goblet cells, scattered arborization); 3, severe (crypts more than four times normal thickness, marked hyperplasia, few to no goblet cells, high mitotic index, frequent arborization). Scoring for extent of lesions was as follows: 0, normal (0% involvement); 1, mild (up to 30% involvement); 2, moderate (30–70% involvement); 3, severe (>70% involvement). The individual scores from the four segments were summed such that the maximum colitis score for a given animal is 48 and the minimum score is 0. For immunohistochemistry, formalin-fixed paraffin-embedded tissues were cut into 4-µm sections and slides were stained with Abs against the macrophage marker F4/80 (Calgene Laboratories, Burlington, CA) and phosho-STAT1 (Cell Signaling Technology, Beverly, MA), respectively.

Cytokine measurements

To measure the cytokine levels in colon tissue, a part of the colon was homogenized mechanically in PBS containing 1% Nonidet P-40 and a complete protease inhibitor mixture tablet (Roche Diagnostics, Indianapolis, IN). Mouse cytokines and chemokines in serum and colon homogenates were determined with Luminex (Bio-Rad, Hercules, CA) and ELISA (R&D Systems, Minneapolis, MN) assays.

Real-time RT-PCR

Total RNA from colon tissue was isolated with TRIzol (Invitrogen, Carlsbad, CA). First-strand cDNA was synthesized from 250 ng of RNA using SuperScript III (Invitrogen). Real-time PCR for cyclooxygenase (COX)-2 and IFN-γ was performed using SYBR Green Master mix (Invitrogen) on an ABI Prism 7500 real-time PCR system (Applied Biosystems, Foster City, CA). mRNA levels were determined by means of the standard curve method. A standard sample was serially diluted and used for constructing a standard curve. Simultaneous quantification of GAPDH mRNA was used as an internal control.

In situ intestinal proliferation assay

The number of proliferating cells in intestinal epithelium was determined using the immunoperoxidase staining protocol with the thymidine analog BrdU as described earlier (29). In brief, 1 mg/ml BrdU in PBS was injected i.p. Three hours later, colon tissue was collected, fixed in 10% neutral buffered formalin, and embedded in paraffin. Immunohistochemistry was performed using an in situ BrdU staining kit (BD Biosciences, San Jose, CA). Tissues were counterstained with hematoxylin.

Western blotting

Tissue homogenates were lysed in lysis buffer (10 mM Tris-HCl, 150 mM NaCl, 5 mM EDTA, 0.1% Nonidet P-40, 0.25% sodium deoxycholate, supplemented with protease and phosphatase inhibitor cocktails; Roche Diagnostics), and membranes were removed by centrifugation at 11,000 × g. Before separation by SDS-PAGE, protein samples were denatured with SDS plus 100 mM DTT and boiled for 5 min. Separated proteins were transferred to polyvinylidene fluoride membranes and immuno blotted with primary Abs against phospho-STAT1, STAT1, rabbit phospho-IκB, IκB (all from Cell Signaling Technology), and β-actin (Sigma-Aldrich).

Recombinant IL-18 and IFN-γ treatment

Recombinant IL-18 (MBL International, Woburn, MA) was injected i.p. at a concentration of 0.5 µg/mouse on days 0, 2, and 4 and at 0.1 µg/mouse on days 6 and 8 after DSS administration. Alternatively, Casp1−/− mice were injected i.p. with recombinant mouse IFN-γ (R&D Systems) at a concentration of 200 IU/mouse on days 0, 2, 4, and 6 after DSS administration.

Statistical analysis

Data are represented as mean ± SE. Statistical significance was determined by a Student’s t test or χ² test. The p values <0.05 were considered statistically significant.

Results

Increased susceptibility to colitis-associated colorectal tumor formation in Nlrp3 inflammasome-deficient mice

Nlrp3-deficient mice were recently shown to be highly susceptible to the induction of inflammation and tissue damage in the acute DSS-induced colitis model (29). Similarly, Nlrp3-deficient mice developed more severe symptoms of chronic colitis when mice were administered multiple cycles of DSS (28, 29). To determine whether the increased and prolonged gut inflammation in inflammasome-deficient mice led to increased tumorigenesis, Nlrp3−/−, ASC−/−, and Casp1−/− mice were administered a single dose of the DNA methylating agent AOM (10 mg/kg), followed by repeated cycles of a 3% DSS solution (31). Twelve weeks after AOM injection (Fig. 1A), the development of adenomatous polyps and well-formed tumors in the colons of Nlrp3 inflammasome-deficient mice was examined and compared with colons of treated wild-type mice. Mice in the wild-type, Nlrp3−/−, ASC−/−, and Casp1−/− groups developed tumors after AOM and DSS administration, but tumor burdens were significantly increased in Nlrp3−/−, ASC−/−, and Casp1−/− mice over wild-type mice (Fig. 1B, 1C). Nevertheless, statistically significant differences in tumor size could...
PLASTIC EVENTS WAS SIGNIFICANTLY HIGHER IN THE NLRP3 CONTAINING TUMORS IN THE MIDCOLON SECTION WAS CALCULATED. DATA REPRESENT TO COLITIS-ASSOCIATED COLORECTAL TUMORIGENESIS.

A

**FiguRE 1.** NLRP3−/−, ASC−/−, and Casp1−/− mice are hypersusceptible to colitis-associated colorectal tumorigenesis. A, WT (n = 15), NLRP3−/− (n = 15), ASC−/− (n = 8), and Casp1−/− mice (n = 13) were administered AOM on day 0 and were then given a 3% DSS solution during three 5-d cycles as described in Materials and Methods. B, Twelve weeks after AOM injection, mice were sacrificed to determine tumor development in the colon. C–E, Total tumor numbers observed in whole colon (C), distal colon (D), and middle colon (E) were determined. F, The percentage of mice containing tumors in the midcolon section was calculated. Data represent means ± SE. *p < 0.05. WT, wild-type.

not be observed (data not shown). Most tumors were located in the distal area of the colon in all genotypes (Fig. 1D), although a fraction of the tumors were found in the midcolon section (Fig. 1E). Notably, the number of mice presenting with tumors in the midcolon region increased from ~40% of wild-type mice to >60% in the NLRP3−/− and CASP1−/− cohorts (Fig. 1F). This may be due to the more severe inflammation and extended tissue damage that DSS induced in NLRP3−/− and CASP1−/− mice (27–29).

Colon sections of representative tumor-bearing wild-type, NLRP3−/−, and CASP1−/− mice were sectioned and stained with H&E to study mucosal dysplasia in more detail. Significantly more dysplastic cells and hyperplastic areas, adenomatous polyps, and well-formed tumors were visible in the distal colons of NLRP3−/− and CASP1−/− mice relative to those of wild-type mice (Fig. 2A). Moreover, the number of mice presenting with dysplastic events was significantly higher in the NLRP3−/− and CASP1−/− cohorts (Fig. 2B). In all three genotypes, tumors were mainly derived from dysplastic epithelial cells at the site of inflammation (Fig. 2C). The tumors appeared as sessile tubulovillous adenomas, and evidence for adenocarcinoma development was not observed. Histopathological scoring for severity of inflammation, inflamed area, ulceration, and hyperplasia in the colon and cecum was in agreement with significantly increased disease progression in NLRP3−/− and CASP1−/− mice (Fig. 2D). As indicated before (Fig. 1D), most tumors were located in the distal area of the colon, but occasionally tumors were found in the midcolon area. Separate histopathological scorings for the distal and midcolon regions were performed to determine whether spatial differences in pathology could be observed. In both the distal (Fig. 2E) and midcolon (Fig. 2F) regions, read-outs for inflammation severity, inflamed area, and hyperplasia were significantly increased in NLRP3−/− and CASP1−/− mice over wild-type controls. Collectively, these results demonstrate that a functional NLRP3 inflammasome is critical for protection against colitis-associated dysplasia and tumorigenesis in the gut. These observations are in agreement with a recent report showing increased AOM/DSS-induced colon tumorigenesis in mice lacking NLRP3 or the inflammasome effectors ASC and caspase-1 (28).

Enhanced tumorigenesis in NLRP3 inflammasome-deficient mice is associated with deregulated IL-18 production and increased macrophage infiltration

The NLRP3 inflammasome is required for maturation and secretion of the inflammatory cytokines IL-1β and IL-18 (32). To determine whether the absence of a functional NLRP3 inflammasome affects local IL-1β and IL-18 production in the gut during early stages of tumorigenesis, the levels of these cytokines were measured in colon homogenates of NLRP3−/− and CASP1−/− mice 5 d after completion of the first DSS cycle (day 10 after AOM treatment). IL-1β amounts in the colon homogenates of AOM/DSS-treated wild-type, NLRP3−/−, and CASP1−/− mice remained low and barely rose above those of untreated animals (Fig. 3A and data not shown). In contrast, significant levels of IL-18 were measured in colon homogenates of AOM/DSS-treated wild-type mice (Fig. 3A). However, IL-18 levels in colon homogenates of NLRP3−/− and CASP1−/− mice were nearly 50% lower than those of treated wild-type controls (Fig. 3A). Unlike IL-18, the levels of the cytokines IL-6, IL-12, and TNF-α did not differ significantly from those found in wild-type controls (data not shown), demonstrating the specificity of these results. Moreover, we measured significantly higher levels of the chemokines MIP-1α and eotaxin in colon homogenates of NLRP3−/− and CASP1−/− mice (Fig. 3B, 3C), suggesting that deregulated IL-18 production triggered an increased recruitment of inflammatory cells in colons of NLRP3−/− and CASP1−/− mice. In agreement, colon sections of the latter genotypes contained significantly more F4/80-positive cells than did wild-type colons (Fig. 3D), indicating a dramatically increased infiltration of macrophages in colons of NLRP3−/− and CASP1−/− mice. Macrophages exert a regulating role in the colorectal tumor microenvironment through the production of a variety of tumorigenic factors including COX-2, which promotes tumor development through the synthesis of its enzymatic product PGE2 (33). Consistent with the increased macrophage infiltration in colons of NLRP3−/− and CASP1−/− mice, real-time PCR analysis demonstrated significantly higher COX-2 mRNA levels in colon tissue of NLRP3−/− and CASP1−/− mice (Fig. 3E).

We next sought to determine the effect of deregulated IL-18 production, increased macrophage infiltration, and COX-2 production on epithelial cell proliferation in the colons of AOM/DSS-treated NLRP3−/− and CASP1−/− mice. To this end, epithelial cell proliferation was examined by BrdU staining at the early and late time points of 10 d and 12 wk after AOM injection, respectively. Interestingly, the number of proliferating cells located in dysplastic regions of NLRP3−/− and CASP1−/− colons was significantly higher than in tumor tissue of AOM/DSS-treated wild-type mice at both analyzed time points (Fig. 4). In contrast, no significant differences in proliferation were noted between the three genotypes in regions of the normal mucosa (Fig. 4). AOM-induced mutagenic events are likely to be critical for inducing neoplasia in the context of the colonic microenvironment of NLRP3−/− and...
Casp1−/− mice because DSS administration alone failed to induce increased cell proliferation in colonic crypts of Nlrp3−/− and Casp1−/− mice (29). Taken together, these results suggest a critical role for Nlrp3 inflammasome-mediated production of IL-18 in protection against colitis-associated immune cell invasion and neoplasia.

**FIGURE 2.** Histopathological examination of tumor and colon tissue of WT, Nlrp3−/−, and Casp1−/− mice. WT, Nlrp3−/−, and Casp1−/− mice (n = 10 genotype) were injected with AOM and then received three cycles of a 3% DSS solution as described in Materials and Methods. Twelve weeks after AOM injection, colons were collected and sections were stained with H&E for histopathological analysis. A, Low magnification (original magnification ×20) scanning of distal colon after H&E staining. B, Overall grading of dysplasia in each genotype was performed as described in Materials and Methods. C, Representative high magnification images of H&E staining showing dysplasia in colon tissue of WT (low-grade dysplasia), Nlrp3−/− (low-grade dysplasia), and Casp1−/− (high-grade dysplasia) mice. Original magnification ×20. D–F, Semiquantitative scoring of inflammation, hyperplasia, and inflamed area in total (D), distal (E), and midcolonic (F) sections. Data represent means ± SE. *p < 0.05. WT, wild-type.

**FIGURE 3.** Decreased production of IL-18 in Nlrp3−/− and Casp1−/− colons is associated with increased inflammation and induction of tumorigenic factors. WT, Nlrp3−/−, and Casp1−/− mice were injected with AOM followed by 3% DSS treatment. A–C, Distal colons were collected at day 15 after AOM injection, and homogenates were used to determine IL-1β and IL-18 levels (A) and the concentrations of the chemotactic factors MIP-1α (B) and eotaxin (C) by ELISA. D, Colon sections were simultaneously immunostained for the macrophage marker F4/80. Original magnification ×10. E, Real-time PCR analysis was performed on distal colon homogenates collected at day 15 after AOM injection to measure COX-2 expression. Data represent means ± SE (n = 5/group). *p < 0.05. WT, wild-type.
IL-18 signaling downstream of the Nlrp3 inflammasome confers protection against colitis-associated tumorigenesis

To further examine the role of IL-18 in protection against colitis-associated dysplasia and tumor development, we characterized colon inflammation and tumor development in il-18−/− mice that were subjected to the AOM/DSS regimen described in Fig. 1A. In agreement with an important role for IL-18 in protection against colitis-associated tumorigenesis, colons of il-18−/− mice contained significantly more tumors than did those of treated wild-type mice (Fig. 5A, 5B). To determine whether increased tumor formation in il-18−/− mice could be linked to increased epithelial cell damage and colon inflammation during the early stages of disease, we examined phenotypic and histological signs of colitis and hyperplasia during acute colitis. To this end, wild-type and il-18−/− mice were administered AOM followed by a 3% DSS solution during 5 d before parameters of colitis development and tumorigenesis were analyzed. The Il-18−/− mice presented with aggravated colitis, as evidenced by higher body weight loss (Fig. 5C), severe inflammation, hyperplasia, and more dysplastic cells (Fig. 5D). Semiquantitative scoring of histological colon sections for inflammation, ulceration, affected area, and hyperplasia was consistent with markedly increased disease development in il-18−/− mice relative to the group of wild-type mice (Fig. 5E).

As a complementary approach to the use of il-18−/− mice, we studied whether recombinant IL-18 could reverse disease progression in AOM/DSS-treated Casp1−/− mice. Importantly, the group of Casp1−/− mice that received recombinant IL-18 lost significantly less weight compared with Casp1−/− mice that were refused the recombinant cytokine (Fig. 5F). Moreover, IL-18 administration provided protection against histological signs of inflammation and dysplasia (Fig. 5G). Consistently, semiquantitative scoring of inflammation, ulceration, affected area, and hyperplasia on histological colon sections was indicative of milder disease in IL-18–treated Casp1−/− mice (Fig. 5H). These results demonstrate that IL-18 signaling downstream of the Nlrp3 inflammasome confers protection against colitis-associated colorectal tumorigenesis.

The Nlrp3 inflammasome activates the tumor suppressor STAT1 in the colon via IL-18–mediated IFN-γ production

Our results showed that impaired production of IL-18 downstream of the Nlrp3 inflammasome contributes to aggravated colitis-associated tumorigenesis (Figs. 3, 5). IL-18 was initially described as the cytokine responsible for induction of IFN-γ production (22), and IFN-γ was attributed potent antitumor activity in a variety of experimental tumorigenesis models (34–38). In agreement with the defective IL-18 production in colons of AOM/DSS-treated Nlrp3−/− and Casp1−/− mice (Fig. 3A), we found that IFN-γ mRNA levels were dramatically lower in colon homogenates of the latter genotypes relative to those of AOM/DSS-treated wild-type mice (Fig. 6A). Diminished IFN-γ production was confirmed at the protein level by IFN-γ–specific ELISA (Fig. 6B). IFN-γ–mediated antitumor signaling involves activation of the transcription factor STAT1 (36). Notably, stat1−/− mice are highly susceptible to tumorigenesis, classifying STAT1 as a tumor suppressor (39, 40). To determine whether decreased production of IL-18 and IFN-γ in colons of AOM/DSS-treated Casp1−/− mice affected STAT1 activation levels, phospho-specific STAT1 Abs were used to examine STAT1 activation by Western blotting. STAT1 activation was a consequence of AOM/DSS treatment, because basal STAT1 activation levels in wild-type colons were significantly upregulated following AOM/DSS treatment (Fig. 6C). However, AOM/DSS-induced STAT1 activation was dramatically reduced in colons of Casp1−/− mice during early stages of tumorigenesis (day 15 after AOM treatment) (Fig. 6C). In contrast, phosphorylation of the NF-κB inhibitor IκB was not affected (Fig. 6D), demonstrating the specificity of these results. Immunohistochemical analysis of wild-type colons indicated increased phospho-STAT1 activation in epithelial cells and infiltrating immune cells upon AOM/DSS treatment (Fig. 6E). Colons of AOM/DSS-treated Casp1−/− mice contained significantly less cells staining positive for phospho-STAT1 (Fig. 6E), suggesting that STAT1 signaling in epithelial and immune cells may both contribute to protection against tumorigenesis.
Body weight change of WT and Il18−/− mice was monitored for 9 d after DSS administration. H&E staining; original magnification ×10. E, Semiquantitative histological scoring of inflammation, ulceration, and hyperplasia in whole colons of WT and Il18−/− mice was monitored for 9 d after DSS administration. F, Representative images of inflamed and hyperplastic areas in the distal colon at day 10 after DSS administration. H&E staining; original magnification ×10. G, Representative images of inflamed and hyperplastic areas in the distal colon at day 10 after DSS administration. H&E staining; original magnification ×10. H, Semiquantitative scoring of inflammation, ulceration, and hyperplasia in the whole colon at day 10 after DSS treatment. Data represent means ± SE (n = 5/group). *p < 0.05. WT, wild-type.

Discussion

Chronic inflammation is increasingly recognized as a critical risk factor for the development of colorectal cancer (4). Members of the NLR protein family are expressed on epithelial and professional APCs residing in the colonic mucosa and lamina propria and play key roles in regulating the immune response against commensal microorganisms in the gut. Notably, defective activation of the NLR member NOD1 has been reported to enhance inflammatory cytokine production against commensal bacteria in the gut and prime the colorectal mucosa for increased cell proliferation and tumor formation during colitis in mice (25). Moreover, mutations in the NLR protein NOD2 are linked with the development of Crohn’s disease in humans (41, 42). It has been established that Crohn’s disease patients are at increased risk of developing sporadic colorectal cancer (43). In agreement, polymorphisms in the gene encoding NOD2 have been associated with increased susceptibility to gastrointestinal tumorigenesis (44). More recently, mutations in the gene encoding Nlrp3 were linked with increased susceptibility to Crohn’s disease in humans (26). Recent reports from our and other groups demonstrated that DSS-induced colitis in Nlrp3-deficient mice is associated with an increased destruction of the epithelial barrier in the gut, inducing systemic dispersion of colonic microflora and an exaggerated inflammatory response (27, 29). Nlrp3 plays a central role in activation of caspase-1 and secretion of the proinflammatory cytokines IL-1β and IL-18 (30).

Caspase-1–deficient mice also were hypersensitive to DSS- and 2,4,6-trinitrobenzene sulfonic acid-induced colitis (27, 29), indicating that Nlrp3 protects against colitis through the production of caspase-1–dependent cytokines. Indeed, the phenotype of Casp1−/− mice was rescued by administration of recombinant IL-18 (27, 29). Moreover, mice lacking the inflammasome inhibitor caspase-12 were resistant to acute colitis, although (paradoxically) they were more susceptible to AOM/DSS-induced colorectal tumorigenesis (27).

In this study, we showed that increased inflammatory responses and destruction of the epithelial barrier led to enhanced dysplasia and tumorigenesis in colons of AOM/DSS-treated Nlrp3−/− and Casp1−/− mice. Our observations are in agreement with a recent report showing that mice lacking Nlrp3, ASC, or caspase-1 were...
and AOM/DSS-treated WT and 3 positive inflammatory cells. Original magnification
STAT1–positive epithelial cells; blue arrows indicate phospho-STAT1–were immunostained for phospho-STAT1. Black arrows indicate phospho-

group). Data represent means ± SE (n = 5/group). *p < 0.05. C and D, Homogenates of the distal colon were pre-
prepared 15 d after AOM injection and analyzed for total STAT1, phospho-
STAT1, total IκB, and phospho-IκB by Western blotting. β-actin was used as a
loading control. E, Colon tissue sections collected from control mice
and AOM/DSS-treated WT and Casp1–/– mice (at day 15 after AOM)
were immunostained for phospho-STAT1. Black arrows indicate phospho-
STAT1–positive epithelial cells; blue arrows indicate phospho-STAT1–
positive inflammatory cells. Original magnification ×40. F, Casp1–/– mice were treated with IFN-γ at 5, 7, 9, and 11 d after AOM
administration. On day 15 after AOM treatment, STAT1 activation in colon
homogenates was compared with that of AOM/DSS-treated WT and
Casp1–/– mice by Western blotting. G, Casp1–/– mice were treated with
IL-18 at 5, 7, 9, and 11 d after AOM treatment. On day 15 after AOM
treatment, STAT1 activation in colon homogenates was compared with that
of AOM/DSS-treated WT and Casp1–/– mice by Western blotting. WT, wild-type.

FIGURE 6. The Nlrp3 inflammasome activates the tumor suppressor
STAT1 via IL-18-mediated IFN-γ production. A and B, WT, Nlrp3–/–, and
Casp1–/– mice were administered AOM on day 0 and were then given
a 3% DSS solution for 5 d as described in Materials and Methods. IFN-γ
production in colon tissue at day 15 after AOM injection was analyzed by
real-time PCR (A) and ELISA (B). Data represent means ± SE (n = 5/
group). *p < 0.05. C and D, Homogenates of the distal colon were pre-
pared 15 d after AOM injection and analyzed for total STAT1, phospho-
STAT1, total IκB, and phospho-IκB by Western blotting. β-actin was used as a
loading control. E, Colon tissue sections collected from control mice
and AOM/DSS-treated WT and Casp1–/– mice (at day 15 after AOM)
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Casp1–/– mice by Western blotting. G, Casp1–/– mice were treated with
IL-18 at 5, 7, 9, and 11 d after AOM treatment. On day 15 after AOM
treatment, STAT1 activation in colon homogenates was compared with that
of AOM/DSS-treated WT and Casp1–/– mice by Western blotting. WT, wild-type.

hypersusceptible to AOM/DSS-induced colorectal tumor formation
(28). However, the mechanism by which the Nlrp3 inflammasome
confers protection against colitis-associated tumorigenesis remained
obscure (45). We demonstrated that IL-18 production was signi-
ificantly reduced in colons of AOM/DSS-treated Nlrp3–/– and
Casp1–/– mice, and, more importantly, that colons of AOM/DSS-
treated il-18–/– mice recapitulated the increased tumor burdens
seen in mice lacking Nlrp3 or caspase-1. These results suggested a
critical role for IL-18 production downstream of the Nlrp3
inflammasome in protection against colitis-associated neoplasia. In
agreement, administration of recombinant IL-18 markedly reduced
disease progression in AOM/DSS-treated Casp1–/– mice.

IL-18 was previously assigned an antitumor function in a variety
of experimental tumor models (46–49). It was reported to inhibit
tumor growth and angiogenesis (50–52) and was associated with
repair and restitution of ulcerated epithelium (53). We and others
showed that IL-18 is involved in repair of the epithelial layer of
the gut by maintaining proper levels of epithelial cell proliferation
during the acute stage of DSS-induced colitis (27, 29). DSS-
duced damage and erosion of the epithelial layer is repaired by
rapid proliferation of stem cells residing at the base of crypts
(54). Intriguingly, while IL-18 promotes enterocyte proliferation
to repair chemically induced injury of colonic epithelium, we
showed in this study that it also inhibits hyperplasia during
chronic stages of colitis. This apparent discrepancy may be
explained by differential roles of IL-18 during the acute and chronic
stages of colitis (53). Moreover, we only observed higher prolifera-
ion in dysplastic regions of the colon epithelium of
AOM/DSS-treated Nlrp3–/– and Casp1–/– mice, but not in non-
tumor regions. These observations suggest that IL-18 exerts its
protective effect in two stages. First, during acute DSS-induced
colitis, it contributes to restoring epithelial barrier integrity by
induced controlled proliferation of stem cells at the crypt base
and turnover of damaged epithelial cells. This prevents systemic
dispersion of commensal microflora and the induction of exag-
gerated inflammatory responses. However, during remission and
chronic stages of colitis, IL-18 inhibits epithelial cell proliferation
in neoplastic regions of the colon epithelium. This may be ac-
quired, at least in part, through the induction of IFN-γ production.
Indeed, IL-18 was originally identified as the "IFN-γ-inducing factor" (22), and IFN-γ has been described as a pleiotropic cy-
tokine with potent antitumor activity (34, 37). In this regard, we
demonstrated a markedly diminished production of IFN-γ in
colons of AOM/DSS-treated Nlrp3–/– and Casp1–/– mice. Not-
ably, IFN-γ signaling was previously shown to confer protection
against experimental colitis (55). In agreement with a biphasic
role for Nlrp3-mediated IL-18 production in colitis-associated
tumorgenesis, a recent report described a biphasic role for IFN-
γ during DSS-induced colitis with promotion of intestinal
epithelial cell proliferation at early stages and induction of anti-
proliferative responses at later stages (56). IFN-γ mediates its
effect through IFN-γR, which is expressed on both normal and
malignant cells (57). Its biological effects are mediated by a
number of intracellular signaling pathways, the best characterized
of which is the JAK-STAT pathway. Once IFN-
γ
activation of the Nlrp3 inflammasome confers protection

against the development of inflammation-associated colorectal tu-
merigeneis. We showed that Nlrp3 inflammasome-dependent IL-18 pro-
duction prevents neoplastic events, possibly through the induction of IFN-γ production and STAT1 signaling. These results suggest that strategies aimed at producing or delivering mature IL-18 in the colon may prove beneficial in preventing colorectal tumor develop-
ment in the context of chronic inflammation.

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Disclosures
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