Genetic and Pharmacological Inactivation of the Purinergic P2RX7 Receptor Dampens Inflammation but Increases Tumor Incidence in a Mouse Model of Colitis-Associated Cancer

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Abstract

Colitis-associated cancer (CAC) is a complication of inflammatory bowel disease (IBD). Binding of extracellular ATP to the purinergic receptor P2RX7 has emerged as a critical event in controlling intestinal inflammation, acting to limit elevation of proinflammatory mast cells and cytokines and promote survival of regulatory T cells (Treg) and enteric neurons. In this study, we investigated the effect of P2RX7 blockade in an established mouse model of CAC. Using genetic and pharmacologic tools, we found unexpectedly that while P2RX7 mediated inflammatory responses, it also acted at an early time to suppress CAC development. P2RX7 blockade enhanced proliferation of intestinal epithelial cells and protected them from apoptosis. The proliferative effects of P2RX7 blockade were associated with an increased production of TGFβ1 that was sufficient to stimulate the proliferation of intestinal epithelial cells. Finally, P2RX7 blockade also altered immune cell infiltration and promoted Treg accumulation within lesions of the digestive system. Taken together, our findings reveal an unexpected role for P2RX7 in preventing CAC, suggesting cautions in the use of P2RX7 inhibitors to treat IBD given the possibility of increasing risks CAC as a result. Cancer Res; 75(5); 835–45. © 2015 AACR.

Introduction

Purinergic receptors form a family of adenosine (P1) and ATP (P2) receptors involved in a complex signaling network that affects various cellular functions such as cell proliferation, cell differentiation and cell death, but also exocrine and endocrine secretion, immune responses, and inflammation (1). They are widely expressed throughout the digestive tract, where they are involved in the regulation of intestinal motility. Moreover, it was shown that this family of receptors regulated several neuronal and non-neuronal gut functions, visceral sensation, and the immune cell activity (2). Therefore, it is now widely accepted that purinergic receptors actively cooperate in the maintenance of gut homeostasis.

P2X receptors (P2RX) display a conserved topology with two transmembrane spanning regions, a large extracellular region sensitive to the ligand and intracellular amino- and carboxyl-termini that contain signaling binding motifs. Upon gating by eATP, P2RX7, also referred to as P2X7R, forms a poorly selective channel leading to membrane depolarization, potassium efflux, and calcium and sodium influx (3). P2RX7 triggering also induces the formation of larger membrane pores that allow the passage of molecules reaching up to 900 Da. This particular feature has been linked to the presence of a long cytoplasmic C-terminal tail and to the possible activation of a pore-forming molecular partner suggested to be pannexin-1 (4, 5). Importantly, both P2RX7 activation and pannexin-1 mediate NLRP3 inflammasome assembly, caspase-1 (casp-1) activation, and maturation of the proinflammatory cytokines IL1B (IL1β) and IL18 (6).

At the level of the gastrointestinal tract, P2RX7 is expressed on immune and nonimmune cells (7, 8). Its low level of sensitivity to eATP limits its activation within inflammatory sites and in the tumor microenvironment where eATP concentrations are in the 100 μM range (9). We previously reported that P2RX7 is differentially expressed in the mucosa of patients with active and quiescent inflammatory bowel disease (IBD) and that its activation could be triggered in response to neutrophil transepithelial migration (8). These results, together with published data based on the use of P2RX7 antagonists or P2rx7−/− mice, support the notion that P2RX7 participates in the initiation as well as in the regulation of the inflammatory...
response notably via the processing and release of IL1B (10–12). It is widely accepted that chronic inflammation can promote tumor development (13). In this scenario, the proinflammatory role of P2RX7 in immune and epithelial cells would be expected to favor carcinogenesis. However, P2RX7 also regulates cell proliferation and/or cell death (14–17). Moreover, adding to the complex interplay between inflammation and carcinogenesis, a study has revealed the role of the proinflammatory P2RX7/NLRP3/casp-1 cascade in the priming of dendritic cells and in the immunogenicity of dying tumor cells following chemotherapy, which favors the emergence of an endogenous antitumor immune response (18). Finally, P2RX7 appears to be overexpressed in a variety of neoplastic disorders and tumors (19–21) and P2RX7 expression increases the tumorigenic properties of human embryonic kidney cells (16). Hence, based on the apparently contradictory evidence, the precise role of P2RX7 in vivo in the context of inflammation-associated carcinogenesis needs to be carefully addressed.

In this study, we investigated the role of P2RX7 in CAC and we showed, using P2rx7−/− mice as well as the P2RX7-specific pharmacologic antagonists, that the P2RX7 activity suppressed tumor development. While deciphering the cellular and molecular events leading to this suppressive function, we demonstrated that P2RX7 inactivation leads to: (i) overproduction of TGFβ1, (ii) recruitment of Tregs within inflammatory lesions, and (iii) TGFβ1-mediated proliferation of colonic epithelial cells.

**Materials and Methods**

**Animal strains**

This study was approved by the Institutional Care and Use Committee of the University of Nice-Sophia Antipolis (Nice, France). Animal protocols were approved by the committee for Research and Ethics of the PACA region (CIEPAL azur, #PEA 12-125) and followed the European directive 2010/63/UE. The generation of C57Bl/6 mice harboring targeted disruption of the P2rx7 gene has been described previously (10). Control C57Bl/6j mice were supplied by Harlan Laboratories.

**Induction of colitis and inflammation-driven tumor formation**

Acute inflammation was induced as followed: intraperitoneal injection of azoxymethane at day 0 before 5% dextran sulfate (DSS) treatment from day 1 to day 5. CAC was induced by a single intraperitoneal injection of azoxymethane followed by 3 cycles of 3% DSS in the drinking water. Each cycle lasted 5 days and was separated by 2 weeks, as illustrated in Fig. 4A. We used the following semiquantitative clinical score, which was adapted from ref. 22. Body weight loss was scored as follows: 0, no loss; 1, loss < 5%; 2, loss < 10%; 3, loss < 20%; and 4, loss > 20%. The scores for stool consistency were measured as 0, normal; 1, loose stools; 2, watery diarrhea; or 3, severe watery diarrhea. Rectal bleeding was scored as 0, no blood; 1, presence of petechia; 2, stools with a trace of blood; or 3, bleeding. Inflammation score was performed by trained pathologists. Briefly, the severity of inflammation (none, mild, moderate, severe), extent of inflammation (none, mucosa, mucosa, and submucosa, transmural), crypt damage (none, basal to 1/3, basal to 2/3, crypt loss, crypts, and epithelium loss), and percentage of tissue affected by inflammation (0, 25, 50, 75, and 100%) were scored.

**Macroscopic polyp analysis and histopathology**

Colon (cecum to rectum) polyps were removed from animals and processed for histopathology as described in the Supplementary Materials and Methods.

**Serum, colon organ cultures, and ELISA**

Blood was collected with a heparin-treated needle from the tail vein and serum was obtained by centrifugation (15 minutes, 3,000 rpm at 4°C). After resection, colon tissues were cultured overnight in DMEM, supernatants were collected, and production of IL1B, TGFβ1, CXCL1, and CXCL2 assayed by an ELISA as described by the manufacturers (see Supplementary Materials and Methods).

**Quantitative real-time PCR and protein gel blotting**

Total RNA and protein were isolated from colonic tissues using TRI Reagent following manufacturer’s instructions and processed as described by manufacturers (see Supplementary Materials and Methods). We used the following antibodies: phospho-STAT3 (9131), STAT3 (9139), and BCL2 (Bcl2, #5003) antibodies were from Cell Signaling Technology, anti-BCL2L1 (Bcl-X/L, sc-634), and anti-BAX (Bax, sc-526) were from Santa Cruz Biotechnology and the anti-ACTB (Actin, clone AC40) antibody was from Sigma Aldrich.

**Immunohistochemical analyses of mouse colon tissues**

Resected mouse colon tissues were fixed in 10% formalin, paraffin-embedded, and processed for immunohistochemical analyses, as described previously (8) and Supplementary Materials and Methods. We used the following antibodies: anti-PCNA (Epitomics), anti-cleaved-caspase-3 (Imgenex), anti-CD3 (Abcam), anti-Foxp3-biotin (eBioscience), anti-F4/80 (Abcam), and anti-Ly6G (Abcam).

**Treatment with the P2RX7 antagonists and depleting antibodies**

Competitive P2RX7 antagonists A438079 and A740003 and depleting antibodies were given intraperitoneally during the DSS treatment as indicated in the Supplementary Materials and Methods.

**Statistical analysis**

All data are represented as mean values and error bars represent SEM. The unpaired Mann–Whitney test and ANOVA were used to evaluate the statistical significance between groups.

**Results**

**Genetic and pharmacologic inactivation of P2RX7 dampen DSS-induced colonic inflammation**

The inflammatory environment generated by DSS is associated with the release of eATP. We reasoned that P2RX7 inactivation should impact the overall inflammatory response and we used the acute DSS colitis model to test this hypothesis. After AOM injection, WT and P2rx7−/− mice were fed a 5% DSS solution during 5 days and then clean drinking water for 4 or 9 days. As expected, when considering that P2RX7 triggered inflammasome assembly and proinflammatory cytokine release, P2rx7−/− mice were less susceptible to this treatment (Fig. 1A). P2rx7−/− mice survived better and lost less weight. Furthermore, they showed milder signs of colitis with less diarrhea and less rectal bleeding.
We also observed a less dramatic shortening of the colon length at necropsy. Such protection required the mutation of the two alleles since heterozygous P2rx7+/−/C0 mice showed the same phenotype as WT mice (Supplementary Fig. S1). Interestingly, these results were reproduced on WT mice treated with competitive P2RX7 antagonists (Fig. 1B and Supplementary Fig. S2). Systemic blockade of P2RX7 with A438079 or A740003 improved the survival of the mice and reduced all the hallmarks of colitis. Indeed, 9 days after DSS treatment, the loss of body weight and the disease activity score decreased by around 25%, whereas the colon length increased, as observed with P2rx7−/− mice.

Histologic analyses of colon tissues were performed to evaluate the degree of inflammation. In the nontreated condition, both WT and P2rx7−/− mice showed a normal colonic mucosa, with the crypts being straight, well defined, and sitting on the muscularis mucosa (Fig. 2A). At the end of the DSS regimen (day 5), histologic colonic transversal tissue sections of both WT and P2rx7−/− mice showed diffuse hemorrhagic walls with multiple ulcerations, mucosal edema, transmural neutrophil infiltration, and the presence of large areas of erosion. Scoring for inflammation, which demonstrated no difference between WT and KO mice, nearly reached the maximum (which was scored as 14). In contrast, 4 days after the end of the DSS challenge (day 9), histologic mid colon tissue sections of WT mice still showed a high level of inflammation (12 ± 0.7), whereas that of P2rx7−/− mice showed signs of re-epithelialization, as indicated by better delineated crypts and milder inflammation of the mucosa (inflammatory index of 5.1 ± 1.5). Finally, most of the colonic mucosa of P2rx7−/− mice presented a normal aspect 9 days after DSS treatment (day 14). In contrast, recovery of WT mice was partial with a mean inflammatory index of 9 ± 0.9 as compared with 2.2 ± 0.6 for KO mice. These differences were reproduced in WT mice treated with the P2RX7 antagonists (Fig. 2B and Supplementary Fig. S2). In particular, mice that received the competitive antagonist showed weak inflammatory infiltrates with no mucosal erosion and no epithelial cell defects within the crypts. Furthermore, histologic scoring of mid colon tissue sections of antagonist-treated mice demonstrated a very low inflammatory index, which was statistically significant as compared with the control group.

Taken together, these results demonstrate that both genetic and pharmacologic inactivation of P2RX7 dampen DSS-induced colonic inflammation. Notably, a time course analysis demonstrated that mice deficient in P2RX7 activity recovered more rapidly from inflammatory lesions than WT mice.

P2rx7−/− mice exhibit increased colonic epithelial cell proliferation and decreased apoptosis after AOM/DSS treatment

The prompt recovery of P2rx7−/− mice to acute AOM/DSS challenge led us to evaluate whether P2RX7 regulated colonic mucosal epithelial cell proliferation. For that, colon tissue
sections were stained for proliferating cell nuclear antigen (PCNA). In nontreated WT and \( P2rx7^{+/+} \) animals, quantification of PCNA-positive cells per 30 to 50 well-formed crypts showed 5% to 10% PCNA-positive cells (Supplementary Fig. S3A). Five days after acute AOM/DSS treatment, no well-defined crypts were visible (Fig. 2B). Therefore, we evaluated cell proliferation at days 9 and 14. The proliferation indices of AOM/DSS-treated animals were significantly higher in \( P2rx7^{+/+} \) as compared with WT mice (Fig. 3A). Such an effect could directly depend on \( P2RX7 \) expressed by colonic epithelial cells (8) and (Supplementary Fig. S3B), or alternatively, depends on infiltrating immune cells. To address this point, we evaluated whether this effect could be reproduced in vitro on cultivated colonic epithelial cells expressing \( P2RX7 \). Indeed, blockade of \( P2RX7 \) enhanced the in vitro proliferation of the T84 colonic epithelial cell line (Supplementary Fig. S3C). The effect of \( P2RX7 \) blockade on epithelial cell proliferation was further confirmed in vivo as A438079 administration to AOM/DSS-treated mice increased colonic epithelial cell proliferation (Supplementary Fig. S3D). We next evaluated whether \( P2RX7 \) also regulates apoptosis of intestinal epithelial cells. For this, inflammatory tissue lesions were stained with cleaved caspase-3 antibody. We observed significantly less apoptotic cells in \( P2rx7^{+/+} \) mice at day 9 and their complete absence at day 14 after AOM/DSS treatment (Fig. 3B). We then examined the expression of anti-apoptotic genes. No changes were observed in the expression of BAX. In contrast, a significant increase in the expression of the genes encoding \( BCL2 \) and \( BCL2L1 \) (\( Bcl-xL \)) was observed in the whole colon of \( P2rx7^{+/+} \) mice at day 14 after AOM/DSS administration (Fig. 3C). Finally, the increase in epithelial cell proliferation correlated with dysplasia in the colonic mucosa of \( P2rx7^{+/+} \) mice. We consistently found abnormal crypts characterized by misalignment of the epithelial nuclei and a partial or total loss of mucosal secretion (Fig. 3D). \( P2rx7^{+/+} \) mice were particularly prone to develop dysplasia, as they were also present in mice that received a short and low dose of DSS (Supplementary Fig. S4) that induced no signs of colitis and only a very low inflammatory index. Taken together, these results demonstrate that the functional activity of the \( P2RX7 \) receptor is required to control the level of intestinal epithelial cell proliferation and apoptosis in response to an inflammatory insult and suggest that alteration in \( P2RX7 \) functionality may favor possibly tumor progression.

**P2RX7 mediates gastrointestinal tumorigenesis in the colitis-associated cancer model**

To investigate the effect of \( P2RX7 \) on inflammation-induced colorectal cancer, azoxymethane-challenged mice received 3
cycles of DSS to mimic chronic colitis (Fig. 4A). Both WT and \( P2rx7^{-/-} \) mice survived azoxymethane-DSS treatment and showed comparable disease activity indices during the first 10 weeks of treatment. However, \( P2rx7^{-/-} \) mice displayed a higher disease activity scores at the end of the protocol (Supplementary Fig. S5). Unexpectedly, despite their lower susceptibility to acute DSS-induced inflammation, \( P2rx7^{-/-} \) mice developed significantly higher numbers of macroscopic polyps (mean of 9 polyps per mouse) as compared with WT mice (mean of 2 polyps per mouse). As expected for the CAC model, tumors were located at the distal end of the colon in WT mice, whereas they invaded up to the medial part of the colon in \( P2rx7^{-/-} \) mice (Fig. 4A). In addition, the 4-fold increase in tumor burden in \( P2rx7^{-/-} \) mice was accompanied by a 2-fold increase in polyp size (Fig. 4B). Histologic examination of colons from WT and \( P2rx7^{-/-} \)-deficient mice showed that 80% of the KO mice developed colonic lesions ranging from hyperplasia and dysplasia to adenocarcinoma (Supplementary Fig. S6A). Adenocarcinoma was observed in more than 60% of KO mice, whereas only 25% of the WT cohort displayed a carcinoma.

Furthermore, we investigated the pharmacologic effect of P2RX7 blockade in the CAC model using the A438079-competitive antagonist. Changes in body weight were followed during the entire protocol and the colonic tumor burden was monitored 10 weeks after AOM injection. As observed for WT and \( P2rx7^{-/-} \) mice, antagonist-treated and nontreated mice displayed comparable body weight variations during the course of the treatment (Supplementary Fig. S5, bottom). However, A438079-treated mice harbored higher numbers of macroscopic polyps and tumors were significantly larger in size than in control mice (Fig. 4C). Collectively, these results demonstrate that alteration of the P2RX7 functionality enhanced tumor promotion and/or progression. Interestingly, tumor progression was also found to be controlled by P2RX7 in an unrelated tumor mouse model based on subcutaneous injection of Lewis Lung Carcinoma (LLC) cells. As shown in Supplementary Fig. S6B, mice injected with LLC cells developed tumors within 2 weeks. Importantly, excised tumors from \( P2rx7^{-/-} \) mice were bigger than tumors from WT mice confirming that P2RX7 behaved as a tumor suppressor in this tumorigenic mouse model.
P2RX7 shapes the inflammatory microenvironment

P2RX7 stimulation is known to trigger inflammasome assembly and casp1 activation and to favor the release of the processed mature form of IL1B, thereby initiating the inflammatory response (4, 10). As the early level of inflammation can influence the quality and the quantity of recruited immune cells, we next characterized the inflammatory microenvironment before tumor onset. We first checked the capacity of colonic explants from acute DSS-treated mice to secrete IL1B. After in vivo DSS treatment, IL1B was readily produced ex vivo in colon tissue cultures derived from WT mice (Fig. 5A). In contrast, and not surprisingly, very little IL1B was produced by colonic explants from DSS-treated P2rx7−/− mice. In agreement with their lowered inflammatory response, we also observed significantly lower activation of STAT3 in P2RX7-deficient mice at day 14 after DSS treatment as compared with WT control mice (Fig. 5B).

We next evaluated how the lower P2RX7-dependent IL1B production influenced the composition of the inflammatory infiltrate in the colon of DSS-treated mice. For that, colon tissue sections from acute DSS-treated mice were stained for markers specific for T lymphocytes (CD3), Treg lymphocytes (FOXP3 [Foxp3]), macrophages [EMR1 (F4/80)], and neutrophils (LY6G). Colonic-lamina propria tissue sections from P2rx7−/− mice displayed statistically more CD3+ (9% vs. 3%), FOXP3+ (15% vs. 3%), and EMR1+ (F4/80) (16% vs. 5%) cells as compared with WT animals (Fig. 5C). In contrast, no difference between the two groups of mice was observed in regard to LY6G-positive cells. However, we noticed that colon tissue sections from both groups harbored a significantly high number of neutrophils (reaching 8% to 10% of total immune cells). This observation is particularly relevant to the field of IBD pathogenesis. Indeed, acute inflammatory lesions of patients with IBD are characterized by a large influx of neutrophils within the intestinal mucosa (23). Keeping in mind the recent concept of the role of neutrophils in tumor biology (24), we wondered whether the P2RX7 activity participated in the polarization of tumor-associated neutrophils (TAN). To assess this question, we analyzed the expression of genes encoding chemokines that have been used to distinguish TAN from other tumor-associated myeloid cells (25). As illustrated in Fig. 5D, the P2RX7 deficiency resulted in increased expression of the Ccl17 transcript and decreased expression of Cxcl10, a molecular profile that has been associated with genuine TAN (24, 25).

Enhanced production of TGFβ1 in the colonic mucosa of AOM/DSS-treated P2rx7−/− mice

TGFβ1 is frequently associated with poor prognosis in patients with cancer (26). This immunoregulatory cytokine can be produced by immune as well as tumor cells and has been implicated in the polarization of various immune cell subsets but also in the establishment of a suppressive microenvironment that favors tumor growth (27). The accumulation of immunosuppressive cells within the inflammatory lesions of mutant mice could
possibly be associated with the local production of TGFB1. Indeed, a 3-fold induction of TGFB1 production was observed in acute inflammatory of colon explant culture from P2rx7−/− versus WT mice (Fig. 6A). These results were confirmed at later time points, as P2rx7−/− mice subjected to the chronic AOM/DSS treatment displayed an overexpression of Tgfb1 and Tgfb2 transcripts, and their cultured explanted colonic tissue showed increased secretion of the TGFB1 cytokine (Fig. 6B).

As TGFB1 is known to promote the suppressive activity of FOXP3+ Tregs, we further characterized the composition of the cellular infiltrate in colon tissue biopsies from chronic AOM/DSS-treated mice. As described before for the inflammatory colonic mucosa, a significant increase in the content of FOXP3+ cells was observed within tumors derived from P2rx7−/− mice (Fig. 6C), whereas there was no difference in the numbers of macrophages (EMR1, F4/80+ cells) nor total T lymphocytes (CD3+ cells). As TGFB1 has been proposed to control differentiation of TAN in mice (24), we next investigated the presence of neutrophil infiltration in their colonic mucosa. We found an enrichment in the proportion of LY6G+ cells in P2rx7−/− mice (Fig. 6C), in agreement with the higher concentration of CXCL1 and CXCL2, two chemokines involved in neutrophil recruitment, in the serum of these animals (Supplementary Fig. S7A). Interestingly, neutrophil enrichment appeared to be restricted to colonic tumor tissues as analysis of bone marrow and spleen cells did not show any difference in the composition of immune cells (Supplementary Fig. S7B). Moreover, the cytokine profile observed in tumor lesions of P2rx7−/− mice is compatible with the molecular profile associated with genuine TAN (Supplementary Fig. S7C; ref. 25).

In addition to its immunosuppressive function, TGFB1 has been reported to increase proliferation of colonic epithelial cells (28). Therefore, overproduction of TGFB1 in inflammatory and tumor lesions of P2rx7−/− mice may account for the increased proliferation of epithelial cells observed in this strain (Fig. 3). To test this hypothesis, neutralizing anti-TGFB antibody was injected in AOM/DSS-treated P2rx7−/− mice. As shown in Fig. 7A, body weight and colon length were not significantly different in mice treated with isotype control or with the anti-TGFB antibodies. In contrast, the number of colonic epithelial cells positive for PCNA staining was reduced by 2-fold in mice that received the neutralizing anti-TGFB antibody (Fig. 7B). Indeed, while 35% ± 4% of intestinal epithelial cells were PCNA+ in mice treated with the isotype control antibody, only 15% ± 2% of cells were detected to be positive in mice treated with the neutralizing antibody, a level comparable to what was observed in WT mice (see Fig. 3).

Taken together, these results suggest that enhanced secretion of TGFB1 in P2RX7−/− favors the establishment of an immunosuppressive microenvironment and stimulates epithelial cell proliferation, thereby enhancing the development of colon cancer.

Discussion

P2RX7 is an ATP gated ion channel that can induce multiple cellular responses. In the early 1990s, studies demonstrated cell-permeabilizing and cytolytic effects of P2RX7 in response to high...
doses of eATP (29, 30). A few years later, it appeared that stimulation of P2RX7 by low doses of eATP enhanced proliferation of human primary cells (31). This observation was further confirmed in vitro using heterologous expression systems (32) as well as in vivo using xenograft tumor models (16). P2RX7 appeared to be overexpressed in a variety of malignant tumors (reviewed in ref. 33). However, P2RX7-dependent signaling could also favor an antitumor effect in vivo. Indeed, P2RX7 participates in inflammasome assembly and may thereby alert the immune system through processing and liberation of the proinflammatory IL1B cytokine (6). It has been demonstrated that P2RX7 plays a crucial role in the immunogenicity of dying tumor cells in response to chemotherapy (a process named immunogenic cell death) through the activation of dendritic cells and the consequent promotion of an adaptive antitumor immune response that prevents tumor relapse (18). Of particular interest, in sporadic breast cancer treated with anthracyclines, patients bearing loss-of-function alleles of P2RX7 (rs3751143, NM_002562.4:c.1487A>C) are more prone to develop metastases than patients without mutation. Such results fuel the hypothesis that P2RX7 plays an important role in the antitumor response.

In this study, we conducted experiments in the context of acute and chronic colitis with the aim of examining the global in vivo contribution of P2XR7 signaling to inflammation and cancer progression. Using a mouse model of acute AOM/DSS-induced colonic inflammation, we found that P2rx7−/− mice displayed reduced signs of inflammation. This finding is in agreement with recent studies demonstrating that prophylactic systemic blockade of the P2RX7 activity prevented TNBS-induced colitis in rats (12) and that overexpression of P2RX7 in the intestinal mucosa was associated with the pathogenesis of CD (34). In the current study, we found that P2RX7 inactivation using selective antagonists as well as genetic deletion of the P2rx7 gene attenuated the weight loss and the overall disease activity score (Fig. 1). However, whereas the histologic inflammatory score of DSS-treated animals was similar in both WT and P2rx7−/− mice at day 5 (i.e., at the end of treatment), the weight loss and the disease activity score were significantly lower in P2rx7−/− mice (Fig. 1A). These results suggest that P2RX7 plays a crucial role in the pathogenesis of colitis.

Figure 6. Increased expression of TGFβ1 in colon tumor biopsies from P2rx7−/− mice. A, cohorts of 8–10 WT and P2rx7−/− mice were treated for colitis. Secretion of TGFβ1 was assayed by ELISA on supernatants from organocultures. Data are expressed as mean ± SEM; *, P ≤ 0.05. B, Tgfb1 and Tgfb2 transcripts were analyzed by RT-qPCR and the levels of secreted TGFβ1 by ELISA from CAC-treated cohorts of 8–10 WT and P2rx7−/− mice. Data are expressed as mean ± SEM; *, P ≤ 0.05. B, the number of CD3-, FOXP3 (Foxp3), EMR1 (F4/80), and LY6G (Ly6G)-positive cells was determined. Arrows, positive cells. Data are presented as means ± SEM; *, P ≤ 0.05 (scale bar, 100 μm).
of DSS treatment), we paradoxically observed a faster re-epithelialization of the digestive mucosa of $P2rx7^{-/-}$ mice during the recovery phase (Fig. 2).

Considering that the faster recovery of $P2rx7^{-/-}$ mice correlated with enhanced epithelial cell proliferation, reduced apoptosis, and higher expression of BCL2L1 (Bcl-xL) and BCL2 survival factors (Fig. 3), our results support the notion that P2RX7 plays a role in the control of epithelial cell proliferation and/or apoptosis in response to injury. We indeed confirmed in vivo in $P2rx7^{-/-}$ mice as well as in WT mice treated with P2RX7 pharmacologic inhibitors, that P2RX7 inactivation increases epithelial cells proliferative index (Fig. 3 and Supplementary Fig. S3D). Concordantly, we confirmed in vitro using the human T84 epithelial cell line derived from a colon cancer that pharmacologic inhibition of P2RX7 significantly stimulates cell proliferation (Supplementary Fig. S3C). This results support the notion that P2RX7 activity directly inhibit epithelial cell proliferation. Whether immune cells, that we found to be recruited at higher level in P2RX7-inactivated mice (i.e., FOXP3$^+$ Tregs and LY6G$^+$ neutrophils) also contribute to the control of epithelial cell proliferation need to be further address in future studies.

Our finding, which demonstrated that a lack of P2RX7 is linked to increased epithelial cell proliferation, may explain, at least partly, the increased tumor burden observed in chronic AOM/DSS-treated $P2rx7^{-/-}$ mice (Fig. 4). Another nonexclusive mechanistic explanation may reside downstream of IL1B signaling. As expected, little if any IL1B was detected from the colonic mucosa of $P2rx7^{-/-}$ mice at early time points following AOM/DSS treatment (Fig. 5). This was associated with reduced STAT3 phosphorylation, which may indicate lower activation of immune cells and may favor the establishment of an immunosuppressive microenvironment prone to tumor development. However, downregulation of IL1B and STAT3 phosphorylation could not represent the sole mechanism as it has been reported that genetic inactivation of IL1BR or of STAT3 in the intestinal epithelial cell compartment (AIEC$^{Stat3}$ mice) decreased tumor development (35, 36). In addition, we found that FOXP3$^+$ Tregs, a cell population that has been associated with colon cancer progression (37), was
increased in the colonic mucosa of acute AOM/DSS-treated P2rx7−/− mice (Fig. 5C) in association with lower STAT3 phosphorylation (Fig. 5B) and higher TGFβ1 production (Fig. 6). Interestingly, we previously demonstrated that P2RX7 activation at the surface of Tregs inhibited their suppressive function and induced cell death (38, 39). Therefore, inactivation of P2RX7 should protect Tregs from the deleterious effect of endogenous P2RX7 ligands (i.e., eATP and NAD) and should promote their further participation in tumor promotion. In addition to its immunosuppressive role, TGFβ has been reported to enhance proliferation of epithelial cells (28). Concedantly, we show here that treatment of DSS-treated P2rx7−/− mice with an anti-TGFβ antibody significantly reduced the proliferation of colonic epithelial cells (Fig. 7B).

During the course of this study, we also observed the recruitment of LYG6+ neutrophils within tumor lesions of P2rx7−/− mice. These cells shared the characteristics of genuine TAN (Supplementary Fig. S7), a population of cell that has been recently associated to tumor progression (24). Therefore, we cannot exclude that TAN also participate in the reinforcement of the immunosuppressive environment in the colonic mucosa of AOM/DSS-treated P2rx7−/− mice and in the stimulation of tumor growth.

We demonstrate in our study that P2RX7 inactivation dampens inflammation but paradoxically enhances tumor susceptibility. Interestingly, we reproduced this finding in an independent tumor mouse model consisting of subcutaneous injection of LLC cells into C57BL/6 mice (Supplementary Fig. S6B). Several morphologies have been described for the P2RX7 gene and their impact on the P2RX7 function, the mechanisms and relationship with diseases were characterized for a number of mutants (45–47). Surprisingly, none of these variants were found in a meta-analysis of IBD (CD and UC) that included a Genome-Wide Association study (48). However, this analysis highlighted the importance of TGFβ signaling in IBD and reinforced the link with colorectal cancer. Furthermore, P2RX7 was reported to be over expressed in chronic B lymphocytic leukemia (19), prostate cancer and adjacent tissue (21), papillary thyroid carcinoma (49) and gastric, colon, kidney, and ovarian cancers (16). However, despite the large number of P2RX7 mutants and of P2RX7 variants, no attempts were made to characterize their functionality in tumor lesions, highlighting the need for additional studies to provide a better understanding of the role of P2RX7 in cancer onset.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors' Contributions
Conception and design: P. Hofman, X. Hébuterne, S. Adiouch, V. Vouret-Craviari
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