Prostaglandin E₂ Protects Intestinal Tumors from Nonsteroidal Anti-inflammatory Drug-induced Regression in Apc\(^{Min/+}\) Mice

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ABSTRACT

Nonsteroidal anti-inflammatory drugs (NSAIDs) are antitumorigenic in humans as well as in animal models of intestinal neoplasia, such as the adenomatous polyposis coli (Apc)\(^{Min/+}\) mouse. NSAIDs inhibit cyclooxygenase (COX) isozymes, which are responsible for the committed step in prostaglandin biosynthesis, and this has been considered the primary mechanism by which NSAIDs exert their antitumorigenic effects. However, mounting evidence suggests the existence of COX-independent mechanisms. In the present study, we attempted to clarify this issue by treating Apc\(^{Min/+}\) mice bearing established tumors with NSAIDs (piroxicam and sulindac, 0.5 and 0.6 mg/mouse/day, respectively) for 6 days and concomitantly bypassing COX inhibition by treatment with the E prostaglandin (EP) receptor agonists 16,16-dimethyl-prostaglandin E\(_2\) (PGE\(_2\)) and 17-phenyl-trinor-PGE\(_2\) (10 mg each, three times daily) administered via gavage and/or i.p. routes. Treatment with piroxicam and sulindac resulted in 95% and 52% fewer tumors, respectively, and a higher ratio of apoptotic:mitotic in tumors from sulindac-treated mice as compared with controls. These effects were attenuated by concomitant EP receptor agonist treatment, suggesting PGE\(_2\) is important in the maintenance of tumor integrity. Immunological sequestration of PGE\(_2\), an anti-inflammatory drug; PGE\(_2\), prostaglandin E\(_2\); CCE, capacitative calcium entry; COX, cyclooxygenase; EP, E prostaglandin receptor; EPR-A, E prostaglandin receptor agonist; NSAID, nonsteroidal anti-inflammatory drug; PGE\(_2\), prostaglandin E\(_2\); CCE, calcium capacitative entry.

INTRODUCTION

Colorectal cancer is the second leading cause of cancer-related mortality in the United States with 56,785 deaths reported in 1998 (1). Over the last several years, the Apc\(^{Min/+}\) mouse has been extensively used to evaluate the effects of pharmacological and nutritional intervention on intestinal tumorigenesis because of its recognized value in modeling human colorectal carcinogenesis (2). Development of colorectal cancer in humans from dysplastic crypts to metastatic carcinoma involves a series of genetic mutations, the earliest often involving APC\(^3\) (3). Individuals with familial adenomatous polyposis, like Apc\(^{Min/+}\) mice, possess a germline mutation in APC\(^\text{a}\), intracellular calcium levels. (4). Although familial adenomatous polyposis accounts for <1% of all of the human colorectal cancer cases, somatic mutations resulting in loss of full-length APC protein also occur early in the majority of spontaneous forms of the disease (5, 6), indicating the central importance of APC in colorectal carcinogenesis (5, 7, 8). Multiple studies using the Apc\(^{Min/+}\) mouse model have clearly established the antitumorigenic efficacy of NSAIDs, inhibitors of COX-1 and COX-2, isozymes responsible for the committed step in prostaglandin biosynthesis. The COX-inhibitory effects of NSAIDs have been considered key to their antitumorigenic efficacy, and this hypothesis is supported by several lines of evidence. COX-2, the inducible isozyme, is overexpressed in intestinal tumor tissue but not normal intestinal tissue of both humans and Apc\(^{Min/+}\) mice (9–11). Corresponding to the overexpression of COX-2, PGE\(_2\), the COX product of arachidonic acid (20:4 n-6) metabolism, is elevated in human colonic tumors (12, 13) and in intestinal tumors from Apc\(^{Min/+}\) mice compared with normal intestinal tissue (14). Furthermore, inhibition of both COX-1 and COX-2 by n-3 polyunsaturated fatty acids and nonselective inhibitors, including the NSAIDs sulindac, indomethacin, piroxicam, and aspirin, reduces tumor number in Apc\(^{Min/+}\) mice by 44–96% (14–21), and selective inhibition of COX-2 reduces tumor number by 52–71% (22, 23). Likewise, crossing COX-2 knockout mice with Apc\(^{Min/+}\) mice or Apc\(^{Min/+}\) mice reduced tumors by ~85% (24, 25), and crossing Apc\(^{Min/+}\) mice with COX-1 knockouts similarly reduced tumor multiplicity by 77% (24).

Despite these supportive data, mounting evidence suggests that NSAIDs may also work via COX-independent mechanisms. For example, S-flurbiprofen, a nonselective COX inhibitor, and its inactive enantiomer (R-flurbiprofen) reportedly act via COX-independent mechanisms (26), but were equally effective in reducing tumor number in Apc\(^{Min/+}\) mice (27). Additionally, NSAIDs have been shown to modulate cell proliferation and cell death in cultured colon cancer cells lacking COX, suggesting that not all of the NSAID effects are based on COX inhibition (28–30). Multiple COX-independent mechanisms have been investigated to date including those involving 15-lipoxygenase-1 (31), ceramide (32, 33), p21 (34), 5-LOX (35, 36), peroxisome proliferator-activated receptors (37), inhibitor of nuclear factor-κB kinase (38), and cyclic GMP phosphodiesterase (39). Whereas many of these alternative mechanisms may involve signaling pathways related to COX inhibition and prostaglandin biosynthesis, these links have yet to be definitively established.

Thus, to more clearly establish the role of NSAIDs and prostaglandins in the maintenance of tumor integrity, we endeavored to attenuate NSAID-induced regression of intestinal tumors through a series of “add-back” experiments involving EPR-A and by systemically sequestering PGE\(_2\) using an anti-PGE\(_2\) antibody. To do this, we capitalized on previous results demonstrating that NSAIDs (i.e., piroxicam and sulindac) could eliminate up to 95% of preexisting tumors within 6 days (14, 21) and that i.p. administration of the EPR-A 16,16-dimethyl-PGE\(_2\) had direct effects on the stem cell population in small intestinal crypts of mice (40). The results of these in vivo experiments will demonstrate the following: (a) PGE\(_2\) is important in maintaining tumor integrity; (b) PGE\(_2\)-mediated modulation of ([Ca\(^{2+}\)]) may be involved in tumorigenesis; and (c) NSAIDs may reduce tumor burden by modulating ([Ca\(^{2+}\)])

Received 6/19/01; accepted 11/14/01.

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1 Supported in part by American Institute for Cancer Research Grant 99A095-REN (to J. W.) and the Tennessee Agricultural Experiment Station, Current Research Information System Accession no. 0173340 (to J. W.).

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3 The abbreviations used are: APC, adenomatous polyposis coli; [Ca\(^{2+}\)], intracellular calcium concentration; CCE, capacitative calcium entry; COX, cyclooxygenase; EP, E prostaglandin receptor; EPR-A, E prostaglandin receptor agonist; NSAID, nonsteroidal anti-inflammatory drug; PGE\(_2\), prostaglandin E\(_2\); CCE, calcium capacitative entry.
MATERIALS AND METHODS

Animals

Male C57BL/6J ApcMin/+ mice (Jackson Laboratories, Bar Harbor, ME), were obtained at 38–45 days of age. They were housed in a temperature-controlled room with 14-h periods of light and 10-h periods of darkness, and given free access to food and water. The health of the animals was checked daily. Food was withheld overnight before sacrifice. All of the animal procedures were approved by the University of Tennessee Animal Care and Use Committee and were in accordance with the NIH Guide for the Care and Use of Laboratory Animals.

Diets

Diets for Experiments 1–3 were composed of purified AIN-93G powder diet (Dyets, Inc., Bethlehem, PA). Experimental diets containing NSAIDs were prepared daily by thoroughly mixing piroxicam (Sigma Chemical Co., St. Louis, MO) or sulindac (Sigma Chemical Co.) with the control diet. Diets for experiment 4 were AIN-93G powdered diet (calcium 0.4–0.5 g/100 g diet) with or without piroxicam. Diets were stored at −20°C, and all of the mice were provided fresh food daily. Food consumption was monitored daily, and body weights were recorded weekly.

Experimental Design

**Experiment 1.** Mice (n = 23) were maintained on the AIN-93G diet until 78–79 days of age at which time they were randomly assigned to one of four groups (control, EPR-A, piroxicam, or piroxicam + EPR-A). Groups receiving piroxicam (0.5 mg/mouse/day) or sulindac (0.6 mg/mouse/day) were pair-fed to ensure equivalent dosing. The EPR-A 16,16-dimethyl-PGE$_2$ and 17-phenyl-trinor-PGE$_2$ (Cayman Chemical, PIROXICAM, and H11001) were pair-fed to ensure equivalent dosing. The groups (control, EPR-A, piroxicam, or piroxicam/H11001) were determined as described previously (14).

**Experiment 2.** Mice (n = 30) were maintained on the AIN-93G diet until 80–81 days of age at which time they were randomly assigned to one of four groups (control, EPR-A, sulindac, or sulindac + EPR-A). Groups receiving sulindac (0.6 mg/mouse/day) were pair-fed to ensure equivalent dosing. The EPR-A 16,16-dimethyl-PGE$_2$ and 17-phenyl-trinor-PGE$_2$ (Cayman Chemical, Ann Arbor, MI), 10 μg each in sterile PBS, or vehicle were administered in two daily i.p. injections (8 a.m. and 4 p.m.) and once daily via gavage feeding (12 p.m.) to maximize exposure to the gastrointestinal tract over a 6-day period. They were sacrificed at 85–86 days of age, and tumor number, size, and location were determined as described previously (14).

**Experiment 3.** Mice (n = 17) were maintained on the AIN-93G diet until 82 days of age at which time they were randomly assigned to one of two groups (control or PGE$_2$, antibody). Control mice received the MOPC21 mouse IgG1-purified immunoglobulin (Sigma Chemical Co.; 280 μg in 280 μl) that was filtered (0.45 μm filter) and administered daily via i.p. injection on days 82–85. The anti-PGE$_2$, monoclonal antibody 2BS (Monsanto Co., St. Louis, MO; Ref: 41; 283 μg/day in 250 μl sterile PBS) was administered daily via i.p. injection on days 82–85. All of the mice were sacrificed on day 87 and treated as in Experiment 1.

**Experiment 4.** In experiment 4A, mice (n = 3) were maintained on the control diet until 80 days of age at which time mice were sacrificed, and normal-appearing intestinal tissue and tumors were collected for [Ca$^{2+}$]$^i$ analysis. In experiment 4B, mice (n = 12) were maintained on the control diet until 85 days of age at which time they were randomized into two groups (control or piroxicam at a dose of 200 mg/kg diet) for 2 days. Mice were sacrificed at 87 days of age, and tumors were collected for [Ca$^{2+}$]$^i$ analysis. In experiment 4C, mice (n = 20) were maintained on the control diet until 72 days of age and then randomized into one of four groups (control, EPR-A, piroxicam, or piroxicam + EPR-A). The EPR-A 17-phenyl-trinor-PGE$_2$, 10 μg in sterile PBS or vehicle, was administered in two daily i.p. injections (8 a.m. and 4 p.m.) and once daily via gavage feeding (12 p.m.) on days 72–74. Piroxicam (200 mg/kg diet) was provided in the diet for 2 days before sacrifice at 76 days of age, at which time tumors were collected for [Ca$^{2+}$]$^i$ analysis.

Measurement of Apoptosis and Mitosis

Tumors were immediately placed in 10% neutral buffered formalin. After 8–10 h of fixation, tissues were routinely processed into paraffin and 4-μm H&E-stained sections prepared for histological examination. Neoplastic epithelial cells undergoing apoptosis or mitosis were identified under ×400 magnification in H&E stained sections of small intestinal tumors according to well-characterized morphological criteria and without previous knowledge of the study group. The number of apoptotic or mitotic events were simultaneously enumerated per 1000 cells for each tumor and recorded as: [number of apoptotic or mitotic cells + total number of cells counted] × 1000.

Intracellular Calcium Measurement

Ca$^{2+}$, in normal-appearing small intestine and tumors was measured using a fura-2 dual-wavelength fluorescence imaging system and methodology described previously (42). Normal intestinal or tumor cells were isolated as described by Evans et al. (43). These cells were then loaded with fura-2 acetoxyethyl ester (10 μM) in HEPES balanced salt solution containing the following components (in mM): 138 NaCl, 1.8 CaCl$_2$, 0.8 MgSO$_4$, 0.9 NaH$_2$PO$_4$, 4 NaHCO$_3$, 5 glucose, 6 glutamine, 20 HEPES, and 10 mg/ml BSA for 2 h at 37°C in a dark incubator with 5% CO$_2$. To remove extracellular dye, cells were rinsed with HEPES balanced salt solution three times and then plated in 35-mm dishes (P35G–0–14–C, MatTek, Ashland, MA). Cells were postincubated at room temperature for an additional 1 h for complete hydrolysis of cytoplasmic fura-2-acetoxyethyl ester. The dishes with dye-loaded cells were mounted on the stage of a Nikon TMS-F fluorescence-inverted microscope with a Cohu model 4915 charge-coupled device camera. Fluorescent images were captured alternatively at excitation wavelength of 340 and 380 nm with an emission wavelength of 520 nm. [Ca$^{2+}$]$^i$ was calculated using a ratio equation as described previously (44). Each analysis evaluated responses of 8–10 representative whole cells. Images were analyzed with InCyt Im2 version 4.62 imaging software (Intracellular Imaging, Cincinnati, OH). Images were calibrated using a fura-2 calcium imaging calibration kit (Molecular Probes, Eugene, OR) to create a calibration curve in solution, and cellular calibration was accomplished using digitonin (25 μM) and pH 8.7 Tris-EGTA (100 mM) to measure maximal and minimal [Ca$^{2+}$]$^i$ levels (44).

Statistical Analyses

Values are expressed as means ± SE. With the exception of tumor number in experiment 1, data for experiments 1, 2, and 4C (differences in tumor number, tumor size, mitotic index, and [Ca$^{2+}$]$^i$) were analyzed statistically by one-way ANOVA followed by Fisher’s least significant difference multiple comparison method to determine differences among groups. Mitotic index data were transformed in [log(Y+1)] to normalize sample distributions before analysis. Tumor number in experiment 1, apoptotic index, and apoptosis/mitosis ratio were analyzed by the Kruskal-Wallis (rank sums) test with post hoc Bonferroni adjustment to control the experimentwise error rate. Student’s t test was used to analyze data in experiments 3, 4A, and 4B. The Statistical Analysis System (SAS Version 6.12; SAS Institute, Inc., Cary, NC) was used to evaluate the data. Differences were considered significant at P < 0.05.

RESULTS

Effects of Piroxicam, Sulindac, EPR-A, and PGE$_2$ Antibody Treatment on Tumor Burden. Mice treated with piroxicam and sulindac had 95% and 52% fewer intestinal tumors, respectively, as compared with control mice, and this effect was significantly attenuated by concomitant EPR-A treatment (Tables 1 and 2). Antagonism of PGE$_2$ with 2BS anti-PGE$_2$ antibody treatment also resulted in 33% fewer tumors/mouse

<table>
<thead>
<tr>
<th>C (n = 6)</th>
<th>E (n = 5)</th>
<th>P (n = 5)</th>
<th>P+E (n = 6)</th>
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<tbody>
<tr>
<td>Tumors/mouse</td>
<td>48.8±6.2</td>
<td>30.0±6.5</td>
<td>2.4±0.8</td>
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<td>Tumor size (mm)</td>
<td>1.10±0.06</td>
<td>0.99±0.04</td>
<td>1.03±0.12</td>
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* Different superscripts within each row indicate significant differences at P < 0.05.
tumors compared with controls (P < 0.05; Table 3). Mucosal erosions and/or ulcers were commonly identified in the small intestine of piroxicam- and, to a lesser extent, sulindac-treated mice. In contrast, there was no evidence of such damage in the other treatment groups, particularly those treated with a NSAID plus EPR-A. Select small intestinal tumors in the sulindac and piroxicam treatment groups contained histological evidence of regression, as described previously (14).

Comparison of Apoptosis and Mitosis in Tumors. In comparison to controls, the mean apoptotic index was significantly higher in tumors from sulindac-treated mice, but the addition of EPR-A (sulindac + EPR-A) attenuated this effect (Fig. 1A). The EPR-A treatment alone had no impact on the apoptotic index. In contrast, the mitotic index was significantly lower in tumors from sulindac-treated mice as compared with controls, and EPR-A treatment (sulindac + EPR-A) attenuated this response (Fig. 1B). Overall, tumors from the control group had an apoptosis/mitosis ratio of 0.56 (a ratio of < 1 is consistent with tumor growth), and this ratio increased to 2.52 with sulindac treatment (Fig. 1C). The addition of EPR-A (sulindac + EPR-A) attenuated the impact of sulindac on this ratio (to 1.13).

Comparison of [Ca^{2+}], in Tumors versus Normal-appearing Small Intestine and the Effects of Piroxicam with or without EPR-A Treatment. [Ca^{2+}], was 54% higher in tumor tissue than in adjacent normal-appearing small-intestinal mucosa of ApcMin/+ mice (Fig. 2, Experiment A). Furthermore, 2-day piroxicam treatment resulted in [Ca^{2+}], in tumors that was significantly lower compared with tumors from control mice (Fig. 2, Experiments B and C). This effect was attenuated by concomitant treatment with the EPR-A 17-phenyl-trinor-PGE2 (Fig. 2, Experiment C).

**DISCUSSION**

Many NSAIDs are clearly antitumorigenic in the ApcMin/+ mouse model. These antitumorigenic effects have largely been ascribed to inhibition of prostaglandin biosynthesis, although recent evidence suggests multiple mechanisms may be involved. In our previous study, we reported that the antitumorigenic effect of sulindac seemed to be independent of prostaglandin biosynthesis (14). Similar results were reported by others, wherein sulindac treatment exhibited antitumorigenic properties but had variable effects on prostaglandins (9, 14, 19, 20, 45–48). Tissue preparation, methodological differences, and pharmacokinetics of the drug could account for the variability. However, the data presented in this report clearly suggest that sulindac, like other NSAIDs, is antitumorigenic, and the mechanism involves PGE2.

To more clearly establish the role of NSAIDs and prostaglandins (particularly PGE2) in maintaining tumor integrity, we circumvented NSAID-induced COX inhibition with concomitant EPR-A administration in ApcMin/+ mice. In the first experiment, mice treated simultaneously with EPR-A and piroxicam had an 8-fold greater tumor number than those treated with piroxicam alone, indicating that PGE2 is important in maintaining intestinal tumor integrity and that its reduction accounts, at least in part, for the antitumorigenic effects of NSAIDs. Treatment with a dose of sulindac designed to yield incomplete tumor regression verified results observed with piroxicam and also allowed for subsequent tumor tissue analysis. Histological evaluation of tumors from sulindac-treated mice indicated that PGE2 modulates apoptosis and proliferation of neoplastic cells in intestinal tumors in vivo (Fig. 1). Whether this is a direct effect on the epithelium, disruption of paracrine signaling, or secondary to stromal changes remains to be determined.

The antitumorigenic effects of NSAIDs have been linked to inhibition of COX-2. Expression of COX-2 was reported to be localized within stromal cells of tumors in ApcMin/+ (9, 49) and ApcMin/+ mice (25), but others have reported that COX-2 is also expressed in the epithelial cells (10). These results mimic localization of COX-2 expression in human colorectal adenomas, wherein COX-2 was preferentially localized within interstitial macrophages and to a lesser extent within dysplastic epithelial cells (50). If COX-2 is not expressed by epithelial cells, any direct effect by NSAIDs on the epithelial cells would have to be independent of COX-2 inhibition. Nevertheless, there is sufficient evidence in the literature suggesting much of these effects on the tumors are likely mediated by COX-2 and its inhibition. Our data cannot rule out the contribution of PGE2 from COX-1 in the epithelial or stromal cells, because the NSAIDs used in these studies inhibit both COX-1 and -2; however, because aspirin can inhibit

| Table 2 Intestinal tumor load in ApcMin/+ mice treated with and without sulindac + EPR-A. Values shown are means ± SE. Tumor size was calculated as a weighted average. |
|---|---|---|---|---|---|
| C (n = 7) | E (n = 7) | S (n = 8) | S+E (n = 8) |
| Tumors/mouse | 46.0±6.7 | 38.0±6.2 | 22.7±5.8 | 38.4±6.2 |
| Tumor size (mm) | 1.30±0.05 | 1.07±0.06 | 0.97±0.04 | 1.10±0.04 |

* Different superscripts within each row indicate significant differences at P < 0.05. Tumors/mouse in S vs. E, P = 0.059.

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**Table 3 Intestinal tumor load in ApcMin/+ mice treated with the anti-PGE2 MAb 2B5.** ApcMin/+ mice were treated with MOPC21 control antibody (C) or an anti-PGE2 monoclonal antibody (2B5). Values shown are means ± SE. Tumor size was calculated as a weighted average.

<table>
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<th>C (n = 9)</th>
<th>2B5 (n = 8)</th>
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<tbody>
<tr>
<td>Tumors/mouse</td>
<td>58.6±6.0</td>
</tr>
<tr>
<td>Tumor size (mm)</td>
<td>1.14±0.04</td>
</tr>
</tbody>
</table>

* Different superscripts within each row indicate significant differences at P < 0.05.

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**Fig. 1.** Effect of sulindac (S), EPR-A (E), and sulindac + EPR-A (S+E) compared with control (C) on (A) apoptosis, (B) mitosis, and (C) ratio of apoptosis/mitosis in tumors of ApcMin/+ mice as determined histologically after H&E staining. Graphs show mean values in each group (bars, ± SE). Different superscripts indicate differences among groups at P < 0.05.
COX-1 but does not necessarily reduce tumor number in Apc\textsuperscript{Min/+} mice (17), this suggests that COX-1 involvement may be minimal.

In a follow-up experiment, we confirmed the importance of PGE\textsubscript{2} in tumorigenesis by administering an antibody (2B5) that neutralizes PGE\textsubscript{2} in vivo (41). If NSAIDs induce tumor regression by reducing PGE\textsubscript{2} formation, then immunological sequestration of PGE\textsubscript{2} should have a similar effect. Accordingly, administration of 2B5 to Apc\textsuperscript{Min/+} mice with preexisting tumors resulted in significantly fewer tumors relative to controls after 4 days of treatment. Similarly, Stolina et al. (51) observed attenuated tumor growth in mice bearing Lewis lung carcinoma xenografts after treatment with 2B5 along with a concomitant decrease in tissue PGE\textsubscript{2} levels. We failed to see differences in PGE\textsubscript{2} in our tissue samples (data not shown), most likely because of the length of time between administration of the final dose of 2B5 and time of sacrifice (48 h). These experiments suggest that PGE\textsubscript{2} mediates intestinal tumorigenesis and may be required for the maintenance of tumor integrity.

PGE\textsubscript{2} evokes its cellular responses via one or more of the four EP receptors (EP1-EP4), and the EPR-A used in this study were ligands for each receptor subtype (52). It has been reported that activation of EP1 augments intracellular calcium mobilization through a phospholipase C/inositol triphosphate (IP\textsubscript{3})-mediated signaling pathway and also effects CCE. NSAIDs and n-3 polyunsaturated fatty acids, both of which inhibit PGE\textsubscript{2} biosynthesis and tumor regression in Apc\textsuperscript{Min/+} mice (17–19, 58–61). However, EP4 and EP1 are expressed in the intestines of mice, with EP4 being highly expressed in epithelial cells and EP1 in the muscularis mucosa (53) and, thus, are potential candidate receptors for the effects observed with the EPR-A. We used an admixture of two stable analogues of PGE\textsubscript{2}, capable of mimicking the actions of endogenous PGE\textsubscript{2}. Because of the putative involvement of EP1, we used the EP1/EP3 receptor agonist 17-phenyl-trinor-PGE\textsubscript{2}. We also used 16,16-dimethyl-PGE\textsubscript{2} (EP2/EP3/EP4 agonist; Ref. 54), because i.p. administration has been shown previously to partially reverse indomethacin-induced reduction in survival of small intestinal crypt stem cells, the primary site for intestinal tumorigenesis in this model (40). There have been no previous reports on the effects of 17-phenyl-trinor-PGE\textsubscript{2} on the intestinal tract in vivo when administered either i.p. or p.o.

It has been reported that activation of EP1 augments intracellular calcium mobilization through a phospholipase C/inositol triphosphate (IP\textsubscript{3})-mediated signaling pathway and also effects CCE in some cell types (55–57). Our data suggest that NSAIDs may be reducing tumorigenesis in part by attenuating [Ca\textsuperscript{2+}], and that these effects may involve prostaglandin-mediated pathways. When nonexcitable cells are triggered to mobilize intracellular calcium, this is followed by an influx of extracellular calcium to replenish stores (CCE). NSAIDs and n-3 polyunsaturated fatty acids, both of which inhibit PGE\textsubscript{2} biosynthesis and tumor regression in Apc\textsuperscript{Min/+} mice, also prevent CCE in cancer cells in vitro and in vivo, and add-back experiments designed to increase PGE\textsubscript{2} biosynthesis result in augmentation of tumor growth (17–19, 58–61). The link between [Ca\textsuperscript{2+}], and tumorigenesis is strengthened by the fact that voltage-gated L-type calcium channel expression is elevated in colon cancer (62) and colonic tumor cell lines, and blockade of these calcium channels can trigger apoptosis via a caspase-3-dependent mechanism (63). Furthermore, calcium mobi-
lization, CCE, and mitogenesis are increased by epidermal growth factor via a phospholipase C/IP3-mediated pathway (64), effects inhibited by NSAIDs (59, 60). Interruption of this pathway reduced tumor frequency by 52% in Apc\(^{-/+}\) mice, and this effect was augmented by concomitant treatment with sulindac (65), additionally implicating calcium involvement in tumorigenesis.

We report for the first time that intestinal tumors from Apc\(^{-/+}\) mice have elevated [Ca\(^{2+}\)]\(_i\), compared with adjacent normal epithelium. Moreover, we have shown that NSAIDs exert their antitumorigenic effects, in part, by interfering with PGE2 and possibly intracellular calcium signaling. Treatment with the NSAID piroxicam appears to normalize [Ca\(^{2+}\)]\(_i\) in actively regressing tumors, and this effect is attenuated by concomitant treatment with 17-phenyl-trinor-PGE2. These results suggest that NSAIDs may affect tumor integrity, at least in part, via reductions in [Ca\(^{2+}\)]\(_i\), and this effect on [Ca\(^{2+}\)]\(_i\) may be attributable to reductions in PGE2 and its subsequent signaling through EP1. Unlike EP1, EP2-4 agonists have been shown to reduce tumor number by as much as 50%, suggesting that the various EP receptors may be associated with dichotomous outcomes (67).

An unexpected enigma in our data are the apparent antitumorigenic effect of EPR-A (control versus EPR-A; pooled data; \(P = 0.06\)) that seems antithetical to its protumorigenic effects when coadministered with either piroxicam or sulindac. It is possible that activation of the various EP receptors may differentially modulate tumorigenesis such that some receptors promote tumor growth, whereas others promote tumor regression. For example, Lehnert (68) reported that 16,16-dimethyl-PGE\(_2\) significantly reduced carcinogen-induced small intestinal tumors in rats. Moreover, it was reported recently that 16,16-dimethyl-PGE\(_2\) reduced tumor number in Apc\(^{-/+}\) mice by 20–50% after i.p. administration three times per week for 12 weeks (67). This is in agreement with research linking increases in cAMP levels and protein kinase A activity to alterations in proliferation and differentiation in several cancer cell lines including an antiproliferative effect on some colon cancer cell lines, both in vitro and in vivo (69, 70). Additionally, activation of EP2, EP3, or EP4 receptors has been associated with cAMP-mediated growth inhibition of B lymphocytes, NIH-3T3 cells, and mesangial cells in vitro, whereas 17-phenyl-trinor-PGE2 or other EP1 agonists stimulated proliferation (71–73). Perhaps stimulation of the EP1 receptor helps to maintain tumor integrity, whereas activation of one or more of the other EP receptors, i.e., EP4, is involved in the attenuation of tumor number in this model. Therefore, our EPR-A mixture containing both an EP1/EP3 agonist (17-phenyl-trinor-PGE2) and an EP2–4 agonist (16,16-dimethyl-PGE2) may be acting antiindependently.

In summary, inhibition of PGE2 biosynthesis accounts, at least in part, for the antitumorigenicity of NSAIDs. Furthermore, we show that NSAID treatment results in a higher apoptosis/mitosis ratio and lower [Ca\(^{2+}\)]\(_i\), in vitro, and these effects are mediated, in part, by inhibition of PGE2 biosynthesis. Because the EPR-A mixture used for these studies contained ligands for all four of the EP receptors, we are unable to definitively ascribe the effects on tumorigenesis to any one receptor or combination of receptors. However, previous research on receptor expression patterns and roles of select subtypes along with the data presented in this paper suggest that EP1 may be involved in mediating the proliferative effects of PGE2 on intestinal tumorigenesis in this model. Additional investigation will be required to conclusively determine which EP receptor subtype(s) are responsible for the observed effects and whether these might prove to be dichotomous.

ACKNOWLEDGMENTS

We thank Dr. Joseph Portanova of Pharmacia (St. Louis, MO) for generously providing us the 2BS monoclonal anti-PGE\(_2\) antibody and technical assistance in its use.

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