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The inflammatory network in the gastrointestinal tumor microenvironment:

Lessons from mouse models

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## **Abstract**

Accumulating evidence has indicated that inflammatory responses are important for cancer development. Epidemiological studies have shown that regular use of non-steroidal anti-inflammatory drugs (NSAIDs) reduces the risk of colon cancer development. Subsequently, mouse genetic studies have shown that COX-2, one of the target molecules of NSAIDs, and its downstream product, PGE<sub>2</sub>, play an important role in gastrointestinal tumorigenesis. Bacterial infection stimulates the TLR/MyD88 pathway in tumor tissues, which leads to induction of COX-2 in stromal cells, including macrophages. Induction of COX-2/PGE<sub>2</sub> pathway in tumor stroma is important for development and maintenance of an inflammatory microenvironment in the gastrointestinal tumors. In such a microenvironment, tumor-associated macrophages express proinflammatory cytokines, including TNF- $\alpha$  and IL-6, and these cytokines respectively activate the NF- $\kappa$ B and Stat3 transcription factors in epithelial cells, as well as in stromal cells. Recent mouse studies have uncovered the role of such inflammatory network for the promotion of gastrointestinal tumor development. Genetically engineered and chemically-induced mouse tumor models which mimic sporadic or inflammation-associated tumorigenesis were used in these studies. In this review article, we focus on mouse genetic studies using these tumor models, which contributed to elucidation of the molecular mechanisms associated with the inflammatory network in gastrointestinal tumors, and also discuss the role of each pathway in cancer development. The involvement of immune cells such as macrophages, mast cells and regulatory T cells in tumor promotion is also discussed.

## Introduction

About 150 years ago, Rudolf Virchow described the presence of leukocytes in tumors, and hypothesized that the origin of cancer was at the site of chronic inflammation. It has been reported that chronic infections are associated with 15-20% of malignant cancers [1, 2]. The principal infectious agents are *Helicobacter pylori*, hepatitis B and C viruses, and the human papilloma virus, which are closely associated with gastric cancer, hepatocellular carcinoma, and cervical cancer, respectively. Moreover, about 30% of all cancers have been attributed to smoking and 20% to obesity [3], and it has been shown that both tobacco smoke and obesity can trigger inflammatory responses in the lungs and liver, respectively, which promotes tumorigenesis [4, 5]. These results, together with those of other recent studies [reviewed in 6-8], indicate that inflammation plays an important role in promoting cancer development, and “tumor-promoting inflammation” is now included in the next generation of the criteria considered to be “hallmarks of cancer” [9].

Epidemiological studies have revealed that regular use of non-steroidal anti-inflammatory drugs (NSAIDs) lowers the mortality rate from cancers in the gastrointestinal tract [10, 11]. The target molecules of NSAIDs are cyclooxygenase (COX)-1 and COX-2, and accumulating evidence has indicated that COX-2 and its downstream product, prostaglandin E<sub>2</sub> (PGE<sub>2</sub>), play an important role in cancer development [12, 13]. On the other hand, proinflammatory cytokines are expressed in the tumor microenvironment, and such cytokine signaling is also important for cancer development through the activation of downstream transcription factors [6]. Among them, TNF- $\alpha$  and IL-6 activate NF- $\kappa$ B and Stat3, respectively, and both the TNF- $\alpha$ /NF- $\kappa$ B and

IL-6/Stat3 pathways have shown to be important for the development of inflammation-associated intestinal tumorigenesis [7, 8]. Moreover, NF- $\kappa$ B induces the expression of COX-2, IL-6 and TNF- $\alpha$ . Accordingly, these signaling pathways construct an inflammatory network in the tumor microenvironment, which plays an important role in tumor promotion (Fig. 1). In this review, we discuss the roles of these inflammatory pathways in gastrointestinal tumorigenesis, which have been identified by a number of mouse model studies as listed in Table 1.

### **Mouse models of gastrointestinal cancer**

The roles of inflammatory responses in gastrointestinal cancers have been studied using several tumor mouse models (Table 1). *Apc*<sup>A716</sup> knockout mice and *Apc*<sup>Min</sup> mice carry heterozygous truncation mutations at codon 716 and 850 of the mouse *Apc* gene, respectively, and somatic deletion of the wild-type *Apc* gene results in activation of Wnt/ $\beta$ -catenin signaling, which causes tumor development in the entire intestinal tract [14, 15]. Approximately 80% of colorectal cancers harbor *APC* gene mutations and half of the remainder have  $\beta$ -catenin mutation, both of which activate Wnt/ $\beta$ -catenin signaling [16-18]. Thus, *Apc*<sup>A716</sup> and *Apc*<sup>Min</sup> mice recapitulate the molecular mechanism of sporadic colon cancer development. Several other types of *Apc* mutant mice also develop intestinal polyposis (as described in this review and Table 1).

On the other hand, inflammatory bowel diseases (IBD), including ulcerative colitis (UC) and Crohn's disease (CD), are also risk factors for colorectal cancer [19, 20]. IBD-related colon cancers are associated with severe inflammatory response, which is

important microenvironment required for inflammation-associated tumor development. The treatment of mice with a genotoxic chemical carcinogen, azoxymethane (AOM), followed by a non-genotoxic agent, dextran sodium sulfate (DSS), induces development of colitis-associated colon cancer (CAC) [21]. Mutations in the  $\beta$ -catenin gene induced by AOM result in the activation of the Wnt/ $\beta$ -catenin pathway, which is thought to trigger tumor initiation [22]. On the other hand, DSS induces colonic inflammation in rodents, which is required for tumor promotion. Accordingly, the AOM/DSS model is a well-established and widely used mouse model for CAC development, and mimicks IBD-related colon cancer (Table 1). *Rag2* gene deficient mice lack functional lymphocytes, and are susceptible to infection-induced inflammation in the colon. When *Rag2*<sup>-/-</sup> mice are infected with the enteric bacterial pathogen, *Helicobacter hepaticus*, mice rapidly develop CAC [23, 24]. This model system is also used for IBD-related colon cancer (Table 1).

Activation of Wnt/ $\beta$ -catenin signaling is found in approximately 30-50% of gastric cancers, suggesting a causal role of Wnt signaling in a subpopulation of gastric cancers [25, 26]. On the other hand, *Helicobacter pylori* infection is an important risk factor for gastric cancer [27]. In *H. pylori*-associated gastritis, COX-2 expression is induced significantly, whereas its level decreases by *H. pylori* eradication [28, 29]. Two transgenic mouse strains, *K19-Wnt1* mice expressing Wnt1 in the stomach, and *K19-C2mE* mice expressing COX-2 and mPGES-1, mimic Wnt activation and *H. pylori*-induced inflammation, respectively, in the stomach [26, 29-31]. *Gan* mice are compound transgenic mice with *K19-Wnt1* and *K19-C2mE*, which express Wnt1, COX-2, and

mPGES-1 simultaneously in the gastric mucosa, resulting in activation of both Wnt signaling and the COX-2/PGE<sub>2</sub> pathways as found in human gastric cancer. *Gan* mice are thus used as a model of inflammation-associated gastric tumors [26, 30, 31] (Table 1).

### **The COX-2/PGE<sub>2</sub>/EP2 pathway in gastrointestinal tumorigenesis**

It has been demonstrated that treatment of familial adenomatous polyposis (FAP) patients with NSAIDs results in significant regression of colon polyps [32]. Moreover, a large number of animal experiments have shown that treatment with NSAIDs suppressed chemical carcinogen-induced colon tumorigenesis [33]. As a target molecule of NSAIDs, inducible enzyme COX-2 plays an important role in inflammation and cancer, while COX-1 is expressed constitutively and functions as a house-keeping gene. Importantly, disruption of the COX-2 gene in *Apc*<sup>A716</sup> mice and *Apc*<sup>Min</sup> mice resulted in a significant suppression of intestinal tumorigenesis, thus indicating an essential role of COX-2 in intestinal polyp development [34, 35]. Interestingly, disruption of the COX-1 gene also suppressed intestinal tumorigenesis [35]. It is possible that COX-1-derived prostaglandins are required for tumor cell proliferation during the initial stage when COX-2 expression is not yet induced [33]. Other lines of genetic evidence also support the role of the COX-2 pathway in intestinal tumorigenesis. Prostaglandins are catalyzed and inactivated by 15-hydroxyprostaglandin dehydrogenase (15-PGDH). The number of colon polyps in *Apc*<sup>Min</sup> mice was markedly increased when the 15-PGDH gene was disrupted, suggesting that PGE<sub>2</sub> has a role in colon tumorigenesis [36]. Moreover, the transgenic expression of COX-2 in the mouse intestine accelerated chemical carcinogen-induced tumorigenesis [37].

COX-2 catalyzes synthesis of prostaglandin (PG)H<sub>2</sub>, which is then converted to PGE<sub>2</sub>. There are four G protein-coupled receptors for PGE<sub>2</sub>; EP1, EP2, EP3, and EP4. Notably, disruption of the P2 gene caused significant suppression of intestinal polyposis in *Apc*<sup>A716</sup> mice, whereas suppression of EP1 or EP3 signaling did not affect tumorigenesis [38]. EP2 signaling increases the expression of VEGF and bFGF, which enhances angiogenesis in intestinal tumors [39]. Moreover, treatment of *Apc*<sup>Min</sup> mice with PGE<sub>2</sub> increased the development of intestinal tumors through activation of PPAR $\delta$ , which promotes survival of tumor cells [40]. Furthermore, PGE<sub>2</sub> signaling through EP2 receptor has been shown to activate Wnt/ $\beta$ -catenin signaling directly in colon cancer cells by suppression of  $\beta$ -catenin phosphorylation [41]. Accordingly, it is possible that the COX-2/PGE<sub>2</sub> pathway contributes to intestinal tumorigenesis through a variety of PGE<sub>2</sub> functions [12, 13] (Fig. 2).

Microsomal PGE synthase-1 (mPGES-1) is an enzyme that converts PGH<sub>2</sub> to PGE<sub>2</sub>, and expression of mPGES-1 is induced in gastric and colon cancers similar to COX-2 [42, 43]. Notably, disruption of the mPGES-1 genes in *Apc*<sup>A14</sup> mice or AOM-treated mice resulted in a marked decrease in the PGE<sub>2</sub> level in the intestinal mucosa, which led to a further significant suppression of intestinal tumorigenesis [44, 45]. Taken together, these results indicate that the simultaneous expression of COX-2 and mPGES-1 is required for intestinal tumorigenesis through the induction of PGE<sub>2</sub> signaling.

In gastric cancer tissues, induction of COX-2 is found in approximately 70% of cases [46, 47], and mPGES-1 expression is also induced [42], suggesting that the COX-2/PGE<sub>2</sub> pathway is also important for gastric tumorigenesis. In the *K19-C2mE*



transgenic mice, an increased PGE<sub>2</sub> level causes inflammatory infiltration and metaplastic hyperplasia in the gastric mucosa [29]. Although Wnt activation alone is not sufficient for tumor development in *K19-Wnt1* mice, *Gan* mice (compound mutants of *K19-Wnt1* and *K19-C2mE* mice) develop inflammation-associated gastric tumors with 100% incidence [26], indicating that cooperation of the Wnt and PGE<sub>2</sub> pathways can lead to gastric tumorigenesis. Moreover, gastric inflammation and tumorigenesis were significantly suppressed in *Gan* mice when the mice were treated with a COX-2 inhibitor, celecoxib, or an EP4 receptor inhibitor [48, 49]. These results indicate that induction of COX-2/PGE<sub>2</sub>/EP4-induced inflammation is involved in the development of gastric cancer. Signaling through EP2 and EP4 both stimulate intracellular cyclic AMP signaling pathway. It is therefore possible that either EP2 or EP4 receptor signaling plays an important role in gastrointestinal tumorigenesis (Fig. 1).

### **The TLR/MyD88 pathway for COX-2 induction in gastrointestinal tumors**

Expression of COX-2 and mPGES-1 is detected predominantly in stromal cells, including macrophages and fibroblasts, but not in the epithelial cells of mouse intestinal polyps, and the same is true for human colon polyps [36, 50-52]. Heterozygous mutations in the *Lkb1*, *Smad4*, or *Cdx2* gene lead to the development of gastrointestinal hamartomas, which show distinct histological characteristics from dysplastic adenomas developed in *Apc* mutant mice [52-55]. Notably, expression of COX-2 and mPGES-1 is detected in the stromal cells, but not in tumor epithelial cells, in these models [56], thus indicating that the COX-2/PGE<sub>2</sub> pathway is induced in the tumor stroma by a common mechanism, regardless

of the type of tumor.

Several studies have suggested the commensal flora to play a role in the homeostasis of the intestinal mucosa. Toll-like receptors (TLRs) are a family of pattern-recognition receptors that detect the molecular products of microorganisms. MyD88 is an adaptor molecule for TLR-mediated induction of inflammatory cytokines. It has been shown that a disruption of the TLR2/4 or MyD88 genes in mice results in impaired mucosal repair from DSS-induced ulcers [57], suggesting that infectious stimulation through the TLR/MyD88 pathway is important for the regeneration process of injured mucosa. Moreover, stromal macrophages are also required for mucosal repair of DSS-induced ulcers in the colon [58]. Accordingly, it is possible that stromal macrophages are activated by the TLR/MyD88 pathway. In the case of intestinal tumorigenesis, cancer cells may use such a TLR/MyD88-induced regeneration system to increase their proliferation.

The treatment of mice with DSS induces COX-2 expression and PGE<sub>2</sub> production, predominantly in macrophages of the inflamed colon mucosa. However, such COX-2 induction is not found in the mice lacking the TLR4/MyD88 pathway [59], thus indicating the role of bacterial infection in inducing COX-2 expression in colitis tissues. Importantly, AOM/DSS treatment-induced colon tumor development was dramatically suppressed in TLR4<sup>-/-</sup> mice [60], while exogenous administration of PGE<sub>2</sub> promoted CAC development in the AOM/DSS-treated TLR4<sup>-/-</sup> mice [61]. Moreover, bone marrow chimera experiments indicated that TLR4 expression in the intestinal epithelial cells, but not in myeloid cells, is required for CAC development [62]. Taken together, these results

suggest that bacterial infection stimulates the TLR/MyD88 pathway in epithelial cells, which leads to activation of stromal macrophages, thus resulting in the induction of the COX-2/PGE<sub>2</sub> pathway in the tumor stroma (Fig. 2).

In contrast to the AOM/DSS model, ulcerative colitis is not associated with intestinal polyposis in the *Apc* mutant mice. It is therefore possible that COX-2 expression is induced by a different mechanism in sporadic colon cancer compared to IBD-related tumors. However, *Apc*<sup>Min</sup> MyD88<sup>-/-</sup> mice showed significant suppression of intestinal polyposis with dramatically decreased mortality compared with control *Apc*<sup>Min</sup> MyD88<sup>+/+</sup> mice [63, 64]. Moreover, induction of COX-2 expression was also suppressed in *Apc*<sup>Min</sup> MyD88<sup>-/-</sup> mouse intestinal tumors [63]. Bone marrow chimera experiments also indicated that MyD88 expression in the epithelial cells was important for intestinal tumorigenesis [64]. These results demonstrated that activation of the TLR/MyD88 pathway in epithelial cells is also important for COX-2 expression in non-IBD colon cancer (Fig. 2).

If bacterial infection is also required for COX-2 induction in the stomach, a low bacterial count due to the acidic environment in the stomach may protect against COX-2 expression in tumorous lesions. Therefore, it is possible that COX-2 induction through the TLR/MyD88 pathway is one of the mechanisms by which *Helicobacter pylori* infection promotes gastric cancer.

It has also been shown that TLRs can be stimulated with endogenous ligands, including heat shock proteins and various products of the extracellular matrix [65]. Accordingly, it is possible that tumor cell proliferation causes tissue damage, releasing

endogenous ligands for TLRs, thus resulting in their activation, which induces COX-2 expression in stromal macrophages. Such “cancer-induced inflammation” may be one of the mechanisms responsible for the generation of an inflammatory microenvironment, especially in cancers that are not associated with infection [65].

### **The paradox of the COX-2 pathway in colitis-associated cancer**

Although COX-2 inhibition causes suppression of gastrointestinal tumorigenesis, treatment with NSAIDs or a COX-2 inhibitor exacerbates DSS-induced colon injury in rodent models [66]. Consistently, COX-2 gene knockout mice exposed to DSS showed exacerbated phenotypes, such as more severe inflammation, compared with wild-type mice [67]. One of the functions of PGE<sub>2</sub> is to protect the gastrointestinal mucosa. Therefore, COX-2 is important for mucosal protection and regeneration in the DSS-treated mouse colon. Notably, treatment of COX-2 gene knockout mice with AOM/DSS resulted in a significant increase in tumors, with severe inflammatory responses [68, 69], which appears to be contradictory to the results showing that COX-2 gene disruption causes significant suppression of intestinal polyposis in *Apc* mutant mice [34, 35]. It is possible that in the case of severe ulcerative colitis, cytokine signaling is highly activated and may be sufficient for tumor promotion if the COX-2/PGE<sub>2</sub> pathway is blocked (Fig. 2).

### **The TNF- $\alpha$ /NF- $\kappa$ B pathway in gastrointestinal tumorigenesis**

TNF- $\alpha$  is one of key regulators of inflammatory responses. Although TNF was originally recognized as a tumor-necrotizing factor, accumulating evidence has indicated

that TNF- $\alpha$  has tumor-promoting functions [70]. TNF- $\alpha$  signaling activates NF- $\kappa$ B, which further induces expression of inflammatory factors including COX-2, IL-6, IL-8 and TNF- $\alpha$  itself (Fig. 1). Several genetic studies have demonstrated a link between the TNF- $\alpha$ /NF- $\kappa$ B pathway and cancer development [71].

Conditional disruption of the IKK $\beta$  gene in myeloid cells, which results in specific inhibition of NF- $\kappa$ B, caused significant suppression of the tumor incidence in AOM/DSS-treated mice, and was associated with decreased expression of cytokines and COX-2 [72]. Conditional deletion of IKK $\beta$  in epithelial cells also suppressed AOM/DSS-induced tumorigenesis [72]. Similar results were found in TNF- $\alpha$  receptor gene knockout mice. [73]. AOM/DSS treatment in mice lacking the TNF receptor p55 (TNF-Rp55) gene resulted in attenuated tumor formation, with reduced inflammatory cell infiltration compared with wild-type mice. Moreover, wild-type mice transplanted with TNF-Rp55-deficient bone marrow developed significantly fewer tumors after AOM/DSS treatment [73], indicating that TNF- $\alpha$  stimulation of myeloid cells is important for tumorigenesis. Accordingly, it is possible that the TNF- $\alpha$ -induced NF- $\kappa$ B activation in myeloid cells is important for CAC development, and NF- $\kappa$ B activation in epithelial cells also contributes to tumor formation (Fig. 2).

It has also been shown that a disruption of a CCL2-specific receptor, CCR2, led to significantly decreased macrophage infiltration and lower tumor numbers when mice were treated with AOM/DSS [74]. CCL2 is a chemokine that is chemotactic for monocytes and macrophages [75]. Taken together, these findings indicate that the activation of NF- $\kappa$ B in activated macrophages by TNF- $\alpha$  in an autocrine or paracrine manner is important for

promotion of intestinal tumorigenesis (Fig. 2). The inhibition of TNF- $\alpha$  in *Apc* mutant mice by treatment with an anti-TNF- $\alpha$  antibody also suppressed intestinal polyposis, with the suppression of angiogenesis [76]. Accordingly, it is possible that TNF- $\alpha$ /NF- $\kappa$ B activation is important in both IBD-related and sporadic colon carcinogenesis.

An important role for the TNF- $\alpha$ /NF- $\kappa$ B pathway was also discovered in *Mdr2* knockout mice that develop inflammation-associated hepatocellular carcinoma (HCC) [77]. In this mouse model, NF- $\kappa$ B is activated in the liver by TNF- $\alpha$  signaling, and inhibition of NF- $\kappa$ B significantly suppressed development of HCC after 7 months of age [77]. On the other hand, preneoplastic dysplastic lesions in younger mice were not affected by NF- $\kappa$ B inhibition. It is possible that the TNF- $\alpha$ /NF- $\kappa$ B pathway is not required for the initiation step, but it does play a role in the promotion step of HCC development.

The role of the TNF- $\alpha$ /NF- $\kappa$ B in gastric tumorigenesis in *Gan* mice has not yet been examined. However, TNF- $\alpha$  *-/-* *K19-C2mE* mice showed significant suppression of gastritis and hyperplasia compared with control *K19-C2mE* mice, although the COX-2/PGE<sub>2</sub> pathway was still activated by transgenic expression of COX-2 and mPGES-1 [78]. It is thus conceivable that the TNF- $\alpha$ /NF- $\kappa$ B pathway is activated in PGE<sub>2</sub>-associated gastritis, and that this contributes to inflammation-associated gastric tumorigenesis.

### **The IL-6/gp130/Stat3 pathway in gastrointestinal tumorigenesis**

One of the NF- $\kappa$ B-inducible cytokines is IL-6, which is important for immune responses, cell survival, apoptosis, and proliferation [79]. The expression of IL-6 is often

upregulated in tumor tissues and the serum of human and mice with cancers, including colon cancer [80]. The IL-6 cytokine family signals through a common receptor, gp130, which activates Stat3 (Fig. 1). Stat3 plays an important role in development of a variety of cancers, including CAC [81-84]. AOM/DSS-induced CAC development was significantly suppressed in IL-6<sup>-/-</sup> mice and also in conditional Stat3 knockout mice that lacked Stat3 in the intestinal epithelial cells through suppression of survival and proliferation [81, 82]. On the other hand, the number and size of AOM/DSS-induced colon tumors increased significantly in gp130<sup>757F/F</sup> mice, in which gp130-dependent Stat signaling is constitutively activated [81]. These results indicate that Stat3 activated in epithelial cells plays an important role in promotion of intestinal tumorigenesis (Fig. 2).

It has been shown that gp130<sup>757F/F</sup> mice develop gastric tumors with abundant infiltration of inflammatory cells [85]. Moreover, heterozygous mutations of the Stat3 gene in gp130<sup>757F/F</sup> mice reduced the incidence and multiplicity of gastric tumors, with suppression of inflammatory responses [86, 87]. These results indicate that Stat3 is also an important tumor-promoting factor in gastric tumorigenesis, and that it is activated by the inflammatory network of the tumor microenvironment. TGF- $\beta$  signaling promotes epithelial differentiation, and thus, suppression of the TGF- $\beta$  signaling pathway has been thought to promote gastrointestinal tumorigenesis. Notably, activation of Stat3 in gp130<sup>757F/F</sup> cells desensitizes to TGF- $\beta$  by inducing inhibitory Smad7. This may be one of the mechanisms by which Stat3 promotes tumor formation [86]. IL-11 is another member of the IL-6 family cytokine and also signals through gp130. Interestingly, disruption of the IL-11 co-receptor in gp130<sup>757F/F</sup> mice significantly ablated gastric tumorigenesis [88].

Because IL-11 is upregulated in human and mouse gastric tumors, these results suggest that the IL-11/Stat3 pathway, together with IL-6/Stat3, promotes gastric tumorigenesis.

### **Inflammatory cells that promote or suppress tumorigenesis**

The major source of inflammatory cytokines and prostaglandins in tumor tissues is the macrophages. Tumor-associated macrophages (TAMs) have been shown to promote the progression and metastasis of cancer [89]. TAMs can be classified into several distinct groups by their functions, such as inducing inflammation, invasion, angiogenesis, or metastasis. Macrophages are polarized to either the classical M1 type or the alternative M2 type, and it has been suggested that TAMs are polarized to M2 or M2-like types [90]. It has been shown that CD4<sup>+</sup> T cells regulate the polarization of macrophages to the M2 type in mammary tumors [91]. It has recently been shown that COX-2 is important for the M2-polarization of TAMs in *Apc<sup>Min</sup>* mouse tumors [92]. Accordingly, it is possible that the COX-2/PGE<sub>2</sub> pathway-induced inflammatory network is important for education of macrophages into the pro-tumorigenic M2 or M2-like types. Importantly, depletion of functional macrophages in *Apc<sup>Δ716</sup>* mice by crossing them with *op/op* mutant mice resulted in significant suppression of intestinal polyposis [93]. Moreover, inhibition of macrophage recruitment in AOM/DSS-treated mice by *CCL2* gene disruption resulted in suppression of colon tumor development [74]. Accordingly, macrophages play an important role for both sporadic and IBD-related intestinal tumorigenesis (Fig. 2). In *Gan* mouse gastric tumors, macrophage depletion caused atrophic changes of the tumor cells and apoptosis of stromal cells, suggesting a role for macrophages in the maintenance of



tumor cells, as well as of tumor stromal cells [49].

In the *Apc*<sup>A468</sup> mouse intestinal tumors, mast cells are preferentially enriched in the polyp tissues, and these mast cells express TNF- $\alpha$  [76]. Notably, the depletion of mast cells in *Apc*<sup>A468</sup> mice by bone marrow transplantation from *Kit*<sup>Wsh/Wsh</sup> mice caused significant suppression of intestinal polyposis, with a decreased level of TNF- $\alpha$  expression. It is therefore possible that both macrophages and mast cells are important components of the inflammatory network in the tumor microenvironment.

Bone marrow transplantation from *Rag2*<sup>-/-</sup> mice did not affect the intestinal tumorigenesis in *Apc*<sup>A468</sup> mice [76]. Consistently, the gastritis phenotype was not altered in the *K19-C2mE Rag2*<sup>-/-</sup> mouse stomach [78]. These results indicate that lymphocytes are not required for construction of the inflammatory network and the promotion of tumorigenesis in the gastrointestinal tract. Importantly, however, the adoptive transfer of CD4<sup>+</sup> CD25<sup>+</sup> regulatory T cells to *Apc*<sup>Min</sup> mice dramatically reduced the number of intestinal polyps, with induction of necrosis of tumor cells [94, 95]. Moreover, such regression of intestinal polyps was not found when CD4<sup>+</sup> CD25<sup>+</sup> cells were prepared from IL-10 <sup>-/-</sup> mice.

The transfer of CD4<sup>+</sup> CD25<sup>+</sup> T cells to *Helicobacter hepaticus*-infected *Rag2*<sup>-/-</sup> mice, another IBD-related colon cancer model, resulted in suppression of colitis and tumor development, but IL-10-disrupted CD4<sup>+</sup> CD25<sup>+</sup> T cells could not suppress the development of CAC [23, 24]. IL-10 suppresses inflammatory responses, thus indicating that regulatory T cells expressing IL-10 suppress intestinal tumorigenesis by inhibiting the formation of the inflammatory network. Although CD25<sup>+</sup> Foxp3<sup>+</sup> T cells are found in

*Apc<sup>Min</sup>* mouse polyp stroma, they no longer express IL-10, and instead switch to the production of IL-17 [95]. It is therefore possible that anti-inflammatory regulatory T cells (Foxp3<sup>+</sup> IL-10<sup>+</sup> IL-17<sup>-</sup>) shift to pro-inflammatory T cells (Foxp3<sup>+</sup> IL-10<sup>-</sup> IL-17<sup>+</sup>) in polyp tissues [96]. Moreover, ablation of IL-17A in *Apc<sup>Min</sup>* mice significantly suppressed the development of intestinal polyps and inflammatory cytokine expression, indicating that T-cell-derived IL-17 plays an important role in intestinal tumorigenesis [97].

### **Concluding remarks**

The development of the inflammatory network in tumor tissues and its possible roles are summarized in Figure 2. Chronic infection or endogenous ligands derived from tumor cells stimulate the TLRs of epithelial cells, leading to the activation of MyD88. The activation of the epithelial TLR/MyD88 pathway further induces COX-2 expression and PGE<sub>2</sub> production in stromal macrophages through the TNF- $\alpha$ /NF- $\kappa$ B pathway. Epidemiological studies and genetic experiments have demonstrated that COX-2 and its downstream product, PGE<sub>2</sub>, play an important role in gastrointestinal tumorigenesis. NF- $\kappa$ B is activated by TNF- $\alpha$  in tumor-associated macrophages, which further induces the expression of TNF- $\alpha$ , IL-6 and COX-2. TNF- $\alpha$  in turn stimulates both tumor epithelial cells and stromal cells, activating NF- $\kappa$ B in these cells, which promotes tumorigenesis. On the other hand, IL-6 activates Stat3 through gp130 in epithelial cells, thus leading to an increase in cell cycling and a decrease of apoptosis. The induction of the COX-2/PGE<sub>2</sub> pathway is important for the development of such an inflammatory tumor microenvironment. When the TNF- $\alpha$ /NF- $\kappa$ B and/or IL-6/Stat3 pathways are activated

beyond a threshold, they can promote tumorigenesis without the support of the COX-2/PGE<sub>2</sub> pathway. In the inflammatory microenvironment, not only TAMs, but also mast cells and IL-17-expressing T cells, infiltrate and contribute to tumor development. Therefore, targeting the inflammatory network in tumor tissues by inhibition of PGE<sub>2</sub>, NF-κB, Stat3 or downstream pathways may provide an effective preventive or therapeutic strategy against gastrointestinal cancer.

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### **Conflict of interest**

The authors declare that they have no conflict of interest.

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## Figure Legends

**Figure 1.** The interaction of the COX-2/PGE<sub>2</sub>, TNF- $\alpha$ /NF- $\kappa$ B, and IL-6/gp130/Stat3 pathways in the inflammatory environment.

**Figure 2.** A schematic diagram of the inflammatory microenvironment in gastrointestinal tumor tissues. Bacterial infection or endogenous ligand activates the TLR/MyD88 pathway in epithelial cells, which further activate stromal macrophages inducing CCL2. In the activated macrophages, NF- $\kappa$ B induces expression of COX-2, IL-6 and TNF- $\alpha$  itself. COX-2/PGE<sub>2</sub> pathway is important for construction and maintenance of the inflammatory network, and PGE<sub>2</sub> accelerates angiogenesis, cell survival and Wnt activation. TNF- $\alpha$  activates NF- $\kappa$ B in both epithelial cells and stromal macrophages, whereas IL-6 activates Stat3 in epithelial cells through gp130. NF- $\kappa$ B and Stat3 play important role in promotion of tumorigenesis through suppression of apoptosis and acceleration of cell cycle.



Figure 1

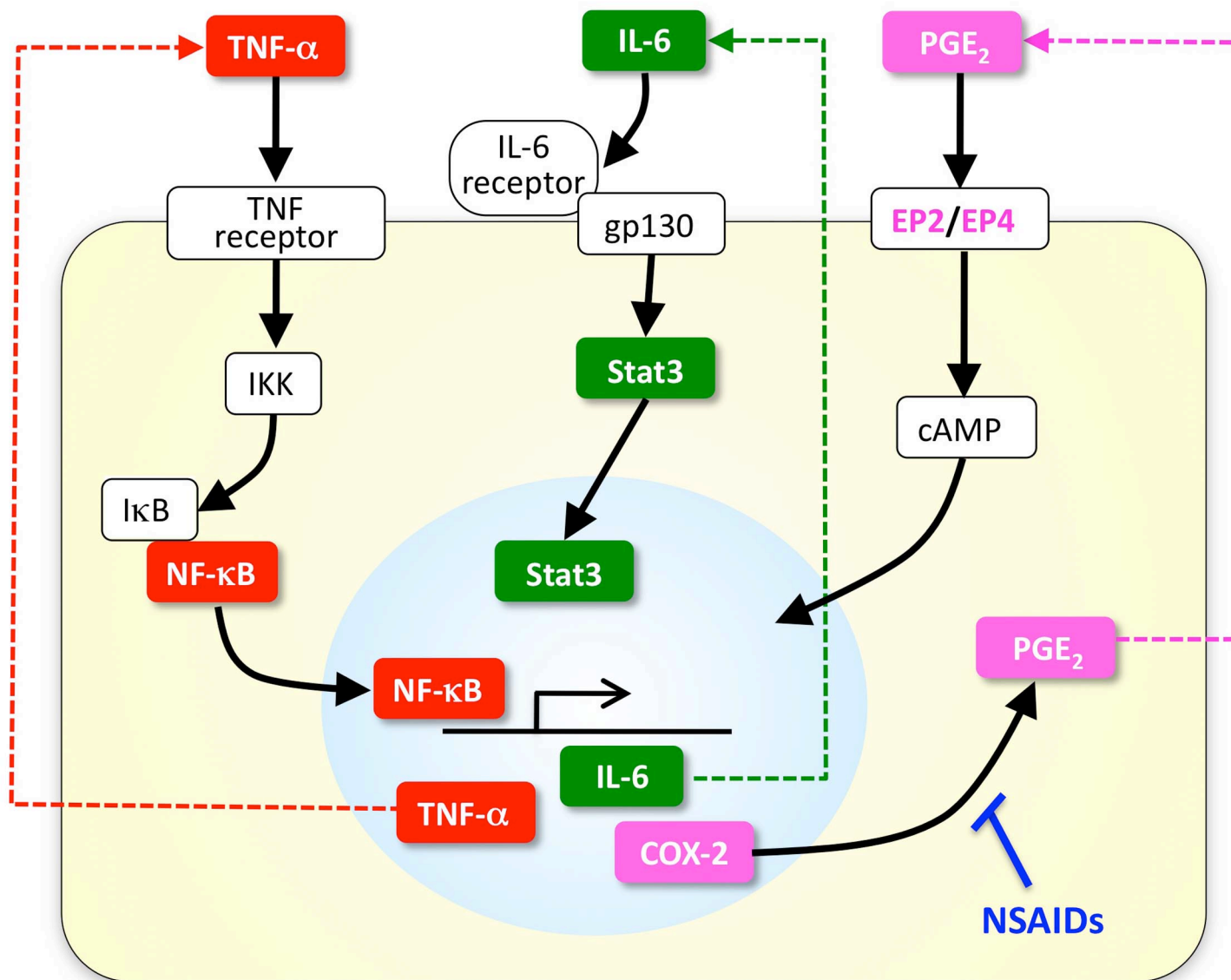


Figure 2

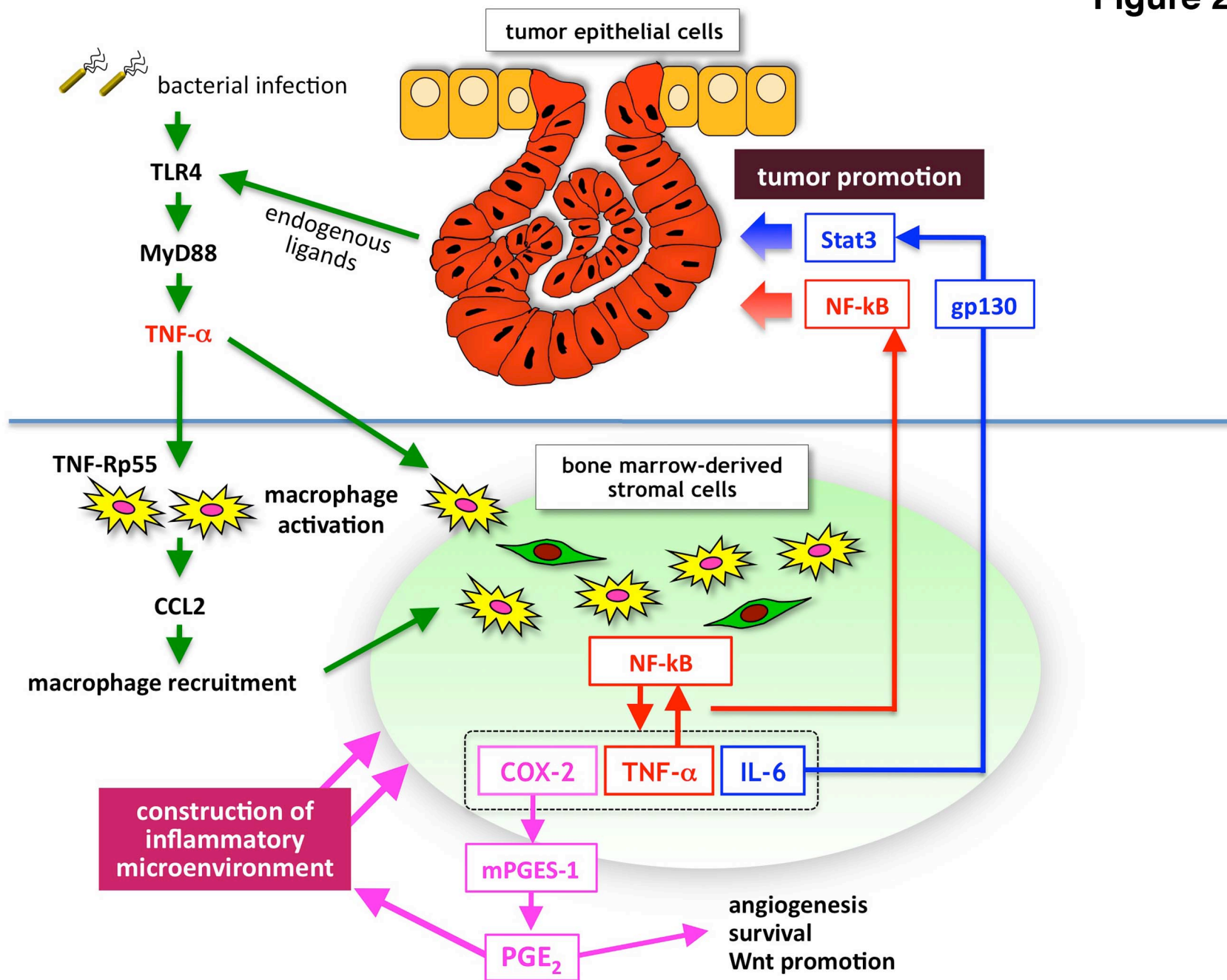


Table 1. Mouse model studies to examine inflammatory network in gastrointestinal tumorigenesis

tumor model	mouse line crossed / treatment	tumor phenotype changes	references
<b>sporadic intestinal tumor model (<i>Apc</i> mutant mice)</b>			
<i>Apc</i> <sup>Δ716</sup>	<i>Ptgs2</i> <sup>a</sup> knockout mice	suppression of intestinal polyposis	34
<i>Apc</i> <sup>Min</sup>	<i>Ptgs1</i> <sup>b</sup> , <i>Ptgs2</i> knockout mice	suppression of intestinal polyposis	35
<i>Apc</i> <sup>Min</sup>	<i>Hpgd</i> <sup>c</sup> knockout mice	increase of colon polyps	36
AOM	<i>Ptgs2</i> transgenic mice	increase of intestinal tumor	37
<i>Apc</i> <sup>Δ716</sup>	<i>Ptger2</i> <sup>d</sup> knockout mice	suppression of intestinal polyposis	38
		-inhibition of angiogenesis	39
<i>Apc</i> <sup>Min</sup>	PGE <sub>2</sub> treatment	promotion of intestinal polyposis	40
<i>Apc</i> <sup>Δ14</sup>	<i>Ptgs</i> <sup>e</sup> knockout mice	suppression of intestinal polyposis	44
AOM	<i>Ptgs</i> knockout mice	suppression of intestinal polyposis	45
<i>Apc</i> <sup>Min</sup>	<i>Myd88</i> <sup>f</sup> knockout mice	suppression of intestinal polyposis	63, 64
		-Epithelial expression of MyD88 is important.	
<i>Apc</i> <sup>Δ716</sup>	<i>op/op</i> (macrophage deficient)	suppression of intestinal polyposis	93
<i>Apc</i> <sup>Δ468</sup>	<i>Kit</i> <sup>W/W</sup> (mast cell deficient)	suppression of intestinal polyposis	76
<i>Apc</i> <sup>Δ468</sup>	<i>Rag2</i> <sup>-/-</sup> (lymphocytes deficient)	Not affected	76
<i>Apc</i> <sup>Δ468</sup>	anti-TNF-α antibody	suppression of intestinal polyposis	76
<i>Apc</i> <sup>Min</sup>	CD4 <sup>+</sup> CD25 <sup>+</sup> T cell transfer	suppression of intestinal polyposis	94, 95
		-IL-10 expression in T cells is required.	
<i>Apc</i> <sup>Min</sup>	<i>Il17a</i> <sup>g</sup> knockout mice	suppression of intestinal polyposis	97
<b>inflammation-associated colon tumor model (AOM/DSS-CAC model mice)</b>			
AOM/DSS	<i>Tlr4</i> <sup>h</sup> knockout mice	suppression of CAC development	60, 62
		-Epithelial expression of TLR4 is important.	
AOM/DSS	<i>Ptgs2</i> knockout mice	exacerbation of CAC development	68, 69
AOM/DSS	<i>Ikkb</i> <sup>i</sup> conditional KO	suppression of CAC development	72
		-Epithelial and myeloid expression is important.	
AOM/DSS	<i>Tnfrsf1a</i> <sup>j</sup> knockout mice	suppression of CAC development	73
		-Myeloid expression of TNF-Rp55 is important.	
AOM/DSS	<i>Ccr2</i> <sup>k</sup> knockout mice	suppression of CAC development	74
		-Less macrophage infiltration	
AOM/DSS	<i>Il6</i> <sup>l</sup> knockout mice	suppression of CAC development	82
AOM/DSS	gp130 <sup>757E/F</sup>	suppression of CAC development	81
AOM/DSS	<i>Stat3</i> conditional KO	suppression of CAC development	81, 82
		-Epithelial expression of Stat3 is important.	
<i>H. hepaticus</i> -infected <i>Rag2</i> <sup>-/-</sup>	CD4 <sup>+</sup> CD25 <sup>+</sup> T cell transfer	suppression of CAC development	23, 24
		-IL-10 expression in T cells is required.	
<b>gastritis and gastric tumor model</b>			
<i>K19-Wnt1</i>	<i>K19-C2mE</i>	gastric tumor development ( <i>Gan</i> mice)	26, 30, 31
<i>Gan</i>	celecoxib, EP4 inhibitor	suppression of gastric tumorigenesis	48, 49
<i>Gan</i>	clodronate liposome (macrophage deficient)	atrophic changes of tumor cells	49
<i>K19-C2mE</i>	<i>Tnf</i> <sup>m</sup> knockout mice	suppression of gastritis/hyperplasia	78
<i>K19-C2mE</i>	<i>Rag2</i> knockout mice	Not affected	78
gp130 <sup>757E/F</sup>	<i>Il11ra</i> <sup>n</sup> knockout mice	suppression of gastric tumorigenesis	88

gene symbols uses are: <sup>a</sup>COX-2, <sup>b</sup>COX-1, <sup>c</sup>15-PGDH, <sup>d</sup>PGE<sub>2</sub> receptor EP2, <sup>e</sup>mPGES-1, <sup>f</sup>MyD88, <sup>g</sup>IL-17A, <sup>h</sup>TLR-4, <sup>i</sup>IKKβ, <sup>j</sup>TNF-Rp55, <sup>k</sup>CCR2, <sup>l</sup>IL-6, <sup>m</sup>TNF-α, and <sup>n</sup>IL-11 receptor-α.