

Suppression of Familial Adenomatous Polyposis by CP-31398, a TP53 Modulator, in *APC^{min/+}* Mice

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Abstract

p53 mutations occur in a large number of human malignancies. Mutant p53 is unable to affect downstream genes necessary for DNA repair, cell cycle regulation, and apoptosis. The styrylquinazoline CP-31398 can rescue destabilized mutant p53 expression and promote activity of wild-type p53. The present study examines chemopreventive effects of CP-31398 on intestinal adenoma development in an animal model of familial adenomatous polyposis. Effects were examined at both early and late stages of adenoma formation. Effects of CP-31398 on early-stage adenomas were determined by feeding 7-week-old female C57BL/6J-*APC^{min}* (heterozygous) and wild-type C57BL/6J mice with American Institute of Nutrition-76A diets containing 0, 100, or 200 ppm of CP-31398 for 75 days. To examine activity toward late-stage adenomas, CP-31398 administration was delayed until 15 weeks of age and continued for 50 days. During early-stage intervention, dietary CP-31398 suppressed development of intestinal tumors by 36% ($P < 0.001$) and 75% ($P < 0.0001$), at low and high dose, respectively. During late-stage intervention, CP-31398 also significantly suppressed intestinal polyp formation, albeit to a lesser extent than observed with early intervention. Adenomas in treated mice showed increased apoptotic cell death and decreased proliferation in conjunction with increased expression of p53, p21^{WAF1/CIP}, cleaved caspase-3, and cleaved poly(ADP-ribose) polymerase. These observations show for the first time that the p53-modulating agent CP-31398 possesses significant chemopreventive activity *in vivo* against intestinal neoplastic lesions in genetically predisposed *APC^{min/+}* mice. Chemopreventive activity of other agents that restore tumor suppressor functions of mutant p53 in tumor cells is currently under investigation. [Cancer Res 2008;68(18):7670–5]

Introduction

Colorectal cancer is a leading cause of cancer death in Western countries, including the United States. About 145,290 new cases of colorectal cancer and 56,290 related deaths are expected in 2008 (1). Epidemiologic and experimental studies indicate that the risk of developing colon cancer may be attributable to genetic and environmental factors, including endogenously occurring promoting agents (2). Progression of normal epithelium to colon cancer is a multistep process involving accumulation of multiple genetic

alterations (3, 4). The p53 tumor suppressor protein is involved in DNA damage repair, cell cycle arrest, and apoptosis through transcriptional regulation of genes implicated in these pathways and by direct interaction with other proteins (5, 6). Although nonmutational activation of p53 may occur very early during cancer progression (7), mutations that inactivate p53 are present in more than 50% of all cancers, including colon cancer, giving rise to aggressive cancers that are difficult to treat by chemotherapy or ionizing radiation (7, 8). p53 mutations alter the structure and thermal stability of the protein (9, 10), affecting its ability to bind to p53 response elements and regulate transcription of downstream genes (11). In addition, we and others have shown that increased levels of electrophilic lipids bind with p53 and block its nuclear translocation, leading to reduced p53 activity (12).

Several attempts to restore mutant p53 as growth suppressor included microinjection of monoclonal antibody 421, COOH-terminal peptide of p53, and small molecules such as CP-31398 and PRIMA-1 (13–19). Early on, we determined that dietary CP-31398 protects against chemically induced early colonic neoplastic lesions (20). More recently, Wang and colleagues (21) showed that p53 modulators suppress growth of human colon tumor xenografts. Similarly, Tang and colleagues (22) found that CP-31398 suppressed UAB-induced squamous skin cancer in mice by restoring mutant p53 function. In this regard, CP-31398 can stabilize p53, protect against thermal denaturation, and maintain monoclonal antibody 1620 epitope conformation in newly synthesized p53 (16). CP-31398 stabilizes wild-type p53 in cells by inhibiting Mdm2-mediated ubiquitination and degradation (18, 23). In a chromatin immunoprecipitation assay, CP-31398 promotes binding of mutant p53 to p53 response elements *in vivo* (24). Other studies using the purified p53 core domain have shown that CP-31398 can restore DNA-binding activity to mutant p53 *in vitro* (25). Given the multifunctional properties of p53 in cell pathway regulation, it is difficult to determine the exact mechanism by which CP-31398 and other p53 modulators affect p53-induced growth arrest or apoptosis.

As part of a study of p53-modulating agents, we identified a tolerable dose of CP-31398 and showed its efficacy in a well-established (*APC^{min/+}*) model of mouse intestinal neoplasia. We also determined the effects of CP-31398 on intestinal tumor proliferation, apoptosis, and levels of p53, p21^{WAF1/CIP}, cleaved caspase-3, and cleaved poly(ADP-ribose) polymerase (PARP).

Materials and Methods

Animals, diets, and CP-31398. Heterozygous female Min (C57BL/6J-*APC^{min/+}*) and wild-type C57BL/6J female mice were obtained at 5 wk of age from The Jackson Laboratory. Ingredients for the semipurified diets were purchased from Dyets, Inc. and stored at 4°C before diet preparation. Diets were based on the modified American Institute of Nutrition (AIN)-76A diet. The high-fat semipurified diet includes 21.3% casein, 43.5% corn starch, 12% dextrose, 12% corn oil, 5% alphasel, 3.5% AIN mineral mix, 1.2% AIN revised

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vitamin mix, 0.3% D,L-methionine, and 0.2 choline bitartrate (26). CP-31398 was premixed with a small quantity of diet and then blended into bulk diet using a Hobart mixer. Both control and experimental diets were prepared weekly and stored in a cold room. CP-31398 was kindly provided by the National Cancer Institute chemopreventive drug repository (Rockville, MD). Agent content in the experimental diets was determined periodically in multiple samples taken from the top, middle, and bottom portions of individual diet preparations to verify uniform distribution.

Maximum tolerated dose. To estimate the appropriate dose level for the efficacy study, maximum tolerated dose (MTD) was determined in female C57BL/6J mice by feeding CP-31398 in a 6-wk toxicity study. MTD was defined as the highest dose that causes no more than a 10% body weight decrement or produces mortality or any external signs of toxicity that would be predicted to shorten the natural life span of the animal. At 7 wk of age, groups of female C57BL/6J mice (six per group) were fed experimental diets containing 0, 75, 150, 300, 600, or 1,200 ppm of CP-31398, and body weights were recorded twice weekly for 6 wk. All animals were monitored daily for signs of toxicity, such as ill appearance, circling rashes, tremors, roughened coat, rhinitis, chromodacryorrhea, and prostration. At the end of 6 wk, mice were sacrificed and their oral cavity, colon, small intestine, stomach, liver, and kidneys were examined for any abnormalities under a dissection microscope.

Efficacy study. The experimental protocol is summarized in Fig. 1. Following 5 d of quarantine, all mice were distributed so that average body weights in each group were about equal (10 *APC^{min/+}* mice in each group and 6 wild-type mice as parallel treatment groups to compare food intake, growth rate, and tumor formation in *APC^{min/+}*). The animals were transferred to a holding room where they were housed individually in plastic cages with filter tops. Laboratory conditions were controlled to maintain a 12-h light/dark cycle at 50% relative humidity and at $21 \pm 1^\circ\text{C}$. Mice were fed control or experimental diets containing 100 or 200 ppm of CP-31398 at either early intervention (7 wk of age) or late intervention (15 wk of age) until termination of the study (~75 d for early intervention, 50 d for late intervention). Animals were weighed twice weekly and monitored daily for signs of weight loss or lethargy that might indicate intestinal obstruction or anemia. After necropsy, intestinal tracts were dissected from esophagus to distal rectum, spread onto filter paper, opened longitudinally with fine scissors, and cleaned with sterile saline, and then

examined under a dissection microscope with $\times 5$ magnification for tumor counts. This procedure was completed by two individuals who were blinded to experimental group and genetic status of mice. Colonic and other small intestinal tumors that required further histopathologic evaluation to identify adenoma, adenocarcinoma, and enlarged lymph nodes were fixed in 10% neutral-buffered formalin, embedded in paraffin blocks, and processed by routine H&E staining. In addition, multiple samples of tumors from the small intestines and colons and normal-appearing colonic mucosa were harvested and stored in liquid nitrogen for analysis of p53, cleaved caspase-3, and cleaved PARP expression levels.

Immunohistochemistry. To evaluate the effect of CP-31398 on proliferation, we assessed proliferating cell nuclear antigen (PCNA) expression in large intestinal tumor tissue (delayed intervention) sections by immunohistochemistry, as described (16). Briefly, paraffin-embedded colons from the delayed intervention study were cut longitudinally to 5- μm -thick sections and mounted on microscopic slides. After deparaffinization, sections were blocked for endogenous peroxidase activity and incubated with 1% milk. PCNA antibody (PharMingen) was applied at a 1:200 dilution for 1 h at room temperature, then washed and incubated with secondary anti-rabbit IgG for 30 min, and then washed and incubated with avidin-biotin complex reagent (Vector Laboratories). After rinsing with PBS, the slides were incubated with the chromogen 3,3'-diaminobenzidine (DAB) for 3 min and then rinsed and counterstained with hematoxylin. Scoring was performed by two investigators blinded to the identity of the samples who scored at least 30 crypts per colon (light microscopy at $\times 400$ magnification). Cells with a brown nucleus were considered positive. The proliferation index was determined by dividing the number of positive cells per crypt by the number of cells of the entire crypt or each of its compartments (upper, middle, and lower) and multiplying by 100.

Apoptosis. Large intestinal tumor tissues from delayed intervention were fixed in 10% formalin for 24 h and then embedded in paraffin. Sections, ~5 μm , were cut and mounted on slides, rehydrated, and stained using the terminal deoxynucleotidyl transferase (TdT)-mediated dUTP nick end labeling (TUNEL) method. Briefly, slides were incubated with 3% H_2O_2 in PBS for 5 min, rinsed, and then incubated in TdT buffer [140 mmol/L cacodylate (pH 7.2), 30 mmol/L Tris-HCl, 1 mmol/L CoCl_2] for 15 min at room temperature. TdT reaction mixture [0.2 unit/ μL TdT, 2 nmol/L biotin-11-dUTP, 100 mmol/L cacodylate, 2.5 mmol/L CoCl_2 , 0.1 mmol/L DTT, and

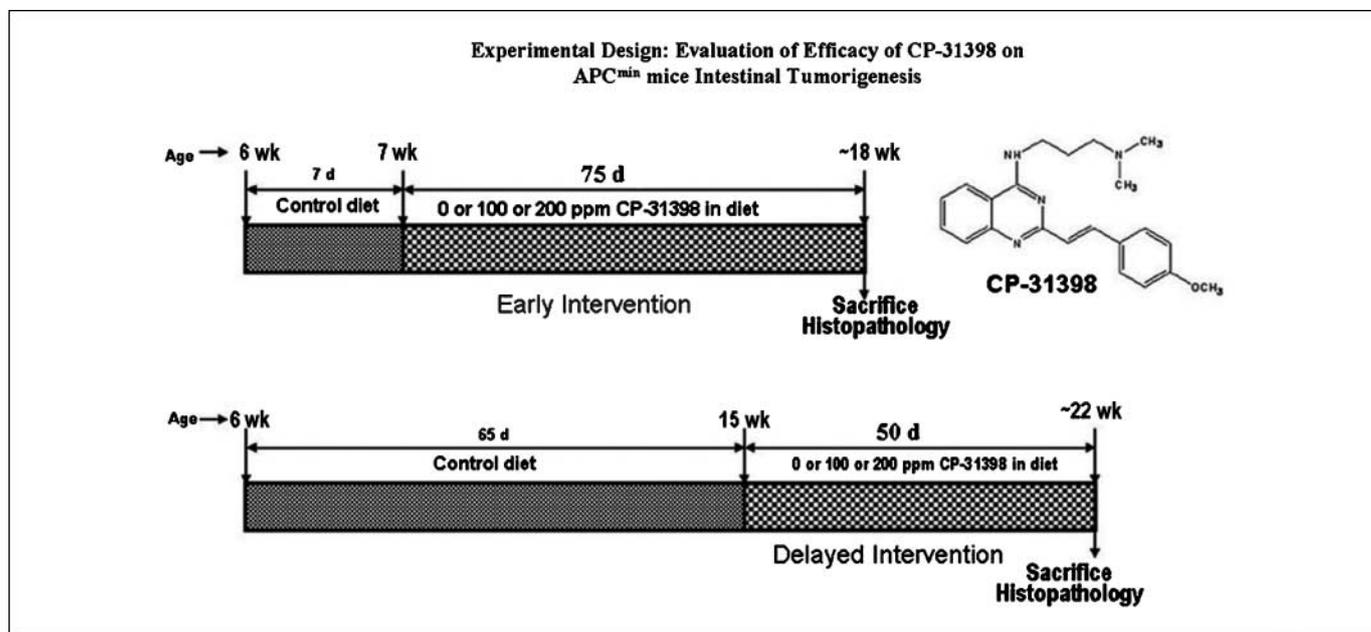


Figure 1. Experimental protocol for the evaluation of chemopreventive activity of CP-31398 in *APC^{min/+}* mice model. Groups of mice were fed control diet (AIN-76A) or diets containing 100 or 200 ppm of CP-31398 administered at 7 wk of age for 75 d (*Early Intervention*) or 15 wk of age for 50 d (*Delayed Intervention*). Detailed information has been given in Materials and Methods.

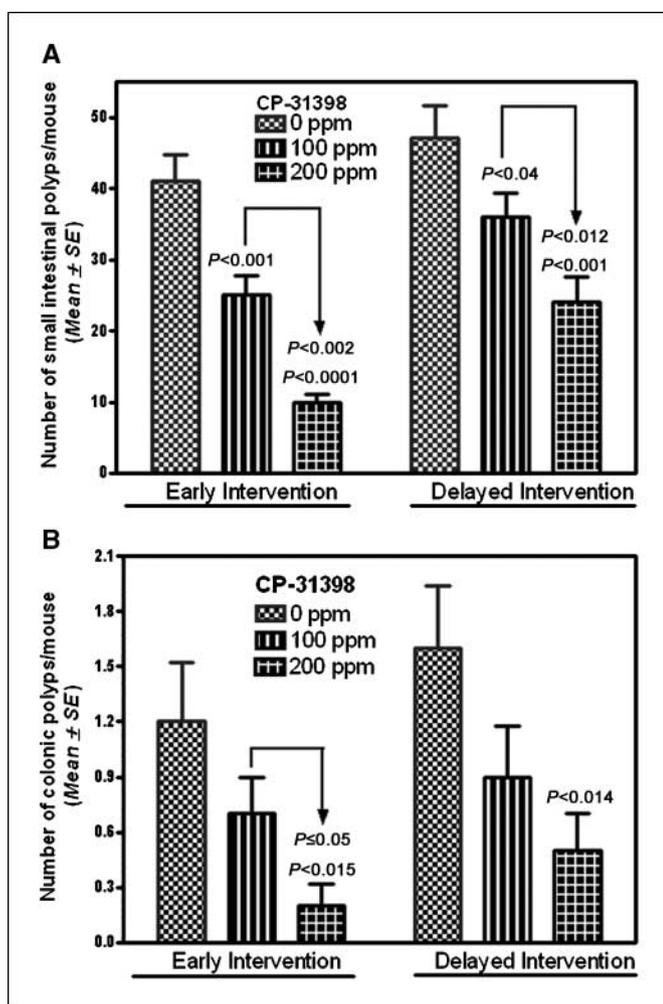


Figure 2. A, effect of CP-31398 on intestinal tumor formation in *APC^{min/+}* mice. Number of intestinal tumors in *APC^{min/+}* mice administered control and experimental diets containing 100 and 200 ppm of CP-31398 either early intervention (7 wk of age) or late intervention (15 wk of age). Columns, mean ($n = 10$); bars, SE. Significance between control and treatment groups was analyzed by *t* test. B, effect of CP-31398 on colon tumor formation in *APC^{min/+}* mice. Number of colon tumors in *APC^{min/+}* mice administered control and experimental diets. Columns, mean ($n = 10$); bars, SE. Significance between control and treatment groups was analyzed by *t* test.

0.05 mg/mL bovine serum albumin (BSA)] was added, and the slides were incubated for an additional 30 min at 37°C. After blocking with 2% BSA and incubation with avidin-biotin peroxidase complexes, the TUNEL reaction was visualized by chromogenic staining with DAB, and slides were counterstained by malachite green. Stained apoptotic epithelial cells (a minimum of 10 microscopic fields per section) were counted manually in a single-blind fashion.

Western blot analysis of p53, p21^{WAF1/CIP}, cleaved caspase-3, and cleaved PARP. Intestinal polyps isolated from individual mice were combined to obtain sufficient tissue (six to eight samples per group). Normal-appearing intestinal mucosal samples were homogenized in 1:3 volume of 100 mmol/L Tris-HCl buffer (pH 7.2) with 2 mmol/L CaCl₂. After centrifugation at 100,000 × *g* for 1 h at 4°C, the resulting separations were subjected to 8% SDS-PAGE for p53 and cleaved PARP, and 12% for p21 and cleaved caspase-3. The proteins were electroplated onto polyvinylidene difluoride nitrocellulose membranes as described previously (26). These membranes were blocked for 1 h at room temperature with 5% skim milk powder and probed with primary antibodies for 1 h. The primary antibodies p53, p21, cleaved caspase-3, and cleaved PARP (Santa Cruz Biotechnology) were used at 1:500 dilution. Blots were washed thrice and incubated with

secondary antibodies conjugated with horseradish peroxidase (Santa Cruz Biotechnology) at 1:2,500 dilution for 1 h. The membranes were washed thrice and incubated with SuperSignal West Pico Chemiluminescent Substrate (Pierce Chemical Co.) for 5 min, exposed to Kodak XAR5 photographic film, and developed to detect proteins. Intensities of each band were scanned by a computing densitometer. α -Tubulin (Ab-1) mouse monoclonal antibody (Oncogene) was used at 1:1,000 dilution as the internal standard for all Western blots.

Statistical analyses. All results are expressed as mean \pm SE and were analyzed by Student's *t* test. Differences were considered significant at the $P < 0.05$ level.

Results

MTD and dose selection for efficacy studies. The administration of CP-31398 at 600 and 1,200 ppm in the diet for 6 weeks reduced body weight of mice by 14% and 42%, respectively, compared with control diet-fed mice. At doses up to 300 ppm, CP-31398 did affect body weight. Based on these findings, 100 and 200 ppm of CP-31398 were selected for efficacy studies. At these doses, CP-31398 had no apparent adverse effects on mice during either the 75-day (early intervention) or 50-day (late intervention) efficacy studies. Body weights of all mice fed diets containing 100 or 200 ppm were comparable; however, body weights of mice

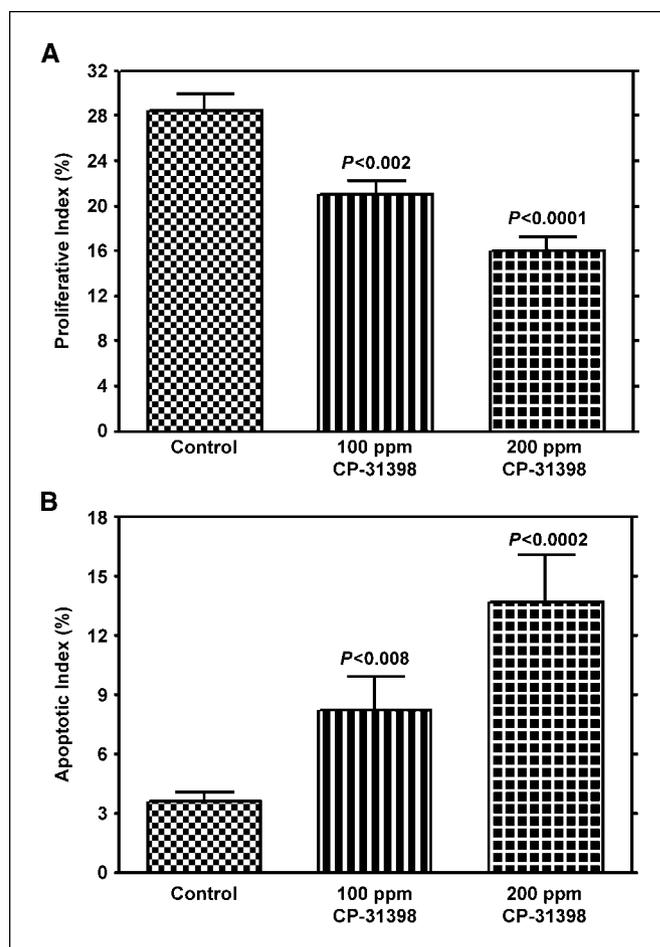


Figure 3. Effect of 100 and 200 ppm of CP-31398 (administered as late intervention) on large intestinal tumor cell proliferation (A) and apoptotic index (B) in *APC^{min/+}* mice. Columns, mean; bars, SE. Significance was analyzed by *t* test.

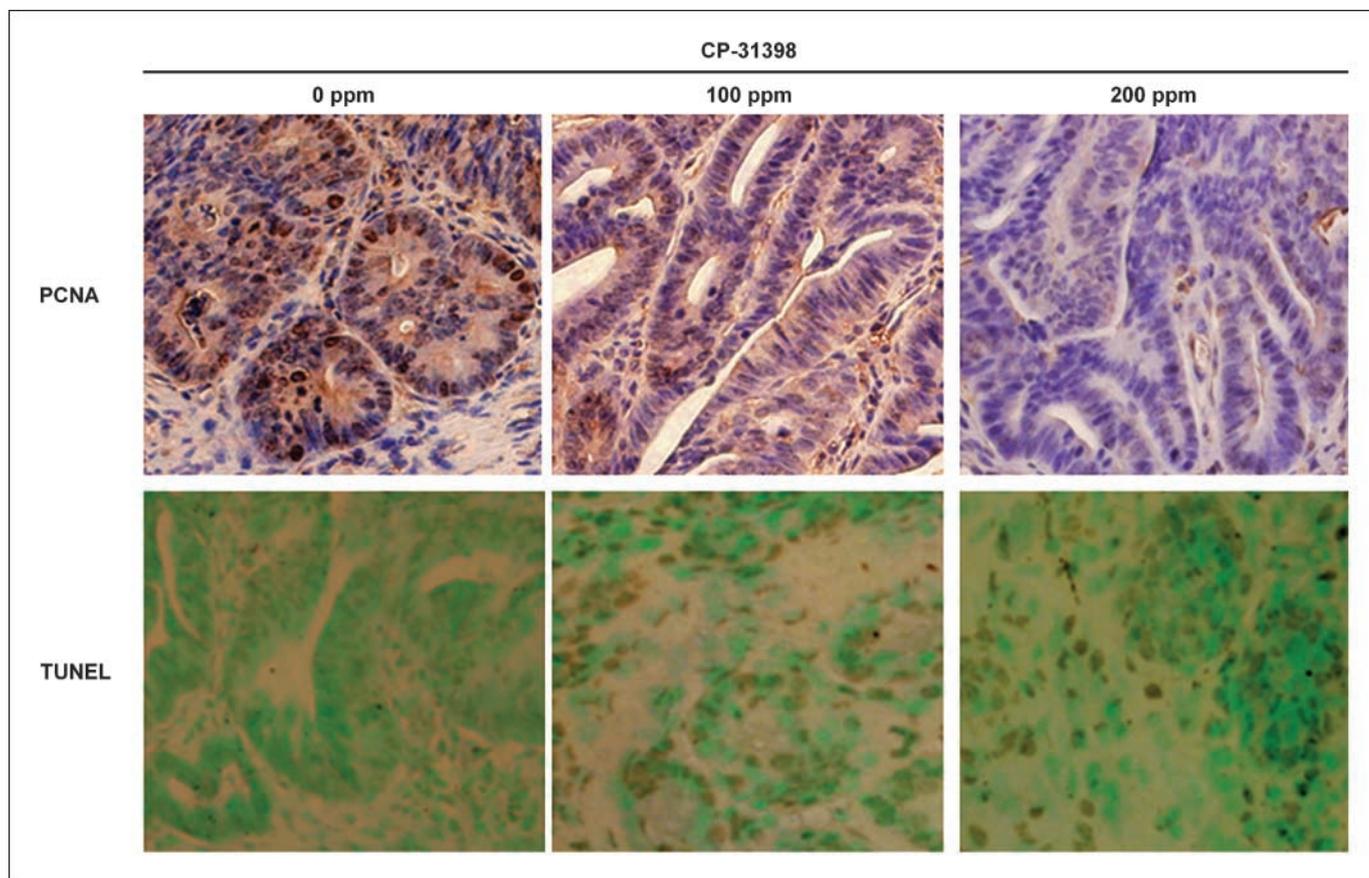


Figure 4. Immunohistochemical staining of cell proliferation (PCNA) and apoptosis (TUNEL) in colonic tumors of mice exposed to 0, 100, or 200 ppm of CP-31398 (delayed intervention). Representative DAB-stained (brown colored) cells either PCNA or TUNEL are depicted at $\times 400$ magnifications.

fed the control diet were significantly lower (data not shown). This was due mainly to increased small intestinal tumor burden in controls that resulted in impaired food absorption and anemia. Chronic administration of CP-31398 produced no signs of toxicity or any gross changes indicative of toxicity in the organs examined.

Effects on intestinal tumor formation. $APC^{min/+}$ mice spontaneously develop intestinal tumors, essentially all of which (>95%) occur in the small intestine. In this study, on average, mice developed 17 to 58 (early intervention) or 25 to 67 (delayed intervention) tumors per mouse in the small intestine, but only 0 to 3 tumors per mouse in the colon. All histopathologically classified tumors in the small intestine, as well as those in the colon, were adenomas (adenomatous polyps), with no evidence of local invasion of the lamina propria. Figure 2A summarizes the chemopreventive effect of CP-31398 administered at 100 or 200 ppm on tumor multiplicity in the small intestine. In the early intervention study, the low and high dose of CP-31398 significantly suppressed polyp formation by 39% ($P < 0.001$) and 75.6% ($P < 0.0001$), respectively, compared with controls. In the delayed intervention study, low and high doses of CP-31398 significantly suppressed small intestinal polyp formation by 23% ($P < 0.04$) and 48% ($P < 0.001$), respectively, compared with controls. Data were also analyzed for the colon alone. In the early intervention study, the mean number of tumors per mouse was 1.2 in controls, 0.7 in the low-dose group, and 0.2 in the high-dose group. Delayed intervention found multiplicity of 1.6, 0.9, and 0.5 in control, low-dose, and high-dose groups, respectively. Although both 100 and

200 ppm of CP-31398 reduced colon tumor multiplicity, only the higher dose produced statistically significant inhibition (Fig. 2B). In addition, we observed statistically significant difference between the mice fed 100 and 200 ppm of CP-31398 in small intestinal tumor multiplicity both in interventions and in colon tumors of early intervention (Fig. 2A and B).

Effects on tumor cell proliferation and apoptosis. Figures 3A and 4 summarize the effects of CP-31398 on tumor cell proliferation in the late intervention study as measured by PCNA overexpression. CP-31398 dose dependently suppressed proliferation. In the 100 ppm group, proliferation was diminished by 24.5% ($P < 0.002$), and in the 200 ppm group, by 37% ($P < 0.0001$). Figures 3B and 4 show the effects of CP-31398 on tumor cell apoptosis. Compared with controls, low and high doses of CP-31398 induced a 2.2- and 3.8-fold increase in intestinal tumor cell apoptosis.

Modulation of p53, p21^{WAF1/CIP}, cleaved caspase-3, and cleaved PARP. Expression levels of p53, p21^{WAF1/CIP}, cleaved caspase-3, and cleaved PARP are important indicators of cell growth arrest and apoptosis. As shown in Fig. 5A, CP-31398 dose dependently induced expression of p53 protein in intestinal tumor tissues in both early and late intervention protocols. In addition, tumors in mice fed CP-31398 showed significant induction of p21^{WAF1/CIP} expression when compared with controls. However, although CP-31398 effected a dose-dependent increase in p21^{WAF1/CIP} during early intervention, no such effect was seen in late intervention (Fig. 5A). Figure 5B and C shows the proteolytic cleavage of PARP and caspase-3 activation, two hallmarks of

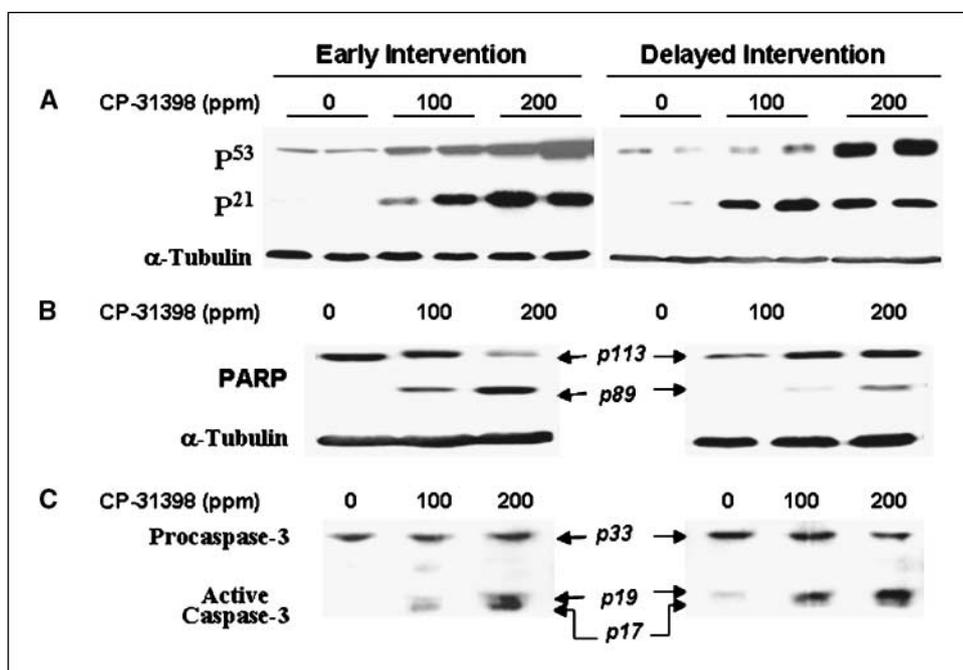


Figure 5. Expression levels of p53, p21, cleaved PARP, and cleaved caspase-3 protein from tumor samples of mice administered with 100 and 200 ppm of CP-31398 either early or late intervention protocols. Intestinal tumor tissue lysates were homogenized in lysis buffer and subjected to SDS-PAGE followed by Western blotting as described in Materials and Methods. Membranes were probed for p53-specific, p21^{CIP1}-specific, cleaved caspase-3-specific, and cleaved PARP-specific primary antibodies and then peroxidase-conjugated appropriate secondary antibodies. Proteins were visualized with enhanced chemiluminescence detection system.

apoptosis, in intestinal tumors. Augmented cleaved PARP and caspase-3 were clearly observed in mice fed CP-31398 compared with control diet-fed mice.

Discussion

p53 mutations are common in many human cancers, including colorectal cancer (8, 27). Restoring mutant p53 function and/or enhancing wild-type p53 by genetic means suppresses growth of various tumor types (11, 12, 27). The identification of CP-31398 and other small molecules such as PRIMA-1 that activate mutant p53 could constitute an effective pharmacologic approach for cancer prevention/treatment (28–33). Although CP-31398 has been extensively studied in *in vitro* models (13–19, 28, 29), only a few studies have assessed the tumor inhibitory potential of CP-31398 *in vivo* (20–22).

In this study, we evaluated the toxicity, optimal dosing, tumor inhibition, and effectiveness on selected molecular targets of CP-31398. Our results are the first to show that CP-31398 effectively suppresses intestinal tumor formation whether given early or late in polyp formation. It is important to note, however, that CP-31398 showed a more pronounced effect on tumor suppression when administered early during tumor development, suggesting its potential usefulness as a chemopreventive agent. The present results further corroborate the anticarcinogenic effects of CP-31398 against UVB-induced skin carcinogenesis in mice and chemically induced colon carcinogenesis in rats (20, 22). In the skin model, CP-31398 was administered either *i.p.* or topically; in the present study, CP-31398 was administered in the diet. By all routes of administration, CP-31398 showed antitumor effects. Compared with previous studies in the *APC*^{min/+} model, the efficacy of CP-31398 in this study is dramatic and comparable with nonsteroidal anti-inflammatory drugs (e.g., celecoxib and sulindac) and other agents (26, 34–37). *APC*^{min/+} mice are an appropriate model for human colon cancer, as the mechanism of *APC* gene inactivation mimics that observed in familial adenomatous polyposis patients and most sporadic human colon adenomas (34, 38).

The mechanisms through which p53 inhibits cell proliferation and induces apoptosis have been studied in *in vitro* models (5–8). In the present study, CP-31398 suppressed tumor cell proliferation and induced apoptosis in conjunction with up-regulation of p53 and its downstream effector p21. These results are consistent with previous studies showing an increase in p53 target genes by CP-31398, as well as in p53 reporter gene expression in cancer cells (11, 13, 29, 39).

The importance of p53 mutations in colon cancers is well established (8, 27). However, in the *APC*^{min/+} model, p53 mutations are likely a late event in tumor development. This suggests that restoration of mutant p53 function plays a minor role in the tumor inhibitory activity of CP-31398 seen in this study. On the other hand, activation of wild-type p53 by CP-31398 might be a major mechanism leading to suppression of tumor growth in *APC*^{min/+} mice. In this regard, activation of wild-type p53 by CP-31398 has been shown in other models, both *in vitro* and *in vivo* (16–22). It is also possible that CP-31398 affects additional targets. Regardless of its exact mechanism, the finding that CP-31398 given either early or late in tumor development can suppress tumor growth indicates that p53 is a rational target for chemoprevention of colorectal cancer. Ultimately, the combined use of low molecular weight p53-modulating agents acting through different mechanisms (e.g., CP-31398 and PRIMA-1) or combinations with agents targeting other molecular pathways is likely to substantially increase antitumor effects. Taken together, these findings support further development of CP-31398 for colon cancer prevention and treatment.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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