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A large prospective study of meat consumption and colorectal cancer risk: an investigation of potential mechanisms underlying this association

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Abstract

Although the relation between red and processed meat intake and colorectal cancer has been reported in several epidemiologic studies, very few investigated the potential mechanisms. This study examined multiple potential mechanisms in a large U.S. prospective cohort with a detailed questionnaire on meat type and meat cooking methods linked to databases for estimating intake of mutagens formed in meats cooked at high temperatures (heterocyclic amines, polycyclic aromatic hydrocarbons), heme iron, nitrate and nitrite. During 7 years of follow-up, 2,719 colorectal cancer cases were ascertained from a cohort of 300,948 men and women. The hazard ratios (HR) and 95% confidence intervals (CI) comparing the fifth to the first quintile for both red (HR=1.24, 95% CI: 1.09-1.42; p-trend <0.001) and processed meat (HR=1.16, 95% CI: 1.01-1.32; p-trend=0.017) intake indicated an elevated risk for colorectal cancer. The potential mechanisms for this relation include heme iron (HR=1.13, 95% CI: 0.99-1.29; p-trend=0.022), nitrate from processed meats (HR=1.16, 95% CI: 1.02-1.32; p-trend=0.001) and heterocyclic amine intake (HR=1.19, 95% CI: 1.05-1.34; p-trend <0.001 for MeIQx and HR=1.17, 95% CI: 1.05-1.29; p-trend <0.001 for DiMeIQx). In general, the elevated risks were higher for rectal cancer than for colon cancer, with the exception of MeIQx and DiMeIQx, which were only associated with colon cancer. In conclusion, we found a positive association for red and processed meat intake and colorectal cancer; heme iron, nitrate/nitrite, and heterocyclic amines from meat may explain these associations.

Keywords

Meat; colorectal cancer; diet

Introduction

Although a recent consensus report concluded there was ‘convincing’ evidence supporting a positive association between both red meat and processed meat intake and colorectal cancer, it noted that there was inadequate evidence to implicate specific components of meat (1). There are very few epidemiologic studies that have comprehensively assessed potential mechanisms relating meat to carcinogenesis.

Meat is a key source of iron because this heme iron is more readily absorbed than iron from other sources. Epidemiologic studies of dietary iron intake and colorectal neoplasia are inconsistent; the World Cancer Research Fund (WCRF)/ American Institute for Cancer Research (AICR) consensus report concluded that “the evidence was sparse, of poor quality, and inconsistent” (1). Iron can induce oxidative DNA damage (2,3) and heme iron is associated with fecal water cytotoxicity (4,5) and the promotion of colorectal cancer in rodents (6). Furthermore, heme iron intake increases endogenous formation of *N*-nitroso compounds (NOCs) (7), which are multi-site carcinogens (8). In addition, NOCs can be formed exogenously in processed meats from nitrate and nitrite added during the processing procedure. Meat cooked well-done at high temperatures is also a source of heterocyclic amines (HCAs) (9-11) and polycyclic aromatic hydrocarbons (PAHs) (12,13), which are known gastrointestinal carcinogens in animal models (12,14).

The WCRF/AICR report noted that there was insufficient evidence to reach any consensus for nitrate, nitrite, HCAs or PAHs as risk factors for colorectal cancer (1). To better understand the association between meat and colorectal cancer, we examined this relationship in a large prospective cohort and investigated components of meat, as well as risks by tumor sub-site.

Materials and Methods

Study population

The NIH-AARP Diet and Health Study is a large prospective cohort of men and women, aged 50 to 71 years, from six U.S. states (California, Florida, Louisiana, New Jersey, North Carolina, and Pennsylvania) and two metropolitan areas (Atlanta, Georgia, and Detroit, Michigan). At baseline (1995-96), a self-administered questionnaire regarding demographic and lifestyle characteristics was completed; further study details have previously been described (15). The Special Studies Institutional Review Board of the U.S. National Cancer Institute approved the study.

Dietary Assessment

A 124-item food frequency questionnaire (FFQ) that compared favorably to other FFQs (16), and was calibrated within the study population against two nonconsecutive 24-hour dietary recalls (15), was completed at baseline. Portion sizes and daily nutrient intakes were calculated from the 1994-1996 U.S. Department of Agriculture’s Continuing Survey of Food Intake by Individuals (17). Approximately six months after baseline, participants who did not have self-reported prostate, breast or colon cancer at baseline were mailed the risk factor questionnaire (RFQ) that collected information on meat type, meat cooking methods and doneness levels. The red meat variable contained all types of beef, pork, and lamb; including bacon, beef, cold cuts, ham, hamburger, hot dogs, liver, pork, sausage, and steak. White meat included chicken and turkey (poultry cold cuts, chicken mixtures, low-fat sausages and low-fat hot dogs made from poultry), and fish. The processed meat variable included bacon, red meat sausage, poultry sausage, luncheon meats (red and white meat), cold cuts (red and white meat), ham, regular hotdogs and low-fat hotdogs made from poultry. The meat variables also included meats added to complex food mixtures, such as pizza, chili, lasagna, and stew.

Total iron was calculated as the sum of dietary iron and supplemental iron. Dietary iron included all dietary sources of iron, including cereals, vegetables and meat. We developed a new heme iron database based on measured values from meats cooked by different methods and to varying doneness levels, which we used in conjunction with the detailed meat cooking questionnaire to quantitatively assess heme iron intake (18). We estimated nitrate and nitrite intake from processed meats using a database containing measured value of nitrate and nitrite from ten types of processed meats, which represent 90% of processed meats consumed in the U.S. (18). In an analysis of total dietary nitrate and nitrite, we estimated intake of these compounds by determining the content of foods that constituted the food item database from the literature, as described previously (19,20). Meat cooking method (grilled/barbecued, pan-fried, microwaved, and broiled) and doneness level (well-done/very well-done and medium/rare) were used in conjunction with the CHARRED database (<http://charred.cancer.gov>) to estimate intake of several HCAs (18), including 2-amino-3,4,8-trimethylimidazo[4,5-f]quinoxaline (DiMeIQx), 2-amino-3,8-dimethylimidazo[4,5-f]quinoxaline (MeIQx) and 2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine (PhIP), as well as one PAH, benzo[a]pyrene (B[a]P), and mutagenic activity (a measure of total mutagenic potential incorporating all meat-related mutagens).

Cohort follow-up and case ascertainment

Cohort members were followed for change of address using the U.S. Postal Service. We ascertained vital status through annual linkage of the cohort to the U.S. Social Security Administration Death Master File, follow-up searches of the National Death Index Plus for participants who matched to the Social Security Administration Death Master File, cancer registry linkage, questionnaire responses, and responses to other mailings. We identified cancer cases through probabilistic linkage with state cancer registries. In addition to the eight original states from which the cohort recruited, our cancer registry ascertainment area was expanded to include Texas, Arizona, and Nevada, where participants have most commonly moved during follow-up. Approximately 4% of participants were lost to follow-up as a result of moving out of the eleven states. Colorectal cancer endpoints were defined by anatomic site and histologic code of the International Classification of Diseases for Oncology (ICD-O-3) (21), and included codes: C180-C189, C199, C209, C260. We further classified cases as proximal colon (C180-184), distal colon (C185-187) and rectum (C199, C209). We included first primary diagnoses and our analysis was based on adenocarcinomas; we excluded cases with unspecified histologies (n=132), lymphomas (n=19), sarcomas (n=5), neuroendocrine tumors (n=48), squamous cell tumors (n=7), a large cell rhabdoid tumor (n=1), a gastrinoma (n=1) and a melanoma (n=1). Follow-up for these analyses began on the date the RFQ was received until censoring at the end of 2003, or when the participant moved out of one of the eleven state cancer registry areas, had a cancer diagnosis, or died, whichever came first.

Statistical analysis

There were a total of 566,402 persons who returned the baseline questionnaire (after excluding duplicates and subjects who died or moved before entry or withdrew from the study) and 337,074 who returned the RFQ. For our study, we excluded individuals who had not completed the RFQ, who died before the RFQ was received (n = 1,619), who moved out of one of the original eight study areas before returning the RFQ (n = 547), whose baseline questionnaire or RFQ was filled in by someone else on their behalf (n = 10,383), who had prevalent cancer (as noted by cancer registry or self-report) at the time they completed the RFQ (n = 18,844), who had a death only report for any cancer (n = 2,246), who had zero person years of follow-up (n = 4), and those with extreme daily total energy intake (n = 2,483), defined as more than two inter-quartile ranges above the 75th or below the 25th percentile on the logarithmic scale. After all exclusions, our analytic cohort consisted of 300,948 persons (175,369 men and 125,579 women).

Hazard ratios (HRs) and 95% confidence intervals (CIs) were estimated using Cox proportional hazards regression with person years as the underlying time metric; analyses using age as the underlying time metric yielded almost identical HRs. The proportional hazards assumption was verified using a time interaction model. The models were constructed as addition models that summed to total meat; for example, red and white meat were included in the same model, as were processed and non-processed meat. The final multivariate models only contained variables that changed the HR by 10% or more, or were established risk factors for colorectal cancer, and they included: gender, education, body mass index (BMI), smoking, and intake of total energy, fiber and dietary calcium. Dietary variables were adjusted for energy by the nutrient density method (22); using the residual energy adjustment method resulted in similar risk estimates (given in table footnote). The covariates that attenuated the risk estimates the most were BMI, and intake of fiber and calcium. Multivariate HRs are reported within quintiles, using the lowest quintile as the referent category. Tests for linear trend were calculated using the median value of each quintile. All reported *P* values are two-sided.

Interactions were evaluated by including cross product terms in multivariate models. Furthermore, we conducted a lag-analysis excluding the first two years of follow up. To test for heterogeneity between the anatomic sub-sites, we calculated the weighted average of the two beta coefficients from the Cox model, with weights being proportional to the inverse of the variances. We then calculated the following chi-square statistic with one degree of freedom:

$T = \sum_{i=1}^2 \left(\hat{\beta}_i - \bar{\beta} \right)^2 / \sigma_i^2$; where $\hat{\beta}_i$ and σ_i^2 are the coefficient and its variance for each sub-type, and $\bar{\beta}$ is the weighted average of the beta coefficients. All statistical analyses were carried out using Statistical Analytic Systems (SAS) software (SAS Institute Inc, Cary, NC).

Results

After up to 7.2 years of follow-up, we ascertained 2,719 incident colorectal cancer cases (1,806 male and 913 female cases), of which 1,995 were colon cancers (1,150 proximal, 787 distal colon, 58 lacked definitive site information) and 724 were rectal cancers. We had stage information on 81% of the cases; of these, 43% were stage I, 16% were stage II, 26% were stage III and 15% were stage IV at diagnosis. Individuals in the highest quintile of red meat intake were more likely to be non-Hispanic White, current smokers and to have a higher BMI compared with those in the lowest quintile; furthermore, they were less educated, less physically active, less likely to have a family history of colorectal cancer and consumed less calcium, fiber, fruits and vegetables (Table 1). The correlation between red meat intake and heme iron was high ($r_{\text{Spearman}}=0.82$), as was the correlation between processed meat and both nitrate ($r_{\text{Spearman}}=0.93$) and nitrite ($r_{\text{Spearman}}=0.97$) in meat.

Red meat and total processed meat (processed red and white meat) intake were both positively associated with colorectal cancer (HR for the fifth compared to the first quintile =1.24, 95% CI: 1.09-1.42, *p*-trend <0.001; HR=1.16, 95% CI: 1.01-1.32, *p*-trend= 0.017, respectively) (Table 2). Dividing red meat into processed red meat and non-processed red meat revealed similar risks (comparing the highest to the lowest quintiles: HR=1.11, 95% CI: 0.96-1.28, *p*-trend=0.083 for processed red meat; HR=1.13, 95% CI: 0.98-1.30, *p*-trend=0.002 for non-processed red meat). There was no evidence of an interaction by gender for either red (*p*-interaction=0.385) or processed meat (*p*-interaction=0.138). White meat was inversely associated with colorectal cancer (HR=0.85, 95% CI: 0.76-0.97, *p*-trend=0.017); this association was evident for chicken (HR=0.85, 95% CI: 0.75-0.97, *p*-trend=0.020), but not for turkey (HR=1.02, 95% CI: 0.90-1.17, *p*-trend=0.412), or fish intake (HR=0.95, 95% CI: 0.84-1.08, *p*-trend=0.903).

With further investigation by location, risks were elevated, though not all reached statistical significance, for both colon and rectal cancer for red meat (HR=1.21, 95% CI: 1.03-1.41, p-trend <0.001; HR=1.35, 95% CI: 1.03-1.76, p-trend=0.024, respectively) and processed meat (HR=1.11, 95% CI: 0.95-1.29, p-trend=0.057; HR=1.30, 95% CI: 1.00-1.68, p-trend=0.145, respectively) (Table 2); although the risks were slightly higher for rectal cancer, there was no evidence of sub-site heterogeneity for either red (p-heterogeneity=0.485) or processed meat (p-heterogeneity=0.320). Within the colon, the risks for proximal or distal tumors were not statistically significantly different for either red meat (HR=1.15, 95% CI: 0.94-1.41, p-trend=0.024; HR=1.29, 95% CI: 1.00-1.66, p-trend=0.018, respectively; p-heterogeneity=0.432) or processed meat (HR=1.09, 95% CI: 0.89-1.33, p-trend=0.245; HR=1.10, 95% CI: 0.86-1.41, p-trend=0.363, respectively; p-heterogeneity=0.497) (data not shown). In a lag analysis excluding the first two years of follow-up (n=1,941 colorectal cancer cases), the findings for both red and processed meat remained (HR=1.21, 95% CI: 1.03-1.42, p-trend=0.001; HR=1.19, 95% CI: 1.02-1.39, p-trend=0.013, respectively) (data not shown).

Using the detailed meat questionnaire, we examined specific components of meat in relation to colorectal cancer (Table 3). Interestingly, total iron intake and dietary iron were both inversely associated with colorectal cancer (HR=0.75, 95% CI: 0.66-0.86, p-trend <0.001; HR=0.75, 95% CI: 0.65-0.87, p-trend <0.001, respectively), although the more bioavailable heme iron was positively associated (HR=1.13, 95% CI: 0.99-1.29, p-trend=0.022). Although nitrate intake from processed meats was positively associated with this malignancy (HR=1.16, 95% CI: 1.02-1.32, p-trend=0.001), the association for nitrite did not quite reach statistical significance (HR=1.11, 95% CI: 0.97-1.25, p-trend=0.055). When we examined the highest compared to the lowest quintile of combined nitrate and nitrite intake (data not shown), there was an elevated risk for colorectal cancer (HR=1.14, 95% CI: 1.00-1.30, p-trend=0.019). Interestingly, an analysis of total dietary exposure revealed an inverse association in the highest quintile of dietary nitrate (HR=0.82, 95% CI: 0.71-0.95, p-trend=0.111) but null findings for total nitrite (HR=1.05, 95% CI: 0.92-1.21, p-trend=0.316) and colorectal cancer (data not shown). The findings for total dietary nitrate are likely due to the largest dietary sources of nitrate in our population, which includes several fruits and vegetables such as spinach, broccoli, potatoes and bananas.

Individuals in the highest, compared with the lowest, quintile of MeIQx and DiMeIQx had an elevated risk of colorectal cancer (HR=1.19, 95% CI: 1.05-1.34, p-trend <0.001; HR=1.17, 95% CI: 1.05-1.29, p-trend <0.001, respectively) (Table 3). Neither PhIP nor B[a]P were associated with colorectal cancer; nevertheless, those in the highest quintile of mutagenic activity (a marker of all meat mutagens) had an elevated risk (HR=1.14, 95% CI: 1.01-1.29, p-trend=0.010). In sub-site analyses, the risk estimates for colon and rectal cancers were similar for most of the meat-related exposures, except for MeIQx, DiMeIQx and mutagenic activity, which were only associated with colon cancer (HR=1.26, 95% CI: 1.09-1.45, p-trend <0.001; HR=1.23, 95% CI: 1.10-1.39, p-trend <0.001; HR=1.19, 95% CI: 1.03-1.38, p-trend=0.002, respectively) (Table 3).

Discussion

In this large cohort, both red and processed meat intake were positively associated with colorectal cancer. Our data suggests that these associations could be related to heme iron, nitrate, as well as the HCAs, MeIQx and DiMeIQx, formed in meats cooked at high temperatures.

The findings for red and processed meat from this study are in agreement with a recent and large summary of the epidemiologic literature (1); however, very few studies have investigated the various components of meat that may explain these associations. In contrast to red meat,

white meat is not associated with an elevated risk of colorectal cancer; one of the main differences between red and white meat is the iron content. The contrasting findings in this study for total iron and dietary iron compared with heme iron from meat highlight the importance of distinguishing between heme iron, which is from meat, and non-heme iron, which is mainly from fortified cereals, fruit juice and bread. Thus far, the newly developed heme iron database has only been used in one small screening study of colorectal adenoma, in which there was an elevated risk (odds ratio in the top compared with the bottom quartile of intake=1.50, 95% CI:0.83-2.73), although it was not statistically significant, possibly due to a small number of cases (n=158) (23). Other studies that have investigated heme iron may not be comparable since they estimated heme iron as a percentage of total iron from meat by using a standard percentage (40%) (24) or by applying a percentage according to the animal the meat was derived from – for example, beef (65%), pork (39%) or chicken/fish (26%) (24-26); none of these previous studies found an overall association between heme iron intake and colorectal cancer.

While heme iron is thought to catalyze endogenous formation of NOCs (7), nitrate and nitrite, which are added to processed meats, also contribute to exogenous formation of these compounds within the meat, although this reaction is minimized by the addition of ascorbic acid. Processed meat is typically the predominant source of human exposure to nitrite, but generally not the largest source of nitrate, which can also be reduced to nitrite by bacteria in the oral cavity and gastrointestinal tract. Nevertheless, processed meat contains all the necessary precursors for NOC formation, including nitrosating agents (derived from nitrite), as well as nitrosatable substrates in the form of amines and amides. In agreement with this hypothesis, we observed elevated risks for colorectal cancer for those in the highest quintile of nitrate intake from processed meats, and a suggestive association with nitrite. The sources of nitrate and nitrite in processed meat in this population varied slightly. The largest source of nitrate from meat was red meat coldcuts (24%), hotdogs (22%), and bacon (19%); although the highest contributor to nitrite intake was also red meat coldcuts (39%), the second and third largest sources were poultry coldcuts (26%), and ham (24%). Other epidemiologic data on these exposures in relation to colorectal neoplasia is limited, but nitrate and nitrite intake from animal sources (27), processed meat (28), as well as individual NOCs (29), have been positively associated with colorectal neoplasia.

In addition to this NOC-related mechanism, meat is a source of carcinogenic HCAs and PAHs, formed in meats cooked at high temperatures (9-11,14). We observed a positive association for MeIQx, DiMeIQx and mutagenic activity in relation to colorectal cancer, but not for PhIP or B[a]P. Examining the contributing variables to intake of each of these HCAs, we noted that the largest source of MeIQx (36%) and DiMeIQx (50%) was well-done barbecued hamburgers, whereas the largest source of PhIP (20%) was medium-done barbecued steak. Data regarding the role of HCAs in colorectal neoplasia is unclear, as other studies have found a positive association for MeIQx, but not other HCAs (23,30). Additionally, some studies have reported B[a]P intake increases the risk of colorectal adenoma (31,32).

HCAs, PAHs and NOCs are activated and detoxified by Phase I and Phase II xenobiotic metabolizing enzymes; however, in epidemiologic studies, the evidence for an interaction between meat and meat-mutagen intake, expression of these enzymes and colorectal neoplasia is inconsistent. Phenotyping studies have found associations between proxies of HCA intake (well-done meat) and higher activity of both Phase I and II enzymes (33,34). Further, some genotyping studies have reported that the association between HCA intake and colorectal cancer risk differs according to Phase II enzyme activity (35-37), however, a recent study was null (38). Furthermore, interactions between processed meat intake, Phase I enzymes and colorectal adenoma have been identified (39), but a study that estimated nitrate and nitrite intake from processed meat found that the relation of these compounds with colorectal adenoma

was not modified by variation in Phase I enzyme activity (28). The inconsistencies in these genetic studies may be due to inadequate statistical power to investigate interactions.

Based on our sub-site analyses, the risk estimates appeared to be more strongly associated with distal tumors (distal colon or rectum), except for MeIQx and DiMeIQx, which increased the risk of colon, but not rectal, cancer. These data suggest that the various meat components may be acting at different locations within the colorectum. It is speculated that risk factors for colon and rectal cancer may vary due to sub-site differences in, for example, rates of metabolism, fermentation and transit time, as well as expression of enzymes and differences in morphology (40). Previous studies have also reported similar sub-site differences, including that NOCs increase rectal cancer specifically (39), whereas HCAs increase the risk of colon, but not rectal, neoplasia (32).

This study had several strengths, including a wide range of meat intake and the administration of a detailed meat questionnaire enabling the investigation of multiple components of meat. Furthermore, the questionnaire was completed prior to diagnoses, which limited recall bias and reverse causation. The limitations of this study include the possibility of some degree of measurement error, as is the case with any observational study; however, we attempted to minimize this error by adjusting our models for total energy intake (41). In the analyses of nitrate intake, we were unable to assess exposure from drinking water. We must also note that the heme iron database is still limited and, therefore, likely underestimates total heme iron intake. Lastly, it is possible that some residual confounding may remain.

In summary, red meat and processed meat were positively associated with colorectal cancer. Our analysis indicates that potential mechanisms underlying these associations include heme iron, nitrate/nitrite and HCAs.

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Abbreviations

AARP	formerly known as the American Association for Retired Persons
B[a]P	benzo[a]pyrene
BMI	body mass index
CI	confidence interval
DiMeIQx	2-amino-3,4,8-trimethylimidazo[4,5-f]quinoxaline
FFQ	food frequency questionnaire
HR	hazard ratio
HCA	heterocyclic amine
MeIQx	2-amino-3,8-dimethylimidazo[4,5-f]quinoxaline
NOC	<i>N</i> -nitroso compound
NSAID	non-steroidal anti-inflammatory drug
PAH	polycyclic aromatic hydrocarbon
PhIP	2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine
RFQ	risk factor questionnaire

References

1. WCRF World Cancer Research Fund. American Institute for Cancer Research. Food, Nutrition, Physical Activity, and the Prevention of Cancer: A Global Perspective. Washington, D.C.: 2007.
2. Glei M, Latunde-Dada GO, Klinder A, et al. Iron-overload induces oxidative DNA damage in the human colon carcinoma cell line HT29 clone 19A. *Mutat Res* 2002;519:151–61. [PubMed: 12160900]
3. Tappel A. Heme of consumed red meat can act as a catalyst of oxidative damage and could initiate colon, breast and prostate cancers, heart disease and other diseases. *Med Hypotheses* 2007;68:562–4. [PubMed: 17045417]
4. Sesink AL, Termont DS, Kleibeuker JH, Van der Meer R. Red meat and colon cancer: the cytotoxic and hyperproliferative effects of dietary heme. *Cancer Res* 1999;59:5704–9. [PubMed: 10582688]
5. Sesink AL. Aal e Red meat and colon cancer: dietary haem, but not fat, has cytotoxic and hyperproliferative effects on rat colonic epithelium. *Carcinogenesis* 2000;21:1909–15. [PubMed: 11023550]
6. 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. [PubMed: 15465771]
7. Cross AJ, Pollock JR, Bingham SA. Haem, not Protein or Inorganic Iron, Is Responsible for Endogenous Intestinal N-Nitrosation Arising from Red Meat. *Cancer Res* 2003;63:2358–60. [PubMed: 12750250]
8. Lijinsky, W. Chemistry and biology of N-nitroso compounds. Cambridge University press; Cambridge: 1992.
9. Sinha R, Knize MG, Salmon CP, 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. [PubMed: 9651045]
10. Sinha R, Rothman N, Brown ED, et al. High concentrations of the carcinogen 2-amino-1-methyl-6-phenylimidazo-[4,5-b]pyridine (PhIP) occur in chicken but are dependent on the cooking method. *Cancer Res* 1995;55:4516–9. [PubMed: 7553619]
11. Sinha R, Rothman N, Salmon CP, et al. Heterocyclic amine content in beef cooked by different methods to varying degrees of doneness and gravy made from meat drippings. *Food Chem Toxicol* 1998;36:279–87. [PubMed: 9651044]

12. Culp SJ, Gaylor DW, Sheldon WG, Goldstein LS, Beland FA. A comparison of the tumors induced by coal tar and benzo[a]pyrene in a 2-year bioassay. *Carcinogenesis* 1998;19:117–24. [PubMed: 9472702]
13. Kazerouni N, Sinha R, Hsu CH, Greenberg A, Rothman N. Analysis of 200 food items for benzo[a]pyrene and estimation of its intake in an epidemiologic study. *Food Chem Toxicol* 2001;39:423–36. [PubMed: 11313108]
14. Ohgaki H, Takayama S, Sugimura T. Carcinogenicities of heterocyclic amines in cooked food. *Mutat Res* 1991;259:399–410. [PubMed: 2017219]
15. Schatzkin A, Subar AF, Thompson FE, et al. Design and serendipity in establishing a large cohort with wide dietary intake distributions: the National Institutes of Health-American Association of Retired Persons Diet and Health Study. *Am J Epidemiol* 2001;154:1119–25. [PubMed: 11744517]
16. Subar AF, Thompson FE, Kipnis V, et al. Comparative validation of the Block, Willett, and National Cancer Institute food frequency questionnaires: the Eating at America's Table Study. *Am J Epidemiol* 2001;154:1089–99. [PubMed: 11744511]
17. Subar AF, Midthune D, Kulldorff M, et al. Evaluation of alternative approaches to assign nutrient values to food groups in food frequency questionnaires. *Am J Epidemiol* 2000;152:279–86. [PubMed: 10933275]
18. Sinha R, Cross A, Curtin J, et al. Development of a food frequency questionnaire module and databases for compounds in cooked and processed meats. *Mol Nutr Food Res* 2005;49:648–55. [PubMed: 15986387]
19. Ward MH, Cerhan JR, Colt JS, Hartge P. Risk of non-Hodgkin lymphoma and nitrate and nitrite from drinking water and diet. *Epidemiology*. 2006 epub.
20. Ward MH, Cantor KP, Riley D, Merkle S, Lynch CF. Nitrate in public water supplies and risk of bladder cancer. *Epidemiology* 2003;14:183–90. [PubMed: 12606884]
21. International Classification of Diseases for Oncology: Third edition. World Health Organization; Geneva: 2000.
22. Willett, WC. *Nutritional Epidemiology*. Oxford University Press; New York: 1998.
23. Ferrucci LM, Sinha R, Graubard BI, et al. Dietary meat intake in relation to colorectal adenoma in asymptomatic women. *Am J Gastroenterol* 2009;104:1231–40. [PubMed: 19367270]
24. Lee DH, Anderson KE, Harnack LJ, Folsom AR, Jacobs DR Jr. Heme iron, zinc, alcohol consumption, and colon cancer: Iowa Women's Health Study. *J Natl Cancer Inst* 2004;96:403–7. [PubMed: 14996862]
25. Balder HF, Vogel J, Jansen MC, et al. Heme and chlorophyll intake and risk of colorectal cancer in the Netherlands cohort study. *Cancer Epidemiol Biomarkers Prev* 2006;15:717–25. [PubMed: 16614114]
26. Kabat GC, Miller AB, Jain M, Rohan TE. A cohort study of dietary iron and heme iron intake and risk of colorectal cancer in women. *Br J Cancer* 2007;97:118–22. [PubMed: 17551493]
27. De Roos AJ, Ward MH, Lynch CF, Cantor KP. Nitrate in public water supplies and the risk of colon and rectum cancers. *Epidemiology* 2003;14:640–9. [PubMed: 14569178]
28. Ward MH, Cross AJ, Divan H, et al. Processed meat intake, CYP2A6 activity and risk of colorectal adenoma. *Carcinogenesis* 2007;28:1210–6. [PubMed: 17277235]
29. Knekt P, Jarvinen R, Dich J, Hakulinen T. Risk of colorectal and other gastro-intestinal cancers after exposure to nitrate, nitrite and N-nitroso compounds: a follow-up study. *Int J Cancer* 1999;80:852–6. [PubMed: 10074917]
30. Nowell S, Coles B, Sinha R, et al. Analysis of total meat intake and exposure to individual heterocyclic amines in a case-control study of colorectal cancer: contribution of metabolic variation to risk. *Mutat Res* 2002;506-507:175–85. [PubMed: 12351157]
31. Sinha R, Kulldorff M, Gunter MJ, Strickland P, Rothman N. Dietary benzo[a]pyrene intake and risk of colorectal adenoma. *Cancer Epidemiol Biomarkers Prev* 2005;14:2030–4. [PubMed: 16103456]
32. Sinha R, Peters U, Cross AJ, et al. Meat, meat cooking methods and preservation, and risk for colorectal adenoma. *Cancer Res* 2005;65:8034–41. [PubMed: 16140978]
33. Lang NP, Butler MA, Massengill J, et al. Rapid metabolic phenotypes for acetyltransferase and cytochrome P4501A2 and putative exposure to food-borne heterocyclic amines increase the risk for colorectal cancer or polyps. *Cancer Epidemiol Biomarkers Prev* 1994;3:675–82. [PubMed: 7881341]

34. Le Marchand L, Hankin JH, Wilkens LR, et al. Combined effects of well-done red meat, smoking, and rapid N-acetyltransferase 2 and CYP1A2 phenotypes in increasing colorectal cancer risk. *Cancer Epidemiol Biomarkers Prev* 2001;10:1259–66. [PubMed: 11751443]
35. Ishibe N, Sinha R, Hein DW, et al. Genetic polymorphisms in heterocyclic amine metabolism and risk of colorectal adenomas. *Pharmacogenetics* 2002;12:145–50. [PubMed: 11875368]
36. Shin A, Shrubsole MJ, Rice JM, et al. Meat intake, heterocyclic amine exposure, and metabolizing enzyme polymorphisms in relation to colorectal polyp risk. *Cancer Epidemiol Biomarkers Prev* 2008;17:320–9. [PubMed: 18268115]
37. Butler LM, Duguay Y, Millikan RC, et al. Joint effects between UDP-glucuronosyltransferase 1A7 genotype and dietary carcinogen exposure on risk of colon cancer. *Cancer Epidemiol Biomarkers Prev* 2005;14:1626–32. [PubMed: 16030093]
38. Nothlings U, Yamamoto JF, Wilkens LR, et al. Meat and heterocyclic amine intake, smoking, NAT1 and NAT2 polymorphisms, and colorectal cancer risk in the multiethnic cohort study. *Cancer Epidemiol Biomarkers Prev* 2009;18:2098–106. [PubMed: 19549810]
39. Le Marchand L, Donlon T, Seifried A, Wilkens LR. Red meat intake, CYP2E1 genetic polymorphisms, and colorectal cancer risk. *Cancer Epidemiol Biomarkers Prev* 2002;11:1019–24. [PubMed: 12376502]
40. Iacopetta B. Are there two sides to colorectal cancer? *Int J Cancer* 2002;101:403–8. [PubMed: 12216066]
41. Kipnis V, Subar AF, Midthune D, et al. Structure of dietary measurement error: results of the OPEN biomarker study. *Am J Epidemiol* 2003;158:14–21. discussion 22–6. [PubMed: 12835281]

Table 1

Selected means and proportions for characteristics of participants in the NIH-AARP Diet and Health Study by red meat quintile from the RFQ (n=300,948)

Characteristics	Quintiles of red meat intake, g/1000 kcal				
	Q1	Q2	Q3	Q4	Q5
Mean intake of red meat (g/1000 kcal)	8.9	20.8	30.8	42.3	66.5
Gender (% male)	45.1	51.1	58.0	64.5	72.7
Age (years)	63.1	63.1	63.0	62.8	62.2
Education, college graduate or post graduate (%)	46.7	41.7	40.6	39.0	37.3
Race (%)					
Non-Hispanic White	89.0	92.1	93.1	94.2	94.4
Non-Hispanic Black	5.2	3.7	3.1	2.5	2.0
Hispanic	2.1	1.6	1.5	1.4	1.6
Asian, Pacific Islander, American Indian, Alaskan Native	2.2	1.5	1.3	1.1	1.1
Family history of colorectal cancer (%)	10.0	10.1	10.1	9.5	9.3
Body mass index, kg/m ²	25.6	26.5	27.0	27.4	28.2
Smoking history (%)					
Never smoker	41.2	38.4	35.9	33.8	30.8
Former smoker	47.6	47.6	48.3	48.5	48.8
Current smoker or having quit <1 year ago	7.7	10.7	12.7	14.4	17.1
Vigorous physical activity, >5 times per week (%)	27.7	21.3	18.6	17.1	15.8
Regular [†] use of NSAIDs (%)	63.3	66.7	68.0	68.2	67.9
Dietary variables (mean intake)					
Energy (kcal/day)	1685	1741	1812	1879	1978
Alcohol (g/day)	11.9	13.5	12.9	12.2	11.0
Calcium (mg/1000kcal)	501	467	435	405	361
Fiber (g/1000kcal)	13.8	11.5	10.7	10.0	9.1
Fruits (cup equivalents/1000kcal)	1.7	1.3	1.1	1.0	0.8
Vegetables (cup equivalents/1000kcal)	1.3	1.1	1.1	1.1	1.0

[†] Defined as 2-3 times per month or more

Table 2

Meat intake and colorectal cancer in the NIH-AARP Diet and Health Study (n=300,948)

Colorectal cancer (n=2,719)					
	Cases	HR* (95% CI)	Colon cancer (n=1,995)	Cases	HR* (95% CI)
Red meat [†] (median, g/1000kcal)					
Q1 (9.5)	451	Ref	340	Ref	111
Q2 (20.9)	484	1.00 (0.87-1.14)	345	0.94 (0.81-1.09)	139
Q3 (30.7)	502	0.99 (0.87-1.13)	367	0.96 (0.82-1.12)	135
Q4 (42.1)	614	1.18 (1.03-1.34)	457	1.16 (1.00-1.36)	157
Q5 (61.6)	668	1.24 (1.09-1.42)	486	1.21 (1.03-1.41)	182
p-trend		<0.001		<0.001	0.024
White meat (median, g/1000kcal)					
Q1 (9.6)	605	Ref	454	Ref	151
Q2 (18.6)	562	0.93 (0.83-1.05)	414	0.91 (0.79-1.04)	148
Q3 (27.5)	563	0.95 (0.84-1.06)	395	0.88 (0.76-1.00)	168
Q4 (39.5)	523	0.91 (0.81-1.03)	392	0.90 (0.78-1.03)	131
Q5 (64.2)	466	0.85 (0.76-0.97)	340	0.81 (0.71-0.94)	126
p-trend		0.017		0.012	0.639
Processed meat [†] (median, g/1000kcal)					
Q1 (1.6)	440	Ref	334	Ref	106
Q2 (4.3)	496	1.04 (0.91-1.18)	357	0.98 (0.84-1.14)	139
Q3 (7.4)	538	1.07 (0.94-1.23)	393	1.03 (0.89-1.20)	145
Q4 (12.1)	612	1.16 (1.02-1.32)	453	1.14 (0.98-1.32)	159
Q5 (22.3)	633	1.16 (1.01-1.32)	458	1.11 (0.95-1.29)	175
p-trend		0.017		0.057	0.145

* Adjusted for gender, education (high school or less/unknown, post-high school/some college, college/postgraduate), BMI (<18.5, ≥18.5-<25, ≥25-<30, ≥30-<35, ≥35, unknown), smoking (never smoker, former smoker who quit ≥10 years ago, former smoker who quit 1-9 years ago, current/those who quit <1 year ago, missing), and intake of total energy (kcal/day), fiber (g/1000kcal) and dietary calcium (mg/1000kcal). Red meat and white meat were mutually adjusted for each other. Processed meat was adjusted for non-processed meat.

[†] Red meat energy adjusted by the residual method; highest (median: 104.1 g/day) versus lowest (median: 15.7 g/day) quintile: HR for colorectal cancer = 1.21 (95% CI: 1.07-1.38); HR for colon cancer = 1.16 (95% CI: 1.00-1.35); HR for rectal cancer = 1.36 (95% CI: 1.06-1.75); on the continuous scale per 100g/day increment: HR for colorectal cancer = 1.23 (95% CI: 1.10-1.36); HR for colon cancer = 1.20 (95% CI: 1.05-1.36); HR for rectal cancer = 1.31 (95% CI: 1.07-1.61).

[‡] Processed meat energy adjusted by the residual method; highest (median: 38.0 g/day) versus lowest (median: 2.7 g/day) quintile: HR for colorectal cancer = 1.15 (95% CI: 1.01-1.31); HR for colon cancer = 1.13 (95% CI: 0.98-1.32); HR for rectal cancer = 1.20 (95% CI: 0.93-1.55); on the continuous scale per 100g/day increment: HR for colorectal cancer = 1.19 (95% CI: 0.96-1.48); HR for colon cancer = 1.13 (95% CI: 0.88-1.45); HR for rectal cancer = 1.38 (95% CI: 0.93-2.05).

Table 3

Meat-related compounds and colorectal cancer in the NIH-AARP Diet and Health Study (n=300,948)

	Colorectal cancer (n=2,719)		Colon cancer (n=1,995)		Rectal Cancer (n=724)	
	Cases	HR* (95% CI)	Cases	HR* (95% CI)	Cases	HR* (95% CI)
Total [†] iron (median, mg/day)						
Q1 (10.8)	646	Ref	483	Ref	163	Ref
Q2 (14.8)	578	0.91 (0.81-1.02)	425	0.89 (0.78-1.02)	153	0.96 (0.77-1.21)
Q3 (21.5)	539	0.88 (0.78-0.99)	387	0.85 (0.74-0.97)	152	0.99 (0.79-1.24)
Q4 (30.6)	496	0.81 (0.72-0.91)	368	0.80 (0.70-0.92)	128	0.85 (0.67-1.07)
Q5 (36.1)	460	0.75 (0.66-0.86)	332	0.73 (0.62-0.84)	128	0.84 (0.65-1.08)
p-trend		<0.001		<0.001		0.070
Dietary iron (median, mg/1000kcal)						
Q1 (5.9)	677	Ref	483	Ref	194	Ref
Q2 (7.2)	537	0.82 (0.73-0.92)	397	0.84 (0.73-0.96)	140	0.76 (0.60-0.95)
Q3 (8.2)	518	0.80 (0.70-0.90)	390	0.84 (0.72-0.96)	128	0.70 (0.55-0.88)
Q4 (9.3)	509	0.79 (0.69-0.90)	374	0.81 (0.70-0.94)	135	0.73 (0.57-0.93)
Q5 (11.4)	478	0.75 (0.65-0.87)	351	0.78 (0.66-0.92)	127	0.68 (0.52-0.90)
p-trend		<0.001		0.009		0.017
Heme iron (median, µg/1000kcal)						
Q1 (48.1)	468	Ref	347	Ref	121	Ref
Q2 (100.9)	508	1.00 (0.88-1.13)	378	0.99 (0.86-1.15)	130	1.01 (0.79-1.30)
Q3 (150.3)	538	1.02 (0.90-1.16)	397	1.01 (0.87-1.17)	141	1.06 (0.82-1.36)
Q4 (212.6)	577	1.07 (0.94-1.21)	421	1.04 (0.90-1.21)	156	1.13 (0.88-1.45)
Q5 (335.8)	628	1.13 (0.99-1.29)	452	1.10 (0.94-1.28)	176	1.24 (0.96-1.60)
p-trend		0.022		0.138		0.049
Nitrate from processed meats (median, µg/1000kcal)						
Q1 (23.9)	451	Ref	341	Ref	110	Ref
Q2 (65.3)	470	0.96 (0.85-1.10)	344	0.93 (0.80-1.08)	126	1.08 (0.83-1.40)
Q3 (109.6)	530	1.04 (0.91-1.18)	386	0.99 (0.86-1.16)	144	1.18 (0.91-1.52)

	Colorectal cancer (n=2,719)			Colon cancer (n=1,995)			Rectal Cancer (n=724)		
	Cases	HR* (95% CI)	Cases	HR* (95% CI)	Cases	HR* (95% CI)	Cases	HR* (95% CI)	
Q4 (169.2)	609	1.13 (1.00-1.29)	439	1.08 (0.93-1.25)	170	1.31 (1.01-1.68)			
Q5 (289.2)	659	1.16 (1.02-1.32)	485	1.13 (0.97-1.32)	174	1.26 (0.97-1.63)			
p-trend		0.001		0.009		0.066			
Nitrite from processed meats (median, µg/1000kcal)									
Q1 (11.9)	457	Ref	344	Ref	113	Ref			
Q2 (33.7)	488	0.99 (0.87-1.12)	359	0.96 (0.83-1.12)	129	1.07 (0.83-1.38)			
Q3 (59.7)	554	1.07 (0.94-1.21)	397	1.01 (0.88-1.18)	157	1.23 (0.96-1.58)			
Q4 (99.9)	603	1.12 (0.98-1.27)	441	1.09 (0.94-1.26)	162	1.21 (0.94-1.55)			
Q5 (194.1)	617	1.11 (0.97-1.25)	454	1.09 (0.94-1.26)	163	1.16 (0.90-1.50)			
p-trend		0.055		0.089		0.369			
PhIP (median, ng/1000kcal)									
Q1 (2.1)	512	Ref	382	Ref	130	Ref			
Q2 (10.9)	498	0.90 (0.79-1.02)	357	0.87 (0.75-1.00)	141	1.00 (0.78-1.27)			
Q3 (24.7)	560	0.99 (0.87-1.12)	402	0.96 (0.83-1.10)	158	1.08 (0.85-1.36)			
Q4 (49.4)	591	1.04 (0.92-1.17)	434	1.03 (0.90-1.19)	157	1.06 (0.83-1.34)			
Q5 (123.6)	558	0.99 (0.87-1.12)	420	1.01 (0.87-1.16)	138	0.94 (0.73-1.20)			
p-trend		0.507		0.212		0.440			
MeIQx (median, ng/1000kcal)									
Q1 (0.5)	482	Ref	346	Ref	136	Ref			
Q2 (2.4)	506	1.01 (0.89-1.15)	370	1.03 (0.89-1.20)	136	0.96 (0.76-1.22)			
Q3 (5.3)	512	0.99 (0.88-1.13)	365	0.99 (0.85-1.15)	147	1.00 (0.79-1.27)			
Q4 (10.3)	571	1.08 (0.95-1.22)	427	1.13 (0.98-1.31)	144	0.94 (0.74-1.20)			
Q5 (24.4)	648	1.19 (1.05-1.34)	487	1.26 (1.09-1.45)	161	1.01 (0.79-1.28)			
p-trend		<0.001		<0.001		0.852			
DiMeIQx (median, ng/1000kcal)									
Q1 (0.0)	922	Ref	665	Ref	257	Ref			
Q2 (0.04)	105	1.02 (0.84-1.25)	77	1.05 (0.83-1.33)	28	0.95 (0.64-1.40)			
Q3 (0.19)	496	0.96 (0.86-1.07)	365	0.98 (0.86-1.11)	131	0.91 (0.73-1.12)			

	Colorectal cancer (n=2,719)		Colon cancer (n=1,995)		Rectal Cancer (n=724)	
	Cases	HR* (95% CI)	Cases	HR* (95% CI)	Cases	HR* (95% CI)
Q4 (0.58)	567	1.06 (0.95-1.18)	412	1.07 (0.95-1.21)	155	1.03 (0.84-1.25)
Q5 (1.74)	629	1.17 (1.05-1.29)	476	1.23 (1.10-1.39)	153	1.00 (0.81-1.22)
p-trend		<0.001		<0.001		0.806
B[a]P (median, ng/1000kcal)						
Q1 (0.21)	551	Ref	401	Ref	150	Ref
Q2 (1.50)	583	1.02 (0.91-1.14)	427	1.03 (0.90-1.18)	156	1.00 (0.80-1.25)
Q3 (6.17)	531	0.96 (0.85-1.08)	397	0.99 (0.86-1.14)	134	0.88 (0.70-1.12)
Q4 (16.83)	491	0.86 (0.76-0.97)	363	0.88 (0.76-1.01)	128	0.81 (0.64-1.02)
Q5 (43.97)	563	0.96 (0.85-1.08)	407	0.96 (0.83-1.11)	156	0.95 (0.75-1.19)
p-trend		0.291		0.322		0.694
Mutagenic activity (median, revertant colonies/1000kcal)						
Q1 (165)	480	Ref	349	Ref	131	Ref
Q2 (601)	511	0.98 (0.86-1.11)	366	0.97 (0.83-1.12)	145	1.01 (0.79-1.28)
Q3 (1152)	556	1.04 (0.92-1.18)	404	1.05 (0.91-1.21)	152	1.02 (0.80-1.30)
Q4 (2042)	563	1.05 (0.93-1.19)	420	1.09 (0.94-1.26)	143	0.95 (0.74-1.21)
Q5 (4349)	609	1.14 (1.01-1.29)	456	1.19 (1.03-1.38)	153	1.01 (0.79-1.29)
p-trend		0.010		0.002		0.967

[†] Dietary iron residually energy adjustment plus iron from supplements.

* Adjusted for gender, education (high school or less/unknown, post-high school/some college, college/postgraduate), BMI (<18.5, ≥18.5-<25, ≥25-<30, ≥30-<35, ≥35, unknown), smoking (never smoker, former smoker who quit ≥10 years ago, former smoker who quit 1-9 years ago, current/those who quit <1 year ago, missing), and intake of total energy (kcal/day), fiber (g/1000kcal) and dietary calcium (mg/1000kcal)