Deficiency of Either Cyclooxygenase (COX)-1 or COX-2 Alters Epidermal Differentiation and Reduces Mouse Skin Tumorigenesis


ABSTRACT

Nonsteroidal anti-inflammatory drugs are widely reported to inhibit carcinogenesis in humans and in rodents. These drugs are believed to act by inhibiting one or both of the known isoforms of cyclooxygenase (COX). However, COX-2, and not COX-1, is the isoform most frequently reported to have a key role in tumor development. Here we report that homozygous deficiency of either COX-1 or COX-2 reduces skin tumorigenesis by 75% in a multistage mouse skin model. Reduced tumorigenesis was observed even when the levels of stable 7,12-dimethylnapthrene-DNA adducts were increased about 2-fold in the COX-deficient mice compared with wild-type mice. The premature onset of keratinocyte terminal differentiation appeared to be the cellular event leading to the reduced tumorigenesis because keratin 1 and keratin 10, two keratins that indicate the commitment of keratinocytes to differentiate, were expressed 8–13-fold and 10–20-fold more frequently in epidermal basal cells of the COX-1-deficient and COX-2-deficient mice, respectively, than in wild-type mice. Papillomas on the COX-deficient mice also displayed the premature onset of keratinocyte terminal differentiation. However, loricrin, a late marker of epidermal differentiation, was not significantly altered, suggesting that it was the early stages of keratinocyte differentiation that were primarily affected by COX deficiency. Because keratin 5, a keratin associated with basal cells, was detected differently in papillomas of COX-1-deficient as compared with COX-2-deficient mice, it appears that the isoforms do not have identical roles in papilloma development. Interestingly, apoptosis, a cellular process associated with nonsteroidal anti-inflammatory drug-induced inhibition of tumorigenesis, was not significantly altered in the epidermis or in papillomas of the COX-deficient mice. Thus, both COX-1 and COX-2 have roles in keratinocyte differentiation, and we propose that the absence of either isoform causes premature terminal differentiation of initiated keratinocytes and reduced tumor formation.

INTRODUCTION

The two known isoforms of COX, COX-1 and COX-2, catalyze the first committed step in the synthesis of PGs (1, 2), and both isoforms are biological targets of a class of medications known as NSAIDs. The observed inhibition of tumor formation by NSAIDs provided an early indication that the COXs have roles in carcinogenesis, and NSAIDs are especially well documented for preventing colon cancer development in both humans (3, 4) and rodents (5–9). In early studies, the NSAIDs used were capable of inhibiting both COX-1 and COX-2 (5, 6); however, because COX-2 is up-regulated in a high percentage of rodent and human tumors (7–9), many recent studies have focused on the involvement of this isoform in tumorigenesis. Indeed, the recently developed COX-2-selective inhibitors have proven to be effective antitumorigenic agents for several rodent tumor types (7–9, 11–15). Moreover, genetic disruption of Ptgs-2, the gene encoding COX-2, resulted in substantially reduced spontaneous intestinal tumorigenesis in mice carrying a mutated Apc (adenomatous polyposis coli) gene (16, 17).

However, observations demonstrating a role for COX-2 in tumorigenesis do not preclude a role for COX-1. We have recently reported that the genetic disruption of Ptgs-1, the gene encoding COX-1, leads to as great a reduction in intestinal tumorigenesis in the Min (multiple intestinal neoplasia) mouse as the genetic disruption of Ptgs-2 (17). To extend our findings on the effects of COX-1 and COX-2 deficiency on tumorigenesis and to gain mechanistic insight, we examined the effects of genetic COX-1 and COX-2 deficiency (18, 19) in the mouse skin initiation/promotion model.

In skin, epidermal cell proliferation, differentiation, and death are tightly regulated, and the multistage mouse skin tumorigenesis model has been used extensively to study these processes as they relate to carcinogenesis (20). Furthermore, NSAIDs are known to decrease skin tumorigenesis in mouse skin models (13–15, 21), suggesting that COX-1 and/or COX-2 have roles in skin tumor formation. The genetically modified, COX-deficient mice provide an alternative approach to NSAID treatment for understanding the roles of COX-1 and COX-2 in tumorigenesis and the chemopreventive effects of COX-1 or COX-2 inhibition (1, 2, 18, 19, 22, 23). Here we report that targeted disruptions of the genes encoding either COX-1 or COX-2 (18, 19) lead to altered epidermal differentiation and reduced skin tumorigenesis.

MATERIALS AND METHODS

Breeding of Wild-type and COX-deficient Mice. Mice carrying the Ptgs-1 and Ptgs-2 mutations (18, 19) have been bred for over 20 generations. These mice have been individually maintained by the continuous breeding of heterozygous offspring from the original F1 agouti (C57BL/6 × DBA/2J) to acquire the desired genotype. The two known Ptgs-2 mutations (18, 19) have been bred for over 20 generations. These mice have been individually maintained by the continuous breeding of heterozygous offspring from the original F1 agouti (C57BL/6 × DBA/2J) to acquire the desired genotype.

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The abbreviations used are: COX, cyclooxygenase; NSAID, nonsteroidal anti-inflammatory drug; K1, keratin 1; K5, keratin 5; K10, keratin 10; DMBA, 7,12-dimethylbenz(a)anthracene; TPA, 12-O-tetradecanoylphorbol-12,13-acetate; BrdUrd, 5-bromo-2′-deoxyuridine; PG, prostaglandin; EGFR, epidermal growth factor receptor.
type mice from the COX-1-deficient and COX-2-deficient breeding lines were compared. Using the Cox proportional hazards Wald test (24) for time to first papilloma and a corrected Mann-Whitney t test (25) for the maximum number of papillomas, the differences in papilloma induction on wild-type mice from the two lines were not significantly different. Therefore, data from wild-type mice of the two strains were combined for subsequent analysis. Statistical analysis of experiments used the Mann-Whitney t test (Fig. 1) or Student’s t test (Fig. 2; Fig. 4, s and t; and Table 1).

**Sample Collection.** Skin samples for analysis were taken at the times described in the individual experiments. Because the hair growth cycle is known to influence epidermal physiology, skin was collected in the telogen phase of the hair cycle to standardize the samples.

**DNA Adduct Formation.** Female 11–12-week-old wild-type COX-1−/− or COX-2−/− mice were treated as follows. An area of dorsal skin was shaved, and the next day, the shaved area was topically treated with 50 μg of DMBA in 100 μl of acetone. After 4 or 24 h, the mice were sacrificed, and the treated area of skin was excised and snap-frozen. Epidermis from each group was ground in liquid nitrogen and divided into two equal samples for purification of DNA and duplicate analyses of the stable DNA adducts by the 32P postlabeling method (26). Four mice of each genotype were examined at each time point.

**PG Determination.** Control, DMBA/TPA-treated skin, or papillomas were snap-frozen, and 0.10 g was homogenized in 4°C PBS [2.7 mM KCl, 1.5 mM KH2PO4, 137 mM NaCl, and 8 mM NaHPO4·7H2O (pH 7.4)] containing 60 μM indomethacin. Homogenates were centrifuged at 35,000 × g, and PG2 levels in the supernatant were determined using a radioimmunoassay kit (Amersham, Piscataway, NJ) according to the manufacturer’s instructions.

**Immunohistochemical Detection of the COXs and Cytokeratins.** Strips of mouse skin or papillomas and adjacent skin were fixed in 10% neutral buffered formalin, embedded in paraffin, sectioned at 5-μm thickness, and mounted on SuperFrost Plus slides (A. Daiger, Lincolnshire, IL). Because expression of K1 and K10 is reduced and becomes variable in larger papillomas (27), papillomas of 3–5 mm in diameter were used in these studies. Antigen retrieval was performed in de-gassed 0.01 M sodium citrate by heating in a microwave oven. Antibodies to the keratins and loricrin were obtained from Covance (Ann Arbor, MI). The COX-2 antibody was obtained from Cayman Chemical (Ann Arbor). Incubations with the primary antibodies were carried out overnight at room temperature in a humidity chamber. Antibody binding was detected using a VectaStain Elite kit (Vector Laboratories, Burlingame, CA) according to the manufacturer’s instructions. The absence of staining in the corresponding COX−/− mice served as the negative control.

**BrdUrd Labeling and Keratinocyte Transit.** DMBA/TPA-treated mice were injected i.p. with 100 mg/kg BrdUrd (Sigma-Aldrich) in 200 μl of PBS 17 h after the last TPA dose (28). Tissue was collected 1 h after BrdUrd injection for measurement of cell replication. Tissue for keratinocyte transit was collected after BrdUrd injection at the times specified. Incorporated BrdUrd was detected with an antibody from Harlan-Sera-Lab (Laughtonh, United Kingdom). Twenty microscope fields were counted for each mouse (4 mice/genotype/time point).

**Apoptosis.** Apoptotic cells were detected in the paraffin-embedded epidermis from DMBA/TPA-treated mice by terminal deoxynucleotidyl transferase-mediated nick end labeling kit using a TACS Assay kit (Trevingen, Gaithersburg, MD) according to the manufacturer’s instructions. We analyzed the epidermis or papillomas from 4 mice/genotype. Twenty microscope fields were counted for each mouse.

**Nucleated Cell Layers in the Epidermis.** Counts (20 fields/mouse, 4 mice/genotype) were made on an Olympus BX-50 microscope with 40× UPlanApo lens and WH10X/22 eyepiece using an eyepiece micrometer reticle.

**RESULTS**

**Deficiency of COX-1 or COX-2 Reduces Mouse Skin Tumorigenesis.** The tumorigenic responses of wild-type (+/+), heterozygous (+/−), or homozygous deficient (−/−) COX-1 or COX-2 mice are shown (Fig. 1, a and b). The tumor numbers in both homozygous-deficient strains were reduced by about 75% compared with wild-type mice (Fig. 1a). The tumor incidences were also reduced in the COX-1−/− and COX-2−/− mice (to 60% and 30%, respectively) compared with an 84% incidence in wild-type mice (Fig. 1b). The number of papillomas on mice heterozygous for COX-1 or COX-2 was decreased to 35% and 60%, respectively, of the wild-type number (Fig. 1a). About 75% of heterozygous COX-1 and COX-2 mice developed tumors (data not shown), an incidence only slightly lower than that of the wild-type mice (Fig. 1b). Overall, the data show that gene dosage-
dependent decreases of papilloma formation resulted from the targeted disruption of the genes encoding COX-1 or COX-2. Alterations in papilloma morphology also resulted from COX-1 or COX-2 deficiency. Papillomas on the wild-type mice were typically stalked with apical enlargement (Fig. 1c), whereas those on the COX-1<sup>-/-</sup> mice were generally smaller and had less apical enlargement (Fig. 1d). Papillomas on COX-2<sup>-/-</sup> mice were small and sessile rather than stalked (Fig. 1e). Papillomas on mice heterozygous for either isoform did not appear to be significantly different morphologically from those on wild-type mice. Thus, the absence of either COX isoform resulted in reduced size and altered gross morphology of papillomas, although the absence of COX-2 appeared to have the greater effect.

**Stable DNA Adducts Are Increased in COX-1<sup>-/-</sup> or COX-2<sup>-/-</sup> Mice.** The COXs can metabolize some chemical carcinogens to DNA-reactive intermediates (4, 29), and the initiating activity of DMBA correlates with the level of stable DMBA-DNA adducts (30). Four h after DMBA treatment, the level of stable DMBA-DNA adducts in the epidermis of wild-type mice was 1.4 ± 0.2 × 10<sup>-8</sup> mol/mol DNA phosphate, whereas stable adducts were elevated about 2-fold in both COX-1<sup>-/-</sup> and COX-2<sup>-/-</sup> mice to 2.8 ± 0.2 × 10<sup>-8</sup> and 2.7 ± 0.4 × 10<sup>-8</sup> mol/mol DNA phosphate, respectively. At 24 h after DMBA application, stable DNA adducts in the COX-deficient mice also were increased about 2-fold compared with wild-type mice (data not shown). The pattern of DMBA adducts did not show genotype-dependent differences and resembled those reported previously (26). These data indicate that the reduced papilloma formation in COX-deficient mice did not result from decreased initiation.

**PGE<sub>2</sub> Levels in Skin and Papillomas.** Because we had previously shown that COX-1 or COX-2 deficiency altered PG levels (18, 19), we wanted to determine the relative contributions of COX-1 and COX-2 to PG levels in skin and in papillomas. PGE<sub>2</sub> was measured as an indicator of PG production (17). PGE<sub>2</sub> levels in untreated skin of wild-type and COX-2<sup>-/-</sup> mice were not significantly different, but PGE<sub>2</sub> levels were reduced by about 99% in COX-1<sup>-/-</sup> mice (Fig. 2). After 20 weeks of TPA treatment, PGE<sub>2</sub> levels in the skin increased in both wild-type and COX-deficient mice. PGE<sub>2</sub> levels in the skins of the COX-deficient groups indicated that both COX-1 and COX-2 contribute to this increase (Fig. 2). PGE<sub>2</sub> levels were further elevated in papillomas, and the data from the COX-2<sup>-/-</sup> and COX-1<sup>-/-</sup> mice indicate that both COX-1 and COX-2 contributed to PGE<sub>2</sub> production in papillomas (Fig. 2). However, COX-1 was the major source of PGE<sub>2</sub> in untreated skin, TPA-treated skin, and papillomas.

**Epidermal Hyperplasia, Keratinocyte Proliferation, Death, and Transit in Wild-type and COX-deficient Mice.** The number of nucleated cell layers in the untreated epidermis of wild-type and COX-deficient mice was not significantly different (Table 1). However, after TPA treatment, epidermal hyperplasia was induced in all genotypes, although the number of nucleated cell layers was smaller in the COX-deficient mice than in the wild-type mice (Table 1). Because the hyperplastic responses of the epidermis of COX-1<sup>-/-</sup> and COX-2<sup>-/-</sup> mice were reduced, we investigated whether decreased levels of keratinocyte proliferation and/or altered cell transit and death could account for the reduced hyperplasia. PGs are known to influence keratinocyte proliferation (31), and Table 1 shows that untreated COX-deficient mice had fewer BrdUrd-labeled epidermal cells than did wild-type mice. After 20 weeks of TPA treatment, BrdUrd labeling was increased in all genotypes; however, the COX-deficient mice still exhibited less BrdUrd labeling than did the wild-type mice (Table 1). In all genotypes, epidermal basal cells were the predominant cells incorporating BrdUrd at 1 h after administration (Fig. 3, a, c, and e). After 30 h, epidermal basal and spinous cells of the wild-type mice retained most of the BrdUrd-labeled nuclei (Fig. 3b), whereas in the COX-1<sup>-/-</sup> and COX-2<sup>-/-</sup> mice, labeled cells had reached the more differentiated granular and cornified layers, respectively (Fig. 3, d and f). Thus, keratinocyte transit was more rapid in both the COX-1<sup>-/-</sup> and COX-2<sup>-/-</sup> mice.

Increased apoptosis and/or premature onset of terminal differentiation of basal or transit amplifying cells could account for both the reduced basal cell replication and the increased keratinocyte transit in the COX-1<sup>-/-</sup> and COX-2<sup>-/-</sup> mice. Because previous studies indicated that COX-2 overexpression reduced apoptosis (32), we hypothesized that the COX-deficient mice could have increased epidermal apoptosis. However, the levels of apoptosis in the epidermis or papillomas of COX-1<sup>-/-</sup> or COX-2<sup>-/-</sup> mice were slightly increased compared with the levels in wild-type mice, but the differences were not statistically different (Table 1). Therefore, increased apoptosis did not appear to be a significant factor in reducing tumor numbers or tumor growth in the COX-deficient mice.
Immunohistochemical Analysis of Epidermal Differentiation.

To determine whether epidermal differentiation was altered, the expression of differentiation-specific proteins from the epidermis of wild-type and COX-deficient mice was analyzed by immunohistochemistry. K5 is normally expressed in basal cells and retained in suprabasal cells (33). K5 expression in the epidermis was similar in all three genotypes (Fig. 4, a, e, and i). K1 is expressed as keratinocytes commit to differentiation (33). K1 was detected in only 2% of the basal cells in wild-type mice (Fig. 4, b and s), but it was detected in 17% and 26% of the basal cells of COX-1/−/− and COX-2/−/− mice, respectively (Fig. 4, f, j, and s). K10, another early marker for keratinocyte differentiation (33), was also prematurely expressed in the COX-deficient mice (Fig. 4, c, g, k, and t). The increased expression of K1 and K10 in basal cells of the COX-deficient mice indicated that this normally replicative cell population had prematurely initiated terminal differentiation. The expression of the late differentiation protein, loricrin (34), did not show significant differences between the genotypes (Fig. 4, d, h, and l). Thus, COX-1 and COX-2 appear to influence the early stages of keratinocyte differentiation rather than the later stages.

Because the deficiency of COX-1 or COX-2 could alter the expression of the remaining isoform, we compared the levels of COX-1 and COX-2 in the epidermis of the COX-deficient and wild-type mice by immunohistochemistry. Wild-type mice expressed COX-1 primarily...
in differentiated suprabasal cells (Fig. 4m). However, COX-1 was detectable in basal and suprabasal cells of the COX-2−/− mice (Fig. 4q). The expression of COX-1 in basal cells of the COX-2−/− mice, like the expression of K1 and K10, supports the conclusion of premature terminal differentiation when COX-2 is absent. However, as compared with wild-type mice, neither the location nor the intensity of COX-2 staining was altered in the COX-1−/− mice (Fig. 4, n and p). The specificity of the COX-1 and COX-2 immunostaining was verified with the appropriate COX-1−/− or COX-2−/− epidermis (Fig. 4, o and r). Therefore, whereas the deficiency of COX-1 expression does not alter the expression of COX-2, the deficiency of COX-2 does result in the expression of COX-1 in basal cells.

It was also observed that the arrangement of keratinocytes in the epidermis appeared less organized in the COX-deficient mice than in the wild-type mice (for example, see Fig. 4, m, o, and q). The basal cells in the COX-deficient mice often lack the columnar shape found in the wild-type mice, and the transition to the differentiated morphologies of the spinous and granular layers was less uniform, suggesting that both COX-1 and COX-2 are important in the transition of keratinocytes to a differentiated phenotype.

Cell Proliferation, Apoptosis, and Keratinocyte Differentiation in Papillomas. In papillomas collected 4 weeks after the last TPA treatment, those from the COX-deficient mice had reduced BrdUrd labeling compared with papillomas from wild-type mice (Table 1). However, at 1 h after BrdUrd treatment, label was detected in basal and suprabasal cells of papillomas from both wild-type mice and COX-deficient mice (data not shown). Thus, whereas fewer BrdUrd-labeled cells were detected in the COX-deficient mice than in the wild-type mice, labeling occurred in similar locations in all of the genotypes. The levels of apoptosis in papillomas from the three genotypes did not appear to differ (Table 1); therefore, apoptosis would not account for the smaller size of papillomas of the COX-deficient mice (Fig. 1, c–e).

We also determined whether COX-1 or COX-2 expression was altered in papillomas of the respective COX-deficient mice. In papillomas from wild-type mice, COX-1 was detected primarily suprabasally, whereas in COX-2−/− mice, COX-1 was frequently detected in basal cells as well as in the suprabasal cells (Fig. 5, a and i). COX-2 expression was more variable in papillomas than in the epidermis. In the wild-type mice, COX-2 was expressed not only in the basal cells of the papillomas but also in some suprabasal keratinocytes (Fig. 5b). The absence of COX-1 did not appear to significantly alter the expression pattern of COX-2 in papillomas (Fig. 5f). The specificities of the COX antibodies are shown by the absence of binding in the respective COX-1−/− mice (Fig. 5, e and j). Thus, in papillomas, as was observed in the epidermis, the absence of COX-1 expression did not alter expression of COX-2, but the absence of COX-2 did result in premature expression of COX-1.

In papillomas of wild-type mice, K1 expression generally began in the third or fourth epidermal cell layer (Fig. 5c), whereas in papillomas of COX-1−/− and COX-2−/− mice, K1 expression began in the second epidermal cell layer (Fig. 5, g and k). K10 expression (data not shown) was similar to that of K1. Thus, in papillomas, as in the epidermis, keratinocytes from the COX-deficient mice began terminal differentiation earlier. The expression of the late differentiation marker, loricrin, was similar in papillomas of COX-deficient and wild-type mice (data not shown) and indicates that in papillomas, as in the epidermis, it is the early stages of differentiation that are affected by the deficiency of COX-1 or COX-2.

Whereas the distributions of K1 and K10 were similar in papillomas of the COX-1−/− and COX-2−/− mice, the distribution of the basal cell marker, K5, differed between the two COX-deficient genotypes. In wild-type mice, the onset of K5 expression began in the basal keratinocytes, and the protein remained throughout the suprabasal layer of the papillomas, although detectability decreased in the suprabasal layers (Fig. 5d). In the COX-deficient mice, the onset of K5 expression also occurred in the basal cells of the papillomas; however, the ability to detect K5 in the suprabasal cells of the COX-1−/− and COX-2−/− mice differed (Fig. 5, h and l). A significant decrease in staining for K5 was evident in the suprabasal layers of COX-1−/− papillomas compared with the suprabasal cells in papillomas on wild-type mice (Fig. 5, d and h), whereas in papillomas on

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The COX-2\(^{-/-}\) mice, K5 staining remained elevated throughout the papilloma (Fig. 5). Thus, the appearance of K5 in the suprabasal cells of the papillomas varied among the three genotypes and shows that the deficiency of COX-1 and COX-2 had different effects on K5 staining in papillomas.

**DISCUSSION**

In the present study, we show that mice deficient in either COX-1 or COX-2 develop about 75% fewer skin papillomas than do the wild-type mice (Fig. 1). Furthermore, we have demonstrated that the deficiency of either COX isoform causes the premature onset of keratinocyte terminal differentiation, and we suggest that it is premature differentiation of initiated cells that is primarily responsible for the reduced papilloma formation.

The present data indicate that both COX-1 and COX-2 have significant roles in regulating epidermal differentiation. The effects of COX-1 and COX-2 deficiency on differentiation were primarily evident at the basal cell to spinous cell transition (Fig. 4). Premature differentiation of basal cells into spinous cells occurred in the absence of either COX-1 or COX-2, suggesting that both isoforms are required for normal differentiation to occur. Immunohistochemical analysis of COX-1 and COX-2 and of K1 and K10, two keratins associated with these early stages of keratinocyte differentiation, indicated that COX-1 expression must be up-regulated and that COX-2 expression must be concomitantly down-regulated for the coordinated differentiation of basal cells into spinous cells. Loricrin, a protein expressed in the later stages of keratinocyte differentiation, was not significantly increased in the COX-1/COX-2-deficient mice (Fig. 5). Papillomas from the COX-1- and COX-2-deficient mice also showed earlier expression of K1, K5, and K10 compared with that seen in papillomas from wild-type mice. Whereas the studies reported here were conducted to determine the roles of COX-1 and COX-2 in skin tumorigenesis using an initiation/promotion model, we have observed similar effects of COX-1 or COX-2 deficiency on epidermal differentiation in untreated skin. From the present studies, it is not possible to identify the specific mechanism(s) by which COX-1 and COX-2 influence epidermal differentiation, and studies are under way to elucidate the specific PGs and the PG receptors involved.

There is little precedent in the literature for a direct influence of the COXs on differentiation. It was reported previously that expression of COX-1, but not COX-2, was up-regulated when a pronormocytic cell line was induced to differentiate (35). This observation is in agreement with our observation that COX-1 is induced when basal cells differentiate into spinous cells. It has been reported recently that overexpression of COX-2 in the epidermis of a transgenic mouse caused delayed expression of the differentiation markers K1, K10, and loricrin (36). These findings are in agreement with our results showing that COX-2 deficiency caused premature expression of K1 and K10 in the epidermis. However, our data additionally show that COX-1 deficiency, like COX-2 deficiency, also alters epidermal differentiation.

Importantly, it was observed that COX-1 and COX-2 deficiency caused an increase in the formation of stable DMBA-DNA adducts in the epidermis. This was unanticipated because the COXs have been demonstrated to metabolically activate some classes of chemical carcinogens (4, 29), and it was expected that their deficiency would result in a reduction of stable DMBA-DNA adducts. This increase in DMBA adduction in the epidermis of COX-deficient mice suggests that the COXs are not a major pathway for the metabolic activation of DMBA.

^3 Unpublished data.
tinal tumorigenesis in the Min mouse (17). The possible involvement of COX-1 as well as COX-2 in mouse skin tumorigenesis was also suggested by the studies of Fischer et al. (14). Furthermore, the involvement of COX-1 in tumorigenesis is also supported by our observation that COX-1, rather than COX-2, is a major source for PGE₂ production in TPA-treated skin and in papillomas (Fig. 2).

In summary, the present studies show that both COX-1 and COX-2 contribute to mouse skin tumorigenesis and that papilloma development is significantly reduced in the absence of either isoform. The premature onset of terminal differentiation, rather than increased apoptosis, appears to be the primary mechanism by which COX deficiency decreases papilloma formation in the skin. Therefore, the results demonstrate key roles for both COX-1 and COX-2 in epidermal differentiation and suggest that selective inhibition of COX-1 as well as selective inhibition of COX-2 may effectively suppress skin tumorigenesis.

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