Processed meat consumption and lung function: modification by antioxidants and smoking

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ABSTRACT Unhealthy dietary patterns are associated with poor lung function. It is not known whether this is due to low consumption of antioxidant-rich fruit and vegetables, or is a consequence of higher intakes of harmful dietary constituents, such as processed meat.

We examined the individual and combined associations of processed meat, fruit and vegetable consumption and dietary total antioxidant capacity (TAC) with lung function among 1551 males and 1391 females in the UK in the Hertfordshire Cohort Study. Diet was assessed using a food frequency questionnaire.

After controlling for confounders, processed meat consumption was negatively associated with forced expiratory volume in 1 s (FEV_1), forced vital capacity (FVC) and FEV_1/FVC ratio in males and females, while fruit and vegetable consumption and dietary TAC were positively associated with FEV_1 and FVC, but not FEV_1/FVC ratio. In males, the negative association between processed meat consumption and FEV_1 was more marked in those who had low fruit and vegetable consumption ($p=0.035$ for interaction), and low dietary TAC ($p=0.025$ for interaction). The deficit in FEV_1/FVC associated with processed meat consumption was larger in males who smoked ($p=0.022$ for interaction).

Higher processed meat consumption is associated with poorer lung function, especially in males who have lower fruit and vegetable consumption or dietary TAC, and among current smokers.

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Relative intake of foods that influence oxidant/antioxidant balance may be important for optimal lung function http://ow.ly/t6tgF

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Introduction

Healthy dietary patterns appear to have protective effects on lung function in older age [1–3]. For example, we have previously described a healthy ''prudent'' dietary pattern, characterised by high consumption of fruit, vegetables, oily fish and wholemeal cereals, but low consumption of white bread, added sugar, full-fat dairy products, chips and processed meat, that is associated with better lung function and reduced prevalence of chronic obstructive pulmonary disease (COPD) among older people in the UK [1]. The apparently beneficial effects of healthy dietary patterns on lung function have been largely attributed to the effects of antioxidants in fruit and vegetables. Epidemiological studies have reported positive associations of antioxidant-rich foods and nutrients, including vitamin C, vitamin E, β-carotene and flavonoids, with lung function [4–6]. Antioxidants are thought to play a protective role in the pathogenesis of lung impairment by scavenging free radicals and other oxygen species that cause cellular damage and inflammation [7–9].

However, one aspect of dietary patterns that may be overlooked is that they describe a balance of foods, and are characterised both by relatively high and low consumption of individual food items. Potentially one of the most important types of food that is less common in healthy diets is processed meat (such as bacon, ham, sausage and other cured meats). There is growing evidence that high consumption of processed meat is associated with poorer lung function and an increased risk of COPD, including exacerbations [10–13]. This could be due to its high nitrite content. Nitrites are added as preservatives, antimicrobial agents and colour fixatives, and generate reactive nitrogen species that can cause oxidative and nitrative damage to the lung [14]. Processed meat is also rich in advanced glycation end-products (AGEs) [15], which can increase oxidative stress and inflammation [16]. Thus, the size of the effect of processed meat consumption on lung function may also depend on other factors that influence pulmonary oxidant/antioxidant balance, such as dietary antioxidant intake and smoking. The protective effect of a healthy ''prudent'' dietary pattern on lung function could therefore reflect a favourable balance of protective antioxidants and harmful pro-oxidant foods in the diet. To our knowledge, the role of the balance of such foods in the diet has not been considered before.

In a large cohort of older males and females, we investigated associations between lung function and key foods (processed meat and fruit and vegetables) that may contribute to pulmonary oxidant/antioxidant balance. Our particular aim was to consider the nature of their individual and combined associations with lung function. In addition, since foods other than fruit and vegetables contribute to overall antioxidant status, we considered the role of the total antioxidant capacity (TAC) of the diet [17].

Methods

The Hertfordshire Cohort Study

Details of the Hertfordshire Cohort Study have been published elsewhere [18]. From 1911 to 1948, midwives recorded information on all infants born in the county of Hertfordshire, UK. In 1998, 3822 males and 3284 females (born 1931–1939) were traced. Permission to contact 3126 males (82%) and 2973 females (91%) was obtained from their general practitioner; 1684 males (54%) and 1541 females (52%) agreed to a home interview; and 1579 males (94%) and 1418 females (92%) attended a clinic for further investigations. In total, 1551 males and 1391 females completed spirometry tests. The study had ethical approval from the Bedfordshire and Hertfordshire local research ethics committee and the West Hertfordshire local research ethics committee. Written informed consent was obtained from all participants.

Dietary assessment

Diet over a 3-month period before the home interview was assessed using a food frequency questionnaire (FFQ) that was administered by a trained research nurse [19, 20]. The FFQ included 129 foods and food groups. 10 predefined frequency responses were listed, ranging from ''never'' to ''$\geqslant$6 per day''. Information on the frequency of consumption and quantities consumed of different types of alcoholic beverages was obtained separately. Energy intake from foods and alcoholic beverages was calculated by multiplying the frequency of consumption of a portion of each food item by its energy content, according to the UK national food composition database or manufacturers' composition data [21, 22].

For the analyses we grouped foods listed on the FFQ as follows. Processed meat: bacon and gammon, ham, corned beef, spam and luncheon meat, sausage, meat pies; fruit: fresh fruit (including citrus, apples, bananas and grapes), fruit juices, dried fruit, tinned and cooked fruit; vegetables: fresh and frozen vegetables (including cabbage, cauliflower, peas and root vegetables), salad vegetables, pulses, vegetarian foods and tinned vegetables. Weekly consumption (servings per week) of processed meat and fruit and vegetables were calculated as the sum of the individual frequencies of the foods within these groups.

Dietary TAC was estimated using published composition data where TAC was assessed using an oxygen radical absorbance capacity (ORAC) assay, which measured the degree of inhibition of

peroxy-radical-induced oxidation *in vitro* [23, 24]. ORAC was selected as one of the most widely used methods because of its biological relevance to antioxidant efficacy *in vivo* [23, 24]. A total dietary TAC score was calculated for each participant by multiplying the TAC values of each food/beverage by their reported frequency of consumption and then summing these values. A full description of the assignment of TAC values to each food item and calculation method is given in the online supplementary material.

Lung function

Lung function was measured using a Micro Spirometer (CareFusion UK, Gillingham, UK) in the seated position without noseclips. After at least one practice blow, three forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) readings were recorded. The highest FEV_1 and FVC values from satisfactory manoeuvres were used in the analyses; these did not necessarily come from the same blow. A bronchodilator was not given before spirometry was performed. For FEV_1, 85.8% of males and 92.2% of females had a difference of $\leqslant$0.15 L between their two highest readings; for FVC, the corresponding figures were 80.4% and 88.6%. However, we did not exclude those with a difference of $>$0.15 L [25]. We calculated standardised residuals of lung function by using Global Lung Initiative 2012 regression equations (which are based on lung function data from lifelong nonsmokers) [26]. COPD was defined as FEV_1/FVC ratio less than the lower limit of normal (*i.e.* the z-score was $<$ -1.645) [26].

Statistical analysis

All statistical analyses were performed using Stata (version 12; StataCorp LP, College Station, TX, USA). Univariate and multiple linear regression analyses were used to examine the relationships between consumption of processed meat, fruit and vegetables, and dietary TAC with lung function outcomes; logistic regression was used to analyse COPD. For the regression analysis, we controlled for the effects of age and height, and the following potential confounders: smoking status (never, ex-, or current), pack-years smoked, exposure to tobacco smoke in the home, age at which the participant left education, social class, body fat mass, physical activity score, dietary supplement use, use of inhaled or oral steroids, use of paracetamol, alcohol consumption and energy intake. A detailed full description of the confounders is given in the online supplementary material. Tests for trend associations were based on continuously distributed variables and after adjustment for potential confounders.

We evaluated the combined associations of processed meat consumption and dietary antioxidants (*i.e.* fruit and vegetables and dietary TAC) on lung function, examining both their independent and interactive associations. We also stratified dietary associations by smoking status and tested for interactions. We analysed males and females separately. Where dietary variables were categorised into fifths (for tables) or thirds (for figures), we used cut-offs that were defined using the distributions for the whole population.

Results

The males and females studied were of similar social class, but the males were more likely to be current or ex-smokers, to smoke more heavily and to drink alcohol (table 1). The males were less likely than the females to be taking oral or inhaled steroids, paracetamol or dietary supplements. They had higher processed meat consumption and total energy intakes than females, but lower consumption of fruit and vegetables (all $p<0.05$). Dietary TAC was mainly derived from fruit (35.8%), tea (15.4%), vegetables (14.9%), potatoes (13.4%) and cereal products (7.1%); dietary TAC did not differ between males and females. Males had a lower FEV_1/FVC ratio and FEV_1/FVC z-score and a higher FVC z-score and prevalence of COPD (both $p<0.001$).

Individual associations of processed meat, fruit and vegetable consumption and dietary TAC with lung function

After controlling for potential confounders, processed meat consumption was negatively associated with FEV_1 in both sexes; this was especially marked in males (difference in FEV_1 comparing top *versus* bottom fifth of consumption (95% CI) -170 mL (-250– -80 mL)) (tables 2 and 3). In contrast, fruit and vegetable consumption and dietary TAC were positively associated with FEV_1 in both males and females. The patterns of association with FVC were similar to those for FEV_1. Processed meat consumption was negatively associated with FEV_1/FVC ratio, but there were no associations with fruit and vegetable consumption or dietary TAC in either males or females (tables 2 and 3). In males, processed meat consumption was positively associated with COPD (p-value for trend 0.013) (online supplementary table E1). Fruit and vegetable consumption and dietary TAC were not associated with COPD risk in either sex. The effect sizes for the associations between dietary exposures and lung function were compared for males and females, but they did not differ substantially (p-value for all interactions $>$0.05).

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TABLE 1 Subject characteristics of males and females who participated in the Hertfordshire Cohort Study, UK

	Males	Females
Subjects	1551	1391
Age years	65.7±2.9	66.6±2.7
Height cm	174.2±6.4	160.9±5.9
Fat mass kg	23.3 (19.0–28.4)	28.2 (23.2–33.8)
Habitual activity score	61.0±15.3	59.1±15.7
Smoking status		
Never-smoker	507 (32.7)	854 (61.4)
Ex-smoker	806 (52.0)	402 (28.9)
Current smoker	238 (15.3)	134 (9.6)
Smoking pack-years	23 (11–40)	15 (5–29)
Exposure to tobacco smoke in the home	203 (13.5)	163 (11.9)
Age left full-time education years		
⩽14	302 (19.5)	241 (17.3)
⩾15	1249 (80.5)	1150 (82.7)
Social class		
I, II and IIINM	611 (40.6)	583 (41.9)
IIIM, IV and V	893 (59.4)	807 (58.1)
Oral or inhaled steroids	107 (6.9)	127 (9.1)
Paracetamol	105 (6.8)	178 (12.8)
Dietary supplements	712 (45.9)	824 (59.2)
Alcohol consumption units per week	8.9 (2.3–19.5)	1.5 (0.0–5.5)
Dietary intake		
Processed meat servings per week	4.0 (2.5–6.2)	3.0 (1.9–4.5)
Fruit and vegetables servings per week	42.6 (31.1–56.3)	47.1 (35.5–60.4)
TAC μmol·day^{-1}	15 915 (12 425–19 640)	15 915 (12 641–19 387)
Total energy intake kcal·day^{-1}	2433 (2093–2796)	1973 (1705–2272)
Lung function		
Maximum FEV_1 L	2.84±0.60	1.98±0.41
Maximum FVC L	4.04±0.74	2.71±0.50
FEV_1/FVC	0.702±0.089	0.732±0.079
GLI 2012 FEV_1 z-score#	-0.74±0.03	-0.77±0.03
GLI 2012 FVC z-score#	-0.28±0.03	-0.42±0.03
GLI 2012 FEV_1/FVC z-score#	-0.81±0.03	-0.68±0.03
Prevalence of COPD	274 (17.7)	185 (13.3)

Data are presented as n, mean±SD, median (interquartile range) or n (%). I: professional; II: managerial and technical; IIINM: skilled nonmanual; IIIM: skilled manual; IV: partly skilled manual; V: unskilled manual; TAC: total antioxidant capacity; FEV_1: forced expiratory volume in 1 s; FVC: forced vital capacity; GLI: Global Lungs Initiative; COPD: chronic obstructive pulmonary disease. #: calculated using the GLI 2012 regression equations (which are based on lung function data from lifelong nonsmokers) [26].

Combined associations of processed meat consumption and dietary antioxidants with lung function

Processed meat consumption was weakly correlated with fruit and vegetable consumption (Spearman correlation coefficients r= -0.06, p=0.01 for males and r= -0.07, p=0.01 for females), but not dietary TAC (r= -0.05, p=0.05 for males and r= -0.03, p=0.21 for females). We therefore investigated the independent associations between lung function and processed meat, fruit and vegetable consumption and dietary TAC by mutual adjustment in multivariate models. The negative association between processed meat consumption and FEV_1 was independent of fruit and vegetable consumption and dietary TAC in males (p-value for trend both <0.001) and females (p-value for trend 0.013 and 0.014, respectively). Similarly, associations between processed meat consumption and FVC and FEV_1/FVC ratio in males and females, and COPD in males, were not confounded by fruit and vegetable consumption or dietary TAC (data not shown). In contrast, the positive associations of fruit and vegetable consumption and dietary TAC with FEV_1 and FVC remained after adjustment for processed meat consumption in females, but these associations disappeared in males.

We then examined whether the association between processed meat consumption and FEV_1 was modified by fruit and vegetable consumption and dietary TAC (fig. 1). In males, the association between processed

TABLE 2 Associations of processed meat, fruit and vegetable consumption and dietary total antioxidant capacity (TAC) with forced expiratory volume in 1 s (FEV_1), forced vital capacity (FVC) and FEV_1/FVC ratio among males in the Hertfordshire Cohort Study, UK

Variable[#]	Subjects n	FEV_1 L			FVC L			FEV_1/FVC ratio		
		Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]	Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]	Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]
Processed meat servings per week										
Q1 <2.1	264	2.95±0.56	Reference		4.18±0.73	Reference		0.709±0.084	Reference	
Q2 2.1–3.1	268	2.90±0.60	-0.06 (-0.15–0.03)		4.11±0.70	-0.07 (-0.18–0.03)		0.706±0.088	-0.006 (-0.020–0.008)	
Q3 3.2–4.3	271	2.81±0.62	-0.09 (-0.18–0.00)		3.99±0.77	-0.13 (-0.24– -0.03)		0.704±0.087	-0.001 (-0.015–0.012)	
Q4 4.4–6.1	350	2.85±0.59	-0.11 (-0.19– -0.02)		4.02±0.71	-0.13 (-0.23– -0.03)		0.707±0.085	-0.008 (-0.022–0.005)	
Q5 ⩾6.2	398	2.74±0.62	-0.17 (-0.25– -0.08)		3.97±0.75	-0.16 (-0.26– -0.06)		0.691±0.096	-0.004 (-0.007– -0.001)	
Effect per fifth increase			-0.04 (-0.06– -0.02)	<0.001		-0.04 (-0.06– -0.01)	0.001		-0.004 (-0.007– -0.001)	0.006
Fruit and vegetables servings per week										
Q1 <30.7	368	2.70±0.65	Reference		3.93±0.75	Reference		0.686±0.103	Reference	
Q2 30.7–40.4	333	2.81±0.64	0.00 (-0.07–0.08)		4.00±0.79	-0.01 (-0.11–0.08)		0.702±0.087	0.003 (-0.009–0.015)	
Q3 40.5–49.3	286	2.92±0.56	0.07 (-0.01–0.15)		4.13±0.69	0.07 (-0.03–0.16)		0.710±0.086	0.007 (-0.006–0.020)	
Q4 49.4–62.2	293	2.88±0.57	0.04 (-0.04–0.12)		4.05±0.71	0.02 (-0.08–0.12)		0.709±0.081	0.008 (-0.005–0.020)	
Q5 ⩾62.3	271	2.95±0.53	0.08 (-0.00–0.17)		4.16±0.70	0.10 (0.00–0.20)		0.709±0.080	0.005 (-0.008–0.018)	
Effect per fifth increase			0.02 (-0.00–0.04)	0.041		0.02 (-0.00–0.05)	0.058		0.002 (-0.001–0.004)	0.356
Dietary TAC $\mu mol \cdot day^{-1}$										
Q1 <11 795	318	2.70±0.65	Reference		3.93±0.77	Reference		0.687±0.103	Reference	
Q2 11 795–14 546	313	2.81±0.60	0.05 (-0.03–0.13)		4.00±0.72	0.02 (-0.08–0.12)		0.701±0.087	0.007 (-0.006–0.020)	
Q3 14 547–17 209	298	2.84±0.61	0.07 (-0.01–0.16)		4.01±0.73	0.02 (-0.08–0.12)		0.708±0.089	0.014 (0.001–0.027)	
Q4 17 210–20 550	299	2.95±0.54	0.11 (0.02–0.19)		4.15±0.67	0.07 (-0.03–0.18)		0.710±0.079	0.013 (-0.001–0.026)	
Q5 ⩾20 551	323	2.92±0.58	0.11 (0.02–0.20)		4.13±0.76	0.10 (0.00–0.21)		0.707±0.082	0.009 (-0.004–0.023)	
Effect per fifth increase			0.01 (0.01–0.05)	0.031		0.03 (0.00–0.05)	0.045		0.002 (-0.001–0.005)	0.311

[#]: cut-off values for quintile (Q) of dietary consumption were derived from distributions among the whole population; [¶]: adjusted for age, height, smoking status, pack-years, exposure to tobacco smoke in home, age left education, social class, body fat mass, physical activity score, dietary supplement use, inhaled or oral steroid use, paracetamol use, alcohol consumption and energy intake; [+]: p-values to test for linear trends were calculated using dietary consumption as a continuous variable after controlling for potential confounders.

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TABLE 3 Associations of processed meat, fruit and vegetable consumption and dietary total antioxidant capacity (TAC) with forced expiratory volume in 1 s (FEV_1), forced vital capacity (FVC) and FEV_1/FVC ratio among females in the Hertfordshire Cohort Study, UK

Variable[#]	Subjects n	FEV_1 L			FVC L			FEV_1/FVC ratio		
		Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]	Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]	Mean±SD	Regression coefficient (95% CI)[¶]	p-value for trend[+]
Processed meat servings per week										
Q1 <2.1	438	2.06±0.41	Reference		2.79±0.51	Reference		0.737±0.081	Reference	
Q2 2.1–3.1	313	1.99±0.40	-0.04 (-0.09–0.02)		2.72±0.51	-0.02 (-0.09–0.04)		0.733±0.075	-0.007 (-0.018–0.004)	
Q3 3.2–4.3	239	1.93±0.43	-0.07 (-0.13– -0.01)		2.64±0.51	-0.07 (-0.14– -0.01)		0.730±0.073	-0.010 (-0.022–0.002)	
Q4 4.4–6.1	242	1.91±0.39	-0.10 (-0.15– -0.04)		2.64±0.47	-0.10 (-0.17– -0.04)		0.725±0.078	-0.009 (-0.021–0.002)	
Q5 ⩾6.2	159	1.92±0.42	-0.05 (-0.12–0.01)		2.64±0.47	-0.04 (-0.12–0.04)		0.724±0.087	-0.012 (-0.026–0.002)	
Effect per fifth increase			-0.02 (-0.04– -0.01)	0.005		-0.02 (-0.04– -0.00)	0.031		-0.003 (-0.006–0.000)	0.041
Fruit and vegetables servings per week										
Q1 <30.7	223	1.89±0.44	Reference		2.61±0.52	Reference		0.724±0.094	Reference	
Q2 30.7–40.4	256	1.93±0.42	0.03 (-0.04–0.09)		2.65±0.50	0.01 (-0.06–0.09)		0.726±0.078	0.007 (-0.006–0.021)	
Q3 40.5–49.3	300	1.97±0.39	0.04 (-0.03–0.10)		2.67±0.47	0.00 (-0.07–0.07)		0.736±0.073	0.013 (0.000–0.026)	
Q4 49.4–62.2	296	2.01±0.38	0.07 (0.00–0.13)		2.73±0.48	0.05 (-0.02–0.13)		0.735±0.073	0.011 (-0.002–0.025)	
Q5 ⩾62.3	316	2.07±0.41	0.10 (0.03–0.16)		2.83±0.52	0.10 (0.03–0.17)		0.733±0.077	0.010 (-0.003–0.024)	
Effect per fifth increase			0.02 (0.01–0.04)	0.001		0.03 (0.01–0.04)	<0.001		0.002 (-0.001–0.005)	0.637
Dietary TAC $\mu mol \cdot day^{-1}$										
Q1 <11 795	318	1.92±0.42	Reference		2.61±0.49	Reference		0.732±0.088	Reference	
Q2 11 795–14 546	313	1.94±0.42	0.02 (-0.04–0.08)		2.66±0.50	0.02 (-0.05–0.09)		0.725±0.079	0.001 (-0.012–0.014)	
Q3 14 547–17 209	298	2.00±0.39	0.05 (-0.02–0.11)		2.70±0.45	0.03 (-0.04–0.10)		0.738±0.073	0.009 (-0.003–0.022)	
Q4 17 210–20 550	299	2.02±0.40	0.06 (-0.01–0.12)		2.74±0.51	0.05 (-0.03–0.12)		0.737±0.070	0.010 (-0.003–0.023)	
Q5 ⩾20 551	323	2.03±0.42	0.07 (0.00–0.14)		2.81±0.52	0.10 (0.02–0.18)		0.724±0.083	0.002 (-0.012–0.016)	
Effect per fifth increase			0.02 (0.00–0.03)	0.003		0.02 (0.00–0.04)	0.001		0.001 (-0.002–0.005)	0.646

[#]: cut-off values for quintile (Q) of dietary consumption were derived from distributions among the whole population; [¶]: adjusted for age, height, smoking status, pack-years, exposure to tobacco smoke in the home, age left education, social class, body fat mass, physical activity score, dietary supplement use, inhaled or oral steroid use, paracetamol use, alcohol consumption and energy intake; [+]: p-values to test for linear trends were calculated using dietary consumption as a continuous variable after controlling for potential confounders.

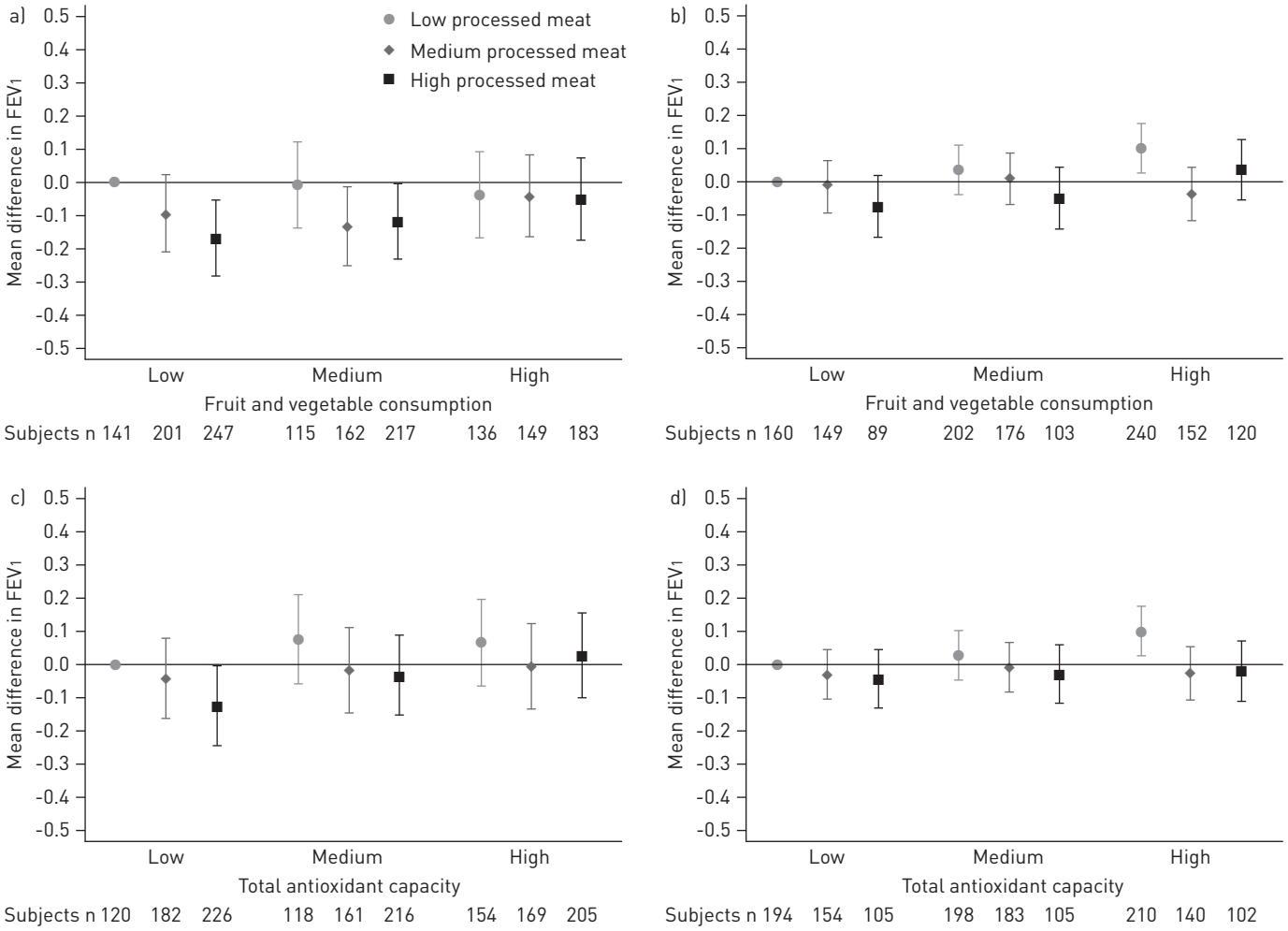

FIGURE 1 Interactions between processed meat consumption and fruit and vegetable consumption in a) males and b) females, and dietary total antioxidant capacity (TAC) in c) males and d) females, on forced expiratory volume in 1 s (FEV1). Dietary variables were stratified by tertiles (processed meat: low <2.6 servings per week, medium 2.6–4.8 servings per week and high ⩾4.9 servings per week; fruit and vegetables: low <37.5 servings per week, medium 37.5–53.1 servings per week and high ⩾53.2 servings per week; and dietary TAC: low <13 700 μmol·day^{-1}, medium: 13 700–18 245 μmol·day^{-1} and high ⩾18 246 μmol·day^{-1}). Values are multivariate-adjusted regression coefficients for the difference in mean FEV1 (95% CI) compared to subjects with the lowest consumption of both processed meat and dietary antioxidants.

meat consumption and FEV1 was more marked in those who had lower fruit and vegetable consumption (p-value for interaction 0.035) (fig. 1a) and lower dietary TAC (p-value for interaction 0.025) (fig. 1c). In females, the association between processed meat consumption and FEV1 did not differ according to fruit and vegetable consumption (p-value for interaction 0.633) or dietary TAC (p-value for interaction 0.412). There was no evidence of effect modification in relation to FVC (data not shown), FEV1/FVC ratio (online supplementary fig. E1) or COPD (data not shown) in either males or females.

Interactions between dietary consumption and smoking status on lung function

In both males and females there was some evidence that negative associations of processed meat consumption, and positive associations of fruit and vegetable consumption and dietary TAC, with FEV1 were more marked in smokers, although the tests for interaction did not achieve conventional statistical significance (*i.e.* p<0.05) (fig. 2). The patterns of association with FVC and COPD were similar to those for FEV1 (data not shown). However, for FEV1/FVC ratio we found that the negative association with processed meat consumption among males was stronger in current smokers (p-value for interaction 0.022) (online supplementary fig. E2), but no clear differences in the associations with fruit and vegetable consumption or dietary TAC according to smoking status were observed (p-values for interaction 0.108 and 0.595, respectively). In females, there were no clear differences in the associations between dietary exposures and FEV1/FVC ratio according to smoking status.

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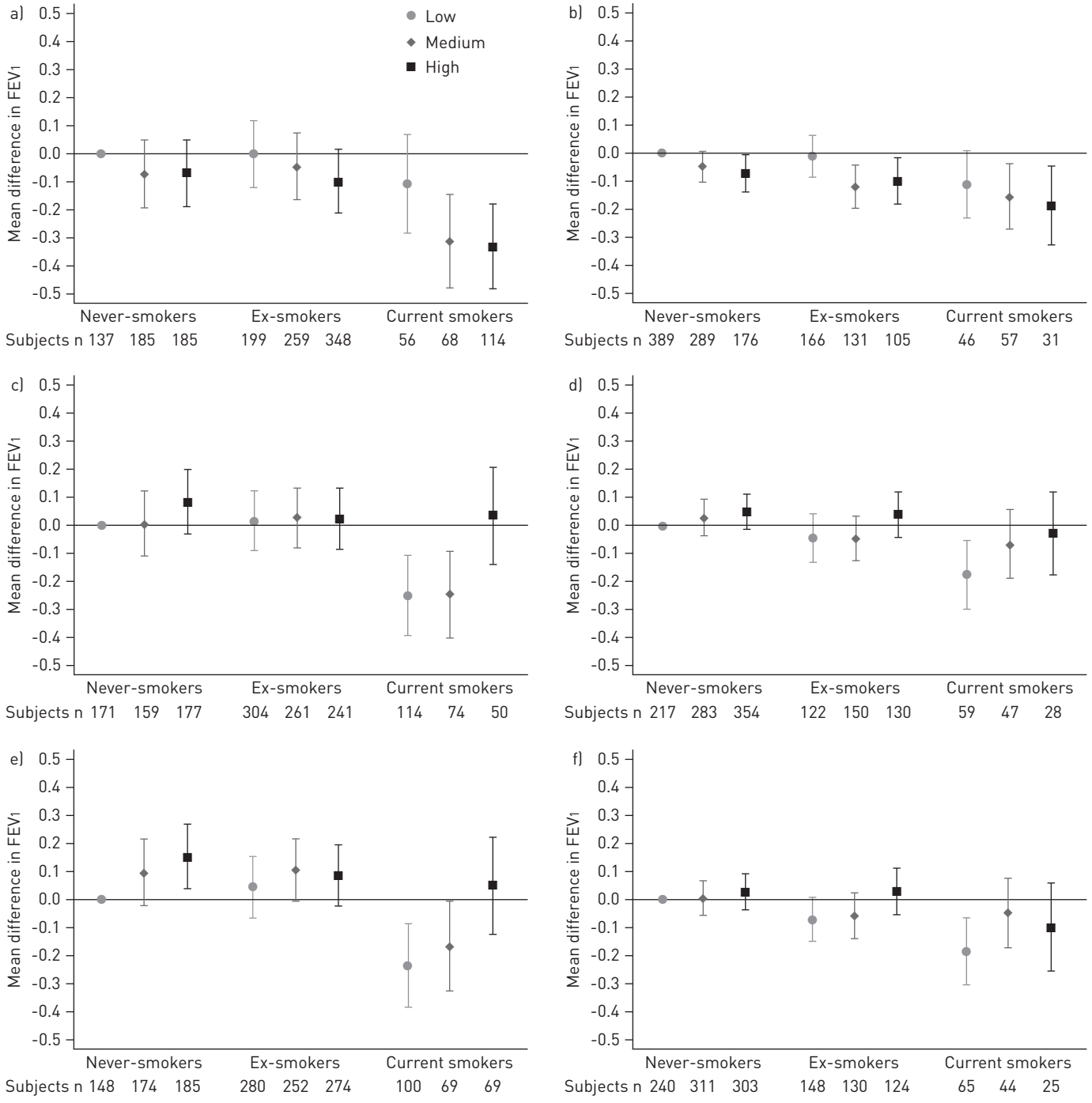

FIGURE 2 Interactions between processed meat consumption for a) males and b) females, fruit and vegetable consumption for c) males and d) females and dietary total antioxidant capacity (TAC) for e) males and f) females and smoking status on forced expiratory volume in 1 s (FEV_1). Dietary variables were stratified by tertiles (processed meat: low <2.6 servings per week, medium 2.6–4.8 servings per week and high ⩾4.9 servings per week; fruit and vegetables: low <37.5 servings per week, medium 37.5–53.1 servings per week and high ⩾53.2 servings per week; and dietary TAC: low <13 700 μmol·day^{-1}, medium: 13 700–18 245 μmol·day^{-1} and high ⩾18 246 μmol·day^{-1}). Values are multivariate-adjusted regression coefficients for the difference in mean FEV_1 (95% CI) compared to never-smokers with the lowest consumption of each dietary component.

Discussion

Main findings

The main findings of this study were that higher processed meat consumption was associated with poorer lung function in older males and females, and that in males the negative association with FEV_1 was greatest in those who also had lower fruit and vegetable consumption and low dietary TAC. These interactions

suggest that the association between a healthier dietary pattern and lung function, as observed previously in this cohort [1] and in other populations [2, 3], might not simply reflect the intake of antioxidants, but rather the relative intakes of protective and harmful constituents in the diet that influence pulmonary oxidant/antioxidant balance. To our knowledge, the effects of the balance of foods in the diet in relation to lung function have not been described before.

Association of processed meat consumption with lung function

Our findings of poorer lung function among males and females who have a high consumption of processed meat are consistent with a growing number of epidemiological studies of lung function and COPD from the USA [10–12] and Europe [13]. In keeping with findings from the cross-sectional study of the National Health and Nutrition Examination Survey (NHANES) III [10], we confirmed a negative association of processed meat consumption with FEV_1 and FEV_1/FVC ratio and a positive association with COPD, defined spirometrically. In contrast, we also found a negative association with FVC. A further difference between studies is our observation of an interaction between smoking and processed meat consumption in relation to FEV_1/FVC ratio in males, which was not seen in NHANES III. However, our study suggests that there may be sex-specific effects of diet on lung function that were not examined previously [10].

A number of potential mechanisms have been suggested to link processed meat consumption with poorer lung function. A key component of processed meat is its high nitrite content [10–13]. Nitrites are pro-oxidants and can generate strong oxidising reactive nitrogen species, such as peroxynitrite [14], which can produce lung damage and contribute to airway inflammation. Tobacco smoke is another source of nitrites as well as oxidants; hence the interaction between processed meat consumption and smoking on lung function in males is biologically plausible. In addition, cured/processed meats are a rich source of AGEs [15]. AGEs contribute to increased oxidative stress and inflammation through binding with their cell surface receptor, which activates nuclear factor (NF)-κB [16, 27]. Thus high consumption of foods rich in AGEs could plausibly increase lung inflammation and hence reduce lung function. Given the likely pro-oxidant effects of nitrites and AGEs in processed meat, it may be unsurprising that the association between processed meat consumption and FEV_1 was modified by fruit and vegetable consumption and dietary TAC, at least in males. The significant trends in the associations of processed meat consumption with lung function, suggestive of a ''dose response'', the magnitude of the association with FEV_1, and the plausible interactions with smoking and dietary antioxidants in males would support a causal interpretation.

Association of dietary antioxidants with lung function

Consistent with the growing recognition of potential beneficial effects of foods rich in antioxidants on lung function [6], we found that fruit and vegetable consumption and dietary TAC were positively associated with FEV_1 and FVC. Comparable associations with dietary TAC have also been described in an Italian study where dietary TAC was positively associated with FEV_1 and FVC, although these effects were seen only in females [28]. Dietary TAC reflects all antioxidants in the diet and even takes into account their synergistic effects [17, 23, 24]; hence dietary TAC is expected to be more useful than a single-food or single-nutrient approach to examine relationships between antioxidants and health outcomes. However, in our study the effects of dietary TAC on lung function were not markedly different from those of fruit and vegetables (tables 2 and 3). One possible explanation is that our estimation of dietary TAC was inaccurate. This may partly be because of a lack of TAC values in the database we used to assign to the foods on the FFQ (coverage rate 44.8%), but also because the database, developed in the USA, may not be appropriate to estimate TAC in foods eaten in the UK, where growing conditions and cooking methods differ. To our knowledge dietary TAC using the ORAC assay has not been described in other UK cohort studies, and further data, using other estimates of dietary TAC, are needed to understand its importance for health.

Sex-specific effects of diet on lung function

Although higher processed meat consumption was associated with reduced lung function in both males and females, the effect modification by dietary antioxidants and smoking was observed only in males. It is not clear why the effect modification of diet differs between males and females, although comparable sex differences in oxidative stress have been described in another study [29].

Study limitations

Our study has a number of limitations. First, the study is cross-sectional, which limits causal inference. However, ''reverse causation'' does not seem a likely explanation for the main findings as we cannot see why individuals developing worse lung function would choose to eat more processed meat or fewer fruit and vegetables. Secondly, while we defined COPD spirometrically, which is the gold-standard approach [30] and avoids potential problems of bias which might arise with self-reported COPD, we did not measure post-bronchodilator lung function. This raises the possibility that a small minority of individuals classified as

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having COPD by our spirometric definition may have had asthma. However, such misclassification of phenotype would seem less likely in males, in whom the association between processed meat consumption and FEV_1/FVC was modified by smoking, the main risk factor for COPD. Thirdly, dietary information was collected using an administered FFQ. There are concerns that participants can over-report intake in response to FFQs, although their ability to describe types of diets and patterns of food consumption is well established [20, 22]. However, as measurement error and misclassification of exposure is likely to be random with respect to the study outcomes, this would be expected to attenuate associations; therefore, we do not think that misreporting on the FFQ could explain the associations we describe. Finally, subjects with high fruit and vegetable consumption and dietary TAC or with low processed meat consumption may be more health conscious and have other healthy behaviours, which could potentially confound associations with lung function. While we controlled for a large number of potential confounders, including detailed measures of smoking status, we cannot rule out unmeasured or residual confounding (such as the other environmental sources of oxidants/antioxidants, air pollution and occupational exposures) in an observational study of this kind.

Conclusion

Processed meat consumption was negatively associated with lung function in both males and females. This association was stronger among males with low fruit and vegetable consumption, low dietary TAC and among current smokers. Smoking cessation remains the most important public health message to prevent reduced lung function. However, the present findings suggest that the relative consumption of foods that influence pulmonary oxidant/antioxidant balance may also be important for optimising lung function, particularly in smokers. While longitudinal data are needed, these findings provide further evidence to suggest that current dietary guidelines to promote ''healthier'' patterns of eating could play a protective role in slowing lung function decline and preventing COPD in older age.

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