Inhibitory Effects of Dietary Curcumin on Forestomach, Duodenal, and Colon Carcinogenesis in Mice

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ABSTRACT

Curcumin (diferuloylmethane), a yellow pigment that is obtained from the rhizomes of Curcuma longa Linn., is a major component of turmeric and is commonly used as a spice and food-coloring agent. The inhibitory effects of feeding commercial grade curcumin (77% curcumin, 17% demethoxycurcumin, and 3% bisdemethoxycurcumin) in AIN 76A diet on carcinogen-induced tumorigenesis in the forestomach, duodenum, and colon of mice were evaluated. Administration p.o. of commercial grade curcumin in the diet inhibited benzo(a)pyrene-induced forestomach tumorigenesis in A/J mice, N-ethyl-N'-nitro-N-nitrosoguanidine-induced duodenal tumorigenesis in C57BL/6 mice, and azoxymethane (AOM)-induced colon tumorigenesis in CF-1 mice. Dietary commercial grade curcumin was given to mice at: (a) 2 weeks before, during, and for 1 week after carcinogen administration (during the initiation period); (b) 1 week after carcinogen treatment until the end of the experiment (during the postinitiation period); or (c) during both the initiation and postinitiation periods. Feeding 0.5–2.0% commercial grade curcumin in the diet decreased the number of benzo(a)pyrene-induced forestomach tumors per mouse by 51–53% when administered during the initiation period and 47–67% when administered during the postinitiation period. Feeding 0.5–2.0% commercial grade curcumin in the diet decreased the number of N-ethyl-N'-nitro-N-nitrosoguanidine-induced duodenal tumors per mouse by 47–77% when administered during the postinitiation period. Administration of 0.5–4.0% commercial grade curcumin in the diet both during the initiation and postinitiation periods decreased the number of AOM-induced colon tumors per mouse by 51–62%. Administration of 2% commercial grade curcumin in the diet inhibited the number of AOM-induced colon tumors per mouse by 66% when fed during the initiation period and 25% when fed during the postinitiation period. The ability of commercial grade curcumin to inhibit AOM-induced colon tumorigenesis is comparable to that of pure curcumin (purity greater than 98%). Administration of pure or commercial grade curcumin in the diet to AOM-treated mice resulted in development of colon tumors which were generally smaller in number and size as compared to the control group of AOM-treated mice. These results indicate that not only did curcumin inhibit the number of tumors per mouse and the percentage of mice with tumors but it also reduced tumor size. Histopathological examination of the tumors showed that dietary curcumin inhibited the number of papillomas and squamous cell carcinomas of the forestomach as well as the number of adenomas and adenoscarcinomas of the duodenum and colon.

INTRODUCTION

Epidemiology studies indicate that dietary habits play an important role in the development of many human cancers (1, 2). Large numbers of minor food components and chemically related compounds block different stages of the carcinogenic process in animal models (3) and some of these substances partially prevent or delay cancer formation in some high risk human populations (4–6).

The powdered dry rhizome of the plant Curcuma longa Linn. (turmeric) has long been used as a naturally occurring medicine for the treatment of inflammatory diseases (7). Curcumin (diferuloylmethane), the major yellow pigment in turmeric, curry, and mustard, is the major antioxidant and anti-inflammatory substance in turmeric (8). Turmeric and curcumin have been widely used as coloring agents and/or spices in foods as well as in cosmetics and drugs (8). The chemical, biological, and pharmacological properties of curcumin and turmeric have been reviewed elsewhere (7–10). Recently, we showed that application of curcumin to the skin of mice strongly inhibited TPA3-induced inflammation (mouse ear edema), epidermal ornithine decarboxylase activity, ornithine decarboxylase mRNA, hyperplasia, and formation of hydrogen peroxide (9, 11, 12). We also showed that curcumin inhibited TPA-induced progression of epidermal cells through the cell cycle (9). The anti-inflammatory and anti-tumor-promoting activities of curcumin could be explained by the potent inhibitory effects of curcumin on arachidonic acid-induced inflammation and on arachidonic acid metabolism through both the cyclooxygenase and lipoxigenase pathways in mouse epidermis (9, 13).

Additional studies by Flynn et al. (14) showed inhibitory effects of curcumin on 5-lipoxygenase activity in human neutrophils and on cyclooxygenase activity in bovine seminal vesicle. In other studies, it was found that topical application of curcumin inhibited the covalent binding of [3H]B(a)P to epidermal DNA and inhibited the tumor-initiating activity of B(a)P and 7,12-dimethylbenz(a)anthracene in mouse skin (15). In an earlier study, we found that dietary curcumin inhibited AOM-induced dysplasia in mouse colon (16). In the present report, we describe inhibitory effects of dietary curcumin on B(a)P-induced forestomach carcinogenesis, ENNG-induced duodenal carcinogenesis, and AOM-induced colon carcinogenesis in mice.

MATERIALS AND METHODS

Chemicals and Reagents. TPA was obtained from the LS Services Corp. (Woburn, MA). Pure curcumin (purity, >98%) and commercial curcumin (turmeric type 97; containing 77% curcumin, 17% demethoxycurcumin, and 3% bisdemethoxycurcumin) were purchased from Kalsec, Inc. (Kalamazoo, MI). Commercial grade curcumin (curcumin) was used for all studies except when indicated that pure curcumin was used. Ten % buffered formalin (10% formalin in neutral phosphate buffer) was purchased from Fisher Scientific (Springfield, NJ). B(a)P (purity, >98%) and AOM were obtained from the Sigma Chemical Co. (St. Louis, MO). ENNG (purity, >97%) was obtained from the Aldrich Chemical Company (Milwaukee, WI).

Animals. Female A/J mice (4–5 weeks old) were purchased from The Jackson Laboratory (Bar Harbor, ME). Male C57BL/6 mice (5 weeks old), female CD-1 mice (4–5 weeks old), and female CF-1 mice (4–5 weeks old) were purchased from the Charles River Laboratories (Kingston, NY). For female mice, 10 animals were placed in each plastic cage. Male mice were housed individually. The animals were maintained under the following standard conditions: 22 ± 2°C, 45 ± 10% relative humidity, and 12-h light/12-h dark cycles each day. All animals were fed AIN 76A diet (Research Diets, Inc., New Brunswick, NJ) and water ad libitum. All feeds were pelleted to avoid stratification and to assure uniform feed and curcumin intake in the treated animals.

B(a)P-Induced Forestomach Tumorigenesis. B(a)P-induced forestomach tumorigenesis in A/J mice was performed according to the procedure described by Wattenberg (17) with slight modification. Female A/J mice (6 weeks old)

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1 This study was supported by Grant CA49756 from the NIH.

2 William M. and Myrtle W. Garbe Professor of Cancer and Leukemia Research.

3 The abbreviations used are: TPA, 12-O-tetradecanoylphorbol-13-acetate; AOM, azoxymethane; B(a)P, benzo(a)pyrene; ENNG, N-ethyl-N'-nitro-N-nitrosoguanidine.
were treated with 100 μl of corn oil or 1.5 mg of B(a)P in 100 μl corn oil by p.o. gavage once weekly for 4 weeks. Twenty mice were used for group 1 (negative control), 41 mice were used for group 2 (B(a)P-treated positive control), and 30 mice were used for all other groups. In group 1, the mice were intubated with 100 μl corn oil once weekly for 4 weeks. In all other groups, the mice were intubated with 1.5 mg of B(a)P in 100 μl of corn oil once weekly for 4 weeks. Mice in groups 1 and 2 were given semisynthetic AIN 76A diet and water ad libitum from 2 weeks before administration of carcinogen until the end of the experiment. Mice in groups 3 and 4 were given 0.5% or 2.0% commercial grade curcumin, respectively, in AIN 76A diet and water ad libitum 2 weeks before, during, and 1 week after the last dose of B(a)P (initiation period). Mice in groups 5 and 6 were given 0.5% or 2.0% commercial grade curcumin, respectively, in AIN 76A diet and water ad libitum beginning 1 week after the last dose of B(a)P until the end of the experiment (postinitiation period). The mice were killed 24 weeks after the last dose of B(a)P. Ten % buffered formalin-phosphate was immediately injected into the stomach by intubation into the mouth, so that the stomach was distended and fixed. Each stomach was removed and placed on a plastic sheet, and the number of tumors in each forestomach was determined. The samples were stored in 10% buffered formalin-phosphate for histological examination.

**ENNG-induced Duodenal Tumorigenesis.** The experiments on ENNG-induced duodenal tumorigenesis in male C57BL/6 mice were performed according to the procedure described by Fujita et al. (18) with slight modifications. The mice (6 weeks old) were given AIN 76A diet and ENNG (120 mg/liter) as the sole source of drinking water ad libitum for 4 weeks. One week later, all mice were shifted to water and fed AIN 76A diet or 0.5%–2.0% commercial grade curcumin in AIN 76A diet for 16 weeks, and the mice were killed by cervical dislocation. Ten % buffered formalin-phosphate was immediately injected into the stomach, duodenal, and colonic samples were excised and fixed in 10% buffered formalin-phosphate for histological examination.

**AOM-induced Colon Tumorigenesis.** AOM-induced colon tumorigenesis was performed according to the procedure of Deschner et al. (19) with slight modifications. Female CF-1 mice (6 weeks old) were given s.c. injections of AOM (10 mg/kg body weight) in 100 μl of normal saline once weekly for 6 weeks. Mice in groups 1 and 2 were given AIN 76A diet. Mice in groups 3–5 were given 0.5, 2.0, or 4.0% commercial grade curcumin in AIN 76A diet and water ad libitum 2 weeks before, during, and 1 week after the last dose of AOM (initiation period). Mice in groups 6 and 7 were given 0.5% or 2.0% commercial grade curcumin, respectively, in AIN 76A diet and water ad libitum beginning 1 week after the last dose of AOM until the end of the experiment (postinitiation period). The mice were killed 24 weeks after the last dose of AOM. Ten % buffered formalin-phosphate was immediately injected into the colon by intubation into the anus, so that the colon and intestine were distended and fixed. Each colon was removed and placed on a plastic sheet, and the number of tumors in each colon was determined. The colon samples were stored in 10% buffered formalin-phosphate for histological examination.

**Histological Examination of Tumors.** All tumors were examined with the aid of a magnifying lens, and tumor size was measured. Tumors found by visual examination were confirmed by histological examination. The forestomach, duodenal, and colonic samples were excised and fixed in 10% buffered formalin-phosphate. The tumor samples were embedded in paraffin and processed for histology with hematoxylin and eosin staining. Slides were read in blind fashion by two pathologists (Y-R. L. and K. R. R.), and the tumors were classified as described elsewhere (21, 22).

**Statistical Analysis.** The significance of our data was determined with the Student’s t test.

**RESULTS**

**Inhibitory Effect of Dietary Curcumin on B(a)P-induced Fore-stomach Tumorigenesis.** Treatment of A/J mice with 1.5 mg of B(a)P by gavage once a week for 4 weeks resulted in 4.9 forestomach tumors/ mouse. When treated with 0.5% curcumin from 2 weeks before, during, and 1 week after the last dose of B(a)P, the number of tumors was reduced by 55% (P < 0.001). Inhibition was also observed in mice that received 2.0% curcumin from 2 weeks before, during, and 1 week after the last dose of B(a)P (52)

**Histological Examination of Tumors.** All tumors were examined with the aid of a magnifying lens, and tumor size was measured. Tumors found by visual examination were confirmed by histological examination. The forestomach, duodenal, and colonic samples were excised and fixed in 10% buffered formalin-phosphate. The tumor samples were embedded in paraffin and processed for histology with hematoxylin and eosin staining. Slides were read in blind fashion by two pathologists (Y-R. L. and K. R. R.), and the tumors were classified as described elsewhere (21, 22).

**Statistical Analysis.** The significance of our data was determined with the Student’s t test.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Body wt/ mouse (g)</th>
<th>Papillomas /mouse</th>
<th>% of mice with papillomas</th>
<th>Squamous cell carcinomas</th>
<th>% of mice with carcinomas</th>
<th>Total tumors</th>
<th>% of mice with tumors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vehicle + AIN 76A</td>
<td>20</td>
<td>26.9 ± 0.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. B(a)P + AIN 76A</td>
<td>37</td>
<td>26.5 ± 0.7</td>
<td>4.4 ± 0.4</td>
<td>97</td>
<td>0.5 ± 0.1</td>
<td>41</td>
<td>4.9 ± 0.4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Curcumin administration during the initiation period.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Body wt/ mouse (g)</th>
<th>Papillomas /mouse</th>
<th>% of mice with papillomas</th>
<th>Squamous cell carcinomas</th>
<th>% of mice with carcinomas</th>
<th>Total tumors</th>
<th>% of mice with tumors</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. B(a)P + 0.5% curcumin</td>
<td>30</td>
<td>26.3 ± 0.4</td>
<td>2.1 ± 0.3</td>
<td>87</td>
<td>0.2 ± 0.1</td>
<td>23</td>
<td>2.3 ± 0.3</td>
<td>90</td>
</tr>
<tr>
<td>4. B(a)P + 2.0% curcumin</td>
<td>29</td>
<td>25.9 ± 0.5</td>
<td>2.2 ± 0.3</td>
<td>83</td>
<td>0.1 ± 0.1</td>
<td>10</td>
<td>2.4 ± 0.3</td>
<td>86</td>
</tr>
</tbody>
</table>

**Curcumin administration during the postinitiation period.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Body wt/ mouse (g)</th>
<th>Papillomas /mouse</th>
<th>% of mice with papillomas</th>
<th>Squamous cell carcinomas</th>
<th>% of mice with carcinomas</th>
<th>Total tumors</th>
<th>% of mice with tumors</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. B(a)P + 0.5% curcumin</td>
<td>27</td>
<td>26.0 ± 0.6</td>
<td>2.2 ± 0.2</td>
<td>89</td>
<td>0.4 ± 0.1</td>
<td>30</td>
<td>2.6 ± 0.3</td>
<td>93</td>
</tr>
<tr>
<td>6. B(a)P + 2.0% curcumin</td>
<td>28</td>
<td>25.9 ± 0.5</td>
<td>1.5 ± 0.2</td>
<td>79</td>
<td>0.1 ± 0.1</td>
<td>14</td>
<td>1.6 ± 0.2</td>
<td>86</td>
</tr>
</tbody>
</table>

* Statistically different from group 2 [B(a)P-treated controls, P < 0.01], using Student’s t test.
* Statistically different from group 2 [B(a)P-treated controls, P < 0.001], using Student’s t test.

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Inhibitory effect of dietary curcumin on the size of B(a)P-induced forestomach tumors in A/J mice

The size of each forestomach tumor in animals described in Table 1 was determined. Each value represents the mean ±SE. Numbers in parentheses, percentage of inhibition.

Table 2 Inhibitory effect of dietary curcumin on the size of B(a)P-induced forestomach tumors in A/J mice

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Papilloma vol/papilloma (mm³)</th>
<th>Papilloma vol/mouse (mm³)</th>
<th>Carcinoma vol/carcinoma (mm³)</th>
<th>Carcinoma vol/mouse (mm³)</th>
<th>Tumor vol/ tumor (mm³)</th>
<th>Tumor vol/ mouse (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vehicle + AIN 76A</td>
<td>20</td>
<td>0³</td>
<td>0⁴</td>
<td>0⁴</td>
<td>0⁴</td>
<td>0⁴</td>
<td>0⁴</td>
</tr>
<tr>
<td>2. B(a)P + AIN 76A</td>
<td>37</td>
<td>5.6 ± 0.8</td>
<td>24.9 ± 4.0</td>
<td>54.9 ± 12.3</td>
<td>29.7 ± 8.5</td>
<td>11.0 ± 1.9</td>
<td>54.6 ± 9.7</td>
</tr>
</tbody>
</table>

Curcumin administration during the initiation period

3. B(a)P + 0.5% curcumin
4. B(a)P + 2.0% curcumin

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Papilloma vol/papilloma (mm³)</th>
<th>Papilloma vol/mouse (mm³)</th>
<th>Carcinoma vol/carcinoma (mm³)</th>
<th>Carcinoma vol/mouse (mm³)</th>
<th>Tumor vol/ tumor (mm³)</th>
<th>Tumor vol/ mouse (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. B(a)P + 0.5% curcumin</td>
<td>30</td>
<td>6.3 ± 2.1</td>
<td>13.1 ± 4.2³</td>
<td>26.5 ± 10.8</td>
<td>6.2 ± 3.2⁴</td>
<td>8.4 ± 2.3</td>
<td>19.2 ± 4.8³</td>
</tr>
<tr>
<td>4. B(a)P + 2.0% curcumin</td>
<td>29</td>
<td>2.1 ± 0.5³</td>
<td>4.7 ± 1.1²</td>
<td>29.6 ± 14.3</td>
<td>4.1 ± 2.7⁶</td>
<td>3.7 ± 1.2²</td>
<td>8.7 ± 2.9⁶</td>
</tr>
</tbody>
</table>

Curcumin administration during the postinitiation period

5. B(a)P + 0.5% curcumin
6. B(a)P + 2.0% curcumin

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Papilloma vol/papilloma (mm³)</th>
<th>Papilloma vol/mouse (mm³)</th>
<th>Carcinoma vol/carcinoma (mm³)</th>
<th>Carcinoma vol/mouse (mm³)</th>
<th>Tumor vol/ tumor (mm³)</th>
<th>Tumor vol/ mouse (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. B(a)P + 0.5% curcumin</td>
<td>27</td>
<td>4.7 ± 1.2</td>
<td>10.5 ± 3.1⁴</td>
<td>62.7 ± 40.2</td>
<td>23.2 ± 15.6</td>
<td>13.0 ± 6.1</td>
<td>33.7 ± 15.4</td>
</tr>
<tr>
<td>6. B(a)P + 2.0% curcumin</td>
<td>28</td>
<td>5.5 ± 1.5</td>
<td>8.3 ± 2.4⁵</td>
<td>71.2 ± 29.7</td>
<td>10.2 ± 6.1</td>
<td>11.3 ± 3.8</td>
<td>18.5 ± 6.1³</td>
</tr>
</tbody>
</table>

* Statistically different from the B(a)P control group (group 2), P < 0.05, using Student’s t test.

Inhibitory Effect of Dietary Curcumin on ENNG-induced Duodenal Tumorigenesis

Administration of ENNG (120 mg/liter) in the drinking water to male C57BL/6 mice for 4 weeks resulted in formation of 0.97 duodenal adenoma and 0.09 duodenal adenocarcinoma per mouse 16 weeks later. Administration 0.5–2.0% curcumin in the diet during the postinitiation period decreased the number of ENNG-induced duodenal adenomas per mouse by 46–79%, the number of adenocarcinomas per mouse by 44–56%, and the total number of duodenal tumors per mouse by 47–77% (Table 3). The data indicated that administration of 0.5% curcumin in the diet was effective at inhibiting duodenal tumorigenesis. Administration of 1.0–2.0% curcumin in the diet also resulted in inhibition, but this was not statistically significant (Table 3). Administration of 2% dietary curcumin for 16 weeks to mice without ENNG pretreatment did not result in any duodenal tumors (data not shown). Administration of curcumin in the diet decreased the size of ENNG-induced duodenal adenomas per mouse, but there was no dose-response relationship (Table 4). This was not observed for ENNG-induced adenocarcinomas where there was a tendency for increased adenocarcinoma size in the curcumin-treated mice (Table 4).

Table 3 Inhibitory effect of dietary curcumin on ENNG-induced duodenal tumorigenesis in C57BL/6 mice

Male C57BL/6 mice (6 weeks old; 36 mice for group 2, and 25 mice for all other groups) were fed AIN 76A diet and given water or ENNG (120 mg/liter water) as the sole source of drinking water for 4 weeks. One week later, all mice were given water and AIN 76A diet or different doses of curcumin (commercial curcumin) in AIN 76A diet for 16 weeks. The mice were killed at 16 weeks after terminating ENNG administration. The number of duodenal tumors was determined. Numbers in parentheses, percentage of inhibition. In group 1, one mouse died during the 9th week. In group 2, one mouse was killed to examine the duodenal tumors during the 10th, 12th, and 14th weeks after termination of ENNG. In group 5, two mice died during the first week and one mouse died during the 3rd week after termination of ENNG. In group 6, one mouse died during the 10th week after ENNG. Each value represents the mean ±SE. Numbers in parentheses, percentage of inhibition.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice/group</th>
<th>Body wt (g)</th>
<th>Adenomas/ mouse</th>
<th>% of mice with adenomas</th>
<th>Carcinomas/ mouse</th>
<th>% of mice with carcinomas</th>
<th>Tumors/ mouse</th>
<th>% of mice with tumors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vehicle + AIN 76A</td>
<td>24</td>
<td>34.1 ± 1.1 ³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
</tr>
<tr>
<td>2. ENNG + AIN 76A</td>
<td>33</td>
<td>36.7 ± 1.0 ³</td>
<td>0.97 ± 0.28</td>
<td>45</td>
<td>0.09 ± 0.07³</td>
<td>6</td>
<td>1.06 ± 0.33³</td>
<td>45</td>
</tr>
<tr>
<td>3. ENNG + 0.5% curcumin</td>
<td>25</td>
<td>34.6 ± 0.6 ³</td>
<td>0.20 ± 0.08³</td>
<td>20</td>
<td>0.04 ± 0.04³</td>
<td>4</td>
<td>0.24 ± 0.09³</td>
<td>24</td>
</tr>
<tr>
<td>4. ENNG + 1.0% curcumin</td>
<td>25</td>
<td>33.2 ± 0.9 ³</td>
<td>0.52 ± 0.18³</td>
<td>28</td>
<td>0.04 ± 0.04³</td>
<td>4</td>
<td>0.56 ± 0.20³</td>
<td>28</td>
</tr>
<tr>
<td>5. ENNG + 2.0% curcumin</td>
<td>22</td>
<td>34.4 ± 1.0 ³</td>
<td>0.50 ± 0.19³</td>
<td>27</td>
<td>0.05 ± 0.05³</td>
<td>5</td>
<td>0.55 ± 0.23³</td>
<td>27</td>
</tr>
<tr>
<td>6. Vehicle + 2.0% curcumin</td>
<td>24</td>
<td>34.4 ± 0.8 ³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
<td>0³</td>
</tr>
</tbody>
</table>

* Statistically different from ENNG control group (P < 0.05), using Student’s t test.
Inhibitory Effect of Dietary Curcumin on AOM-induced Colon Tumorigenesis. Injections of AOM (10 mg/kg) were given s.c. to female CF-1 mice once a week for 6 weeks. The first dose of carcinogen unexpectedly killed 21% of the mice ingesting control AIN 76A diet (the animals died within 3 days). Subsequent weekly injections did not result in additional deaths. However, similar AOM injection into mice consuming 0.5—4% curcumin in AIN 76A diet for 2 weeks prior to the first AOM injection resulted in only 5—7.5% deaths indicating that administration of curcumin in the diet reduced the acute lethal effect of the first AOM dose by 63—76%. Administration of 2.0% pure curcumin in the diet had no significant inhibitory effect on azoxymethane-induced acute toxicity, possibly due to low solubility of pure curcumin resulting in less short term bioavailability.

The s.c. injection of AOM (10 mg/kg) once weekly for 6 weeks resulted in the formation of 4.91 colon adenomas/mouse and 0.72 colon adenocarcinomas/mouse (total of 5.63 colon tumors/mouse) at 27 weeks after the last dose of AOM (Table 5). Administration of 0.5—4.0% curcumin in AIN 76A diet 2 weeks before the first injection of AOM until the end of the experiment inhibited the number of AOM-induced adenomas per mouse or adenocarcinomas per mouse by 50—62% or 57—100%, respectively (Table 5).

Administration of 2.0% curcumin in the diet for 2 weeks before, during, and for one week after the last dose of AOM (during the initiation period) inhibited the formation of colon adenomas per mouse by 64% and adenocarcinomas per mouse by 85% (Table 5). Administration of 2.0% curcumin in the diet during the postinitiation period (starting at 1 week after the last dose of AOM and until the end of the experiment) inhibited the number of colon adenomas per mouse by 19% and the number of adenocarcinomas per mouse by 67% (Table 5). Curcumin administration during the initiation period, during the postinitiation period, or during the initiation and the postinitiation periods decreased the size of AOM-induced adenomas and adenocarcinomas per tumor or per mouse by 43—100% (Table 6).

Histopathological examinations of AOM-induced colon adenomas and adenocarcinomas indicated that the colon adenomas in CF-1 mice could be classified into tubular adenomas, villous adenomas and tubulovillous adenomas and that colon adenocarcinomas could be classified into tubular adenocarcinomas, papillary adenocarcinomas, tubopapillary adenocarcinomas, and mucin-secreting adenocarcinomas.
CURCUMIN AND GASTROINTESTINAL CARCINOGENESIS

Table 6 Inhibitory effect of dietary curcumin on the size of AOM-induced colon tumors in CF-1 mice

The size of each colon tumor in the animals described in Table 5 was determined. Each value represents the mean ±SE. Numbers in parentheses, percentage of inhibition.

| Treatment | No. of mice/group | Adenomas | | | | Adenocarcinomas | | | | | Total tumors | |
|-----------|-------------------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|----------|
|           |                   | Adenoma vol/adenoma (mm³) | Adenoma vol/mouse (mm³) | Carcinoma vol/carcinoma (mm³) | Carcinoma vol/mouse (mm³) | Tumor vol/tumor (mm³) | Tumor vol/mouse (mm³) |
| 1. Vehicle + AIN 76A | 14 | 7.0 ± 1.1 | 34.6 ± 7.1 | 22.3 ± 6.1 | 29.3 ± 10.8 | 11.2 ± 1.7 | 64.0 ± 14 |
| 2. AOM + AIN 76A | 56 | 4.0 ± 0.1 | 11.1 ± 3.1 | 7.4 ± 2.7 | 8.1 ± 3.4 | 6.4 ± 1.1 | 19.1 ± 5.2 | 6.7 ± 1.9 | 27.3 ± 6.8 | 70 |
| 3. AOM + 0.5% curcumin | 36 | 2.7 ± 0.6 | 6.7 ± 1.9 | 0.0 | 0.0 | 2.7 ± 0.6 | 6.7 ± 1.9 | 3.1 ± 0.2 | 27.3 ± 6.8 | 70 |
| 4. AOM + 2.0% curcumin | 34 | 3.8 ± 0.9 | 9.2 ± 2.4 | 3.1 ± 0.2 | 3.1 ± 0.2 | 4.7 ± 1.1 | 12.3 ± 3.7 | 81 | 89 |
| 5. AOM + 4.0% curcumin | 38 | 3.7 ± 0.8 | 9.0 ± 4.6 | 3.2 ± 1.2 | 3.2 ± 1.2 | 4.5 ± 1.3 | 11.7 ± 4.9 | 84 | 89 |
| 6. AOM + 2.0% pure curcumin | 29 | 3.7 ± 0.8 | 9.0 ± 4.6 | 3.2 ± 1.2 | 3.2 ± 1.2 | 4.5 ± 1.3 | 11.7 ± 4.9 | 84 | 89 |
| 7. AOM + 0.5% curcumin | 36 | 2.9 ± 0.3 | 6.4 ± 1.3 | 2.4 ± 1.1 | 2.4 ± 1.1 | 4.0 ± 0.6 | 9.1 ± 2.2 | 64 | 86 |
| 8. AOM + 2.0% curcumin | 46 | 3.7 ± 0.6 | 15.7 ± 4.9 | 3.3 ± 1.7 | 3.3 ± 1.7 | 4.4 ± 0.7 | 18.6 ± 5.0 | 55 | 85 |

* Statistically different from the AOM control animals (group 2; P < 0.05), using Student’s t test.

as described elsewhere (21, 22). In AOM-treated positive control animals (group 2), the colon adenomas were about 90% tubular adenomas, 5% villos adenomas, and 5% tubovillous adenomas. In the AOM-treated positive control group, the colon adenocarcinomas were 78% tubular adenocarcinomas, 2% papillary adenocarcinomas, 10% tubopapillary adenocarcinomas, and 10% mucin-secreting adenocarcinomas. Administration of dietary curcumin during both the initiation and the postinitiation periods, the initiation period, or the postinitiation period decreased the average number of all different types of colon adenomas or adenocarcinomas per mouse without altering the proportion of the different kinds of tumors. Examination of the location and distribution of total colon tumors, adenomas, or adenocarcinomas in the AOM-treated positive control group revealed that about 22% of the total number of colon tumors were localized from 0–10 mm from the anus, 60% were between 11 to 30 mm from the anus, and only about 3% of the colon tumors were localized more than 40 mm from the anus (i.e., proximal colon). Dietary curcumin did not alter the location of the colon tumors.

Body weights, liver weights, and spleen weights were determined at the end of the AOM-induced carcinogenesis experiment and are shown in Table 7. No significant effects of AOM or curcumin on body weight were found. Treatment of mice with AOM increased the spleen weights by 176% and this increase was inhibited by administration of dietary curcumin during the initiation and postinitiation periods (Table 7). The results also indicate that administration of dietary curcumin during the initiation and postinitiation periods or during the postinitiation period increased liver weights (Table 7).

DISCUSSION

The results of the present study demonstrate that administration of dietary curcumin to mice inhibits B(a)P-induced forestomach tumorigenesis (when curcumin was given during the initiation or postinitiation period), ENNG-induced duodenal tumorigenesis (when curcumin was given during the postinitiation period), and AOM-induced colon tumorigenesis (when curcumin was given during the initiation period). The inhibition of AOM-induced colon tumorigenesis was not observed when curcumin was given during the initiation period before AOM administration (Table 7).

Table 7 Effect of dietary curcumin on body weight, liver weight, and spleen weight

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of mice</th>
<th>Body wt (g)</th>
<th>Liver wt (g)</th>
<th>Spleen wt (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vehicle + AIN 76A</td>
<td>14</td>
<td>32.5 ± 1.3</td>
<td>1.52 ± 0.09</td>
<td>69 ± 7</td>
</tr>
<tr>
<td>2. AOM + AIN 76A</td>
<td>56</td>
<td>34.9 ± 0.6</td>
<td>1.67 ± 0.04</td>
<td>190 ± 14</td>
</tr>
<tr>
<td>Curcumin administration during the initiation and postinitiation periods</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. AOM + 0.5% curcumin</td>
<td>36</td>
<td>34.0 ± 1.8</td>
<td>2.13 ± 0.08</td>
<td>129 ± 7</td>
</tr>
<tr>
<td>4. AOM + 2.0% curcumin</td>
<td>34</td>
<td>34.9 ± 0.4</td>
<td>2.10 ± 0.05</td>
<td>110 ± 5</td>
</tr>
<tr>
<td>5. AOM + 4.0% curcumin</td>
<td>38</td>
<td>33.7 ± 0.6</td>
<td>1.88 ± 0.07</td>
<td>143 ± 20</td>
</tr>
<tr>
<td>6. AOM + 2.0% pure curcumin</td>
<td>29</td>
<td>33.8 ± 1.3</td>
<td>2.11 ± 0.07</td>
<td>156 ± 17</td>
</tr>
<tr>
<td>Curcumin administration during the postinitiation period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. AOM + 2.0% curcumin</td>
<td>46</td>
<td>33.7 ± 0.6</td>
<td>1.63 ± 0.05</td>
<td>158 ± 18</td>
</tr>
<tr>
<td>8. AOM + 2.0% curcumin</td>
<td>33</td>
<td>34.7 ± 0.6</td>
<td>1.94 ± 0.06</td>
<td>151 ± 14</td>
</tr>
</tbody>
</table>

* Statistically different from the AOM-treated positive control group (group 2; P < 0.05), using Student’s t test.
period, the postinitiation period, or both the initiation and postinitiation periods).

Although most of the studies described here were done with commercial food grade curcumin (77% curcumin, 17% demethoxycurcumin, and 3% bisdemethoxycurcumin), pure curcumin had a similar inhibitory effect on AOM-induced colon tumorigenesis (Table 5). In other studies, topical application of pure curcumin had a similar inhibitory effect on TPA-induced tumor promotion as commercial food grade curcumin (23). It is of interest that in most of our studies 0.5% dietary curcumin was as effective an inhibitor of gastrointestinal tumorigenesis as higher dose levels. Recent studies by Mukundan et al. (24) indicated that feeding 0.03% dietary curcumin or 0.5% dietary turmeric to rats for 4 weeks markedly decreased the level of B(a)P-DNA adducts in the liver at 24 h after the i.p. injection of B(a)P. Our results and those of Mukundan et al. suggest a need for additional studies to determine whether lower levels of dietary curcumin can inhibit chemically induced gastrointestinal tumorigenesis.

The mechanism(s) of the inhibitory effects of dietary curcumin on chemically induced gastrointestinal tumorigenesis in mice is unknown, but curcumin may influence the metabolic activation and detoxification of carcinogens as well as the postinitiation phase of carcinogenesis. Curcumin or turmeric has been reported to inhibit the metabolic activation of B(a)P to mutagens in vitro, the metabolic activation of B(a)P to B(a)P-DNA adducts in mouse skin in vivo (15, 24, 25), and the formation of B(a)P-DNA adducts or single strand breaks in DNA in the forestomach or liver of mice (26). In additional studies, dietary administration of curcumin or turmeric to mice or rats has been reported to increase the levels of hepatic phase I and phase II enzymes (25). Curcumin has also been reported to enhance the rate of DNA repair in yeast (27). Each of these effects may play a role in the inhibitory action of curcumin on the initiation of carcinogenesis by B(a)P, AOM, or other chemicals. It would be of interest to determine whether or not curcumin administration inhibits the metabolic activation or enhances the detoxification of carcinogens. Topical application of curcumin has been shown to inhibit TPA-induced ornithine decarboxylase activity, cell proliferation, and tumor promotion in mouse epidermis (9, 11). Several compounds that possess antioxidant or anti-inflammatory activity have been shown to inhibit tumor promotion by TPA and to affect biochemical parameters associated with tumor promotion by TPA and the postinitiation phase of carcinogenesis (11, 19, 28–31). Curcumin has strong antioxidant and free radical-scavenging activity (32–34), inhibits epidermal arachidonic acid metabolism via the lipoxygenase and cyclooxygenase pathways (13), inhibits the inflammatory action of arachidonic acid (13), and inhibits TPA-induced inflammation, ornithine decarboxylase activity, and tumor promotion on mouse skin (11). Several studies suggest that anti-inflammatory inhibitors of arachidonic acid metabolism may inhibit colon carcinogenesis in animals and humans (35–46). Recent studies by Rao, Simi, and Reddy have indicated an inhibitory effect of administration of dietary curcumin to rats on AOM-induced increases in ornithine decarboxylase activity, tyrosine protein kinase activity, arachidonic acid metabolism, and the formation of aberrant crypt foci in the rat colon (47). Our studies in mice and those by Reddy et al. in rats indicate that dietary curcumin is a potent inhibitor of colon carcinogenesis in rodents.

Studies on the absorption and metabolism of curcumin indicated that it is absorbed after p.o. administration to rodents and that it is rapidly metabolized to glucuronide and sulfate conjugates that are excreted primarily in bile and to a lesser extent in urine (48–50). Low or undetectable blood levels of unchanged curcumin were observed after p.o. administration (49, 50). It is unclear if this is due to poor absorption or efficient first pass metabolism.

Toxicity studies with turmeric or curcumin in animals indicated no histopathological changes when these substances were fed to rats, dogs, guinea pigs, or monkeys (0.5 to 2 g/kg) for 8–60 weeks (51). In addition, studies with turmeric and curcumin in rats for three generations did not show any teratogenic or carcinogenic effects (49). However, feeding turmeric oleoresin to pigs at a dose of 296 to 1551 mg/kg for 16 weeks decreased body weight gain and concomitantly increased the weight of the liver and thyroid gland (51). Hyperplasia of the thyroid and epithelial changes in kidney, urinary bladder, and liver were also observed in the pigs fed turmeric oleoresin (51). Further studies are needed to determine whether these adverse effects were caused by curcumin per se or by other components in the turmeric oleoresin. Our findings that dietary curcumin can inhibit chemically induced carcinogenesis in the gastrointestinal tract (forestomach, duodenum, and colon) of rodents suggests a need for further pharmacological and toxicological studies to determine whether dietary curcumin may be a useful chemopreventive agent against gastrointestinal carcinogenesis. A major source of human consumption of curcumin is from turmeric which is used extensively in curry and mustard and as a coloring agent and spice in many foods. It has been estimated that some individuals ingest as much as 600 mg of dietary turmeric (10–30 mg of curcumin) in their diet daily (52). There is a need for carefully controlled epidemiology studies to determine whether individuals who ingest high levels of curcumin have a lower risk of gastrointestinal carcinogenesis than individuals who do not ingest curcumin.

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Inhibitory Effects of Dietary Curcumin on Forestomach, Duodenal, and Colon Carcinogenesis in Mice

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