Public Health Nutrition: 14(2), 340–346 doi:10.1017/S1368980010002454

Plasma concentrations of 25-hydroxyvitamin D in meat eaters, fish eaters, vegetarians and vegans: results from the EPIC–Oxford study

Francesca L Crowe*, Marinka Steur, Naomi E Allen, Paul N Appleby, Ruth C Travis and Timothy J Key

Cancer Epidemiology Unit, Nuffield Department of Clinical Medicine, University of Oxford, Richard Doll Building, Roosevelt Drive, Oxford OX3 7LF, UK

Submitted 7 April 2010: Accepted 16 July 2010: First published online 21 September 2010

Abstract

Objective: Vegetarians and vegans exclude certain food sources of vitamin D from their diet, but it is not clear to what extent this affects plasma concentrations of 25-hydroxyvitamin D (25(OH)D). The objective was to investigate differences in vitamin D intake and plasma concentrations of 25(OH)D among meat eaters, fish eaters, vegetarians and vegans.

Design: A cross-sectional analysis.

Setting: United Kingdom.

Subjects: Plasma 25(OH)D concentrations were measured in 2107 white men and women (1388 meat eaters, 210 fish eaters, 420 vegetarians and eighty-nine vegans) aged 20–76 years from the European Prospective Investigation into Cancer and Nutrition (EPIC)–Oxford cohort.

Results: Plasma 25(OH)D concentrations reflected the degree of animal product exclusion and, hence, dietary intake of vitamin D; meat eaters had the highest mean intake of vitamin D (3·1 (95 % CI 3·0, 3·2) μg/d) and mean plasma 25(OH)D concentrations (77·0 (95 % CI 75·4, 78·8) nmol/l) and vegans the lowest (0·7 (95 % CI 0·6, 0·8) μg/d and 55·8 (95 % CI 51·0, 61·0) nmol/l, respectively). The magnitude of difference in 25(OH)D concentrations between meat eaters and vegans was smaller (20 %) among those participants who had a blood sample collected during the summer months (July–September) compared with the winter months (38 %; January–March). The prevalence of low plasma concentrations of 25(OH)D (<25 nmol/l) during the winter and spring ranged from <1 % to 8 % across the diet groups.

Conclusions: Plasma 25(OH)D concentrations were lower in vegetarians and vegans than in meat and fish eaters; diet is an important determinant of plasma 25(OH)D in this British population.

Keywords
25-Hydroxyvitamin D
Vitamin D
Vegetarian
Vegan

There is a well-established link between vitamin D and bone health; evidence from meta-analyses of randomised controlled trials indicates that supplemental vitamin D can lower the risk of fractures[1] and falls[2]. Moreover, results from other studies suggest that vitamin D may have a role in reducing all-cause mortality[3] and the prevention of several chronic diseases[4].

Plasma concentrations of 25-hydroxyvitamin D (25(OH)D), the major circulating form of vitamin D, vary throughout the year owing to the cutaneous biosynthesis of vitamin D when skin is exposed to sufficient quantities of UVB radiation (usually sunlight)[5]. Vitamin D in the diet will also influence circulating concentrations of 25(OH)D. In the UK, oily fish, meat, fortified breakfast cereals and fat spreads (e.g. margarine) are the major dietary sources of vitamin D[6]; thus, individuals who avoid consuming some of these foods, such as vegetarians and vegans, might be expected to have lower 25(OH)D concentrations in comparison with meat and fish eaters, as seen in several small studies conducted among Europeans and British Indians[7–10]. However, in a larger analysis, Chan *et al.*[11] reported no significant difference in the serum concentration of 25(OH)D between meat eaters and vegetarians living in North America.

The European Prospective Investigation into Cancer and Nutrition (EPIC)–Oxford cohort includes meat eaters, fish eaters, vegetarians and vegans and provides an excellent opportunity to investigate the effect of diet on plasma concentrations of 25(OH)D. The objective of the present study was to investigate the differences in plasma

**Corresponding author:* Email francesca.crowe@ceu.ox.ac.uk

concentrations of 25(OH)D among meat eaters, fish eaters, vegetarians and vegans and to examine the association between dietary intake of vitamin D and plasma 25(OH)D concentrations.

Methods

Study population

The Oxford arm of the EPIC study was designed to assess the associations among diet, lifestyle and risk of cancer in people with different dietary habits. Between 1993 and 1999, 65 429 participants aged >20 years and living in the UK were recruited into the study. A detailed description of the study design and characteristics of the cohort have been published previously[12]. In brief, participants were recruited through general practices in Oxfordshire, Buckinghamshire, Greater Manchester and by postal methods that aimed to recruit health-conscious people throughout the UK. The protocol was approved by a Multicenter Research Ethics Committee, and all participants provided written informed consent.

The present analysis includes participants who were included in a nested case–control study of plasma concentrations of 25(OH)D and the risk of incident fracture[13]. In that study, 730 participants who had a fracture during the first 5 years after completing the main baseline questionnaire were matched by sex, age at recruitment (±72 months), date of blood sampling (±1 month), duration of follow-up (±24 months) and, for women, menopausal status (pre- or postmenopausal) to 1445 controls and 25(OH)D was measured in plasma samples collected at baseline. For the present analysis, participants with missing information on important confounding variables and those who reported their ethnicity as being non-white were excluded, leaving a total of 2107 participants in the study (1388 meat eaters, 210 fish eaters, 420 vegetarians and 89 vegans).

Diet and lifestyle assessment

The participants were categorised into one of the four diet groups based on their replies to questions asking whether they ate any (i) meat, (ii) fish, (iii) eggs and (iv) dairy products. The participants were categorised as meat eaters, fish eaters (those who do not eat meat but eat fish), vegetarians (who do not eat meat or fish but eat dairy products and/or eggs) and vegans (who do not eat meat, fish, eggs or dairy products). Time of adherence to the diets was calculated by subtracting the age at which the participant last ate meat (for fish eater) or meat or fish (for vegetarian), or meat, fish, dairy or eggs (for vegan), from the age at recruitment.

At recruitment, the participants completed a validated semi-quantitative FFQ that estimated their intake of 130 different food items over the past 12 months[14,15]. The mean daily nutrient intake was estimated by multiplying the frequency of consumption by standard portion sizes and the nutrient content of the food or beverage, derived mainly from the fifth edition of the *McCance and Widdowson's The Composition of Foods* and its supplements[16]. There was no attempt to differentiate between the intake of vitamin D_2 or D_3 from the diet due to a lack of such information in the nutrient composition tables.

In the main questionnaire, the participants were asked to report their height and weight. Height and weight were measured in a subgroup of participants from the EPIC–Oxford cohort (n 4808) with results showing good agreement between the self-reported and measured height and weight ($r > 0{\cdot}9$)[17]. Either measured or self-reported height and weight were used to calculate BMI (weight (kg)/height^2 (m^2)), which was divided into four categories: <22·5, 22·5–24·9, 25·0–27·4 and ≥27·5 kg/m^2. Lifetime history of cigarette smoking was categorised as 'never', 'former' or 'current'. Outdoor activity (as a proxy for exposure to sunlight) was estimated from questions that assessed the amount of time spent walking, cycling and gardening during the summer, and divided into quartiles (0–7, 8–12, 13–20, ≥21 h/week). Participants were asked about time spent participating in vigorous exercise, which was defined as any physical activity undertaken to a degree that caused sweating or a faster heartbeat and assigned into categories (none, <2 and ≥2 h/week). Supplement use was assessed by asking whether vitamins, minerals, fish oil or fibre supplements were consumed regularly over the past 12 months and categorised as 'yes' or 'no'. Current use of exogenous hormones (hormone replacement therapy or oral contraceptives) was categorised as 'yes' or 'no'. An 'unknown' category was added for each variable in which data were missing or incomplete.

Laboratory methods

At recruitment or shortly after, blood samples were collected at local general practice surgeries into 10 ml Safety-Monovettes (Sarstedt, Nümbrecht, Germany). The participants were not required to fast, but time since the last consumption of foods or drinks was recorded. Blood was transported to a laboratory in Norfolk by mail at ambient temperature, where samples were centrifuged (sodium citrate was used as an anticoagulant) and the plasma was aliquoted into 0·5 ml straws. These were heat-sealed at both ends and stored in liquid nitrogen (−196°C).

Analyses were carried out in the Medical Research Council Human Nutrition Research laboratories in Cambridge, UK. Plasma 25(OH)D concentrations were measured using enzyme immunoassay (OCTEIA 25-Hydroxy Vitamin D kit; Immunodiagnostic Systems Limited, Boldon, Tyne and Wear, UK). This kit was 100 % cross-reactive with 25(OH)D_3 and 75 % cross-reactive with 25(OH)D_2[18]. The intra-assay CV was 3·5 % at 11 nmol/l and 5·9 % at 35 nmol/l. The inter-assay CV was 7·6 % at 11 nmol/l and 9·2 % at 35 nmol/l.

Statistical analysis

To normalise the distributions, plasma 25(OH)D concentration and the dietary intake variables were log transformed where appropriate. The distributions of demographic and lifestyle characteristics were compared among diet groups using the Pearson χ^2 test for categorical variables. For continuous variables ANOVA was used to assess the pair-wise differences between each diet group.

Geometric means and 95 % CI of the log-transformed values of 25(OH)D by diet group and season of blood collection (January–March, April–June, July–September and October–December) and quintiles of vitamin D intake were calculated using multiple linear regression models, adjusting for age (20–44, 45–54, 55–64, ≥65 years), sex, season and year of blood collection, case–control status, BMI, smoking status, outdoor activity, vigorous exercise, current use of hormones, supplement use and the interactions of age with sex, season of blood collection with year of blood collection, season of blood collection with age, season of blood collection with sex, as appropriate. The *P* value for heterogeneity between the geometric mean 25(OH)D concentrations was calculated by using likelihood ratio tests. Tests for the trend in the association between dietary intake of vitamin D and plasma 25(OH)D were obtained using the logarithm of vitamin D intake as a continuous variable in the regression model. The proportion of each diet group with plasma 25(OH)D <25 nmol/l, associated with an increased risk of bone-related diseases[19], and ≥75 nmol/l, proposed by some researchers to be optimal for preventing a range of health conditions[20] during the winter and spring, and summer and autumn, was also calculated. All statistical analyses were performed using the STATA statistical software package version 9·0 (StataCorp., College Station, TX, USA). Two-sided *P* values <0·05 were considered statistically significant.

Results

The characteristics of participants by diet group are shown in Table 1. Fish eaters, vegetarians and vegans had adhered to their diet for an average of 11·6, 15·5 and 9·5 years, respectively. There were significant differences

Table 1 Participant characteristics by diet group in the European Prospective Investigation into Cancer and Nutrition–Oxford cohort

	Meat eaters (*n* 1388)		Fish eaters (*n* 210)		Vegetarians (*n* 420)		Vegans (*n* 89)		
Characteristics	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* value*
Time on diet (years)†			11·6	10·4	15·5	14·3	9·5	9·0	
Age (years)	55·0	10·0	51·0	12·0	48·0	13·0	44·0	14·0	<0·001
BMI (kg/m^2)	25·0	4·3	23·1	2·9	23·4	3·6	22·3	2·6	<0·001
	%		%		%		%		
Sex									
Male	21		14		22		39		<0·001
Month of blood sample collection									
January–March (winter)	28‖		22		23		36		0·001
April–June (spring)	28		35		24		21		
July–September (summer)	25		24		25		20		
October–December (autumn)	19		19		28		22		
Current use of hormones†‡									
Yes	23		22		19		17		0·264
No	76		78		81		81		
Smoking status†									
Never	57		58		62		69		0·063
Former	32		34		31		24		
Current	10		8		6		8		
Use of supplements†									
Yes	55		73		57		51		<0·001
No	44		24		40		48		
Summer outdoor activity (h/week)†§									
≤7	22		24		29		21		0·140
8–12	27		24		22		30		
13–20	24		26		24		17		
≥21	20		21		18		20		
Vigorous exercise (h/week)†									
None	41		31		26		21		<0·001
≤2	37		34		39		42		
>2	21		32		34		35		

*Differences in means for continuous variables were assessed using ANOVA and differences in proportions were assessed by using the χ^2 test.
†Denotes unknown in some participants.
‡In women only: meat eaters, *n* 1096; fish eaters, *n* 181, vegetarians, *n* 328; vegans, *n* 54.
§Defined as the time spent gardening, walking or cycling.
‖Percentages may not add to 100 due to rounding.

Table 2 Daily dietary intake of selected nutrients by diet group

	Meat eaters (*n* 1359)		Fish eaters (*n* 208)		Vegetarians (*n* 417)		Vegans (*n* 87)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* value*
Vitamin D (μg)†	3·1	3·0, 3·2	2·2	2·1, 2·4	1·2	1·1, 1·3	0·7	0·6, 0·8	<0·001
Calcium intake (mg)	1026	311	1019	353	1019	379	557	188	<0·001
Total energy (MJ)	8·4	2·2	8·1	2·3	7·9	2·1	7·4	2·2	<0·001
Carbohydrate (% of total energy)	48·1	6·0	51·8	6·0	53·0	6·6	55·0	7·1	<0·001
Total fat (% of total energy)	31·7	5·7	30·3	5·7	30·3	6·7	29·4	6·8	<0·001
Protein (% of total energy)	17·4	2·9	14·7	2·4	13·9	2·3	12·8	2·0	<0·001

*Differences in means for continuous variables were assessed by using ANOVA.
†Values are reported as geometric means and 95 % CI.

in age and BMI among the four diet groups with meat eaters being on average, older and heavier than vegans. A higher percentage of the vegans, compared with other diet groups, were men and had their blood sample collected in the winter (January–March), whereas a higher percentage of fish eaters had their blood sample collected in spring (April–June) and were supplement users. There was no significant difference among the diet groups in the amount of time spent doing outdoor activities during summer but the proportion of meat eaters not doing any vigorous exercise was almost twice as high as that of the vegans (41 % *v.* 21 %, respectively).

The results in Table 2 show the dietary intake of selected nutrients by diet group. The dietary intake of vitamin D was significantly different among the diet groups ($P < 0{\cdot}001$): meat eaters had the highest intake (3·1 μg/d), followed by fish eaters, then vegetarians and then vegans, whose intake was less than a quarter that of meat eaters. Vegans also had a significantly lower intake of calcium compared with the other three diet groups. Total energy consumption was significantly higher in meat eaters than in vegetarians and vegans, as was the contribution to energy from fat and protein ($P < 0{\cdot}001$).

In Fig. 1, plasma 25(OH)D concentrations are shown by season of blood collection for each diet group. Throughout the year, vegetarians and vegans had a significantly lower plasma concentration of 25(OH)D compared with meat eaters ($P < 0{\cdot}05$). The largest difference in 25(OH)D concentrations was between vegans and meat eaters during the winter (38 % lower in vegans), but this difference was reduced to 20 % during the summer. In all four seasons, plasma concentrations of 25(OH)D did not differ significantly between meat eaters and fish eaters. Within each diet group, plasma 25(OH)D concentrations differed according to the season of blood collection ($P < 0{\cdot}001$) with the lowest 25(OH)D concentrations in participants who had a blood sample collected during the winter (January–March) and the highest in those collected during the summer (July–September). The magnitudes of the difference in mean plasma 25(OH)D concentrations in the meat eaters, fish eaters and vegetarians who had their blood sample collected in the winter compared to those, in the same diet group, who had their blood sample collected during summer were similar (54 %, 58 % and 56 % higher, respectively). However, among vegans, the concentration of 25(OH)D in the summer was 97 % higher compared to those who had their blood sample collected during the winter.

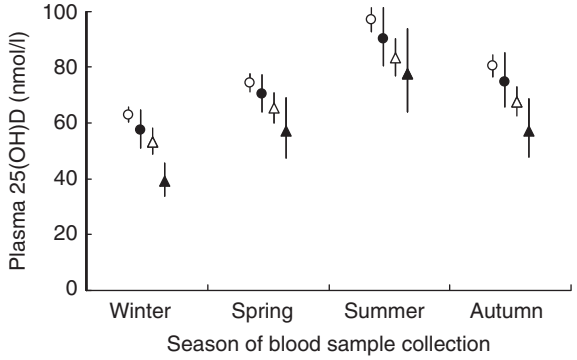

Fig. 1 Mean plasma concentrations of 25-hydroxyvitamin D (25(OH)D) in meat eaters (*n* 1388), fish eaters (*n* 210), vegetarians (*n* 420) and vegans (*n* 89) by season of blood sample collection. Data are presented as geometric mean and 95 % CI adjusted for year of blood sample collection, age, sex, case–control status, BMI, smoking status, summer outdoor activity, vigorous exercise, current use of hormones, supplement use and the interaction of sex × age according to diet group (○, meat eaters; ●, fish eaters; △, vegetarians; ▲, vegans)

Table 3 shows the mean plasma 25(OH)D concentrations according to quintiles of dietary intake of vitamin D. There was a significant positive association between vitamin D intake and plasma concentrations of 25(OH)D in all participants, although plasma concentrations appeared to reach a plateau at intake above 3·0 μg/d. Supplement users had significantly higher ($P < 0{\cdot}001$) mean plasma concentrations of 25(OH)D (78·1 (95 % CI 76·3, 80·0) nmol/l) compared with non-supplement users (66·9 (95 % CI 65·1, 68·9) nmol/l). Among non-supplement users, plasma concentrations of 25(OH)D increased linearly with increasing dietary vitamin D intake. There were also significant differences ($P < 0{\cdot}01$) in plasma concentrations of 25(OH)D between the diet groups among non-supplement users with the exception being between meat eaters and fish eaters (results not shown).

Table 3 Geometric mean plasma concentrations of 25-hydroxyvitamin D by quintiles of dietary intake of vitamin D among all participants and according to use of supplements*

	All participants			Non-supplement users			Supplement users		
	n	Mean	95 % CI	*n*	Mean	95 % CI	*n*	Mean	95 % CI
Quintiles of dietary vitamin D intake (μg/d)									
0·11–1·29	410	65·5	62·9, 68·3	175	58·6	54·9, 62·5	227	70·0	66·2, 74·0
1·30–2·18	415	71·6	68·9, 74·5	158	66·4	62·2, 70·8	248	76·8	72·9, 80·8
2·19–2·99	413	75·7	72·7, 78·8	166	68·4	64·2, 72·9	235	82·2	78·0, 86·6
3·00–4·54	417	78·7	75·6, 81·9	183	70·7	66·5, 75·2	227	84·9	80·4, 89·7
4·55–24·57	416	76·3	73·3, 79·4	168	71·2	66·7, 75·9	243	79·9	75·8, 84·2
P for trend†			<0·001			<0·001			<0·001
P for heterogeneity‡			<0·001			<0·001			<0·001

*Adjusted for season and year of blood sample collection, age, sex, case–control status, BMI, smoking status, summer outdoor activity, vigorous exercise, current use of hormones, supplement use and the interactions of sample year × sample season, sample season × age, sample season × sex and age × sex, as appropriate by using multiple linear regression.
†Tests for trend were obtained by using vitamin D intake as a continuous variable in the regression model.
‡Tests of heterogeneity between the quintiles were calculated by using a likelihood ratio test.

Table 4 Mean plasma concentrations of 25(OH)D and distribution of participants according to categories of 25(OH)D by diet group

	Meat eaters (*n* 1388)		Fish eaters (*n* 210)		Vegetarians (*n* 420)		Vegans (*n* 89)	
Plasma 25(OH)D (nmol/l)	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI
Geometric mean*	76·4[a]	74·7, 78·2	74·3[a]	70·1, 78·8	66·9[b]	64·1, 69·8	55·9[c]	51·0, 61·3
Geometric mean†	77·0[a]	75·4, 78·8	72·2[b]	68·2, 76·4	66·0[c]	63·3, 68·8	55·8[d]	51·0, 61·0
	%		%		%		%	
Winter and spring (nmol/l)	(*n* 775)		(*n* 121)		(*n* 195)		(*n* 51)	
<25	<1		3		3		8	
≥75	40		50		37		20	
Summer and autumn (nmol/l)	(*n* 613)		(*n* 89)		(*n* 225)		(*n* 38)	
<25	0		2		2		5	
≥75	65		63		56		45	

25(OH)D, 25-hydoxyvitamin D.
[a,b,c,d]Mean values within a row with unlike superscript letters were significantly different ($P < 0·05$).
*Adjusted for season and year of blood sample collection and age by using multiple linear regression.
†Adjusted for season and year of blood sample collection, age, sex, case–control status, BMI, smoking status, summer outdoor activity, vigorous exercise, current use of hormones, supplement use, and the interactions of year × season of blood collection, season of blood collection × age, season of blood collection × sex and age × sex by using multiple linear regression.

The geometric mean concentrations of 25(OH)D by diet group and the distribution of participants with plasma 25(OH)D concentrations below 25 nmol/l or 75 nmol/l and above are shown in Table 4. After adjusting for season, year of blood collection and age, the difference in vitamin D concentrations between meat eaters and vegans was 20·5 nmol/l. After controlling for a range of other factors that influence plasma 25(OH)D, this difference increased slightly to 21·2 nmol/l. For all diet groups, a greater proportion of participants had plasma 25(OH)D below 25 nmol/l in the winter and spring months compared with the summer and autumn months. Among vegans, 8 % and 5 % had plasma 25(OH)D <25 nmol/l in the winter and spring, and the summer and autumn months, respectively, compared with <1 % of the meat eaters. There was also a greater proportion of participants with 25(OH)D ≥75 nmol/l in the summer and autumn compared with the winter and spring. In all, 40 % and 65 % of meat eaters had plasma 25(OH)D ≥75 nmol/l in the winter and spring, and the summer and autumn months, respectively, compared with 20 % and 45 % of the vegans.

Discussion

In the present large cross-sectional study of white British men and women, plasma 25(OH)D concentrations reflected the degree of animal product exclusion and, hence, dietary intake of vitamin D; meat eaters had the highest vitamin D intake and plasma 25(OH)D concentrations and vegans had the lowest, both in the winter and the summer months. However, the mean 25(OH)D concentration in vegans was comparable, if not slightly higher, than that reported in other studies among the general British population[21,22]. Moreover, compared with other studies[21,22], a smaller proportion of these study participants had a concentration of 25(OH)D below 25 nmol/l, considered by the UK Department of Health to increase the risk of bone-related diseases[19], which reflects the relatively 'health-conscious' behaviour of the individuals recruited in the EPIC–Oxford cohort. The pattern of difference in plasma concentrations of 25(OH)D among the diet groups (meat eaters > fish eaters > vegetarians > vegans) was similar throughout the year. However, the magnitude of difference

in plasma 25(OH)D concentrations between vegans who had their blood samples collected during the summer compared with the winter was greater than that of any other diet group. This observation is important as it suggests that the cutaneous synthesis of plasma vitamin D was similar in vegans compared with the other diet groups and it is the extent to which the intake of animal foods is restricted that explains the lower circulating concentrations of 25(OH)D in vegans, especially during the winter months.

These results have indicated the importance of dietary vitamin D as a determinant of plasma 25(OH)D by showing a significant positive association between vitamin D intake and plasma concentrations of 25(OH)D. Results from the UK National Diet and Nutrition Survey (NDNS) showed that almost 60 % of the dietary intake of vitamin D comes from fish, meat and eggs[21]. Given that all these foods are excluded from a vegan diet and some of these foods are excluded from the diet of fish eaters and vegetarians, it is not surprising that both the intake of vitamin D and plasma 25(OH)D concentrations were lower in these groups compared with the meat eaters. The UK has not set a recommended nutrient intake for vitamin D for men and non-pregnant, non-breast-feeding women (<65 years of age), with the implication that sunlight exposure is sufficient to meet the requirements[19]. Others have calculated that the amount of vitamin D intake that would ensure that the majority of the population (97·5 %) maintains plasma 25(OH)D concentrations >25 nmol/l throughout the year is 8·7 μg/d[23]. Almost all of the present study population had a dietary intake of vitamin D less than this but only 2 % had plasma concentrations of 25(OH)D <25 nmol/l during the winter and spring months. Overall, it would appear that sun exposure has a greater influence on plasma concentrations of 25(OH)D than the dietary intake of vitamin D given that the mean difference in plasma 25(OH)D between the winter and the summer months for each diet group (34·2, 33·1, 30·0 and 38·2 nmol/l for meat eaters, fish eaters, vegetarians and vegans, respectively) was greater than the difference between meat eaters and vegans during the winter (23·6 nmol/l).

Findings from randomised placebo-controlled trials conducted during the winter have shown that each 1 μg of supplemental vitamin D is associated with an increase in serum 25(OH)D of between 0·7 nmol/l[24] and 2 nmol/l[23]. Therefore, it is important to note that the magnitude of difference in dietary vitamin D intake between meat eaters and vegans of 2·4 μg and the corresponding overall difference in the plasma concentration of 25(OH)D of 21 nmol/l (i.e. 8·8 nmol/l per 1 μg) is larger than that which would be predicted from intervention studies. It may be that other dietary-related factors influenced the association between vitamin D intake and plasma concentrations of 25(OH)D in the present study population. Vegans had a lower dietary intake of calcium compared with the other diet groups, which may affect plasma concentrations of 25(OH)D by stimulating the release of parathyroid hormone and, thus, the conversion of 25(OH)D to the hormonal biologically active form of vitamin D, 1,25 dihydroxyvitamin D ($1,25(OH)_2D$)[5]. Increased synthesis of $1,25(OH)_2D$ may decrease circulating concentrations of vitamin D by reducing the half-life of 25(OH)D[25]. It is also possible that the true intake of vitamin D, especially from fortified foods, was over- or underestimated using information from the food composition tables. As the type of vitamin D used to fortify some foods is the animal-derived vitamin D_3 (cholecalciferol), vegans may avoid consuming products such as breakfast cereals and margarines that have been fortified with vitamin D_3. There was also no information on the amount of vitamin D from cod liver oil, other fish oil or vitamin D supplements, which, if combined with the dietary intake, may have increased the difference in the total intake of vitamin D between the diet groups.

The findings from other smaller studies have also shown that in comparison with meat eaters, both Asian and non-Asian vegetarians and vegans from Northern Europe have lower circulating concentrations of 25(OH)D, particularly during the winter months[7–10]. On the other hand, recent findings from the Adventist Health Study-2 involving African Americans and non-Hispanic whites living in California and other parts of North America showed that meat eaters had a significantly higher intake of vitamin D from diet compared with vegetarians, but because the total vitamin D intake (from diet and supplements) did not differ between the groups, serum concentrations of 25(OH)D were similar for meat eaters and vegetarians[11]. Overall, the totality of evidence from these studies on vegetarians and vegans would suggest that the total intake of vitamin D has an influence on circulating concentrations of 25(OH)D and, without supplementation, the diet of meat eaters provides a greater amount of vitamin D than vegetarian and vegan diets.

There were several limitations to the present study. It was difficult to disentangle the contribution of dietary factors and exposure to sunlight to plasma concentrations of 25(OH)D. This was partly overcome by separating participants according to season of blood sample collection and controlling for year of blood sample collection, time spent doing vigorous exercise and summer outdoor activity. Nevertheless, there was no information collected on other factors such as the use of sun protection or the frequency of sun vacations throughout the year, which could contribute to the variation in the cutaneous biosynthesis of 25(OH)D between diet groups. On the other hand, it is unlikely that factors that also influence the cutaneous synthesis of 25(OH)D such as cloud cover, ozone and altitude[26] would differ according to diet group. It has been noted that the absolute values of 25(OH)D can vary depending on the type of assay used[27], and therefore the proportion of individuals with

plasma 25(OH)D <25 nmol/l and ≥75 nmol/l reported herein should be interpreted with caution.

In conclusion, the results from the present large cross-sectional analysis show that people in the UK who exclude food of animal origin from their diet have a lower intake of vitamin D and lower plasma concentrations of 25(OH)D. Whether lower plasma concentrations of 25(OH)D in vegetarians or vegans relate to any adverse health outcomes is not well understood but could be the subject of future investigation.

Acknowledgements

The present study was supported by Cancer Research UK and the Medical Research Council. The study was conducted during the tenure of a Girdlers' New Zealand Health Research Council Fellowship (Francesca Crowe). T.J.K. is a member of the Vegan Society, UK. The other authors have no conflict of interest to declare. F.L.C. and M.S. were responsible for the drafting of the manuscript and conducting the statistical analyses; T.J.K. and N.E.A. were responsible for study concept and design, and for the recruitment of the EPIC–Oxford cohort; and P.N.A. for consultation for statistical analysis. All authors contributed to the interpretation of the results and the writing and review of the manuscript and approved the final manuscript. F.L.C. and M.S. contributed equally to the present study. The authors thank all the participants in the EPIC–Oxford cohort for their invaluable contribution to the study, as well as the laboratory staff at the Medical Research Council Human Nutrition Research laboratories in Cambridge for measuring plasma concentrations of 25-hydroxyvitamin D.

References

1. Bischoff-Ferrari HA, Willett WC, Wong JB *et al.* (2009) Prevention of nonvertebral fractures with oral vitamin D and dose dependency: a meta-analysis of randomized controlled trials. *Arch Intern Med* **169**, 551–561.
2. Bischoff-Ferrari HA, Dawson-Hughes B, Staehelin HB *et al.* (2009) Fall prevention with supplemental and active forms of vitamin D: a meta-analysis of randomised controlled trials. *BMJ* **339**, b3692.
3. Autier P & Gandini S (2007) Vitamin D supplementation and total mortality: a meta-analysis of randomized controlled trials. *Arch Intern Med* **167**, 1730–1737.
4. Scientific Advisory Committee on Nutrition (2007) *Update on Vitamin D: Position Statement by the Scientific Advisory Committee on Nutrition.* London: The Stationery Office.
5. DeLuca HF (2004) Overview of general physiologic features and functions of vitamin D. *Am J Clin Nutr* **80**, 1689S–1696S.
6. Hoare J, Henderson L, Bates CJ *et al.* (2004) *The National Diet and Nutrition Survey: Adults Aged 19 to 64 Years.* London: HMSO.
7. Dent CE & Gupta MM (1975) Plasma 25 hydroxyvitamin D levels during pregnancy in Caucasians and in vegetarian and non vegetarian Asians. *Lancet* **2**, 1057–1060.
8. Finch PJ, Ang L, Colston KW *et al.* (1992) Blunted seasonal variation in serum 25-hydroxy vitamin D and increased risk of osteomalacia in vegetarian London Asians. *Eur J Clin Nutr* **46**, 509–515.
9. Lamberg-Allardt C, Karkkainen M, Seppanen R *et al.* (1993) Low serum 25-hydroxyvitamin D concentrations and secondary hyperparathyroidism in middle-aged white strict vegetarians. *Am J Clin Nutr* **58**, 684–689.
10. Outila TA, Kärkkäinen MUM, Seppänen RH *et al.* (2000) Dietary intake of vitamin D in premenopausal, healthy vegans was insufficient to maintain concentrations of serum 25-hydroxyvitamin D and intact parathyroid hormone within normal ranges during the winter in Finland. *J Am Diet Assoc* **100**, 434–441.
11. Chan J, Jaceldo-Siegl K & Fraser GE (2009) Serum 25-hydroxyvitamin D status of vegetarians, partial vegetarians, and nonvegetarians: the Adventist Health Study-2. *Am J Clin Nutr* **89**, S1686–S1692.
12. Davey GK, Spencer EA, Appleby PN *et al.* (2003) EPIC-Oxford: lifestyle characteristics and nutrient intakes in a cohort of 33 883 meat-eaters and 31 546 non meat-eaters in the UK. *Public Health Nutr* **6**, 259–268.
13. Roddam AW, Neale R, Appleby P *et al.* (2007) Association between plasma 25-hydroxyvitamin D levels and fracture risk: the EPIC-Oxford study. *Am J Epidemiol* **166**, 1327–1336.
14. Bingham SA, Gill C, Welch A *et al.* (1994) Comparison of dietary assessment methods in nutritional epidemiology: weighed records *v.* 24 h recalls, food-frequency questionnaires and estimated-diet records. *Br J Nutr* **72**, 619–643.
15. Bingham SA, Cassidy A, Cole TJ *et al.* (1995) Validation of weighed records and other methods of dietary assessment using the 24 h urine nitrogen technique and other biological markers. *Br J Nutr* **73**, 531–550.
16. Holland B, Welch AA & Unwin ID (1991) *McCance and Widdowson's The Composition of Foods.* Cambridge, UK: The Royal Society of Chemistry and Ministry of Agriculture, Fisheries, and Food.
17. Spencer EA, Appleby PN, Davey GK *et al.* (2002) Validity of self-reported height and weight in 4808 EPIC–Oxford participants. *Public Health Nutr* **5**, 561–565.
18. IDS OCTEIA Kit Literature (2002) *25-Hydroxy Vitamin D, Catalogue Number AC-57F1.* Boldon, Tyne & Wear, UK: Immunodiagnostic Systems (IDS) Ltd.
19. UK Department of Health (1991) *Dietary Reference Values for Food Energy and Nutrients for the United Kingdom. Report on Health and Social Subjects* no. 41. London: HMSO.
20. Bischoff-Ferrari H (2009) Vitamin D: what is an adequate vitamin D level and how much supplementation is necessary? *Best Pract Res Clin Rheumatol* **23**, 789–795.
21. Ruston D, Hoare J, Henderson L *et al.* (2004) *Nutritional Status (Anthropometry and Blood Analytes), Blood Pressure and Physical Activity.* London: TSO.
22. Hyppönen E & Power C (2007) Hypovitaminosis D in British adults at age 45 y: nationwide cohort study of dietary and lifestyle predictors. *Am J Clin Nutr* **85**, 860–868.
23. Cashman KD, Hill TR, Lucey AJ *et al.* (2008) Estimation of the dietary requirement for vitamin D in healthy adults. *Am J Clin Nutr* **88**, 1535–1542.
24. Heaney RP, Davies KM, Chen TC *et al.* (2003) Human serum 25-hydroxycholecalciferol response to extended oral dosing with cholecalciferol. *Am J Clin Nutr* **77**, 204–210.
25. Clements MR, Davies M, Hayes ME *et al.* (1992) The role of 1,25-dihydroxyvitamin D in the mechanism of acquired vitamin D deficiency. *Clin Endocrinol (Oxf)* **37**, 17–27.
26. Engelsen O, Brustad M, Aksnes L *et al.* (2005) Daily duration of vitamin D synthesis in human skin with relation to latitude, total ozone, altitude, ground cover, aerosols and cloud thickness. *Photochem Photobiol* **81**, 1287–1290.
27. Hollis BW (2008) Measuring 25-hydroxyvitamin D in a clinical environment: challenges and needs. *Am J Clin Nutr* **88**, S507–S510.