Cancer Research

A Central Role for Heme Iron in Colon Carcinogenesis Associated with Red Meat Intake

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Abstract

Epidemiology shows that red and processed meat intake is associated with an increased risk of colorectal cancer. Heme iron, heterocyclic amines, and endogenous N-nitroso compounds (NOC) are proposed to explain this effect, but their relative contribution is unknown. Our study aimed at determining, at nutritional doses, which is the main factor involved and proposing a mechanism of cancer promotion by red meat. The relative part of heme iron (1% in diet), heterocyclic amines (PhIP + MeIQx, 50 + 25 µg/kg in diet), and NOC (induced by $NaNO_2$ + $NaNO_3$; 0.17 + 0.23 g/L of drinking water) was determined by a factorial design and preneoplastic endpoints in chemically induced rats and validated on tumors in Min mice. The molecular mechanisms (genotoxicity, cytotoxicity) were analyzed in vitro in normal and Apc-deficient cell lines and confirmed on colon mucosa. Heme iron increased the number of preneoplastic lesions, but dietary heterocyclic amines and NOC had no effect on carcinogenesis in rats. Dietary hemoglobin increased tumor load in Min mice (control diet: 67 ± 39 mm^2; 2.5% hemoglobin diet: 114 ± 47 mm^2, $P = 0.004$). In vitro, fecal water from rats given hemoglobin was rich in aldehydes and was cytotoxic to normal cells, but not to premalignant cells. The aldehydes 4-hydroxynonenal and 4-hydroxyhexenal were more toxic to normal versus mutated cells and were only genotoxic to normal cells. Genotoxicity was also observed in colon mucosa of mice given hemoglobin. These results highlight the role of heme iron in the promotion of colon cancer by red meat and suggest that heme iron could initiate carcinogenesis through lipid peroxidation. Cancer Res; 75(5); 1–10. ©2015 AACR.

Introduction

Colorectal cancer is the third most common type of cancer worldwide after lung and prostate cancer in men and after lung and breast cancer in women (1). Environmental factors, particularly diet, play roles in the development of colorectal cancer (2, 3). On the basis of epidemiologic studies, the World Cancer Research Fund panel considers the colorectal cancer risk associated with red and processed meat intake to be convincing and recommends limiting the consumption of red meat and avoiding the consumption of processed meat (2, 3). Our previous works showed that red and processed meats promote precancerous lesions (aberrant crypt foci, ACF, and mucin-depleted foci, MDF) in the colons of rats fed a low-calcium diet (4–6). These data strongly support the results from epidemiologic studies.

Three major mechanisms may explain the association between meat and colorectal cancer (7). First, potentially carcinogenic N-nitroso compounds can form in the gastrointestinal tract by N-nitrosation of peptide-derived amine or by nitrosylation yielding S-nitrosothiols and nitrosyl iron (FeNO). Collectively, these are measured as the apparent total N-nitroso compounds (ATNC; ref. 8). Second, meat cooked at high temperatures contains mutagenic heterocyclic amines (HCA) like 2-amino-1-methyl-6-phenylimidazo(4,5-b)pyridine (PhIP) and 2-amino-3,8-dimethylimidazo [4,5-f]quinoxaline (MeIQx; ref. 9). Third, epidemiologic and experimental data support the hypothesis that heme iron present in red and processed meats promotes colorectal cancer (5–7, 10). This effect can be explained by the direct cytotoxic, genotoxic effects of heme on epithelial cells and by the catalytic effect of heme iron on the formation of ATNC and lipid peroxidation end-products like 4-hydroxynonenal (4-HNE; refs. 4, 5, 7, 11–14). Cross and colleagues investigated these 3 hypotheses in a cohort study and found a significant association between colorectal cancer and the intake of heme iron, nitrate from processed meat, and HCA (15). Nevertheless, numerous biases are possible in the determination of risk factors using epidemiologic approach, and contribution of each of these factors has never been evaluated experimentally in the same study.

The present study aimed at investigating the roles of these 3 potential mechanisms, namely heme iron, NOC, and HCA, in colorectal cancer in vivo at a precancerous lesion stage (MDF) in

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Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

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carcinogen-induced rats (see a flowchart in Supplementary Fig. S1). Doses were chosen to mimic red meat consumption. Subsequently, the results were confirmed at the tumor stage using C57BL/6J $Apc^{Min/+}$ mice, a genetic model of colorectal cancer. The tumor incidence was associated with genotoxicity endpoints in mucosa as γH2AX and anaphase bridges. Like tumors in the majority of human colorectal cancer cases and in $Apc^{Min/+}$ mice, the preneoplastic lesion MDF in rats show activation of the Wnt signaling pathway driven by mutations in Apc and/or in the β-catenin gene. We also used an intestinal cellular model with normal and premalignant cells ($Apc^{+/+}$ and $Apc^{-/+}$ cells) to complement the in $vivo$ studies. In combination with animal models, such cellular models allowed us to (i) to understand the effect of dietary compounds on cancer promotion at early stages of carcinogenesis and (ii) to explain and further investigate the effects observed in $vivo$.

Materials and Methods

Animals and diets

Male 4-week-old F344 rats ($n = 80$; Charles Rivers), male and female 4-week-old C57BL/6J $Apc^{Min/+}$ mice (Jackson, Laboratory, $n = 35$) and $Apc^{+/+}$ mice (Charles River, $n = 33$), and male and female C57BL/6J mice ($n = 10$) were housed (2 rats per cage and 2 to 3 mice per cage) under standard laboratory conditions with free access to food and water. After acclimatization with AIN76 diet, rats were fed experimental diets for 100 days, $Apc^{Min/+}$ and $Apc^{+/+}$ mice were fed experimental diets for 49 days, and C57BL/6J mice were fed experimental diets for 14 days. Rats were killed by CO_2 asphyxiation, and mice were killed by cervical dislocation. Animal care was in accordance with the European Council and ARRIVE guidelines.

To assess the relative contributions of the 3 potential mechanisms (heme iron, NOC, and HCA), we conducted a $2 \times 2 \times 2$ protocol on azoxymethane-induced F344 rats fed a diet containing 1% hemoglobin, HCA (PhIP, 50 μg/kg; MeIQx, 25 μg/kg), or both. To induce a strong endogenous NOC formation, drinking water was supplemented with sodium nitrate and nitrite (0.17 g/L of $NaNO_2$ and 0.23 g/L of $NaNO_3$) and compared with a nitrate-free water, according to the experimental groups described in Table 1A (16). Mice were fed a control diet or a 2.5% hemoglobin diet (Table 1B).

Azoxymethane-induced colon carcinogenesis in rat

After 1 week on the experimental diet, rats received intraperitoneal injection of azoxymethane (Sigma; 20 mg/kg body weight).

Neoplastic lesions

The large intestines of rats and large and small intestines of mice were removed and fixed in 0.05% buffered formalin (Sigma).

MDF $scoring$ in $colon$ of $rats.$ MDF were scored in duplicate by 2 readers who were blinded to the origin of the colon following the high-iron diamine Alcian blue procedure (17) described by Santarelli and colleagues (4).

$Tumor$ $scoring$ in $small$ $intestine$ and $colon$ of $mice.$ At sacrifice, the intestinal tract from duodenum to colon was removed. Sections of duodenum, jejunum, and ileum were harvested, opened along the longitudinal axis, and washed in PBS. After fixation in 10% formalin, mouse colons were stained for 6 minutes in a 0.05% filtered methylene blue solution, and small intestines were stained for 48 hours in a 300 ppm solution of methylene blue in formalin. One reader who was blinded to the origin of the sample scored tumors and determined their diameters using a binocular microscope at 25× magnification. All tumors in each section of the intestines were counted, the smallest tumors that could be counted were approximately 0.5 mm in diameter.

Fecal assays in rat and mice

Feces were collected during the last 10 days and frozen at −20°C. Urine was collected on days 67 to 70 for rats and on days 44 to 45 for mice and frozen at −20°C before DHN-MA assay (Supplementary Materials and Methods).

$Fecal$ $water$ $preparation.$ Feces of 24 hours were collected. To prepare fecal water, distilled water (1 mL for rats or 0.85 mL for mice) was added to 0.3 g of dried feces. Fecal water was prepared as described by Pierre and colleagues (5).

$Heme,$ $TBARS$ in $fecal$ $water$ of $rats$ and $mice.$ The heme concentration in the fecal water was measured by fluorescence according to Van den Berg and colleagues (18) and as described by Pierre and colleagues (5). To determine the lipid peroxides in the lumen, thiobarbituric acid reactive substances (TBARS) were quantified in fecal water according to the technique of Ohkawa and colleagues (19) as described previously (20). The results are expressed as the MDA equivalent.

$ATNCs$ in $fecal$ $water$ of $rats.$ ATNCs include N-nitroso compounds, S-nitrosothiols, and FeNO nitrosyl heme. They were analyzed as described previously (11) with an Ecomedics CLD Exhalyzer (Ecomedics). The values measured in 100 μL of the sample are expressed as concentration (in μmol/L).

Table 1. Experimental diets (g/100 g): study in F344 rats and in Min mice

	Study in F344 rats				Study in Min mice	
	Control	Heme	HCA	Heme + HCA	Control	Hemoglobin
AIN76 base	89	89	89	89	65.2	65.3
Sucrose	5.7	4.7	5.7	4.7	29.7	27.2
Casein	0.33	0.33	—	—		
Hemoglobin	—	1	—	1	—	2.5
Ferric citrate	0.015	—	0.015	—	0.035	—
PhIP + MeIQx	—	—	7.5×10^{-6}	7.5×10^{-6}		
Safflower oil	5	5	5	5	5	5

NOTE: HCA: PhIP and MeIQx were obtained from Toronto Research Chemicals. All other chemicals were analytical grade and were obtained from either Merck or Sigma. For their drinking water, each dietary group of rats was split in two subgroups. Half of them received tap water in their drinking bottle. The other half received $NaNO_2$ and $NaNO_3$ solutions in tap water. The $NaNO_2$ and $NaNO_3$ solutions were prepared with 170 mg $NaNO_2$/L water and 230 mg $NaNO_3$/L water. Water was replaced twice a week.

Cell lines

$Apc^{+/+}$ (derived from C57BL/6J mice) and $Apc^{-/+}$ (derived from C57BL/6J $Apc^{Min/+}$ mice) colon epithelial cells (21) express the heat-labile SV40 large T antigen (AgT tsa58) under the control of an IFNγ-inducible promoter. Both cell lines expressed cytokeratin 18, a marker of their epithelial phenotype (Forest 2003). Consequences of the Apc mutation were also detected in the $Apc^{-/+}$ cell line. As expected, actin network was disorganized in $Apc^{-/+}$ cells (Supplementary Fig. S2A; refs. 21, 22), accumulation of multinucleated cells was observed in $Apc^{-/+}$ cells (Supplementary Fig. S2A). As expected, the culture conditions affected cell proliferation due to the thermolabile tsA58 T antigen, which confers conditional immortalization: at 33°C with IFNγ, the large T antigen is active and drives cellular proliferation, and at 37°C, the temperature-sensitive mutation yields an inactive protein and cells act like nonproliferating epithelial cells (Supplementary Fig. S2B).

Aldehydes for cytotoxicity and genotoxicity assays

4-HNE derived from the oxidation of n-6 polyunsaturated fatty acids and 4-hydroxy-2-hexenal (4-HHE) derived n-3 polyunsaturated fatty acids were synthesized as described by Chandra and Srivastava (23). Malondialdehyde (MDA) derived from polyunsaturated fatty acids with 3 or more double bonds was prepared as described by Fenaille and colleagues (24).

Aldehyde trapping of fecal water from hemoglobin fed rats for cytotoxicity assay

Polymer resin (4-Fmoc-hydrazinobenzoyl AM NovaGel, Nobabiochem Merck Chemicals) contains hydrazine functional groups protected by Fmoc groups. To unprotect them, the resin was washed with 0.8 mL DMSO + 0.2 mL piperidine, vortexed for 1 minute, and allowed to settle for 15 minutes. The settled resin was washed twice with DMSO, 4 times with ethanol, and with distilled water. The amount of polymer resin used for each sample was based on using 100× the amount of MDA equivalents present in the fecal water sample. Polymer resin was added to fecal water, and the samples were agitated for 2 hours at 4°C. After letting the resin settle for 15 minutes, supernatant was transferred to a new tube with polymer resin and agitated for 2 hours at 4°C. After settling, the supernatant was diluted into culture medium without FCS and used for the MTT assay.

Cytotoxicity and genotoxicity assays on cell lines treated with fecal water, heme, or aldehydes

To determine cytotoxic activity of fecal water, of HNE (20 μmol/L), and of hemin (100 μmol/L), the MTT assay on $Apc^{+/+}$ and $Apc^{-/+}$ cells was used, as described previously (5). H2AX phosphorylation (γH2AX) is a rapid and sensitive cellular response to genotoxicity (25, 26). Genotoxicity and cytotoxicity of aldehydes were measured after 24 hours of treatment of $Apc^{+/+}$ and $Apc^{-/+}$ cells using a γH2AX in-cell Western blot assay according to Audebert and colleagues (27, 28). Graillot and colleagues (28) demonstrated that this assay can be used to measure cell viability via DNA quantification. Cells were seeded into 96-well plates at 5 × 10³ cells per well in DMEM supplemented with 10% (v/v) FCS, 1% (v/v) penicillin/streptomycin, and 10 U/mL IFNγ at the permissive temperature of 33°C. After 72 hours, cells were transferred to 37°C without IFNγ for 24 hours and then treated with aldehyde (5, 10, and 20 μmol/L) in duplicate. Culture medium without IFNγ and FCS was used for untreated control wells. This assay was repeated 4 times.

Apoptosis assay on cell lines treated with aldehydes

Apoptosis was measured in $Apc^{+/+}$ and $Apc^{-/+}$ cells using a luminescent assay (Caspase-Glo3/7; Promega). Cells were treated with aldehydes for 6 hours. After cell lysis, plates were incubated at room temperature for 2 hours, and the luminescence intensity of each well was determined using an INFINITEM200 plate reader (TECAN). This measure was performed in triplicate with aldehydes at 2.5, 5, 10, 20, 40, and 80 μmol/L.

Histologic analyses of the small intestine of mice

Immunohistochemistry H2AX. Four-micrometer paraffin-embedded sections from formalin-fixed mouse small intestine (Swiss rolls) specimens were de-waxed in toluene and rehydrated. Sections were incubated in Dako peroxidase blocking solution (Dako S2023) and in goat serum (1:10, Dako X0907) for 20 minutes at room temperature. Sections were incubated with the rabbit polyclonal anti-γH2AX antibody (1:400, Cell Signaling Technology #9718) for 50 minutes at room temperature. The secondary antibody (biotinylated goat anti-rabbit, Thermo Scientific TR-060-BN) was applied for 30 minutes at room temperature followed by horseradish peroxidase (HRP)–streptavidin solution (DAB, Dako K0675) for 25 minutes. Peroxidase activity was revealed by DAB substrate (DAKO, K3468). Sections were counterstained with Harris hematoxylin, dehydrated, and coverslipped.

Enterocytes with nuclear γH2AX-positive foci or complete nuclear labeling were considered positive cells. Cells were assessed by counting the positive nuclei in segments of the small intestine specimen that were at least 200 glands long. The positive counts were expressed as counts per one villi-gland unit.

Anaphase bridges. Chromosomal or mitotic alterations can arise from numerous events, including errors during cell division or repair of damaged DNA. As a consequence, the separating sister chromatids are often connected by DNA bridges in anaphase. Anaphase bridges (AB) were evaluated on 4-μm paraffin-embedded sections from formalin-fixed mouse small intestine (Swiss rolls). Sections were stained with hematoxylin and eosin and AB were evaluated under light microscope using 400× magnification. Four segments from the duodenum, jejunum, and ileum that were at least 100 consecutive glands long were selected for counting. Criteria for ABs included having a well-separated parallel anaphase plate displaying a perpendicularly aligned amphophilic (stretched) connecting filament (29). The scores were expressed as number of AB per villi-gland unit.

Statistical analysis

Results were analyzed using Systat 10 software for Windows, and all data are reported as mean ± SEM. For the *in vivo* experiments on chemically induced rats, the importance of each factor was tested independently of the experimental groups (ANOVA per factor). If a significant difference was found between groups ($P < 0.05$), each experimental group was compared with the control using Dunnett test, the difference between control and hemoglobin diets effect on Min mice tumors was analyzed using the Student t test. For the *in vitro* study, the dose effect of aldehydes was analyzed using one-way ANOVA. If a significant difference was found between groups ($P < 0.05$), each experimental group was compared with the control treatment using Dunnett test. Second, the effect of the mutation effect at each concentration of

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aldehyde was analyzed with the comparison between the $Apc^{+/+}$ and $Apc^{-/+}$ cell lines using the Student t test.

Results

Heme iron plays a major role in mucin-depleted foci formation

Only diets containing hemoglobin significantly increased the number of MDF per colon ($P < 0.001$) independent of the 2 other factors (Fig. 1A). Indeed, although nitrates/nitrites in drinking water induced a considerable increase in fecal ATNCs in all groups, they failed to increase the number of MDF per colon (Fig. 1A and D). Nevertheless, we noticed that the ATNC composition was different between groups, containing 30% to 80% FeNO and no S-nitrosothiols in the hemoglobin-fed groups compared with no FeNO and about 30% of S-nitrosothiols in other groups.

Diets containing hemoglobin significantly increase the amount of TBARS in fecal water (Fig. 1B) and the amount of urinary 1,4-dihydroxynonemercapturic acid (DHN-MA), a metabolite of the lipid oxidation product 4-HNE (Supplementary Fig. S3B). These oxidation biomarkers depended only on dietary and fecal heme (Supplementary Fig. S3A) and remained unchanged when the diet contained nitrates/nitrites or HCA without hemoglobin (Fig. 1B and Supplementary Fig. S3B).

Premalignant epithelial cells resist cytotoxicity induced by fecal water from heme-fed rats: the central role of aldehydes

Fecal water from rats fed hemoglobin-containing diets was more cytotoxic to the nonmutated $Apc^{+/+}$ cells than to premalignant $Apc^{-/+}$ cells (Fig. 1C). These data are consistent with previous results (20). Fecal water from rats fed HCA or nitrites/nitrates without hemoglobin was not cytotoxic to these cells (Fig. 1C).

With the trapping of aldehydes from fecal water of rats fed heme with a polymer resin with hydrazine functional groups, we found that in $Apc^{+/+}$ and $Apc^{-/+}$ cells, a 95% reduction in fecal water
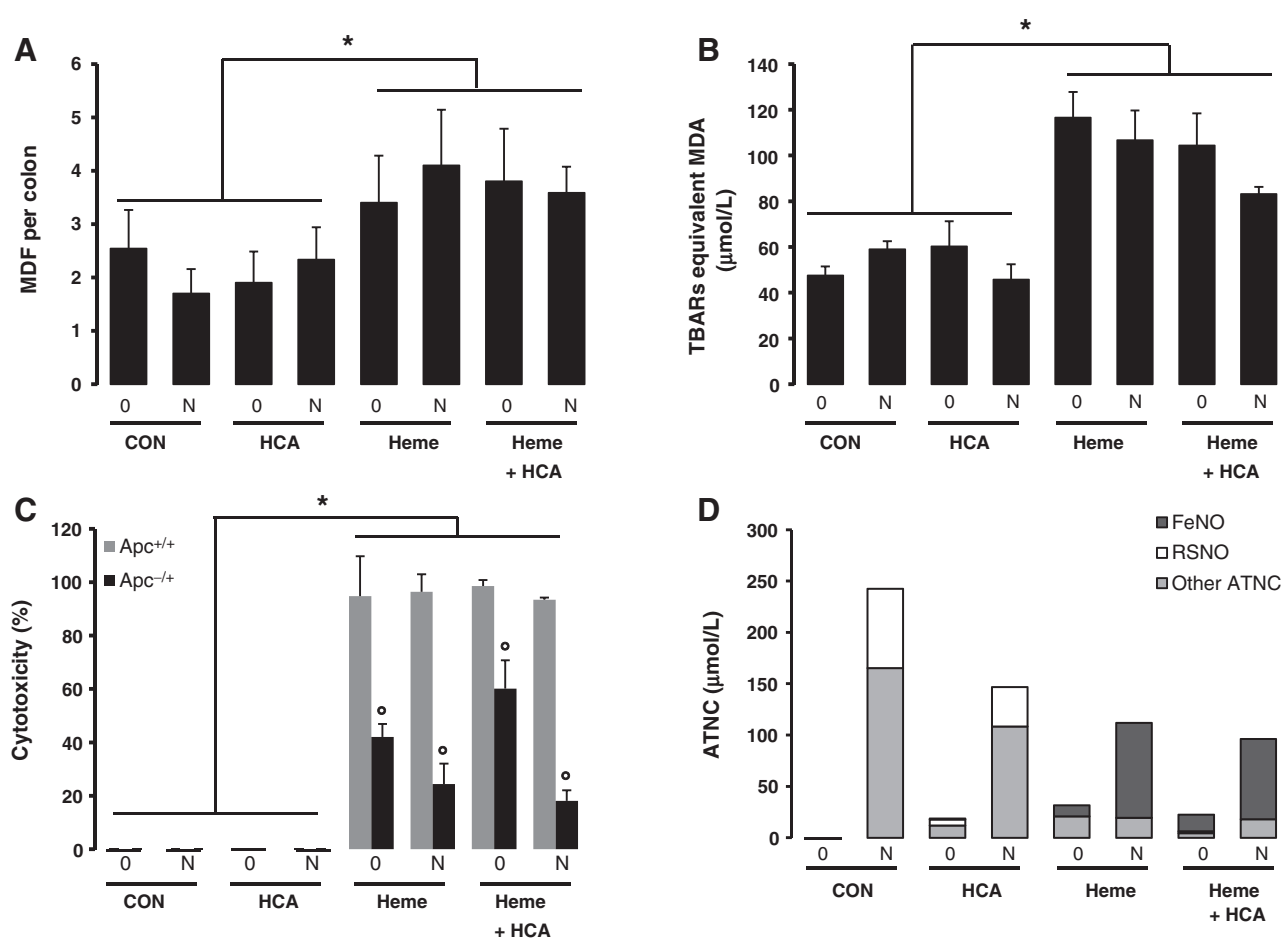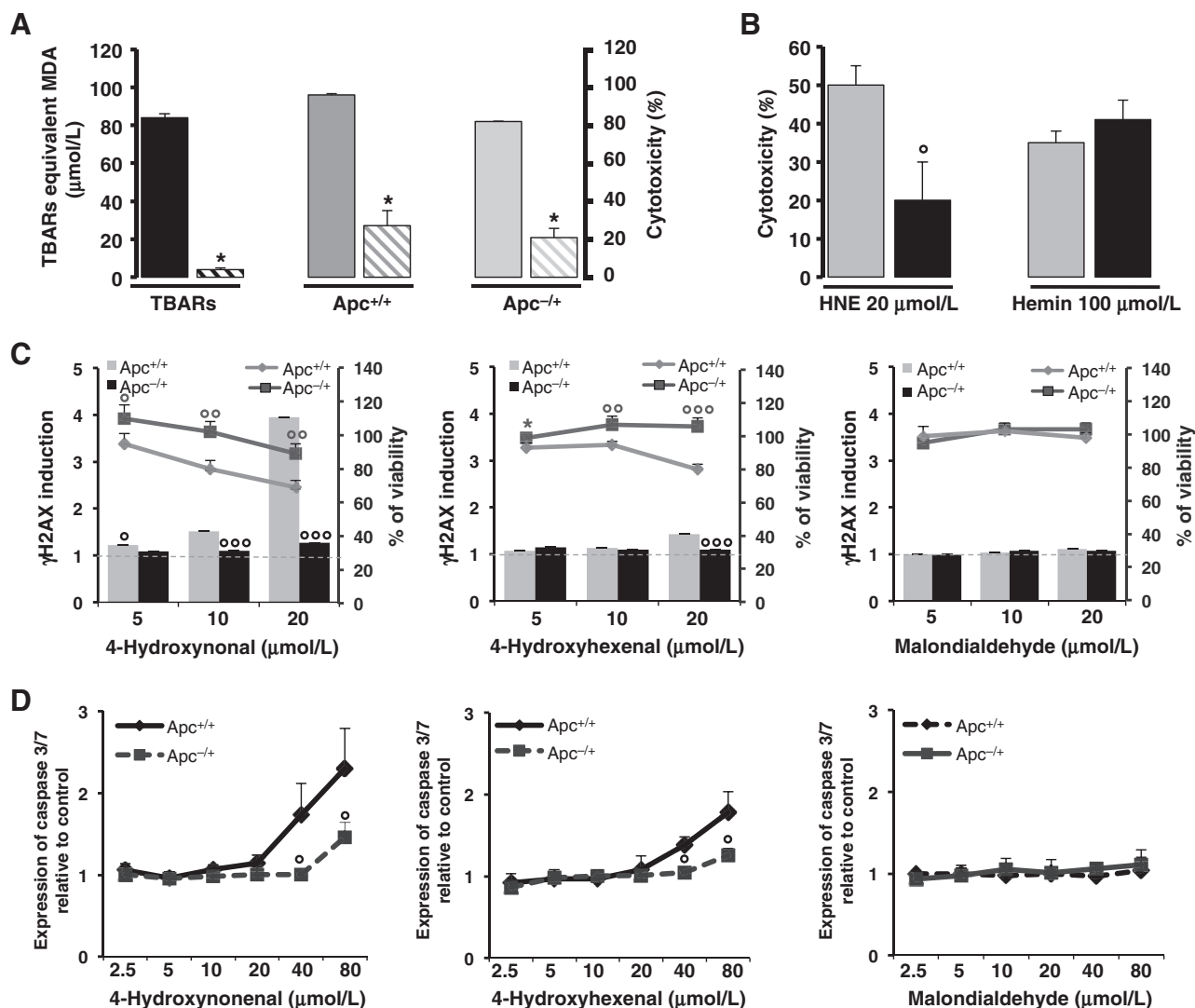

Figure 1.
Heme iron plays a major role in MDF formation in rats and is associated with fecal water lipid peroxidation biomarkers independent of the fecal concentration of ATNCs. A, the number of MDF per rat colon. A 3-factor ANOVA was used and showed only an effect of heme. B, lipid peroxidation in fecal water [measured as TBARs (MDA equivalents)]. C, fecal water cytotoxicity. The cytotoxic effects of fecal water from the 8 groups of rats on $Apc^{+/+}$ cells (gray bars) and on $Apc^{-/+}$ cells (black bars). Viability was measured by MTT assay after 24 hours of incubation with a 1:50 dilution of fecal water. D, ATNCs in fecal water shown as nitrosyl iron (FeNO), S-nitrosothiols (RSNO), and other ATNCs. TEM, control diet; HCA, diet with PhIP (50 μg/kg) and MeIQx (25 μg/kg); Heme, diet containing 1% hemoglobin; Heme + HCA, diet containing 1% hemoglobin, PhIP, and MeIQx: 50 + 25 μg/kg; 0, drinking water control; N, drinking water with nitrites and nitrates at 0.4 g/L. Values are means ± SEM, $n = 10$. *, significantly different from TEM and HCA, $P < 0.001$; °, significantly different from $Apc^{-/+}$ cells, $P < 0.01$.
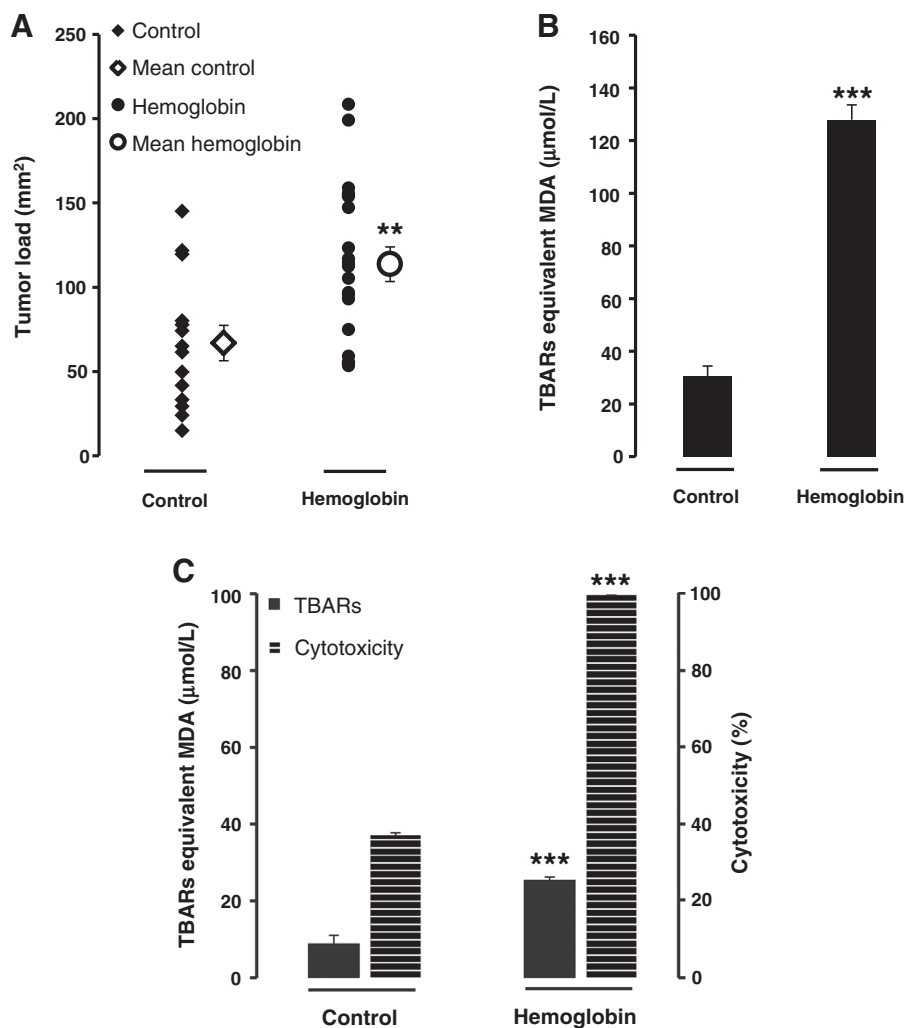
Figure 2.
The central role of aldehydes in the cytotoxic effect of fecal water of hemoglobin fed rats and the cytotoxic, genotoxic, and proapoptotic dose-dependent effects of HNE, HHE, and MDA in $Apc^{+/+}$ and $Apc^{-/+}$ cells. A, TBARS and cytotoxicity on $Apc^{+/+}$ and $Apc^{-/+}$ cells of fecal water of hemoglobin fed rats treated or not with trapping aldehydes resin. Solid bars, fecal water of hemoglobin group; hatched bars, fecal water of hemoglobin group treated with resin. Values are means ± SEM, $n = 3$. B, cytotoxicity on $Apc^{+/+}$ (gray bars) and $Apc^{-/+}$ (black bars) cells of HNE (20 µmol/L) and hemin (100 µmol/L). Values are means ± SEM, $n = 3$. C, genotoxic and cytotoxic effects of aldehydes on $Apc^{+/+}$ and $Apc^{-/+}$ cells. Values are means ± SEM, $n = 4$. D, proapoptotic dose-dependent effects of aldehydes on $Apc^{+/+}$ and $Apc^{-/+}$ cells. Values are means ± SEM, $n = 3$. *, significant difference between fecal water treated or not with resin using the Student t test (*, $P < 0.05$). °, significant difference between $Apc^{+/+}$ and $Apc^{-/+}$ using Student t test (°, $P < 0.05$; °°, $P < 0.01$; °°°, $P < 0.001$).

peroxidation was associated with a 75% reduction in cytotoxicity (Fig. 2A). Furthermore, we observed that only 4-HNE, but not heme, had differential cytotoxic effects in $Apc^{+/+}$ and $Apc^{-/+}$ cells that was similar to that observed with fecal water of rats fed heme (Fig. 2B).

We then measured the cytotoxic and genotoxic effects of 3 main lipid peroxidation end products (4-HNE, 4-HHE and MDA) on $Apc^{+/+}$ and $Apc^{-/+}$ cells using a γH2AX in-cell Western blot assay. HNE and HHE were more cytotoxic and more genotoxic to normal $Apc^{+/+}$ cells than to premalignant $Apc^{-/+}$ ones (Fig. 2C, $P < 0.05$). HNE at 10 and 20 µmol/L and HHE at 20 µmol/L were significantly more genotoxic to $Apc^{+/+}$ cells than to $Apc^{-/+}$ ones

(Fig. 2C, $P < 0.05$). MDA was neither cytotoxic nor genotoxic in the tested cell lines (Fig. 2C). We confirmed these viability results with the MTT assay and with the CellTiter-Glo assay (Supplementary Fig. S4), and we used an expanded range of treatment concentrations (from 0 to 80 µmol/L) in these assays. We confirmed that HNE and HHE were more cytotoxic (from 10 to 80 µmol/L and from 40 to 80 µmol/L, respectively) to normal cells than to premalignant ones, whereas MDA had no effect (Supplementary Fig. S4).

We determined the caspase-3/7 activity and again found a significant difference between $Apc^{+/+}$ and $Apc^{-/+}$ cells after HNE and HHE treatment at 80 and 40 µmol/L, respectively

Figure 3.
The effect of hemoglobin on intestinal tumorigenesis in *Min* mice and changes in fecal and luminal biomarkers associated with this effect. A, intestinal tumor load (mm² per intestine). Values are means ± SEM, $n = 14$ for the control diet and $n = 21$ for the hemoglobin diet. B, lipid peroxidation in fecal water from feces [measured as TBARs (MDA equivalents)]. $n = 5$ for the control diet and $n = 7$ for the hemoglobin diet. C, cytotoxic activity and peroxidation in small intestine contents from mouse. Cytotoxicity was measured in the $Apc^{-/+}$ cell line (fecal water diluted 1:50, MTT assay). $n = 5$ for the control diet and $n = 7$ for the hemoglobin diet. ** and ***, significantly different from control diet (**, $P < 0.01$; ***, $P < 0.001$).

(Fig. 2D, $P < 0.05$). Specifically, caspase-3/7 activity was higher in $Apc^{+/+}$ cells than in $Apc^{-/+}$ cells, and MDA treatment had no effect (Fig. 2D).

Heme iron and tumoral promotion: hemoglobin increases intestinal tumorigenesis in $Apc^{Min/+}$ mice

A diet containing 2.5% hemoglobin given to $Apc^{Min/+}$ mice significantly increased the intestinal tumor load (control diet: 67 ± 39 mm²; hemoglobin diet: 114 ± 47 mm², $P = 0.004$; Fig. 3A). These mice develop polyps mainly in the small intestine, and in our study, we did not observe any effects of hemoglobin diet in the colon. The hemoglobin diet also significantly increased the number of all tumors in the jejunum (Supplementary Fig. S5A). In the entire small intestine, the hemoglobin diet significantly increased the number of tumors with a diameter greater than 1 mm (1 mm < tumor size ≤ 2 mm, $P = 0.04$; 2 mm < tumor size, $P = 0.006$; Supplementary Fig. S5B). Giving the same hemoglobin diet to normal C57BL/6J $Apc^{+/+}$ mice induced no neoplasia. As observed in rats, the effect of dietary heme on mice tumors was associated with a significant increase in fecal heme (from 20 ± 22 to 198 ± 29 µmol/L) and with increases in lipoperoxidation biomarkers: fecal TBARS (Fig. 3B) and urinary DHN-MA (Supplementary Fig. S5C). We also assessed TBARS and the cytotoxicity of fecal water in the

small intestine to measure biomarkers at the same location as tumors. As Min mice have a mutation in the *Apc* gene, we decided to use the mouse $Apc^{-/+}$ model to investigate the cytotoxic activity of fecal water *in vivo*. Heme diet was associated with a significant increase in fecal TBARS and cytotoxicity in the small intestine (Fig. 3C).

A heme diet is genotoxic *in vivo* in the epithelium of C57BL/6J $Apc^{+/+}$ mice
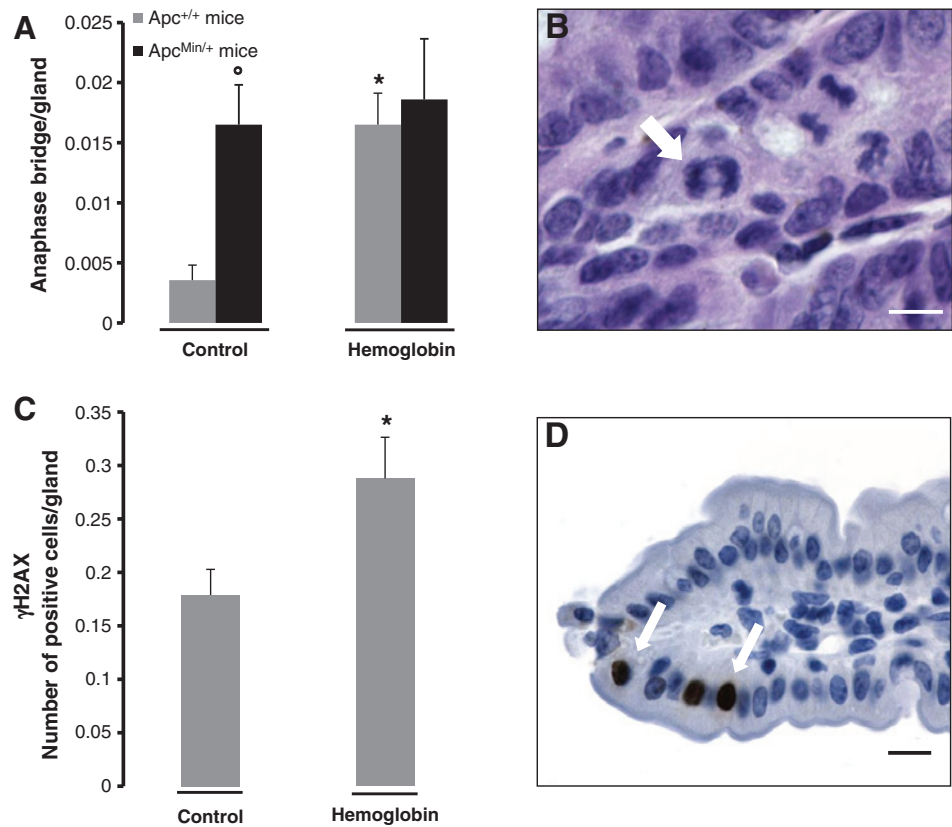
The induction of luminal lipid peroxidation by the hemoglobin diet (Fig. 3B and C) was associated with increased genotoxicity only in nonmutated C57BL/6J $Apc^{+/+}$ mice with a higher AB index in the epithelium (Fig. 4A and B). As expected the AB index was higher in C57BL/6J $Apc^{Min/+}$ mice than in C57BL/6J $Apc^{+/+}$ mice fed a control diet (Fig. 4A) because of the *Apc* mutation. In $Apc^{Min/+}$ mice, the hemoglobin diet had no additional genotoxic effect (Fig. 4A). The genotoxic effect of the hemoglobin diet in C57BL/6J $Apc^{+/+}$ was confirmed by γH2AX induction (Fig. 4C and D).

Discussion

This study examines *in vivo* the relative contributions of the 3 main factors that may explain how consumption of red and

Figure 4.
The effect of a hemoglobin-containing diet on ABs and on the induction of γH2AX in the small intestinal epithelium in mice. A, the number of ABs per gland in $Apc^{Min/+}$ and $Apc^{+/+}$ mice after 50 days of the indicated experimental diet. *, significantly different from the control diet in the same genetic context; °, significantly different from $Apc^{+/+}$ mice on the same diet. B, an AB (arrow) in an $Apc^{+/+}$ mouse fed a hemoglobin diet. Scale bar, 2 μm. C, the number of γH2AX-positive cells per gland in C57BL/6J mice after 14 days on the experimental diet. D, γH2AX-positive cells (arrows) in $Apc^{+/+}$ mice fed the heme diet. Scale bar, 4 μm.

processed meat promotes colorectal cancer. Cross and colleagues showed that these factors, that is, heme, HCA, and NOC, were associated with colorectal cancer in a prospective cohort study in humans (15). However, the identification of risk factors using an epidemiologic approach has to be correlated with the experimental approach to establish the causative effect of such factors. Here, heme iron was the only experimental factor associated with a significant increase in precancerous lesions (MDF) in rats. Heme iron showed no additive or synergic effects with nitrates/nitrites or with HCA. Using a complementary approach that included 2 animal models and a cellular model, we found that heme is the determining factor in the promotion of colorectal carcinogenesis and that the selective toxicity of heme-induced alkenals to non-mutated cells seemed to play an important role in this mechanism.

HCA are complete carcinogens that induce colon, mammary, and prostate tumors in rodents and monkeys (30). The absence of effects of HCA in this study could be explained by the dose we chose, which was based on the estimated dietary exposure to HCA in a diet that is high in red meat and was relevant of the human food exposure. Indeed, carcinogenic doses of HCAs in rodents are 1,000 to 100,000 times higher than levels found in human foods (31). Nitrite undergoes an enterosalivary cycle in humans but not in rats. We hypothesized that the addition of sodium nitrates/nitrites to the rodents' drinking water, which mimics human saliva, would increase the effects of heme iron in rats by boosting nitrosation in the gut. In humans, red meat consumption increases fecal ATNC concentrations (11), as in our study with rats. Nevertheless, we could not detect any

association between the ATNC level (Fig. 1D) and carcinogenesis (Fig. 1A). The highest level of ATNC was seen in the control group given nitrates/nitrites-supplemented water; this group had the fewest MDF. The lack of a relationship between ATNCs and the number of MDF does not support a strong role for ATNCs in the promotion of colon carcinogenesis by red meat.

The present results strongly suggest that at concentrations that are in line with human red meat consumption, heme iron is associated with the promotion of colon carcinogenesis at a preneoplastic stage. Most human colon cancers have an Apc mutation, as do MDF in humans and rats (32). To unravel the mechanisms, we used a cellular model that represented the colorectal cancer stages that we investigated in vivo. We chose a cellular model that mimicked the early steps of carcinogenesis. This conditionally immortalized intestinal cellular model uses premalignant $Apc^{-/+}$ cells derived from C57BL/6J $Apc^{Min/+}$ mice and "normal" $Apc^{+/+}$ cells from C57BL/6J mice (33). Characterization of both cell lines showed the expected consequences of Apc mutation, such as actin network disassembly, aneuploidy, and multinucleated cells (Supplementary Fig. S2). These cell lines can therefore be used to study the mechanisms involved in the early steps of colorectal cancer and thus comprise a cellular model that is a relevant complement to our in vivo model.

In rats, promotion of colon carcinogenesis by dietary hemoglobin was associated with changes in noninvasive biomarkers: fecal water heme iron, TBARS, and cytotoxic activity. Only the hemoglobin diet increased TBARS levels in fecal water (Fig. 1B).

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We speculated that the cytotoxic effects of fecal water on normal and premalignant colonic cells *in vitro* mimic the *in vivo* situation with normal epithelium ($Apc^{+/+}$) and with Apc-mutated MDF. In this study, only fecal water from hemoglobin-fed rats was more cytotoxic to $Apc^{+/+}$ cells than to mutated cells (Fig. 1C). We propose that premalignant cell selection explains the heme-induced promotion of MDF. Aldehydes or heme iron itself, both present at high concentration in feces from hemoglobin-fed rats, might be responsible for this differential cytotoxicity. Using a resin to specifically trap fecal aldehydes, we showed that aldehydes alone are responsible for fecal water cytotoxicity. In addition, we observed that 4-HNE, but not heme iron, induced differential cytotoxicity in $Apc^{+/+}$ and $Apc^{-/+}$ cells similar to that observed with fecal water (Fig. 2B). Therefore, we propose that heme-induced lipid peroxidation in the gut explains the observed differential cytotoxicity and the colorectal cancer–promoting effects of heme that are observed *in vivo*.

To explore the link between aldehydes and the promotion of colon carcinogenesis, we tested the effects of 3 relevant aldehydes, 4-HNE, HHE, and MDA, in $Apc^{+/+}$ and $Apc^{-/+}$ cells. These α,β-unsaturated hydroxyalkenals are highly reactive compounds with proteins and nucleic acids (34), and they are potentially cytotoxic and genotoxic. In our cellular model, 4-HNE and HHE were more cytotoxic to normal cells than to premalignant cells and induced higher levels of apoptosis in normal cells than in premalignant cells. HNE was more cytotoxic than HHE, as reported previously (35). Furthermore, HNE, like HHE, was more genotoxic to normal cells than to premalignant ones (Fig. 2C), with a higher index of DNA double-strand breaks as revealed by the phosphorylation of histone H2AX. DNA double-strand breaks pose a critical hazard to the genome, and erroneous rejoining of DNA double-strand breaks can lead to mutation. These results thus suggest that at concentrations higher than 20 μmol/L, HNE and HHE will kill normal cells, whereas at lower concentration, they could create mutations in $Apc^{+/+}$ cells and might thus initiate carcinogenesis. Therefore, Apc-mutated cells are resistant to apoptosis and can survive to contact with cytotoxic and genotoxic aldehydes, which allows them to undergo further mutation and to become more malignant. Surprisingly, MDA was not toxic to the cells tested in this study but others found also that MDA had little or no toxicity in cells (35, 36). The results obtained by aldehyde trapping and *in vitro* with HNE and HHE confirmed our hypothesis that aldehydes are responsible for the differential cytotoxic effects of fecal water from heme-fed rats. Heme iron catalyzes the formation of aldehydes in the gastrointestinal tract, which would "select" premalignant cells and also increase the mutation frequency in normal cells (22).

This study shows that a hemoglobin-rich diet significantly increased the tumor load in the small intestine of $Apc^{Min/+}$ mice. In contrast, tumor load was not changed by heme diet in the colon of mice, despite the expected modulation of biochemical markers. The number of tumors in the colon of Min mice is low (<0.5 tumors per mouse), which reduces statistical power (37). These mice have a truncated Apc gene as in human familial adenomatous polyposis (FAP; ref. 38). Moreover, sporadic colorectal cancer tumors have the same early Apc mutation in 50% to 80% of cases (37). This mutation is also present in MDF (39). Our nutritional experiments in rats and

mice were thus conducted in the defined genetic context of the Apc mutation. Promotion of carcinogenesis in rats and in $Apc^{Min/+}$ mice (Fig. 3A) was associated with 2 noninvasive biomarkers, fecal water TBARS and cytotoxic activity, in colon and in small intestine (Fig. 3B and C).

Furthermore, as we found that HNE is more genotoxic *in vitro* to wild-type cells than to $Apc^{-/+}$ cells (Fig. 2C), we decided to investigate the genotoxicity of dietary heme *in vivo* by measuring (i) the AB index in the epithelium of C57BL/6J $Apc^{+/+}$ mice and C57BL/6J $Apc^{Min/+}$ mice and (ii) by assessing γH2AX induction in the epithelium of C57BL/6J $Apc^{+/+}$ mice (Fig. 4). In these 2 studies, the induction of lipid peroxidation in the gut by heme (Fig. 3B and C) was associated with increased epithelial genotoxicity in $Apc^{+/+}$ mice but not in $Apc^{Min/+}$ mice. Together with *in vitro* data, these data show that dietary hemoglobin can induce DNA damage. We also observed ABs, which are biomarkers of chromosomal instability and a major consequence of Apc mutation. As expected, in mice fed the control diet, more ABs were seen in $Apc^{Min/+}$ mice than in $Apc^{+/+}$ mice (Fig. 4A). Moreover, the hemoglobin diet increased the AB index in $Apc^{+/+}$ mice (Fig. 4A). The hemoglobin diet induced the same number of ABs as the Apc mutation, suggesting that dietary hemoglobin generates strong initiators. Taken together, these data suggest that heme-induced aldehydes can induce mutations *in vitro* and *in vivo* and may initiate carcinogenesis.

In conclusion, we identified heme iron as the main factor responsible for the promotion of colorectal cancer by red meat and showed that aldehydes such as 4-HNE or HHE play roles in the underlying mechanism of action. Furthermore, we suggest that dietary heme could result in initiating agents in the gut. Improved dietary recommendations should focus (i) on the amount of heme iron in meat-based diets rather than on the modes of cooking or preparation and (ii) on dietary changes that could reduce the heme effect in the gut (i.e., on changes that limit the bioavailability of heme and of heme-induced peroxidation; ref. 40).

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Disclaimer

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References

1. DeSantis CE, Lin CC, Mariotto AB, Siegel RL, Stein KD, Kramer JL, et al. Cancer treatment and survivorship statistics, 2014. CA Cancer J Clin 2014;64:252–71.
2. WCRF. Food, nutrition, physical activity, and the prevention of cancer: a global perspective. Washington DC: WCRF and American Institute for Cancer Research; 2007. p. 1–537.
3. WCRF. WCRF/AICR Systematic Literature Review Continuous Update Project Report: The associations between food, nutrition and physical activity and the risk of colorectal cancer. Washington DC: WCRF and American Institute for Cancer Research; 2010. p. 1–855.
4. Pierre FH, Santarelli RL, Allam O, Tache S, Naud N, Gueraud F, et al. Freeze-dried ham promotes azoxymethane-induced mucin-depleted foci and aberrant crypt foci in rat colon. Nutr Cancer 2010;62:567–73.
5. Pierre F, Freeman A, Tache S, Van der Meer R, Corpet DE. Beef meat and blood sausage promote the formation of azoxymethane-induced mucin-depleted foci and aberrant crypt foci in rat colons. J Nutr 2004;134:2711–6.
6. Corpet DE, Pierre F. Point: from animal models to prevention of colon cancer. systematic review of chemoprevention in min mice and choice of the model system. Cancer Epidemiol Biomarkers Prev 2003;12: 391–400.
7. Bastide NM, Pierre FH, Corpet DE. Heme iron from meat and risk of colorectal cancer: a meta-analysis and a review of the mechanisms involved. Cancer Prev Res (Phila) 2012;4:177–84.
8. Bingham SA, Hughes R, Cross AJ. Effect of white versus red meat on endogenous N-nitrosation in the human colon and further evidence of a dose response. J Nutr 2002;132:3522S–5S.
9. Sinha R, Knize MG, Salmon CP, Brown ED, Rhodes D, Felton JS, et al. Heterocyclic amine content of pork products cooked by different methods and to varying degrees of doneness. Food Chem Toxicol 1998;36:289–97.
10. Sesink ALA, Termont DSML, Kleibeuker JH, Vandermeer R. Red meat and colon cancer: the cytotoxic and hyperproliferative effects of dietary heme. Cancer Res 1999;59:5704–9.
11. Kuhnle GG, Story GW, Reda T, Mani AR, Moore KP, Lunn JC, et al. Diet-induced endogenous formation of nitroso compounds in the GI tract. Free Radic Biol Med 2007;43:1040–7.
12. Glei M, Klenow S, Sauer J, Wegewitz U, Richter K, Pool-Zobel BL. Hemoglobin and hemin induce DNA damage in human colon tumor cells HT29 clone 19A and in primary human colonocytes. Mutat Res 2006;594: 162–71.
13. Pierre FHF, Martin OCB, Santarelli R, Tache S, Naud N, Gueraud F, et al. Calcium and α-tocopherol suppress cured meat promotion of chemically-induced colon carcinogenesis in rats and reduce associated biomarkers in human volunteers. Am J Clin Nutr 2013;98:1255–62.
14. Santarelli RL, Naud N, Taché S, Guéraud F, Nassy G, Vendeuvre JL, et al. Calcium inhibits promotion by hot dog of 1-2-dimethylhydrazine-induced mucin-depleted foci in rat colon. Int J Cancer 2013;133:2533–41.
15. Cross AJ, Ferrucci LM, Risch A, Graubard BI, Ward MH, Park Y, et al. A large prospective study of meat consumption and colorectal cancer risk: an investigation of potential mechanisms underlying this association. Cancer Res 2010;70:2406–14.
16. Mirvish SS, Davis ME, Lisowyj MP, Gaikwad NW. Effect of feeding nitrite, ascorbate, hemin, and omeprazole on excretion of fecal total apparent N-nitroso compounds in mice. Chem Res Toxicol 2008;21:2344–51.
17. Caderni G, Femia AP, Giannini A, Favuzza A, Luceri C, Salvadori M, et al. Identification of mucin-depleted foci in the unsectioned colon of azoxymethane-treated rats: correlation with carcinogenesis. Cancer Res 2003; 63:2388–92.
18. Van den Berg JW, Koole-Lesuis R, Edixhoven-Bosdijk A, Brouwers N. Automating the quantification of heme in feces. Clin Chem 1988;34: 2125–6.
19. Ohkawa H, Ohishi N, Yagi K. Assay for lipid peroxides in animal tissues by thiobarbituric acid reaction. Anal Biochem 1979;95:351–8.
20. Pierre F, Santarelli R, Tache S, Gueraud F, Corpet DE. Beef meat promotion of dimethylhydrazine-induced colorectal carcinogenesis biomarkers is suppressed by dietary calcium. Br J Nutr 2008;99:1000–6.
21. Forest V, Pierre F, Bassonga E, Meflah K, Olivier C, Menanteau J. Apc+/min colonic epithelial cells express TNF receptors and ICAM-1 when they are co-cultured with large intestine intra-epithelial lymphocytes. Cell Immunol 2003;223:70–6.
22. Pierre F, Tache S, Guéraud F, Rerole AL, Jourdan ML, Petit C. Apc mutation induces resistance of colonic cells to lipoperoxide-triggered apoptosis induced by faecal water from haem-fed rats. Carcinogenesis 2007;28: 321–7.
23. Chandra A, Srivastava SK. A synthesis of 4-hydroxy-2-trans-nonenal and 4-(3H) 4-hydroxy-2-trans-nonenal. Lipids 1997;32:779–82.
24. Fenaille F, Mottier P, Turesky RJ, Ali S, Guy PA. Comparison of analytical techniques to quantify malondialdehyde in milk powders. J Chromatogr A 2001;921:237–45.
25. Rogakou EP, Pilch DR, Orr AH, Ivanova VS, Bonner WM. DNA double-stranded breaks induce histone H2AX phosphorylation on serine 139. J Biol Chem 1998;273:5858–68.
26. Khoury L, Zalko D, Audebert M. Validation of high-throughput genotoxicity assay screening using γH2AX in-cell western assay on HepG2 cells. Environ Mol Mutagen 2013;54:737–46.
27. Audebert M, Dolo L, Perdu E, Cravedi JP, Zalko D. Use of the gammaH2AX assay for assessing the genotoxicity of bisphenol A and bisphenol F in human cell lines. Arch Toxicol 2011;85:1463–73.
28. Graillot V, Takakura N, Hegarat LL, Fessard V, Audebert M, Cravedi JP. Genotoxicity of pesticide mixtures present in the diet of the French population. Environ Mol Mutagen 2012;53:173–84.
29. Montgomery E, Wilentz RE, Argani P, Fisher C, Hruban RH, Kern SE, et al. Analysis of anaphase figures in routine histologic sections distinguishes chromosomally unstable from chromosomally stable malignancies. Cancer Biol Ther 2003;2:248–52.
30. Sugimura T, Wakabayashi K, Nakagama H, Nagao M. Heterocyclic amines: Mutagens/carcinogens produced during cooking of meat and fish. Cancer Sci 2004;95:290–9.
31. Schwabn CE, Huber WW, Parzefall W, Hietsch G, Kassie F, SchulteHermann R, et al. Search for compoiunds that inhibit the genotoxic anc carcinogenic effects of heterocyclic aromatic amines. Crit Rev Toxicol 2000;30:1–69.
32. Femia AP, Giannini A, Fazi M, Tarquini E, Salvadori M, Roncucci L, et al. Identification of mucin depleted foci in the human colon. Cancer Prev Res (Phila) 2008;1:562–7.
33. Jamin EL, Riu A, Douki T, Debrauwer L, Cravedi JP, Zalko D, et al. Combined genotoxic effects of a polycyclic aromatic hydrocarbon (B(a) P) and an heterocyclic amine (PhIP) in relation to colorectal carcinogenesis. PLoS One 2013;8:e58591.
34. Schaur RJ. Basic aspects of the biochemical reactivity of 4-hydroxynonenal. Mol Aspects Med 2003;24:149–59.
35. Eckl PM, Ortner A, Esterbauer H. Genotoxic properties of 4-hydroxyalkenals and analogous aldehydes. Mutat Res 1993;290:183–92.
36. Fischer SM, Ogle S, Marnett LJ, Nesnow S, Slaga TJ. The lack of initiating and/or promoting activity of sodium malondialdehyde on SENCAR mouse skin. Cancer Lett 1983;19:61–6.

37. Corpet DE, Pierre F. How good are rodent models of carcinogenesis in predicting efficacy in humans? A systematic review and meta-analysis of colon chemoprevention in rats, mice and men. Eur J Cancer 2005;41:1911–22.

38. Su LK, Kinzler KW, Vogelstein B, Preisinger AC, Moser AR, Luongo C, et al. Multiple intestinal neoplasia caused by a mutation in the murine homolog of the APC gene. Science 1992;256:668–70.

39. Femia AP, Dolara P, Giannini A, Salvadori M, Biggeri A, Caderni G. Frequent mutation of Apc gene in rat colon tumors and mucin-depleted foci, preneoplastic lesions in experimental colon carcinogenesis. Cancer Res 2007;67:445–9.

40. Corpet DE. Red meat and colon cancer: should we become vegetarians, or can we make meat safer? Meat Sci 2011;89:310–6.

A Central Role for Heme Iron in Colon Carcinogenesis Associated with Red Meat Intake

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