Beef Meat and Blood Sausage Promote the Formation of Azoxymethane-Induced Mucin-Depleted Foci and Aberrant Crypt Foci in Rat Colons[1,2]

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ABSTRACT Red meat intake is associated with colon cancer risk. Puzzlingly, meat does not promote carcinogenesis in rat studies. However, we demonstrated previously that dietary heme promotes aberrant crypt foci (ACF) formation in rats given a low-calcium diet. Here, we tested the hypothesis that heme-rich meats promote colon carcinogenesis in rats treated with azoxymethane and fed low-calcium diets (0.8 g/kg). Three meat-based diets were formulated to contain varying concentrations of heme by the addition of raw chicken (low heme), beef (medium heme), or black pudding (blood sausage; high heme). The no-heme control diet was supplemented with ferric citrate and the heme control diet with hemoglobin to match iron and heme concentrations in the beef diet, respectively. After 100 d, colons were scored for ACF and mucin-depleted foci (MDF). Fecal water was assayed for lipoperoxides and cytotoxicity. Only diets with heme promoted the formation of MDF, but all meat diets promoted ACF formation. The number of MDF/colon was 0.55 ± 0.68 in controls, but 1.2 ± 0.6 ($P = 0.13$), 1.9 ± 1.4 ($P < 0.01$), and 3.0 ± 1.2 ($P < 0.001$) in chicken-, beef-, and black pudding–fed rats. MDF promotion by the high-heme black pudding diet was greater than that by the medium-heme beef diet. The number of ACF/colon was 72 ± 16 in controls, but 91 ± 18, 100 ± 13, and 103 ± 14 in chicken-, beef-, and black pudding–fed rats (all $P < 0.001$). ACF and MDF did not differ between rats fed the beef diet and those fed the heme control diet. MDF promotion was correlated with high fecal water lipoperoxides and cytotoxicity ($r = 0.65$, $P < 0.01$). This is the first study to show the promotion of experimental carcinogenesis by dietary meat and the association with heme intake. J. Nutr. 134: 2711–2716, 2004.

KEY WORDS: • *colorectal carcinogenesis* • *heme* • *lipoperoxidation* • *red meat* • *chicken*

Colorectal cancer is a major cause of death in affluent countries, and recommendations are to reduce red meat intake to reduce the risk (1). A meta-analysis of epidemiological studies by Norat et al. (2) found a moderate but significant association between red meat intake and colorectal cancer risk. In puzzling contrast with epidemiological studies, experimental studies do not support the hypothesis that red meat increases colorectal cancer risk. Among the 12 rodent studies reported in the literature, none demonstrated a specific promotional effect of red meat (3–14). McIntosh et al. (3) showed that rats given a diet containing kangaroo meat, soybean protein, or casein have a similar incidence of dimethylhydrazine-induced tumors. Clinton et al. (4) also found the colon tumor incidence to be the same for beef meat–(raw or grilled) and soybean diet–fed rats. Nutter et al. (5) found beef proteins to afford significant protection from colon cancer in mice compared with milk protein. Reddy et al. (6) and Pence et al. (7) found high-protein and high-fat diets, whatever the protein source, to increase colon tumor incidence in rats, but beef meat had a greater protective effect than casein (7). Pence et al. (8) found that well-cooked beef meat decreased the risk of colon cancer compared to casein in rats fed a high-fat diet but increased the risk in those fed a low-fat diet. Lai et al. (9) found that a lean beef diet did not increase tumor incidence in rats compared with a casein-iron citrate diet. Alink et al. (10) showed that human diets containing meat produced more colon carcinomas in rats than diets that did not include meat. These results do not support specific meat promotion, however, because the human diets contained more fat and less fiber than the rat diets. Mutanen et al. (11) did not find a diet of beef meat to increase substantially the number of intestinal tumors in Min mice, although it contained 5 times more fat than the control diet. Kettunen et al. (12) found fewer tumors in female Min mice fed beef meat than in controls. Parnaud et al. (13) did not find red meat to promote azoxymethane-induced aberrant crypt foci

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(ACF) formation compared to casein-fed controls. Belobrajdic et al. (14) found kangaroo meat to promote aberrant crypt foci (ACF)[4] formation in comparison with whey protein, but whey is known to protect against colon carcinogenesis (15).

Sesink et al. (16) speculated that heme, found in red meat myoglobin, would enhance colon carcinogenesis. They demonstrated that pure hemin added to rats diet increases colonic epithelial proliferation and that calcium phosphate inhibits the hemin-induced proliferation (17). In line with Sesink's hypothesis, we showed that hemin diets increase the number and size of azoxymethane-induced ACF in rats fed a low-calcium diet, while hemoglobin diets increase ACF number only (18). Dietary hemin also produces cytotoxic fecal water and high amounts of TBARS, indicative of lumen lipoperoxidation (16), while dietary hemoglobin increases fecal TBARS only (18). ACF are putative preneoplastic lesions, and the effect of agents on ACF is correlated with the effect on tumor incidence in most (19) but not all studies. Recently, alternative short-term biomarkers of colon carcinogenesis were proposed: mucin-depleted foci (MDF) (20). MDF are easy to score and may predict tumor outcome better than ACF (20,21).

The present study was designed to test the hypothesis that heme in the food matrix can promote colon carcinogenesis. The diets used in previous animal studies (3–13) contained high levels of calcium; we supposed that calcium inhibited the promoting effect of red meat. Three types of meat were chosen with different heme contents: chicken, beef, and black pudding. A fourth diet, containing pure hemoglobin, was included as a control that contained the same concentration of heme as the beef diet. The myoglobin in beef is very close in structure to hemoglobin.

MATERIALS AND METHODS

Animals. Sixty Fisher 344 female rats were purchased at 4 wk of age from Iffa Credo. Animal care was in accordance with the guidelines of the European Council on animals used in experimental studies. They were distributed randomly in pairs into stainless-steel wire-bottom cages. The room was kept at a temperature of 22°C on a 12-h light-dark cycle. Rats were allowed 7 d of acclimatization to the room and to the control diet (**Table 1**) before being injected i.p. with the carcinogen azoxymethane (Sigma Chemical, 20 mg/kg body wt) in NaCl (9 g/L). Seven days after the injection the rats were allowed free access to their respective diets for 100 d. Feed was changed every 2 or 3 d and water once a week. Body weights were monitored weekly. Feed intake per cage of 2 rats was also monitored at periodic intervals (d 5, 62, and 77). Fecal mass was measured as the total over a 24-h period per 2 rats on d 56, 61, 62, 76, and 77.

Diets. Experimental diets, as shown in Table 1, were based on the diet fed to control rats (n = 20 rats) consisting of a modified AIN-76 diet (22) prepared and formulated in a powdered form by the UPAE (INRA). Dibasic calcium phosphate was included at a low concentration of 2.7 g/kg. Three meat diets given to 3 groups of rats (n = 10 rats/group) were formulated to contain varying concentrations of heme as hemoglobin or myoglobin by the addition of freeze-dried beef, chicken, or black pudding at 600 g/kg meat of the total diet. The beef and chicken (skinless) meat was obtained from UPAE. Meat was freeze-dried by LyoFal. The beef contained 0.6 μmol/g of heme while none was detected in the chicken diet (see the assay below). The low fat black pudding (blood sausage) contained 16 μmol/g of heme. It was specially made by Recape with 90% pork blood and 10% starch (w:w) and contained no potentially protective additives such as onion or milk. One group of rats (n = 10) received

TABLE 1

Composition of diets

	Control	Chicken	Beef	Black pudding	Hemoglobin
			g/kg		
Chicken	0	600	0	0	0
Beef	0	0	600	0	0
Black pudding	0	0	0	600	0
Hemoglobin	0	0	0	0	6.3
Lard	150	122	40	112	150
Safflower oil	50	50	50	50	50
Casein[1]	500	1.1	48.5	115	493.8
Corn starch	60	60	60	5	60
Sucrose	139.5	68	102	20	139.5
Cellulose	50	50	50	50	50
L-Methionine	3	3	3	3	3
Mineral mix[2]	35	35	35	35	35
Vitamin mix	10	10	10	10	10
$CaHPO_4$	2.7	1.4	1.6	1.8	2.7
Ferric citrate[3]	0.45	0.35	0	0	0.36

[1] Low-calcium casein.

[2] AIN-76 mix, but 500 g/kg of dibasic calcium phosphate replaced by sucrose in mineral mix.

[3] All diets contained 140 mg/kg iron except the black pudding diet (950 mg/kg). Iron concentration was measured in freeze-dried meat before the diets were prepared: chicken: 37.5, beef: 172.6, and black pudding 1527 mg/kg. Other nutrients were balanced: 50% protein, 20% fat, 18–25% carbohydrate, and 0.8 g/kg calcium (based on added components, no analysis was done on whole diets).

a hemoglobin diet containing the same concentration of heme as the beef diet (0.36 μmol/g diet). This was achieved by adding powdered bovine hemoglobin (Sigma Chemical) to the control diet. All diets were balanced for protein (50%), fat (20%), calcium (0.8 g/kg), and iron (0.14 g/kg) by the addition of casein, lard, calcium phosphate, and ferric citrate. However, the black pudding died could not be balanced for iron (0.95 g/kg). The diets were prepared twice a month and maintained at −20°C. A TBARS assay showed no lipoperoxidation (data not shown).

ACF and MDF assays. All rats were killed by CO_2 asphyxiation in a random order on d 99 or 100. Colons were coded and then scored for ACF by Bird's procedure (23). ACF scoring was done in duplicate by 2 investigators who did not know the treatment group. After being scored for ACF, colons were stained with the high-iron diamine-Alcian blue procedure (HID-AB) to evaluate mucin production (20). MDF number and the number of crypts per MDF were scored by a single reader, who did not know the rat treatment or the ACF results, under a light microscope at 32X magnification. Lesions were identified as MDF by the absence or very small production of mucins and by at least 2 of the following criteria outlined by Caderni et al. (20): multiplicity higher than 3 crypts, distortion of the lumen of the crypts, and elevation of the lesion in comparison to normal mucosa. All lesions were photographed (**Fig. 1**), and representative pictures were mailed to Dr. Giovanna Caderni (University of Florence, Italy) for confirmation.

Preparation of fecal water, assay of TBARS, and heme. For assay of TBARS, heme, and cytotoxic activity on CMT93, fecal water was prepared from feces collected for 24 h under each cage of 2 rats, as previously described (18), but black pudding samples were diluted twice more than the other samples. For assay of cytolytic activity on erythrocytes, fecal water was prepared by Sesink's procedure and pH was measured (16). TBARS were measured in fecal water according to Ohkawa et al. (24), exactly as previously described (18). Heme contents of freeze-dried feces and of fecal water were measured by fluorescence according to Van den Berg et al. (25) and Sesink et al. (16), respectively, as already described (18).

Cytolytic assay of fecal water. The cytotoxicity of fecal water was quantified by 2 methods, on erythrocytes and on a cell line. First,

[4] Abbreviations used: ACF, aberrant crypt foci; HID-AB, high-iron diamine-Alcian blue procedure; MDF, mucin-depleted foci; MTT, 3-(4,5-dimethyldiazol-2-yl)-2,5 diphenyl tetrazolium bromide.

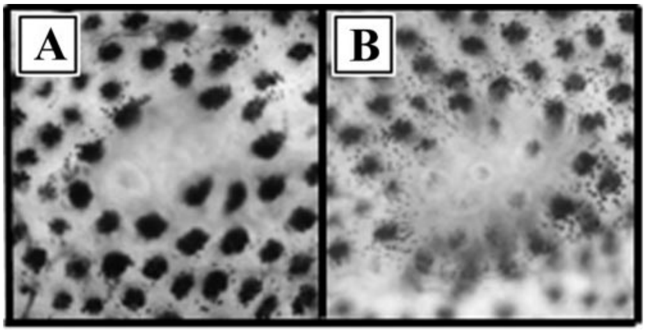

FIGURE 1 Formalin-fixed colon after HID-AB staining, of rats 107 d after the injection of azoxymethane (original magnification, X32). *A*: Identification of an MDF of 5 mucin-depleted crypts. *B*: Identification of an MDF of 11 mucin-depleted crypts.

the cytolytic activity of fecal water was quantified by potassium release from erythrocytes as described by Govers et al. (26). Second, the cytotoxicity of fecal water obtained with a different method (see above) was also quantified by the 3-(4,5-dimethyldiazol-2-yl)-2,5 diphenyl tetrazolium bromide (MTT) test on a cell line according to Bonneson et al. (27). Briefly, the cancerous mouse colonic epithelial cell line, CMT93 (ECAC), was seeded in 96-well microtiter plates (1.6×10^4 cells per well in 200 μL of medium) and at confluence the cells were treated for 24 h with the fecal water sample to be tested and diluted in the culture medium at a concentration of 10% (v:v). Each fecal water sample was tested in 7 wells and 10 wells remained untreated to act as controls. One hundred microliters of MTT (9% in PBS) was added to each well. After 3 h of incubation at 37°C in the dark, 100 μL of a 10% SDS-0.1 mol/L NaOH mixture was added. After 1 h of incubation in the dark, the absorbance of each well was read using a microplate reader at wavelength 570 nm for cytotoxicity and 690 nm for background.

Statistical analysis. Results were analyzed using Systat 10 software for Windows and reported as means ± SD. ACF scoring was done in duplicate. ACF variables were tested first using 2-way (groups and readers) ANOVA. The (group × reader) interaction was never significant, and when total ANOVA was significant ($P < 0.05$), pairwise differences between groups were analyzed using Fishers's least-significant-difference test. MDF variables and all other data were analyzed using 1-way ANOVA and groups were compared using Fishers's least-significant-difference test. The Pearson correlation coefficient was used to determine the relations between ACF, MDF, heme intake, and fecal values, and *P* values were calculated with Bonferroni correction for multiple comparisons. Because the black pudding diet contained a very high concentration of heme, heme values were log-transformed before statistical analysis.

RESULTS

Weight gain and feed intake. Beef-fed rats quickly became heavier than control rats, and the difference was significant at d 30. The final body weight of beef-fed rats was greater than that of controls ($P < 0.05$, **Table 2**). Black pudding–fed rats had watery stools, a known effect of dietary heme, and they drank more water than controls (22 ± 1 mL/d vs. 16 ± 0.5 mL/d, $P < 0.001$). Furthermore, all groups had similar food intakes; at day 75, intake was 8.4 ± 0.5 g/d (full data not shown).

ACF. All meat-based diets (chicken, beef, and black pudding) increased the number of ACF ($P < 0.001$, **Fig. 2***A*) and the number of aberrant crypts per colon ($P < 0.001$, Table 2) after 100 d. Chicken and black pudding, but not beef, also increased the number of crypts per ACF ($P < 0.01$, Table 2). Aberrant crypts and ACF promotion by the black pudding diet were more potent than promotion by the chicken diet ($P < 0.05$, Table 2). Rats fed the beef diet did not differ from those fed the hemoglobin diet in aberrant crypt number or ACF per colon. However, the ACF contained more crypts in the hemoglobin-fed group (Table 2).

MDF. Beef- and black pudding–fed rats had more MDF than control rats ($P < 0.01$), and promotion by black pudding was more potent than promotion by beef ($P < 0.05$, Fig. 2*B*). The chicken-based diet, the low-heme diet, did not promote MDF formation (Fig. 2*B*). The effects on the number of MDF also occurred on the number of mucin-depleted crypts (Table 2). The groups did not differ in the number of crypts per MDF. The beef and hemoglobin groups did not differ for any of the variables tested (Table 2).

Fecal heme, TBARS, and cytotoxicity. The fecal concentration of heme matched the heme intake. As expected, no heme was detected in feces of control and chicken diet–fed rats (**Table 3**). The analysis of fecal samples stored during the study of Parnaud et al. (13) where diet containing 60% beef meat but 130 μmol/g calcium yielded similar results: No heme was detected in feces of control and chicken diet–fed rats, but there was 1.7 ± 1.5 μmol/g in feces of beef-fed rats. However, in the present study, the heme concentration was higher in the feces of hemoglobin-fed rats than in beef-fed rats (Table 3). This is consistent with the observation that less heme iron reaches the colon when it is supplied as red meat rather than in hemoglobin form (14). We measured the characteristics of fecal water because, according to studies on bile acids, the soluble fraction of colonic contents would interact more strongly with the mucosa than the insoluble fraction (28). As expected, the heme concentration in fecal water depended directly on the level of heme in the diet (Table 3), with, as noted above, a difference between meat- and hemoglobin-fed rats. There was no heme in fecal waters in Parnaud's meat study, even in samples from rats given a 60% beef diet (13).

Heme can induce the formation of peroxyl radicals in fats, which may be cytotoxic and cleave DNA in vivo (29). Lipid

TABLE 2

Effect of meat-based diets on ACF and MDF formation in the colon of rats 107 d after the injection of azoxymethane[1]

Diets	Heme	Rats	Final body weight	ACF/colon	ACF crypts/colon	Crypts/ACF	MDF/colon	MDF crypts/colon	Crypts/MDF
	µmol/g diet	*n*	*g*	*n*					
Control	0.0	20	198 ± 12[a]	72 ± 16[a]	192 ± 55[a]	2.7 ± 0.4[a]	0.55 ± 0.68[a]	2.9 ± 4.0[a]	4.65 ± 2.40
Chicken	0.0	10	199 ± 10[a]	91 ± 18[b]	267 ± 65[b]	2.9 ± 0.4[b]	1.20 ± 0.63[a]	6.0 ± 3.9[a,b]	4.92 ± 1.64
Beef	0.36	10	210 ± 9[b]	100 ± 13[b,c]	280 ± 49[b]	2.8 ± 0.2[a]	1.90 ± 1.37[b]	8.5 ± 6.9[b,c]	4.23 ± 1.15
Hemoglobin	0.36	10	196 ± 11[a]	93 ± 24[b,c]	285 ± 78[b]	3.1 ± 0.5[b]	2.40 ± 1.50[b,c]	11.5 ± 9.0[c,d]	4.60 ± 1.93
Black pudding	9.54	10	189 ± 9[a]	103 ± 14[c]	301 ± 48[b]	2.9 ± 0.2[b]	3.00 ± 1.24[c]	13.1 ± 6.0[d]	4.29 ± 0.59

[1] Values are means ± SD. Means in columns with superscripts without a common letter in differ, $P < 0.05$.

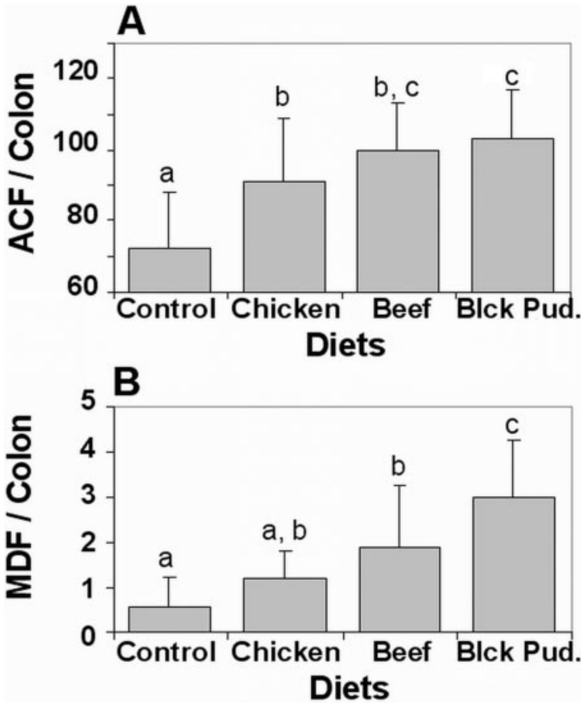

FIGURE 2 Effect of meat-based diets on putative precancerous lesions per rat colon 107 d after the injection of azoxymethane. *A*: Number of aberrant crypt foci. *B*: Number of mucin-depleted foci. Values are means ± SD, n = 10 or 20 (controls). Means without a common letter differ, $P < 0.05$.

peroxidation was thus measured in fecal water by the TBARS assay. Lipid peroxidation was associated with heme concentration in fecal water (Table 3): The black pudding diet thus increased TBARS in the fecal water by 23-fold. The hemoglobin diet and beef diet increased TBARS by 2- to 4-fold (all $P < 0.01$), but the chicken diet did not affect fecal water TBARS compared with the control diet.

The fecal water of hemin-fed rats is cytotoxic, which would explain the hemin-induced increased proliferation (18). Cytotoxicity of fecal water was measured by 2 methods: lysis of erythrocytes and toxicity on CMT93 cell in culture. The black pudding diet, a very high source of heme, enhanced erythrocytes cytolysis by >50-fold and toxicity on CMT93 cells by 8-fold (both $P < 0.001$, Table 3). Beef and hemoglobin diets produced equivalent effects: no lytic activity on erythrocytes, but a 4-fold increase in CMT93 cell toxicity ($P < 0.001$). The cytotoxicity of fecal water from chicken-fed rats was not different from that of controls (Table 3). All meat-based diets increased the fecal pH, which was higher when the heme concentration was higher in the diet (Table 3). Taken together, these data suggest that cytotoxicity, pH, and lipoperoxides of fecal water are associated with heme intake and fecal heme. Indeed, significant correlations were seen between heme intake and fecal water cytotoxicity (r = 0.98), pH (r = 0.86), and TBARS (r = 0.73, all $P < 0.01$, n = 30 cages of 2 rats).

DISCUSSION

This study is the first to show that meat can specifically promote colon carcinogenesis. In addition, the promoting effect was stronger than other promoting agents (30) and clearly associated with the heme concentration in meat. This study was done with a low-calcium diet containing 60% meat and 5% easily oxidized oil. We used 2 putative precancerous endpoints: the established ACF and the recently described MDF. Heme in the diet led to ACF and MDF promotion in the colon. The low-heme chicken-based diet did not promote MDF, but increased the ACF number.

This study is, to our knowledge, the first non-Italian study to use a new carcinogenesis endpoint which was recently described by Caderni et al. (20). MDF may predict tumor outcome better than ACF, as shown in the studies of synbiotics, cholic acid, and piroxicam (20,21). We found that MDF were quite easy to score, but we detected fewer MDF per control rat than did Caderni et al. (20). This is likely the result of the carcinogen dose: azoxymethane was injected once instead of twice, and the resulting number of ACF was 75% fewer here than in the study of Caderni et al. (72 vs. 298 ACF/colon).

That heme content in meat was responsible for promotion of colon carcinogenesis, at least in part, is supported by the following facts: (i) all tested meat diets promoted ACF formation, but this was significantly greater in rats fed the high-heme diet, based on black pudding, than for those fed the low-heme chicken diet (Fig. 2). (ii) Only heme-containing diets promoted MDF formation, and the effect was dose dependent, because the black pudding effect was significantly stronger than the beef effect. MDF per colon was correlated with heme intake (r = 0.63, n = 60, $P < 0.01$). (iii) Beef and hemoglobin diets, which provided the same amount of heme,

TABLE 3

Effect of meat-based diets on fecal heme, lipoperoxides, and cytotoxicity of fecal water in rats 77 d after the injection of azoxymethane[1]

Diet	Heme intake[2]	Dry fecal mass	Heme in feces[2]	Heme in fecal water[2]	TBARS in fecal water, MDA equivalents	pH of fecal water	Cytolytic activity on erythrocytes	Cytotoxicity on CMT93 cells
	μmol/d	*g/d*	*μmol/g*	*μmol/L*		*pH*	*% K release*	*% cells lysed*
Control	0[a]	0.50 ± 0.11[a]	0[a]	0[a]	40 ± 15[a]	7.85 ± 0.03[a]	1 ± 2[a]	12 ± 12[a]
Chicken	0[a]	0.58 ± 0.06[b]	0[a]	0[a]	69 ± 16[a]	8.02 ± 0.03[b]	1 ± 2[a]	26 ± 15[a]
Beef	3.0 ± 0.4[b]	0.64 ± 0.09[b]	0.5 ± 0.2[b]	19 ± 7[b]	138 ± 17[b]	8.17 ± 0.03[c]	1 ± 2[a]	59 ± 14[b]
Hemoglobin	2.9 ± 0.4[b]	0.53 ± 0.07[b]	0.9 ± 0.3[c]	52 ± 47[c]	195 ± 96[b]	8.13 ± 0.03[c]	1 ± 1[a]	58 ± 27[b]
Black pudding	87.0 ± 8.0[c]	1.00 ± 0.06[c]	23.6 ± 8.6[d]	1097 ± 484[d]	975 ± 229[c]	8.30 ± 0.06[d]	73 ± 36[b]	88 ± 03[c]

[1] Values are means ± SD, n = 5 or 10 cages (controls). Means in columns with superscripts without a common letter in differ, $P < 0.05$.
[2] Log-transformed data were tested by ANOVA.

promoted ACF and MDF equally (Table 3). This meat study is thus consistent with our previous study, where ACF were promoted dose-dependently by graded doses of dietary hemin (18). We think that previous studies in rats failed to show that red meat promotes carcinogenesis because meat was included in a high-calcium diet. The standard AIN-76 diet contains 130 mmol/kg calcium, which is similar to the concentration that inhibits heme-induced colonic proliferation (17) and heme-induced ACF promotion (18). Calcium precipitates heme in the gut lumen and reduces heme concentration in fecal water (17,18). In the study of Parnaud et al. (13), the heme concentration was high in the feces of beef-fed rats, but was not detectable in the fecal water (see results above). We suggest that this is due to high dietary calcium, and it resulted in the lack of ACF promotion by the beef diet (13). However, the link between heme intake and ACF yield is not a direct one: black pudding provided a huge quantity of heme to the gut that was not mirrored linearly in the ACF outcome.

The mechanism of heme promotion is not known, but might be linked to peroxidation, cytotoxicity, and pH. In a previous study, we showed that pure hemin and hemoglobin promote ACF formation and induce lipoperoxidation and cytotoxicity of fecal water (18). Indeed, heme promotes the nonenzymatic peroxidation of PUFA (16,18,29). The lipid peroxyl radicals (LOO•) generated from simultaneous fat and heme iron ingestion, and the resulting oxygen radicals, can cleave DNA or modify DNA bases, which could increase carcinogenesis (29). The beef-based diet contained 0.36 μmol/g heme. Its intake led to 19 μmol/L heme in fecal water and a 2.5-fold increase in lipoperoxidation (Table 3). Similar TBARS values were seen in fecal water from beef-fed rats and, in our previous study (18), from hemoglobin diet–fed rats (138 and 187 μmol/L MDA equivalents, respectively). In addition, red meat intake induced fecal cytotoxicity and increased the pH of fecal water (Table 3). Black pudding contains 25 times more heme than beef. Compared with beef, the consumption of black pudding led to 60 times more heme in fecal water, 7 times more TBARS, and a much higher cytotoxicity (Table 3). Fecal water from beef-fed rats or hemoglobin-fed rats (18) did not induce cytolysis of erythrocytes, probably because heme intake was too low. In contrast, fecal water from black pudding–fed rats strikingly induced erythrocyte cytolysis. Thus, we conclude that there was a dose-dependent effect of the heme concentration in the diet and in fecal water on the fecal lipoperoxidation, cytotoxicity, and pH. All correlations among these variables were significant. In addition, MDF and ACF numbers per rat were also correlated with these fecal values (all $r > 0.5$, all $P < 0.01$, $n = 60$ rats, highest correlation, $r = 0.65$ between number of MDF and cytotoxicity). These correlations suggest that fecal cytotoxicity, lipoperoxides, and pH may explain heme promotion of colon carcinogenesis. That hemoglobin and meat diets, with same heme content as hemoglobin and myoglobin, produced the same effects also supports this idea (Table 3). Surprisingly, a published study with a protocol very similar to this one noted no ACF promotion (14). Fecal heme concentrations were similar in both studies, but the fecal TBARS value was 2 times higher in the study of Belobrajdic et al. (14). We speculate that lipoperoxidation was inhibited by *tert*-butylhydroquinone in the AIN-93 diet used by Belobradjic et al. (14). This chance observation supports the hypothesis that heme-induced lipoperoxidation plays a role in the promotion of colon carcinogenesis.

The low-heme chicken-based diet surprisingly increased the ACF number and size (Table 2). The chicken meat used in this study may contain a promoter that is not heme and remains to be explained. The prominent features of the chicken diet were high arachidonic acid and niacin. The chicken diet contained 1 g/kg of arachidonic acid [calculated from (31)] compared to 0.25 g/kg in other diets. Arachidonic acid has pro-tumorigenic properties, likely by increasing prostaglandin synthesis (32). In addition, the chicken diet contained 207 mg/kg of niacin, 4 times the 51 mg/kg found in the control diet and twice the value in beef diet (assays done by LARA Lab). Niacin can afford protection against carcinogenesis when added to a niacin-deficient diet (33), but high doses are toxic. Here, the high dose provided by the chicken-based diet would translate to 12 times the recommended daily allowance in humans. High niacin stimulates histamine release and prostaglandin synthesis, which might explain the ACF promotion (34). The intake of white meat is not associated with colorectal cancer risk in most epidemiological studies (1,2). In contrast, dietary heme iron intake is associated with an increased risk of proximal colon cancer (35). However, in a prospective cohort study of 34,198 Californian Adventists, the consumption of white meat, mostly chicken, was associated with a tripled risk of colorectal cancer (36).

In summary, this study shows for the first time a promoting effect of red meat on carcinogenesis. It corroborates epidemiological observations: high red meat intake is associated with increased colon cancer risk. In previous meat studies (3–13), the promoting effect of meat was inhibited by dietary calcium, as shown by the study of Parnaud et al. (13). Furthermore, MDF promotion was related to heme intake. Promotion was significantly greater for the high-heme black pudding diet than for the medium-heme beef diet. This heme effect is in line with recent epidemiological data (35). The low-heme chicken diet did not promote MDF, but did increase ACF formation. For red meat diets, promotion was associated with high fecal water lipoperoxidation, cytolytic activity, and increase of pH, which may explain the increased carcinogenesis.

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