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Activation of epidermal growth factor receptor signaling by the prostaglandin E_2 receptor EP4 pathway during gastric tumorigenesis

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Cyclooxygenase-2 (COX-2) plays an important role in tumorigenesis through prostaglandin E_2 (PGE_2) biosynthesis. It has been shown by *in vitro* studies that PGE_2 signaling transactivates epidermal growth factor receptor (EGFR) through an intracellular mechanism. However, the mechanisms underlying PGE_2-induced EGFR activation in *in vivo* tumors are still not fully understood. We previously constructed transgenic mice that develop gastric tumors caused by oncogenic activation and PGE_2 pathway induction. Importantly, expression of EGFR ligands, epiregulin, amphiregulin, heparin-binding EGF-like growth factor, and betacellulin, as well as a disintegrin and metalloproteinases (ADAMs), ADAM8, ADAM9, ADAM10, and ADAM17 were significantly increased in the mouse gastric tumors in a PGE_2 pathway-dependent manner. These ADAMs can activate EGFR by ectodomain shedding of EGFR ligands. Notably, the extensive induction of EGFR ligands and ADAMs was suppressed by inhibition of the PGE_2 receptor EP4. Moreover, EP4 signaling induced expression of amphiregulin and epiregulin in activated macrophages, whereas EP4 pathway was required for basal expression of epiregulin in gastric epithelial cells. In contrast, ADAMs were not induced directly by PGE_2 in these cells, suggesting indirect mechanism possibly through PGE_2-associated inflammatory responses. These results suggest that PGE_2 signaling through EP4 activates EGFR in gastric tumors through global induction of EGFR ligands and ADAMs in several cell types either by direct or indirect mechanism. Importantly, gastric tumorigenesis of the transgenic mice was significantly suppressed by combination treatment with EGFR and COX-2 inhibitors. Therefore, it is possible that inhibition of both COX-2/PGE_2 and EGFR pathways represents an effective strategy for preventing gastric cancer. (*Cancer Sci* 2011; 102: 713–719)

It has been established that induction of cyclooxygenase 2 (COX-2) plays an important role in cancer development.[1,2] Genetic mouse model studies indicated that prostaglandin E_2 (PGE_2), a downstream products of COX-2, plays a key role in intestinal tumorigenesis,[3–5] suggesting that the PGE_2 pathway is a possible target for the chemoprevention. On the other hand, epidermal growth factor receptor (EGFR) signaling is also an important target for cancer prevention.[6] Inhibition of EGFR signaling in Apc^{Min} mice, a model of familial adenomatous polyposis, significantly suppresses intestinal polyposis.[7–9] Importantly, combination treatment using an EGFR inhibitor with non-steroidal anti-inflammatory drugs or a COX-2 inhibitor dramatically suppresses intestinal tumorigenesis.[8,9] It has been shown by *in vitro* experiments that PGE_2 signaling transactivates EGFR through activation of cSrc[10,11] or MMPs[12], as well as induction of amphiregulin, an EGFR ligand[13,14] or tumor necrosis factor-α converting enzyme/a disintegrin and metalloproteinase 17 (TACE/ADAM17), a shedding enzyme for amphiregulin.[15] However, the mechanism responsible for the activation of EGFR by the PGE_2 pathway in *in vivo* tumors has not been fully elucidated. Induction of the PGE_2 pathway in the gastric mucosa causes development of inflammatory microenvironment consisting of macrophages and myofibroblasts.[16,17] It is therefore possible that PGE_2 signaling in such microenvironment contributes to EGFR activation in tumors, and that PGE_2-associated inflammatory responses are also involved in EGFR activation.

Gastric cancer is one of the most frequently diagnosed and lethal malignancies worldwide, with a 5-year survival of only about 20%.[18] COX-2 expression is induced in more than 70% of gastric cancers,[19] and regular use of non-steroidal anti-inflammatory drugs decreases the risk of gastric cancer,[20] suggesting a role of COX-2 pathway in gastric tumorigenesis. In addition to COX-2, activation of Wnt signaling is found in 30–50% of gastric cancers.[21,22] Based on these results, we constructed *K19-Wnt1/C2mE* transgenic mice expressing *Wnt1*, *Ptgs2*, and *Ptges* encoding Wnt1, COX-2, and microsomal prostaglandin E synthase-1, respectively, in gastric mucosa.[22] *K19-Wnt1/C2mE* mice (*Gan* mice for gastric neoplasia) develop gastric tumors caused by the simultaneous activation of Wnt and PGE_2 pathways, although Wnt activation alone results in the development of only small dysplastic lesions. Gene expression profiles of *Gan* mouse tumors were similar to those of human intestinal-type gastric cancer.[23] We also constructed *K19-Nog/C2mE* transgenic mice that express *Nog* encoding noggin, together with *Ptgs2* and *Ptges*.[24] Noggin is an endogenous antagonist for bone morphogenetic protein signaling. *K19-Nog/C2mE* mice develop gastric hamartomas, although *Nog* expression alone does not cause any morphological changes. These results indicate that induction of the PGE_2 pathway plays a key role in the promotion of gastric tumorigenesis, regardless of the types of underlying oncogenic pathway such as Wnt activation or bone morphogenetic protein suppression.[25]

Using these mouse models, we have investigated the mechanism of EGFR activation by the PGE_2 pathway in gastric tumorigenesis. We also examined the role of EGFR signaling in the *in vivo* tumor development by drug dosing experiments.

Materials and Methods

Mouse models. Construction of *K19-Wnt1*, *K19-C2mE*, *K19-Nog*, *K19-Wnt1/C2mE* (*Gan*), and *K19-Nog/C2mE* mice was described previously.[25] Briefly, both *Ptgs2* and *Ptges* are expressed in the *K19-C2mE* mouse stomach, whereas *Wnt1* and *Nog* are expressed in *K19-Wnt1* and *K19-Nog* mice, respectively. Expression of these genes is regulated by the *Krt19* gene promoter that is transcriptionally active in gastric epithelial cells. *Gan* mice and *K19-Nog/C2mE* mice were obtained by

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Table 1. Transgenic mouse models and their gastric phenotypes

Transgenic mice	Transgenes	Affected pathway(s)	Gastric phenotype (reference)
K19-C2mE	*Ptgs2, Ptges*	PGE_2 induction	Inflammation, hyperplasia[16,25]
K19-Wnt1	*Wnt1*	Wnt activation	Small dysplastic lesion[22,25]
K19-Nog	*Nog*	BMP suppression	No phenotype[24,25]
K19-Wnt1/C2mE (*Gan*)	*Wnt1, Ptgs2, Ptges*	Wnt activation/PGE_2 induction	Dysplastic tumor[22,25]
K19-Nog/C2mE	*Nog, Ptgs2, Ptges*	BMP suppression/PGE_2 induction	Hamartoma[24,25]

BMP, bone morphogenetic protein.

crossing *K19-C2mE* with *K19-Wnt1* or *K19-Nog*, respectively (Table 1). All animal experiments were carried out according to a protocol approved by the Committee on Animal Experimentation of Kanazawa University.

Microarray analyses. We have deposited the results of microarray data sets from a series of mouse models to the Gene Expression Omnibus, as accession GSE16902.[23] Expression profiles of EGFR ligands, EGFR family members, and ADAM family proteases were extracted from the data sets, and the expression levels were compared by using absolute values.

Drug administration. For inhibition of COX-2, mice were fed a diet containing celecoxib (Pfizer New York, NY, USA) at 1500 ppm. For inhibition of EGFR or EP4 receptor, mice were administered orally with ZD1839 (Astra Zeneca, London, UK) or RQ00015986/CJ-42794[26] (RaQualia, Taketoyo, Japan), respectively, at 100 mg/kg/day in 0.5% methylcellulose. Drug-dosing experiments using *Gan* mice were performed for 3 weeks from 47 weeks of age ($n = 5$ for each experiment). The relative gastric tumor volume was calculated by multiplication of tumor height and tumor area measured using the ImageJ application program (NIH, Bethesda, MD, USA). X-ray computed tomography images of gastric tumors in live mice were examined using LaTheta LCT-100 (Aloka, Tokyo, Japan) at weeks 0, 1, 2 and 3 of drug administration.

Reverse transcription-polymerase chain reaction. Total RNA was extracted from mouse stomach or cultured cells using ISOGEN (Nippon Gene, Tokyo, Japan). Extracted RNA was reverse-transcribed with a PrimeScript RT reagent kit (Takara, Tokyo, Japan) and PCR-amplified by ABI prism 7900HT (Applied Biosystems, Carlsbad, CA, USA) using SYBR Premix Ex Taq II (Takara). Primers for real-time RT-PCR were purchased (Takara).

Cell Culture experiments. Mouse macrophage RAW264 cells (RIKEN BioRessource Center, Tsukuba, Japan) were cultured in RPMI1640, and treated with lipopolysaccharide (LPS) (Sigma, St. Louis, MO, USA) at 100 ng/mL with or without treatment of celecoxib or RQ00015986 at 10 μM for 24 h. Medium concentration of amphiregulin was measured by using Mouse Amphiregulin ELISA kit (RayBiotech, Norcross, GA, USA). Knockdown of *Adam8* expression was performed using *Adam8* ON-TARGETplus SMARTpool siRNA reagents (Dharmacon, Boulder, CO, USA). For the primary culture of gastric epithelial cells, glandular stomachs of *K19-Wnt1* mice were treated with 0.1% collagenase for 45 min followed by trypsin digestion, and cells were cultured in matrigel (BD Biosciences, Franklin Lakes, NJ, USA) with the primary culture medium with or without 1 μg/mL EGF (BD Biosciences)[16] supplemented with 500 ng/mL R-spondin1 (R&D, Mineapolis, MN, USA), 1 μM of Jagged1 (AnaSpec, Fremont, CA, USA), and 100 ng/mL of Noggin (PeproTech, Rocky Hill, NJ, USA). The primary cultured cells were stimulated with mouse recombinant amphiregulin and epiregulin (R&D) at 20 and 1 ng/mL, respectively, and the mean number of cystic structures >75 μm in diameter per microscopic field was calculated at day 5.

Immunoblotting analysis. Tissue samples were homogenized and sonicated in lysis buffer. After centrifugation at 2000*g*, 10 μg of the supernatant protein was separated in a 10% SDS-polyacrylamide gel. Antibodies for phosphorylated Akt (Ser473) and phosphorylated p44/42 Erk1/2 (cell signaling) were used as the primary antibodies. β-Actin was used as an internal control. The ECL detection system (GE Healthcare, Buckinghamshire, UK) was used to detect specific signals. The band intensities were measured using the ImageJ application (NIH).

Histology and immunohistochemistry. Tissues and the primary cultured cells were paraffin-embedded or frozen in OCT compound (Sakura Finetechnical, Tokyo, Japan), and sectioned. These sections were stained with H&E or processed for immunostaining. Antibody for phosphorylated EGFR (Tyr845) (cell signaling), Ki-67 (DakoCytomation, Carpenteria, CA, USA), or active β-catenin (Millipore, Billerica, MA, USA) was used as the primary antibody. Immunostaining signals were visualized using the Vectastain Elite kit (Vector Laboratories, Burlingame, CA, USA). For fluorescence immunostaining, anti-rabbit IgG Alexa 488 (Molecular Probes, Eugene, OR, USA) was used for the secondary antibody. The mean Ki-67 labeling index of the five independent microscopic fields was calculated.

Statistical analysis. Statistical analyses were performed using the unpaired Student's *t*-test, with *P*-values <0.05 considered significant.

Results

Induction of EGFR ligands and ADAM proteases in gastric tumors by PGE_2 pathway. We examined gene expression profiles of EGFR ligands and EGFR members in the stomach or gastric tumors of the all mouse models listed in Table 1. Among these models, PGE_2 pathway is induced in the stomach of *K19-C2mE*, *Gan*, and *K19-Nog/C2mE* mice by expression of *Ptgs2* and *Ptges*. Hereafter, these three strains are termed the *C2mE* group. Interestingly, expression of amphiregulin (*Areg*), epiregulin (*Ereg*), HB-EGF (*Hbegf*), and betacellulin (*Btc*), as well as Her2 (*Erbb2*), and Her3 (*Erbb3*) increased significantly in the stomach of the *C2mE* group mice (Fig. 1a). In contrast, such induction was not observed in the stomach of *K19-Wnt1* and *K19-Nog* mice, indicating that induction of PGE_2 pathway is responsible for upregulation of these genes.

ADAMs activate EGFR signaling through ectodomain shedding of EGFR ligands, and are induced in a variety of cancer tissues.[27] Notably, expression of *Adam8*, *Adam9*, *Adam10*, *Adam17*, and *Adam28* was increased significantly in the stomach of the *C2mE* group mice but not in other strains, indicating the PGE_2 pathway-dependent induction of these ADAMs (Fig. 1b). It has been shown that ADAM8, ADAM 10 and ADAM17 can cleave and activate amphiregulin, epiregulin, HB-EGF, or betacellulin.[28–30] It is thus possible that EGFR is activated in the gastric mucosa of *C2mE* group mice through induction of both EGFR ligands and ADAM proteases. Induction of *Erbb2* may also contribute to EGFR activation by increasing the heterodimerization of EGFR and HER2. Consistently, the immunostaining intensity of phosphorylated EGFR increased significantly in the gastric epithelial cells of *K19-C2mE* and *Gan* mice but not in those of WT and *K19-Wnt1* mice, indicating PGE_2 pathway-dependent EGFR activation (Fig. 1c).

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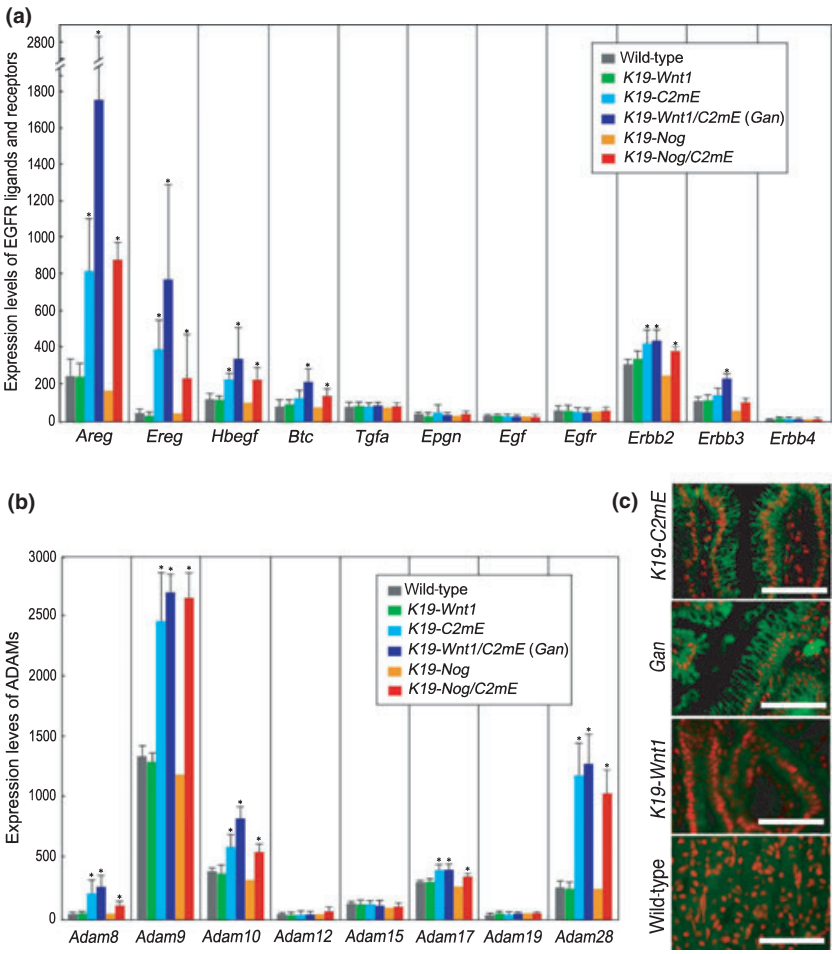

Fig. 1. Gene expression levels of epidermal growth factor receptor (EGFR) ligands, EGFR family members (a) and a disintegrin and metalloproteinases (ADAMs) (b) in the stomach of the respective models (mean ± SD) calculated from microarray results. Asterisks indicate $P < 0.05$ versus the wild-type level. (c) Fluorescence immunostaining for phosphorylated EGFR at Tyr845 (green) in the gastric mucosa of the indicated genotype mice. DAPI staining for nuclei is visualized in red. Bars indicate 100 μm.

Induction of EGFR ligands and ADAM proteases by PGE_2 receptor EP4 signaling. We next treated *Gan* mice with a COX-2 inhibitor, celecoxib, and found that expression of *Areg*, *Ereg*, *Hbegf*, and *Btc* as well as *Adam8*, *Adam9*, *Adam10*, *Adam17* and *Adam28* in gastric tumors decreased significantly (Fig. 2a). Among the four PGE_2 receptors, EP1-EP4, expression of EP4 was significantly increased in gastric tumors of *C2mE* group mice.[24] We thus treated *Gan* mice with an EP4-specific inhibitor, RQ00015986. Importantly, inhibition of the EP4 receptor caused a decrease in the expression of these EGFR ligands and ADAMs to a similar level to that in the celecoxib-treated mice (Fig. 2a). These results indicate that PGE_2 signaling through EP4 is required for induction of EGFR ligands and ADAMs in gastric tumor tissues.

Induction of EGFR ligands by EP4 signaling in activated macrophages. Macrophages are infiltrated in the gastric mucosa in the *C2mE* group mice,[16,22] and tumor-associated macrophages play an important role in tumorigenesis through expression of growth factors.[31] We thus examined induction of EGFR ligands and ADAMs in macrophages using the RAW264 cells. Stimulation of macrophages with LPS induced expression of *Ptgs2* and *Ptges*, resulting in an increased PGE_2 level in the cell culture medium (Fig. 2b and not shown). In the LPS-activated macrophages, expression of *Areg*, *Ereg*, and *Hbegf*, as well as *Adam8* increased significantly, while expression of other ADAM members did not (Fig. 2b,c). Notably, inhibition of COX-2 or the EP4 receptor by treatment with celecoxib or RQ00015986, respectively, significantly suppressed induction of *Areg* and *Ereg* in the LPS-stimulated macrophages. These results suggest that EP4 signaling induces expression of *Areg* and *Ereg* in the activated macrophages in an autocrine or paracrine manner. In contrast, expression of *Hbegf* and *Adam8* was not decreased by inhibition of COX-2 or EP4, suggesting that other factors from activated macrophages induced these genes. Expression of *Btc* was not detected in the LPS-stimulated or control RAW264 cells (data not shown).

We confirmed that medium concentration of the cleaved amphiregulin increased significantly in the LPS-stimulated RAW264 cells (Fig. 2d). To examine the role of Adam8 in shedding of amphiregulin, we used *Adam8* siRNA that successfully decreased *Adam8* mRNA level in macrophages (Fig. 2e). Importantly, transfection of *Adam8* siRNA reduced amphiregulin concentration significantly (Fig. 2d). These results indicate that LPS stimulation induces amphiregulin secretion from macrophages through induction of *Areg* and *Adam8* in a PGE_2-dependent and independent mechanisms.

Basal epiregulin expression by EP4 signaling in gastric epithelial cells. To examine gene expression in gastric epithelial cells, we established the primary culture system in matrigel. Although gastric epithelial cells from WT mice proliferated for 3–5 days in matrigel forming small cystic structures (Fig. 3a), they could not continue proliferation. In contrast, gastric epithelial cells from *K19-Wnt1* transgenic mice continued proliferation in matrigel forming large cystic structures. These structures consisted of monolayer of epithelial cells with nuclear accumulation of β-catenin (Fig. 3b), suggesting that Wnt activation increases self-renewal activity of gastric epithelial cells. Expression of EGFR ligands and ADAMs was not increased by PGE_2 stimulation in the primary cultured epithelial cells. However, EP4 inhibition resulted in a significant decrease of *Ereg* expression level, suggesting that EP4 signaling is required for basal expression of *Ereg* (Fig. 3c). Expression of *Hbegf* was not detected in the gastric epithelial cells (data not shown).

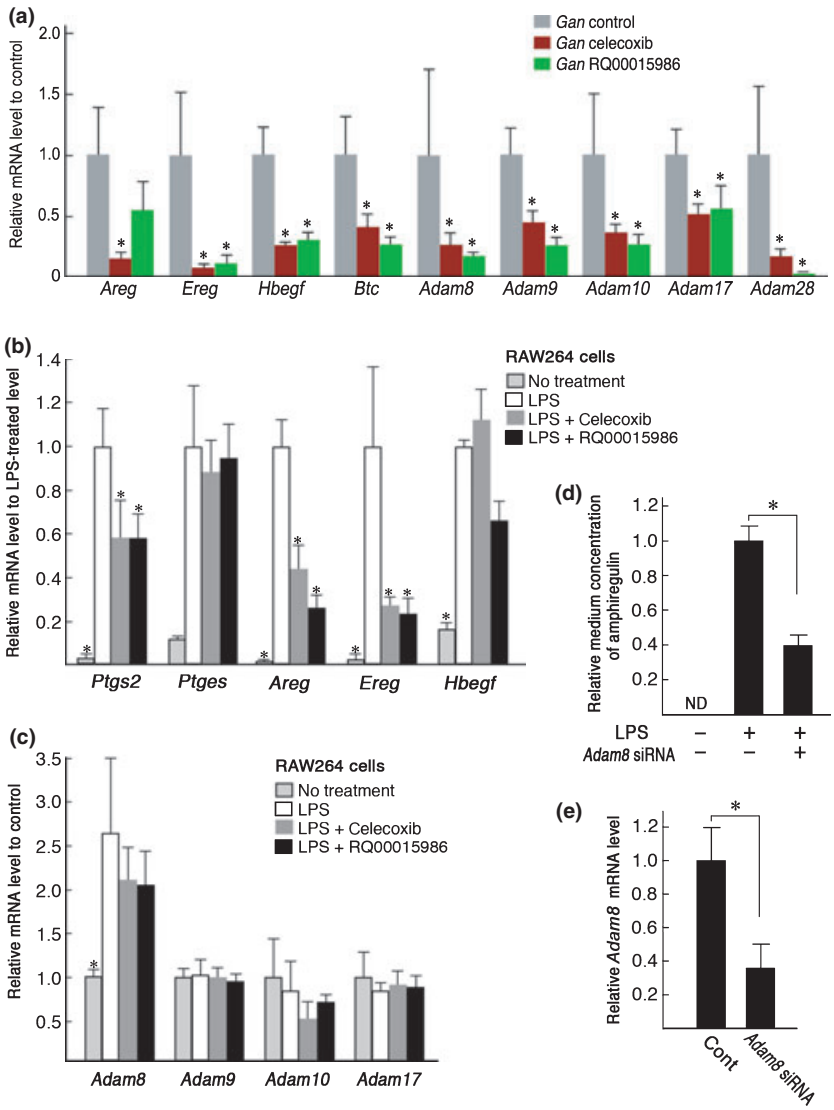

Fig. 2. (a) The mRNA levels of epidermal growth factor receptor (EGFR) ligands and a disintegrin and metalloproteinases (ADAMs) examined by real-time RT-PCR in gastric tumors of celecoxib-treated or RQ00015986-treated *Gan* mice relative to the no-drug control *Gan* mouse level (mean ± SD). Asterisks indicate $P < 0.05$ versus the control level. (b) The mRNA levels of *Ptgs2*, *Ptges*, and EGFR ligands in the control and the drug-treated lipopolysaccharide (LPS)-stimulated RAW264 cells relative to that of LPS-stimulated RAW264 cells (mean ± SD). Asterisks indicate $P < 0.05$ versus the level of LPS-stimulated cells. (c) The mRNA levels of *Adams* in no-drug and drug-treated LPS-stimulated RAW264 cells relative to that of control RAW264 cells (mean ± SD). Asterisk indicates $P < 0.05$ versus the level of LPS-stimulated cells. (d) Concentration of amphiregulin in the culture medium of the LPS-stimulated and *Adam8* siRNA-transfected RAW264 cells relative to that of LPS-stimulated RAW264 cells (mean ± SD). Asterisk indicates $P < 0.05$. (e) The *Adam8* mRNA level in the *Adam8* siRNA-transfected RAW264 cells relative to that of control cells (cont) (mean ± SD). Asterisk indicates $P < 0.05$. [Correction added after online publication on March 18, 2011. *Areg* mRNA is changed to *Adam8* on Fig. 2(e).]

Notably, stimulation of the gastric epithelial cells either by amphiregulin or epiregulin increased the size of cystic structures in matrigel, indicating that these EGFR ligands accelerate proliferation of gastric epithelial cells (Fig. 3d). These results support the idea that induction of amphiregulin and epiregulin by PGE_2 pathway promotes gastric tumorigenesis through activation of epithelial EGFR.

Suppression of *Gan* mouse gastric tumorigenesis by EGFR inhibition. Treatment of *Gan* mice with celecoxib decreased gastric tumor volume to 10.2% of the no-drug control mice, confirming that COX-2 pathway is important for gastric tumorigenesis (Fig. 4a,b). Importantly, treatment of *Gan* mice with an EGFR inhibitor, ZD1839, also reduced the gastric tumor volume to 23.6% of the control mice. Moreover, combination treatment with ZD1839 and celecoxib resulted in complete regression of *Gan* mouse gastric tumors. We confirmed the dramatic regression of gastric tumors by combination therapy with celecoxib and ZD1839 in the same mice by chronological examinations using X-ray computed tomography (Fig. 4c). The transgenic expression of *Ptgs2* and *Wnt1* in the ZD1839-treated *Gan* mice stayed at a similarly high level as that in the control *Gan* mice (Fig. 4d). On the other hand, expression of *Ptges* decreased significantly by ZD1839 treatment, suggesting that endogenous *Ptges* was induced by activation of EGFR signaling in gastric tumors. However, *Ptges* expression level in the ZD1839-treated *Gan* mice was still at the high level compared with WT mice. These results collectively indicate that EGFR activation is required for gastric tumorigenesis, even if the Wnt and PGE_2 pathways are activated.

Suppression of tumor cell proliferation by EGFR inhibition. Two major pathways downstream of EGFR signaling are the MAPK and PI3K/Akt pathways.[32] The levels of phosphorylated Akt and Erk1/2 were significantly decreased by ZD1839 treatment in the *Gan* mouse gastric tumors (Fig. 5a,b). Notably, celecoxib treatment also suppressed the phosphorylation of Akt and Erk1/2 to a similar level as in the ZD1839-treated mice, suggesting that induction of PGE_2 pathway is a major mechanism for activation of EGFR in gastric tumors.

Most tumor cells were immunostained for Ki-67 in the control *Gan* mice, while the number of Ki-67 positive cells was significantly decreased both in the ZD1839-treated and celecoxib-treated mice (Fig. 5c,d). Accordingly, it is possible that the PGE_2 pathway accelerates tumor cell proliferation through EGFR activation.

Discussion

We found that there was simultaneous gene upregulation of EGFR ligands, *Areg*, *Ereg*, *Hbegf* and *Btc*, in the mouse gastric tumors, which occurred in a PGE_2-dependent manner. PGE_2

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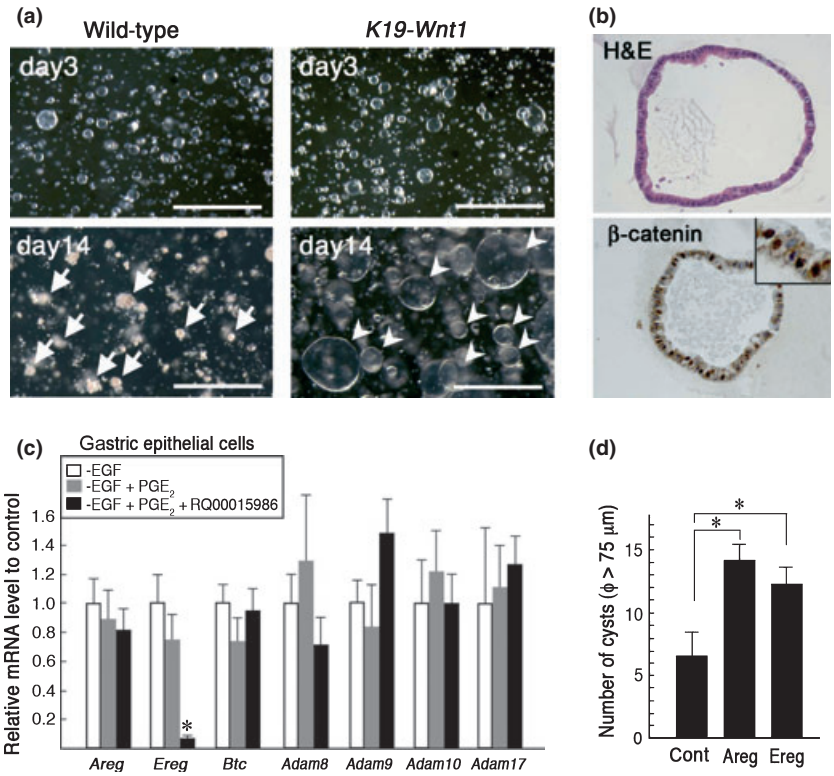

Fig. 3. (a) Representative photographs of the primary cultured gastric epithelial cells in matrigel from wild type (*left*) and *K19-Wnt1* mice (*right*). Arrowheads indicate cystic structures, while arrows indicate clusters of dead cells. Bars indicate 500 μm. (b) Histology (top, H&E) and immunostaining with anti-active β-catenin antibody (bottom) of cystic structures. Inset indicates nuclear accumulation of active β-catenin in the epithelial cells. (c) Relative expression of epidermal growth factor receptor (EGFR) ligands and a disintegrin and metalloproteinases (ADAMs) in gastric epithelial cells cultured in matrigel with the indicated treatment (mean ± SD). Asterisk indicates $P < 0.05$ versus the level in control cells cultured in EGF (–) medium. (d) The mean number of cystic structures >75 μm in diameter in matrigel of the amphiregulin-treated (*Areg*), epiregulin-treated (*Ereg*) and control (*cont*) gastric epithelial cells (mean ± SD). Asterisks indicate $P < 0.05$.

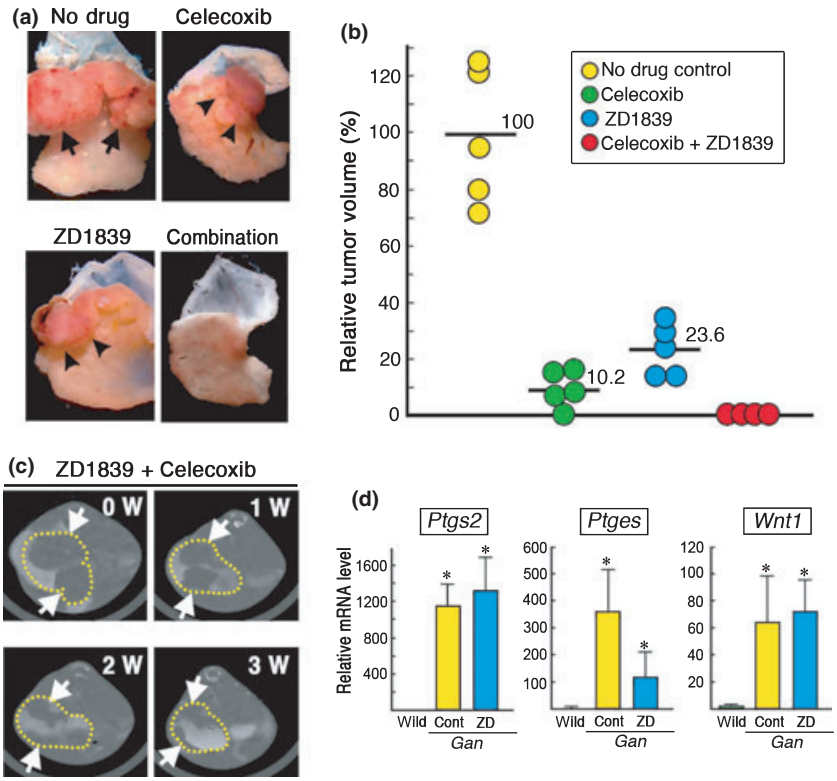

Fig. 4. (a) Representative photographs of *Gan* mouse stomach; no-drug control (top left), celecoxib-treated (top right), ZD1839-treated (bottom left), and treated with a combination of ZD1839 and celecoxib (bottom right). Arrows indicate gastric tumors in control mouse, whereas arrowheads indicate regressed tumors in the drug-treated mice. (b) Tumor volumes of *Gan* mice treated with celecoxib, ZD1839, and a combination of ZD1839 and celecoxib relative to control mice. Each filled circle indicates the value of individual mice, and the means of the respective groups are indicated. (c) X-ray computed tomography images of the same *Gan* mouse treated with a combination of ZD1839 and celecoxib at weeks 0, 1, 2 and 3 after starting drug administration. Yellow dashed lines indicate the stomach. Arrows indicate gastric tumors. (d) The mRNA levels of *Ptgs2*, *Ptges*, and *Wnt1* examined by real-time RT-PCR in the gastric tumors of no-drug control (Cont) and ZD1839-treated (ZD) *Gan* mice relative to wild-type level (wild) (mean ± SD). Asterisks indicate $P < 0.05$ versus wild-type level.

signaling through the EP4 receptor is required for basal expression of *Ereg* in epithelial cells, whereas both *Areg* and *Ereg* are induced by EP4 signaling in macrophages. On the other hand, *Hbegf* is induced in the activated macrophages in a PGE_2-independent manner. Accordingly, it is possible that expression of the respective EGFR ligands is regulated not only by PGE_2 signaling but also by PGE_2-induced inflammation in the different cell types including macrophages and epithelial cells.

It has been reported that PGE_2 signaling activates MMPs and ADAM17, resulting in shedding of TGF-α or amphiregulin,

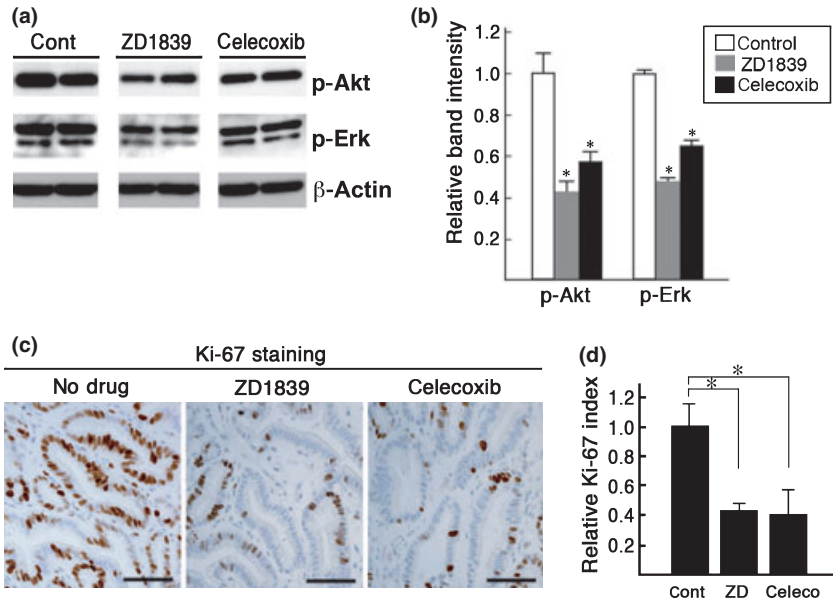

Fig. 5. (a) Western blotting of phosphorylated Akt and phosphorylated Erk1/2 in gastric tumors of two independent no-drug control, ZD1839-treated, and celecoxib-treated *Gan* mice. β-Actin was used as an internal control. (b) Relative band intensities of Western blotting results to the control level (mean ± SD). Asterisks indicate $P < 0.05$ versus the control level. (c) Immunostaining for Ki-67 of gastric tumors. Bars indicate 100 μm. (d) Ki-67 labeling index of ZD1839-treated (ZD), and celecoxib-treated (celeco) *Gan* mice relative to that of control *Gan* (cont) mice (mean ± SD). Asterisks indicate $P < 0.05$.

which causes EGFR activation.[12,15] However, the present results indicate that the expression of ADAM8, ADAM9, ADAM10, ADAM17, and ADAM28 are induced in gastric tumors in a PGE_2 pathway-dependent manner. Although we could not find direct induction of these ADAMs by PGE_2 in epithelial cells or macrophages, it is possible that PGE_2-associated inflammation induces these ADAMs indirectly. It has consistently been shown that the inflammatory cytokine IL-8 induces ADAM10-dependent shedding of HB-EGF and amphiregulin.[33] Notably, all of these induced ADAMs have been shown to be important in tumorigenesis.[27] In addition to shedding of EGFR ligands, they induce tumor cell migration, invasion and dissemination.[27,34,35] Therefore, it is conceivable that induction of such ADAM functions by activated PGE_2 pathway contributes to gastric tumorigenesis and malignant progression.

To examine the role of macrophages for induction of EGFR ligands and ADAMs, we used RAW264 mouse macrophage cell line because it was technically difficult to prepare macrophages from the *in vivo* gastric tumors. Therefore, it remains to be confirmed the induction of EGFR ligands and ADAMs in the tumor-infiltrated macrophages.

Helicobacter pylori infection induces expression of HB-EGF and amphiregulin in gastric cancer cells.[36–38] *H. pylori* infection in mice carrying the kinase-defective mutant EGFR allele ($EGFR^{wa2}$) showed increased apoptosis of gastric epithelial cells, suggesting that EGFR activation by *H. pylori* infection is important for protection from apoptosis.[39] Moreover, *H. pylori* infection to *Adam17*-disrupted gastric epithelial cells failed to activate the EGFR, suggesting that ADAMs play a role in *H. pylori* infection-induced EGFR activation.[39] Importantly, we previously showed that *H. felis* infection caused induction of *Ptgs2* and *Ptges* in gastric epithelial cells.[16]

Accordingly, it is possible that *H. pylori* infection induces PGE_2 pathway, which further activates EGFR through global induction of EGFR ligands and ADAMs, similar to the effects observed in the *C2mE* group mice. It is therefore possible that inhibition of the PGE_2 pathway, as well as eradication of *H. pylori* infection, can suppress EGFR activation in the *H. pylori*-infected gastric mucosa, thereby preventing gastric carcinogenesis.

The level of PGE_2 is regulated by 15-hydroxyprostaglandin dehydrogenase (15-PGDH), which inactivates prostaglandins. Importantly, expression of 15-PGDH is downregulated by EGFR signaling in colon cancer cells,[40] indicating that EGFR signaling activates PGE_2 pathway. Moreover, disruption of the 15-PGDH gene accelerates intestinal tumorigenesis in mouse models.[41] Accordingly, it is possible that inhibition of both PGE_2 and EGFR pathways represents an effective therapeutic strategy for gastrointestinal tumorigenesis by suppression of both the individual signaling pathways and the positive feedback loop between two signaling pathways. Among the four PGE_2 receptors, EP4 is the most abundant receptor in mouse gastric tumor models[24] and in human colon cancer tissues.[42] We have shown here that EP4 signaling is responsible for global induction of EGFR ligands and ADAMs through direct or indirect mechanisms, and macrophages are major source of EGFR ligands. Moreover, we have recently demonstrated that inhibition of EP4 signaling significantly suppressed gastric tumorigenesis in *Gan* mice.[43] These results, taken together, suggest that combination treatment with inhibitors of EGFR and EP4 will be an effective strategy for preventing gastric tumorigenesis.

Acknowledgments

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