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ORIGINAL CONTRIBUTION

Vitamin D status is associated with sociodemographic factors, lifestyle and metabolic health

Tuija Jääskeläinen · Paul Knekt · Jukka Marniemi · Laura Sares-Jäske · Satu Männistö · Markku Heliövaara · Ritva Järvinen

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Abstract
Purpose Low serum 25(OH)D concentration has been shown to predict the occurrence of several chronic diseases. It is, however, still unclear whether the associations are causal or due to confounding. The aim of this study was to investigate the associations between serum 25(OH)D concentration and sociodemographic, lifestyle and metabolic health-related factors.
Methods The study population comprised 5,714 men and women, aged 30–79 years, from the Health 2000 Survey representing the Finnish population. Serum 25(OH)D concentration was determined by radioimmunoassay from serum samples frozen at −70 °C. Sociodemographic, lifestyle and metabolic factors were determined by questionnaires, interviews and measurements. Linear regression was used to assess the associations between serum 25(OH)D and the factors studied.
Results The mean serum 25(OH)D concentration was 45.3 nmol/l and it varied between categories of sociodemographic, lifestyle and metabolic health variables. Older age, being married or cohabiting and higher education were related to higher serum 25(OH)D concentration. Those with the healthiest lifestyle estimated by a lifestyle index based on body mass index, physical activity, smoking, alcohol consumption and diet had 15.8 nmol/l higher serum 25(OH)D concentration compared to those with the unhealthiest lifestyle. Of the indicators of metabolic health, only waist circumference and HDL cholesterol were significantly associated with 25(OH)D after adjustment for sociodemographic, lifestyle and other metabolic health factors.
Conclusion This study suggests that serum 25(OH)D concentration is associated with a multitude of sociodemographic, lifestyle and metabolic health factors. Thus, it is possible that such factors confound associations observed between serum 25(OH)D concentration and chronic diseases.

Keywords Vitamin D status · Serum 25(OH)D · Sociodemographic factors · Lifestyle · Metabolic health · Cross-sectional study

Introduction

Several recent studies have suggested that inadequate serum or plasma 25-hydroxyvitamin D (25(OH)D) concentration is associated with not only osteoporosis and related fractures [1], but also an increased risk of many chronic diseases, such as type 2 diabetes [2], cardiovascular diseases [3], some cancers [4, 5] and Parkinson's disease [6]. However, it is still unclear whether the associations are causal, since the current epidemiologic knowledge is based on observational studies.

There are some plausible hypotheses of the biological mechanisms by which vitamin D may influence the risk of chronic diseases. Vitamin D may affect insulin sensitivity by stimulating the expression of insulin receptors, thereby enhancing insulin responsiveness for glucose transport, and

T. Jääskeläinen · P. Knekt (✉) · L. Sares-Jäske · S. Männistö · M. Heliövaara
National Institute for Health and Welfare, P.O. Box 30, 00271 Helsinki, Finland
e-mail: paul.knekt@thl.fi

J. Marniemi
National Institute for Health and Welfare, Turku, Finland

R. Järvinen
University of Eastern Finland, Kuopio, Finland

also by modulating the function of the immune system [7, 8]. 1,25-dihydroxyvitamin D, which is the biologically active form of vitamin D [9], has been observed to be a negative endocrine regulator of the renin-angiotensin system that plays an important role in the regulation of blood pressure [10]. In addition, 1,25-dihydroxyvitamin D may act as an anticancer agent by inhibiting cell proliferation by arresting the cell cycle in tumour cells [11]. It has also been suggested that chronically inadequate vitamin D status may cause a loss of dopaminergic neurons in the brain and lead to the development of Parkinson's disease [12].

The associations between serum 25(OH)D concentration and chronic disease incidence may alternatively be caused by confounding factors. In earlier studies, serum 25(OH)D concentration has shown associations with a variety of sociodemographic and lifestyle factors and components of metabolic health. In population-based studies, low serum 25(OH)D concentration has been found to be associated with older age, living without a partner, winter season, obesity, physical inactivity, current smoking and low dietary intake of vitamin D [13–16]. In addition, serum 25(OH)D concentration has been observed to be higher among individuals with normal blood pressure and a favourable serum lipid profile [17, 18]. However, in most studies only a limited number of factors related to serum 25(OH)D concentration have been examined and, accordingly, there is still a lack of information on the simultaneous effect of several factors on vitamin D status.

The aim of the present study is to give a view of the serum 25(OH)D distribution in categories of sociodemographic and lifestyle factors and components of metabolic health in a representative sample of the Finnish adult population. By revealing the factors that are related to serum 25(OH)D, potential confounding factors could be taken more comprehensively into account in studies on the associations between serum 25(OH)D concentration and health outcomes.

Subjects and methods

Study population

The present cross-sectional study is based on the Health 2000 Survey, which was carried out in Finland in 2000–2001 [19]. The study population was a two-stage stratified cluster sample representing the adult population aged 30 years and over living in mainland Finland. The sample frame was regionally stratified according to the five university hospital regions. In the first stage of sampling, 80 healthcare districts were sampled as a cluster. In the second stage, a random sample of individuals from each of the 80 healthcare districts was drawn from a nationwide population register. In this study, the study population consisted of 7,210 individuals aged 30–79 years of whom 6,156 (85 % of the sample) participated in a health examination between September 2000 and March 2001. A total of 2,677 men and 3,037 non-pregnant women whose serum 25(OH)D concentrations were determined were finally included in the present study.

Written informed consent was obtained from all the participants of the survey. The study was approved by the Ethical Committee for Research in Epidemiology and Public Health at the Hospital District of Helsinki and Uusimaa in Finland.

Methods

The Health 2000 Survey included interviews, self-administered questionnaires and a comprehensive health examination [19]. A health interview and self-administered questionnaires provided information on marital status, education, smoking status and alcohol consumption. The frequency and type of leisure-time physical activities were also assessed from a self-administered questionnaire. There were four categories in the question relates to leisure-time physical activity: (1) no leisure-time physical activity, (2) moderate leisure-time physical activity (e.g. walking, cycling) at least 4 h per week, (3) fitness-training at least 3 h per week and (4) regular competitive sports training several times a week. Weight, height and waist circumference were measured in light clothing without shoes at the health examination, and body mass index (kg/m^2) was calculated. Blood pressure was measured twice with a 2-min interval by using the auscultatory method and the mean value was used. Fasting blood samples were taken and stored at −70 °C. The average time of fasting in the present study population was 9 h. Serum 25(OH)D was determined by radioimmunoassay (RIA, Diasorin, Minnesota) between January 2001 and November 2002. The interassay coefficient of variation for 25(OH)D concentration measurements was 7.80 % at the mean level of 47.3 nmol/l. The laboratory where analyses were carried out participated in an external quality control programme run by Labquality Ltd (Helsinki, Finland). Serum fasting glucose and triglyceride concentrations were analysed by using enzymatic methods (Triglycerides GPO PAP, Olympus System Reagent, Germany, and Glucose, Hexokinase, Olympus System Reagent, Germany) and serum HDL cholesterol by using direct method (HDL-C Plus, Roche Diagnostics GmbH, Germany). Serum fasting glucose, triglycerides and HDL cholesterol were determined within 6 months after the blood samples were taken.

Data on diet and use of vitamin D supplements were collected by a self-administered food frequency questionnaire (FFQ) designed to estimate the average food intakes over the preceding year [20, 21]. The FFQ included 128 commonly used food items and dishes with specified serving sizes (e.g. glass, slice) or weight or volume measures. Food items and dishes were presented in subgroups (e.g. dairy products, grain products, vegetables, fruit and berries and desserts). Blank lines were provided below each subgroup to enable the respondents to write in any food items not listed in the FFQ. There were nine frequency categories in the questionnaire ranging from never/rarely to six or more times per day. The FFQ also included questions about the regular use of vitamin supplements. Supplemental vitamin D included vitamin D obtained from single-ingredient vitamin D supplements and also from multivitamin supplements that included vitamin D. The average food consumption and intakes of nutrients per day were calculated using software developed at the National Public Health Institute (Finessi) and the National Finnish Food Composition Database (Fineli®) [22]. In the present study, the FFQ provided information on dietary intake of vitamin D, use of vitamin D supplements and intakes of fish, margarine and components of the mAHEI.

The dietary index

A dietary index (modified AHEI, mAHEI) was created based on the definition of the 9-item Alternate Healthy Eating Index (AHEI) [23, Sääksjärvi et al. 2012 (in press)]. The mAHEI included seven components (intake of vegetables; intake of fresh fruits and berries; intake of legumes, nuts, seeds and soya beans; ratio of white to red meat; intake of rye; ratio of polyunsaturated to saturated fat; and intake of trans fat). Consumption of alcohol and use of multivitamins were excluded because alcohol consumption was considered an independent lifestyle factor in the present study and habitual multivitamin use is not recommended in Finland. The components of the mAHEI were divided into quintiles and with the exception of trans fat intake received scores in ascendant order such that the lowest quintile received 1 point and the highest quintile 5 points. Trans fat intake was scored in the opposite order (5 points for the lowest quintile and 1 point for the highest quintile). All component scores were summed to the total score which ranged from 7 (lowest) to 35 (highest). A higher score was considered to represent healthier dietary behaviour compared to those who had a lower score on the mAHEI.

The lifestyle index

The lifestyle index included five components (body mass index, leisure-time physical activity, smoking, alcohol consumption and dietary habits) based on the criteria presented by Hu et al. [24]. Healthy lifestyle was defined as a body mass index <25.0 kg/m^2, regular moderate leisure-time physical activity for at least 4 h per week or vigorous leisure-time physical activity for at least 3 h per week, no current smoking, alcohol consumption 1–99 g/week in women or 1–199 g/week in men, and an above-median total score on the mAHEI (21 points). For each component, participants who met the criteria for a healthy lifestyle received 1 point while those who did not meet the criteria were scored 0. The total score thus ranged from 0 to 5, with higher scores suggesting a healthier lifestyle than lower scores.

The metabolic syndrome

The metabolic syndrome was defined according to the new harmonization definition [25] as the presence of any three of the following five risk factors: elevated waist circumference, elevated triglycerides, reduced HDL cholesterol, elevated blood pressure and elevated fasting glucose level. Waist circumference was considered elevated if it was $\geq$94 cm in men and $\geq$80 cm in women. Elevated triglycerides consisted of serum levels $\geq$1.7 mmol/l and elevated fasting glucose consisted of serum levels $\geq$5.6 mmol/l. HDL cholesterol was considered reduced if it was $<$1.0 mmol/l in men and $<$1.3 mmol/l in women. Elevated blood pressure was defined as systolic blood pressure $\geq$130 mmHg and/or diastolic $\geq$85 mmHg or use of antihypertensive medication.

Statistical methods

The statistical analyses of this cross-sectional study were based on the general linear model [26]. Serum 25(OH)D was a dependent variable, and the potential determinants were independent variables. Model-adjusted serum 25(OH)D means were estimated in categories of the independent variables [27]. Test for trend was performed by including the determinants as continuous variables in the models. Two different models were used. Model 1 included age, gender, month of blood sampling and separately each of the vitamin D sources–related factors (Table 2), sociodemographic factors (Table 3), lifestyle factors (Table 4) or the components of metabolic health (Table 5). Model 2 included simultaneously sociodemographic factors, lifestyle factors and the components of metabolic health. The analyses were carried out using SUDAAN 10.0.1 procedures (Research Triangle Institute 2001).

Results

Most of the participants were married or cohabiting, were overweight (BMI $\geq$25.0 kg/m^2) or obese (BMI $\geq$30.0 kg/m^2), took part in leisure-time physical activities and were non-smokers (Table 1). A total of 42.7 % of the participants suffered from metabolic syndrome. The mean intake of vitamin D from diet was 6.87 µg/day. The main dietary sources were fish and margarine. A total of 10.2 % of participants used vitamin D supplements habitually. The mean concentration of serum 25(OH)D was 45.3 nmol/l.

Most of the serum samples were taken during the months with low exposure to sunlight (i.e. from September to March) (Table 2). Significant seasonal variation could be seen, with the highest concentrations in September (52.2 nmol/l) and the lowest in February (39.5 nmol/l). There was a statistically significant positive association between serum 25(OH)D concentration and intake of dietary vitamin D and its main sources, fish and margarine intake, in both models. In addition, vitamin D supplement users had 9.1 nmol/l higher mean concentration of serum 25(OH)D than participants who did not use vitamin D supplements when adjusting for sociodemographic, lifestyle and metabolic health factors ($P < 0.0001$).

No notable difference in serum 25(OH)D was found between men and women (Table 3). There was, however, a significant positive gradient with age. Individuals aged 30–39 years had a mean gender- and month of blood sampling-adjusted concentration of 42.5 nmol/l, whereas among persons aged 60–69 years it was 49.0 nmol/l ($P < 0.0001$). The positive gradient remained significant after further adjustment for sociodemographic and lifestyle factors and components of metabolic health. Being married or cohabiting as well as having higher education were positively associated with serum concentrations of 25(OH)D. Individuals with the highest education had 7.4 nmol/l higher serum 25(OH)D concentrations in comparison with those with the lowest education when adjusting for age, gender and month of blood sampling ($P < 0.0001$). However, further adjustment for sociodemographic and lifestyle factors and components of metabolic health slightly reduced this difference.

Higher serum 25(OH)D concentrations were strongly related to a healthier lifestyle (Table 4). The mean concentration of serum 25(OH)D was 15.8 nmol/l higher among those with the healthiest habits compared with those with the unhealthiest habits estimated by the lifestyle index when adjusting for age, gender and month of blood sampling ($P < 0.0001$). There were also independent

Table 1 Characteristics of the study population, the Health 2000 Survey

Variable	Mean	SD
Vitamin D sources–related factors		
Winter season (November to February) (%)	65.1	
Use of vitamin D supplements (%)	10.2	
Fish and shellfish intake (g/day)	46.3	37.3
Margarine intake (g/day)	9.40	9.86
Vitamin D intake from diet (µg/day)	6.87	4.14
Sociodemographic factors		
Age (years)	50.7	12.9
Women (%)	53.2	
Married or cohabiting (%)	72.1	
Education >12 years (%)	35.8	
Lifestyle		
Body mass index (kg/m^2)	26.9	4.65
Moderate (>4 h/week) or vigorous (>3 h/week) leisure-time physical activity (%)	73.5	
Non-smokers (%)	74.0	
Consumption of alcohol (ethanol intake) (g/week)	79.6	148
mAHEI (total score)	21.0	4.93
Metabolic health		
Waist circumference (cm)	92.5	13.4
Normal blood pressure[a] (%)	40.2	
Serum 25(OH)D (nmol/l)	45.3	16.7
Serum HDL cholesterol (mmol/l)	1.33	0.38
Serum triglyceride (mmol/l)	1.68	1.04
Serum fasting glucose (mmol/l)	5.53	1.21
Metabolic syndrome (%)	42.7	

mAHEI, the modified Alternate Healthy Eating Index

[a] Normal blood pressure: systolic blood pressure <130 mmHg and diastolic blood pressure <85 mmHg and no antihypertensive medication

Table 2 The mean concentration of serum 25-hydroxyvitamin D by vitamin D sources–related factors: the month of blood sampling and the main dietary sources of vitamin D

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for trend	S-25(OH)D (nmol/l)		*P* for trend
		Mean	SD		Mean	SD	
Month of blood sampling				<0.0001			<0.0001
September	522	52.2	16.2		52.5	16.4	
October	1,388	49.9	17.6		50.0	17.4	
November	1,351	44.5	16.5		45.1	16.4	
December	512	44.1	17.1		44.9	17.3	
January	1,237	42.3	15.2		42.9	15.3	
February	620	39.5	14.1		39.8	13.7	
March	84	40.2	15.9		39.9	16.1	
Use of vitamin D supplements				<0.0001*			<0.0001*
No	5,131	44.3	16.5		44.5[c]	16.5	
Yes	583	54.4	16.1		53.6	16.2	
Fish and shellfish intake (g/day)				<0.0001			<0.0001
Quintiles[d]:							
1 The lowest	1,037	42.4	16.0		43.3[c]	16.0	
2	1,065	43.9	15.5		44.2	15.4	
3	1,051	46.3	17.0		46.1	17.1	
4	1,051	47.6	16.3		46.9	16.3	
5 The highest	1,052	48.7	18.0		48.6	17.9	
Margarine intake (g/day)				<0.0001			<0.0001
Quartiles[e]:							
1 The lowest	1,407	41.8	17.1		41.8[c]	17.1	
2	1,253	45.6	16.5		45.8	16.5	
3	1,316	47.3	16.5		47.4	16.5	
4 The highest	1,280	48.8	16.0		48.6	16.1	
Vitamin D dietary intake (μg/day)				<0.0001			<0.0001
Quintiles[f]:							
1 The lowest	1,051	41.8	16.0		42.6[c]	16.0	
2	1,051	44.3	15.6		44.4	15.6	
3	1,051	45.5	16.8		45.4	16.8	
4	1,051	48.6	16.8		48.2	16.8	
5 The highest	1,052	48.7	17.2		48.5	17.1	

[a] Model 1: age (continuous), gender, month of blood sampling (September to March) and the variable of interest

[b] Model 2: age (continuous), gender, month of blood sampling (September to March), marital status (married or cohabiting, divorced, widow/er, unmarried), education (<7, 7–12, >12 years), body mass index (<18.5, 18.5–24.9, 25.0–29.9, ≥30.0 kg/m^2), leisure-time physical activity (no, moderate ≥4 h/week, vigorous ≥3 h/week), smoking (never, former, current), alcohol consumption (*M* 0, 1–199, ≥200, *F* 0, 1–99, ≥100 g/week), total score on mAHEI (quintiles), blood pressure (normal, elevated), serum HDL cholesterol (*M* ≤ 1.0, >1.0, *F* ≤ 1.3, >1.3 mmol/l), serum triglycerides (<1.7, ≥1.7 mmol/l), serum fasting glucose (<5.6, ≥5.6 mmol/l)

[c] By way of exception from the model 2, mAHEI was excluded and dietary sources of vitamin D included one at time in the model

[d] Quintiles: *M* ≤ 22.2, 22.3–33.9, 34.0–45.6, 45.7–62.8, ≥62.9, *F* ≤ 21.9, 22.0–33.0, 33.1–43.6, 43.7–59.6, ≥59.7

[e] Quartiles: *M* 0, 0.10–6.10, 6.20–12.9, ≥13.0, *F* 0, 0.10–6.50, 6.60–12.5, ≥12.6

[f] Quintiles: *M* ≤ 4.20, 4.21–5.59, 5.60–7.02, 7.03–9.15, ≥9.16, *F* ≤ 3.81, 3.82–5.21, 5.22–6.59, 6.60–8.62, ≥8.63

* *P* for heterogeneity

associations between serum 25(OH)D concentration and all the five individual components of this index. In respect of body mass index, the mean serum 25(OH)D concentration was highest in individuals with BMI <25 kg/m^2 and lowest in obese persons. When sociodemographic factors, other lifestyle factors and components of metabolic health were

Table 3 The mean concentration of serum 25-hydroxyvitamin D by sociodemographic factors

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for heterogeneity	S-25(OH)D (nmol/l)		*P* for heterogeneity
		Mean	SD		Mean	SD	
Age (years)				<0.0001			<0.0001
30–39	1,358	42.5	15.9		42.4	16.0	
40–49	1,488	44.2	16.0		44.3	16.1	
50–59	1,350	47.1	16.6		47.4	16.6	
60–69	924	49.0	17.8		49.8	17.6	
70–79	594	45.0	17.5		48.0	17.2	
Gender				0.47			0.34
Men	2,677	45.5	16.9		46.1	16.9	
Women	3,037	45.2	16.6		45.6	16.6	
Marital status				<0.0001			<0.0001
Married or cohabiting	4,120	46.5	16.5		46.5	16.6	
Divorced	570	43.3	16.8		44.1	16.8	
Widow/er	362	42.0	17.2		44.0	16.6	
Unmarried	644	42.1	17.1		43.6	17.2	
Education				<0.0001			0.004
<7 years	441	39.6	17.7		42.3	17.3	
7–12 years	3,177	45.2	16.6		46.2	16.6	
>12 years	2,048	47.0	16.7		45.9	16.8	

[a] Model 1: age (continuous), gender, month of blood sampling (September to March) and the variable of interest

[b] Model 2: age (continuous), gender, month of blood sampling (September to March), marital status (married or cohabiting, divorced, widow/er, unmarried), education (<7, 7–12, >12 years), body mass index (<18.5, 18.5–24.9, 25.0–29.9, ≥30.0 kg/m^2), leisure-time physical activity (no, moderate ≥4 h/week, vigorous ≥3 h/week), smoking (never, former, current), alcohol consumption (*M* 0, 1–199, ≥200, *F* 0, 1–99, ≥100 g/week), total score on mAHEI (quintiles), blood pressure (normal, elevated), serum HDL cholesterol ($M \leq 1.0$, >1.0, $F \leq 1.3$, >1.3 mmol/l), serum triglycerides (<1.7, ≥1.7 mmol/l), serum fasting glucose (<5.6, ≥5.6 mmol/l)

adjusted for, obese persons had 3.4 nmol/l lower concentration of serum 25(OH)D than those with normal weight. Serum 25(OH)D concentrations were positively associated with leisure-time physical activity. In addition, higher serum 25(OH)D concentrations were observed especially among individuals who engaged in outdoor activities (physical activities, hunting, fishing, gardening or other outdoor activities). After adjustment for age, gender, month of blood sampling and components of the lifestyle index, the concentration was 47.2 nmol/l among individuals who engaged in outdoor activities every day or several times a week; it was 9.5 nmol/l lower in individuals who never or rarely engaged in outdoor activities. Furthermore, smokers had lower serum 25(OH)D concentrations than non-smokers, and moderate alcohol consumption was related to higher serum 25(OH)D concentrations. Healthy diet, defined based on the mAHEI, also showed a significant positive association with serum 25(OH)D concentration. Participants in the highest quintile of the total score of mAHEI had 5.2 nmol/l higher mean concentration of serum 25(OH)D compared to those in the lowest quintile when adjusting for sociodemographic, lifestyle and metabolic health factors ($P < 0.0001$).

Individuals suffering from metabolic syndrome had lower serum 25(OH)D concentrations (43.0 nmol/l) than those free from the syndrome (47.1 nmol/l) when adjusting for age, gender and month of blood sampling ($P < 0.0001$) (Table 5). A similar independent pattern was found for all components of the score (i.e. waist circumference, blood pressure, serum HDL cholesterol, serum triglycerides and serum fasting glucose). Further adjustment for sociodemographic and lifestyle factors and other components of metabolic health, however, revealed a significant independent association only for waist circumference and serum HDL cholesterol. Although the inverse association between serum 25(OH)D and elevated blood pressure was significant only in the age-, gender- and month of blood sampling-adjusted model, those suffering from hypertension (systolic blood pressure ≥140 mmHg or diastolic blood pressure ≥90 mmHg or antihypertensive medication) had significantly lower serum 25(OH)D concentration in both models (data not shown).

Table 4 The mean concentration of serum 25-hydroxyvitamin D by lifestyle factors

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for heterogeneity	S-25(OH)D (nmol/l)		*P* for heterogeneity
		Mean	SD		Mean	SD	
Body mass index (kg/m^2)				<0.0001			<0.0001
<18.5 (underweight)	37	45.5	26.2		50.5	27.2	
18.5–24.0 (normal weight)	2,097	47.2	17.6		47.2	17.6	
25.0–29.9 (overweight)	2,313	45.4	16.3		45.6	16.2	
≥30.0 (obesity)	1,265	42.3	15.3		43.8	15.4	
Physical activity				<0.0001			<0.0001
No leisure-time physical activity	1,415	41.2	15.9		43.4	15.8	
Moderate ≥4 h/week	3,167	46.4	16.7		46.3	16.8	
Vigorous ≥3 h/week	1,036	48.4	16.7		47.6	16.7	
Smoking				<0.0001			<0.0001
Never or less than a year smoked	2,954	46.4	16.8		46.6	16.8	
Former smoker	1,276	47.4	17.1		47.1	17.0	
Current smoker	1,458	41.5	15.5		43.0	15.5	
Alcohol consumption (g/week)				<0.0001			<0.0001
0	1,625	42.4	16.0		43.9	16.0	
M 1–199, *F* 1–99	3,141	47.1	16.6		46.7	16.5	
M ≥ 200, *F* ≥ 100	853	45.0	18.1		46.2	18.3	
Total score on the mAHEI[c]							
Quintiles[d]				<0.0001*			<0.0001*
1 The lowest	1,012	41.8	15.4		42.8	15.4	
2	1,048	43.9	15.9		44.2	15.8	
3	1,176	46.3	17.0		46.4	17.0	
4	998	48.1	17.2		47.6	17.3	
5 The highest	1,022	48.7	17.0		48.0	17.0	
Total score on the lifestyle index				<0.0001*			
0 point (unhealthiest lifestyle)	91	37.2	13.9				
1 point	444	39.0	14.3				
2 points	1,169	42.3	15.5				
3 points	1,628	45.9	16.4				
4 points	1,385	49.2	17.1				
5 points (healthiest lifestyle)	430	53.0	17.9				

mAHEI, the modified Alternate Healthy Eating Index

[a] Model 1: age (continuous), gender, month of blood sampling (September to March) and the variable of interest

[b] Model 2: age (continuous), gender, month of blood sampling (September to March), marital status (married or cohabiting, divorced, widow/er, unmarried), education (<7, 7–12, >12 years), body mass index (<18.5, 18.5–24.9, 25.0–29.9, ≥30.0 kg/m^2), leisure-time physical activity (no, moderate ≥4 h/week, vigorous ≥3 h/week), smoking (never, former, current), alcohol consumption (*M* 0, 1–199, ≥200, *F* 0, 1–99, ≥100 g/week), total score on mAHEI (quintiles), blood pressure (normal, elevated), serum HDL cholesterol (*M* ≤ 1.0, >1.0, *F* ≤ 1.3, >1.3 mmol/l), serum triglycerides (<1.7, ≥1.7 mmol/l), serum fasting glucose (<5.6, ≥5.6 mmol/l)

[c] Serum 25(OH)D distributions in quintiles of components of mAHEI are shown in Table 6 in Appendix

[d] Quintiles: *M* 7–16, 17–19, 20–22, 23–25, 26–34, *F* 8–16, 17–19, 20–22, 23–25, 26–35

* *P* for trend

Discussion

Findings

This cross-sectional study representing the Finnish adult population suggests that higher serum concentration of 25(OH)D is associated with favourable sociodemographic status, healthy lifestyle and good metabolic health. With a few exceptions, the results of the present study are in line with those from earlier studies [14, 15].

Cutaneous synthesis of vitamin D_3 after exposure of skin to solar ultraviolet-B radiation is a considerable source of vitamin D for most humans [28]. The levels of vitamin D effective ultraviolet-B radiation decrease during winter

Table 5 The mean concentration of serum 25-hydroxyvitamin D by components of metabolic health

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for heterogeneity	S-25(OH)D (nmol/l)		*P* for heterogeneity
		Mean	SD		Mean	SD	
Waist circumference (cm)				<0.0001			0.0001
$M < 94$, $F < 80$	1,900	47.7	17.9		47.4[c]	18.0	
$M \geq 94$, $F \geq 80$	3,795	44.2	16.1		45.0	16.0	
Blood pressure[d]				0.003			0.41
Normal	2,288	46.2	16.6		46.1	16.7	
Elevated	3,411	44.8	16.8		45.7	16.7	
Serum HDL cholesterol (mmol/l)				<0.0001			<0.0001
$M \leq 1.0$, $F \leq 1.3$	1,977	42.0	15.4		43.9	15.4	
$M > 1.0$, $F > 1.3$	3,735	47.1	17.1		46.8	17.1	
Serum triglyceride (mmol/l)				<0.0001			0.11
<1.7	3,866	46.6	17.1		46.1	17.0	
≥1.7	1,846	42.9	15.8		45.2	15.8	
Serum fasting glucose (mmol/l)				0.0007			0.10
<5.6	3,789	45.9	16.8		46.1	16.8	
≥5.6	1,923	44.4	16.6		45.3	16.6	
Metabolic syndrome				<0.0001			
No	3,273	47.1	17.4				
Yes	2,435	43.0	15.7				

[a] Model 1: age (continuous), gender, month of blood sampling (September to March) and the variable of interest

[b] Model 2: age (continuous), gender, month of blood sampling (September to March), marital status (married or cohabiting, divorced, widow/er, unmarried), education (<7, 7–12, >12 years), body mass index (<18.5, 18.5–24.9, 25.0–29.9, ≥30.0 kg/m^2), leisure-time physical activity (no, moderate ≥4 h/week, vigorous ≥3 h/week), smoking (never, former, current), alcohol consumption (*M* 0, 1–199, ≥200, *F* 0, 1–99, ≥100 g/week), total score on mAHEI (quintiles), blood pressure (normal, elevated), serum HDL cholesterol ($M \leq 1.0$, >1.0, $F \leq 1.3$, >1.3 mmol/l), serum triglycerides (<1.7, ≥1.7 mmol/l), serum fasting glucose (<5.6, ≥5.6 mmol/l)

[c] By way of exception from the model 2, body mass index was excluded and waist circumference ($M < 94$, ≥94, $F < 80$, ≥80 cm) included in the model

[d] Elevated: systolic blood pressure ≥130 mmHg or diastolic blood pressure ≥85 mmHg or antihypertensive medication. Normal: Not elevated

months in northern latitudes. Although our data did not include any summer months with high sunlight, we found the expected seasonal variation in serum concentrations of 25(OH)D.

In the current study, we found a positive association between serum 25(OH)D concentration and age. This observation is inconsistent with several earlier studies, which have indicated that serum 25(OH)D concentrations decrease with increasing age [13, 15] in line with the fact that ageing decreases the capacity of human skin to synthesize vitamin D_3 [29]. Our discrepant finding suggesting higher serum concentrations in older age groups may be explained by their higher consumption of fish, which made a major contribution to vitamin D intake in the Health 2000 Survey [30]. In addition, the prevalence of health-promoting physical activity increased with age [31], so it is possible that older participants also spent more time outdoors. In accordance with one previous population-based study [14], we found that being married or cohabiting was related to higher serum 25(OH)D concentrations. The most likely explanation for this finding is that married persons may have a healthier lifestyle than singles [32].

As far as we know, this is the first study that indicates a positive association between serum 25(OH)D concentration and a generally healthy lifestyle as defined by a lifestyle index formed based on body mass index, leisure-time physical activity, smoking, alcohol consumption and dietary habits. The difference in the serum 25(OH)D concentration between those with the unhealthiest and those with the healthiest lifestyle was substantially higher than the differences observed between the single components of the lifestyle index. This suggests that high serum 25(OH)D concentration may serve as an indicator for a generally healthy lifestyle.

In accordance with previous large population-based studies [13, 16], we found an inverse association between serum 25(OH)D concentration and body mass index. This finding may be explained by biological mechanisms. First, obesity may decrease the bioavailability of vitamin D obtained from diet or cutaneous synthesis [33]. Furthermore, decreased concentration of serum 25(OH)D in obese persons might be related to increased secretion of parathyroid hormone, which leads to elevated concentrations of 1,25(OH)$_2$D [34]. By negative feedback, 1,25(OH)$_2$D may inhibit hepatic synthesis of 25(OH)D. In addition, an inverse association between 25(OH)D and body mass index may be due to other lifestyle factors, such as lower intake of dietary vitamin D among obese persons [35]. It has also been speculated that obese persons may engage in fewer outdoor activities or wear more covering clothes than those with normal weight [14].

This study and previous studies [14, 16] have consistently indicated that physical activity is positively associated with serum 25(OH)D concentration. However, it is still unclear whether the relationship is caused by biological mechanisms or is the result of confounding by other factors related to lifestyle (e.g. sun exposure, obesity) [36]. In the present study, a positive association between serum 25(OH)D concentration and outdoor activity was found, which may explain at least part of the relationship between 25(OH)D and physical activity. In addition, one study has demonstrated that outdoor rather than indoor activity is related to serum concentration of 25(OH)D [16].

As in most previous studies [37, 38], we observed that serum 25(OH)D concentration was positively associated with vitamin D intake from diet and supplements. In the Health 2000 Survey, fish consumption was responsible for 56 % and margarine consumption for 19 % of the dietary vitamin D intake [30]. Extending the results of the previous reports, we found a positive association between serum 25(OH)D concentration and a generally healthy diet as defined by the mAHEI, which was modified based on AHEI of McCullough et al. [23]. In addition to the total score of the mAHEI, high intakes of vegetables, fruits, berries and rye were also related to higher serum concentrations of 25(OH)D when adjusting for age, gender and month of blood sampling. High intake of vegetables, for example, has been suggested to be related to lower risk of cardiovascular diseases [39], and high intake of wholegrain products to lower risk of type 2 diabetes [40]. High serum 25(OH)D concentration is thought to decrease the risk of these same diseases [2, 3]. That is why it is possible that a generally healthy diet might, at least in part, explain the association between vitamin D and chronic diseases.

We observed that good metabolic health was associated with higher serum 25(OH)D concentrations. Previous studies on components of the metabolic syndrome have indicated that higher serum concentration of 25(OH)D is related to a favourable serum lipid profile [18] and lower blood pressure [17]. In line with earlier findings, we observed a positive association between 25(OH)D and serum HDL cholesterol. This finding may be explained by the fact that 1,25(OH)$_2$D is a potential modulator of human adipocyte metabolism [41]. It has also been demonstrated that 1,25(OH)$_2$D regulates the renin-angiotensin system that plays an important role in the regulation of blood pressure [10]. It cannot, however, be excluded that these associations did not show any causality but were due to confounding. This was supported by our observation that the inverse association of 25(OH)D with blood pressure and serum fasting glucose were attenuated by adjustment for sociodemographic and lifestyle factors and other components of metabolic health. Thus, our study seriously challenges the view that low vitamin D is a real risk factor for metabolic syndrome.

Methodological issues

This study has several strengths. First, the results are based on a large representative sample of the whole Finnish adult population including both men and women. Another strength is that we used serum 25(OH)D concentration as an indicator of vitamin D status. Serum 25(OH)D concentration reflects vitamin D obtained from diet and supplements as well as from cutaneous synthesis. Compared to some other vitamin D metabolites, for example the most biologically active form 1,25(OH)$_2$D, serum concentration of 25(OH)D is high and its half-life is relatively long, up to 2–3 weeks [42]. Serum 25(OH)D concentration was analysed using a widely used radioimmunoassay method (RIA, DiaSorin, Minnesota) that recognizes both 25(OH)D$_2$ and 25(OH)D$_3$ [42]. A major advantage of this study is that we analysed a large variety of potential determinants of vitamin D status that have been measured using reliable methods [19, 31]. Food intake was measured by means of a food frequency questionnaire, whose validity and reliability have been demonstrated to be at the same level as in previous studies [21].

The current study also involves several potential limitations. Because of the cross-sectional study design, temporal order of the associations found between various factors and serum 25(OH)D cannot be inferred. In addition, there are some limitations concerning the measurement of serum 25(OH)D concentration. First, serum 25(OH)D concentration was measured only once and it cannot be excluded that a single measurement reflects only recent exposure instead of long-term exposure. It has, however, been shown that the 3-year repeatability of 25(OH)D is fairly high [43], suggesting that a single measurement of 25(OH)D is reasonably reliable in determining individual vitamin D status. In addition, one source of measurement error might be that a single measurement of 25(OH)D does not provide any information on intraindividual seasonal variation in vitamin D status. However, inclusion of the season as a potential confounding factor did not notably change the results. Further, serum samples were collected at the health examination and stored first at −20 °C for 1–2 weeks and then at −70 °C for 1–2 years before determining the serum 25(OH)D concentration. 25(OH)D is known to be extremely stable but it cannot be excluded that the concentrations may have slightly declined before the analysis [44]. However, in one study, serum 25(OH)D concentration remained intact when serum samples were frozen at −70 °C although they underwent multiple freeze–thaw cycles [45], and in another study, serum 25(OH)D concentration showed only a small decline when stored at −20 °C for 4 years [46].

The mean concentration of serum 25(OH)D (45.3 nmol/l) observed in the present study was relatively low compared to those of some other studies carried out in Europe [13], the USA [47] and Canada [48]. In Finland, however, even lower serum concentrations of 25(OH)D have been previously measured [5]. The low serum 25(OH)D concentration observed in Finland may be explained by the country's geographical location in the northern latitudes where the level of ultraviolet-B radiation is limited, especially during winter months. It must also be taken into account that the mean serum concentration of 25(OH)D in the present study is an underestimate of the full-year average, because our data do not include any values for the summer months.

In the present study, we had no information on serum calcium and parathyroid hormone levels, which are known to have a significant influence on 25(OH)D metabolism [9]. Further, we could not take into account genetic factors that may have an influence on serum concentration of 25(OH)D and the association between 25(OH)D and health outcomes [49].

Conclusions

In conclusion, the results of the present study suggest that there are several sociodemographic and lifestyle factors and components of metabolic health that are related to serum concentration of 25(OH)D. There is a possibility that such factors may explain, at least in part, observed associations between serum 25(OH)D concentration and chronic diseases but further research is still needed.

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Table 6.

Table 6 The mean concentration of serum 25-hydroxyvitamin D by components of mAHEI

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for trend	S-25(OH)D (nmol/l)		*P* for trend
		Mean	SD		Mean	SD	
Vegetables intake (g/day)							
Quintiles[c]				0.002			0.19
1 The lowest	1,051	43.2	16.2		44.6	16.1	
2	1,051	45.8	16.8		45.8	16.8	
3	1,051	45.8	16.1		45.4	16.1	
4	1,051	46.8	16.9		46.4	16.7	
5 The highest	1,052	47.3	17.4		46.8	17.4	
Fruits and berries intake (g/day)							
Quintiles[d]				0.0004			0.07
1 The lowest	1,052	43.6	16.2		44.7	16.1	
2	1,050	45.5	16.7		45.7	16.7	
3	1,051	46.2	16.6		46.0	16.7	
4	1,051	46.9	17.2		46.3	17.2	
5 The highest	1,052	46.8	16.7		46.4	16.7	
Legumes, nuts, seeds and soya beans intake (g/day)							
Quintiles[f]				0.77[e]			0.70[e]
1 The lowest	1,050	45.8	17.4		46.3	17.3	
2	1,042	45.6	16.5		45.8	16.5	

Table 6 continued

Variable	Model 1[a]				Model 2[b]		
	n	S-25(OH)D (nmol/l)		*P* for trend	S-25(OH)D (nmol/l)		*P* for trend
		Mean	SD		Mean	SD	
3	1,060	45.5	16.2		45.3	16.3	
4	1,053	46.3	16.3		46.1	16.2	
5 The highest	1,051	45.7	17.4		45.7	17.3	
Ratio of white to red meat							
Quintiles[g]				<0.0001			0.0001
1 The lowest	1,051	41.7	15.5		42.6	15.5	
2	1,051	44.3	15.5		44.6	15.5	
3	1,051	46.1	16.4		46.1	16.4	
4	1,051	47.6	17.1		47.4	17.1	
5 The highest	1,052	49.2	18.1		48.4	18.0	
Rye intake (g/day)							
Quintiles[h]				0.003			0.02
1 The lowest	1,051	44.7	16.8		45.3	16.6	
2	1,051	45.8	16.8		45.6	16.9	
3	1,049	44.8	15.5		44.6	15.5	
4	1,053	46.7	17.6		46.7	17.5	
5 The highest	1,052	46.9	16.8		46.9	16.9	
Trans fat intake (g/day)							
Quintiles[i]				<0.0001			<0.0001
1 The lowest	1,051	46.3	16.9		46.7	16.8	
2	1,051	46.6	17.3		46.8	17.3	
3	1,051	46.7	16.9		46.5	17.0	
4	1,051	45.6	16.6		45.2	16.6	
5 The highest	1,052	43.7	15.8		43.9	15.8	
Ratio of polyunsaturated to saturated fat							
Quintiles[j]				<0.0001			<0.0001
1 The lowest	1,051	41.4	16.1		42.3	16.2	
2	1,051	44.4	16.0		44.5	16.0	
3	1,051	46.5	16.4		46.3	16.3	
4	1,051	47.1	16.9		46.8	17.0	
5 The highest	1,052	49.5	17.4		49.2	17.1	

mAHEI, the modified Alternate Healthy Eating Index

[a] Model 1: age (continuous), gender, month of blood sampling (September to March) and the variable of interest

[b] Model 2: age (continuous), gender, month of blood sampling (September to March), marital status (married or cohabiting, divorced, widow/er, unmarried), education (<7, 7–12, >12 years), body mass index (<18.5, 18.5–24.9, 25.0–29.9, ≥30.0 kg/m^2), leisure-time physical activity (no leisure-time physical activity, moderate ≥4 h/week, vigorous ≥3 h/week), smoking (never, former, current), alcohol consumption (*M* 0, 1–199, ≥200, *F* 0, 1–99, ≥100 g/week), blood pressure (normal, elevated), serum HDL cholesterol (*M* ≤ 1.0, >1.0, *F* ≤ 1.3, >1.3 mmol/l), serum triglycerides (<1.7, ≥1.7 mmol/l), serum fasting glucose (<5.6, ≥5.6 mmol/l) and components of mAHEI were included one at time in the model

[c] Quintiles: *M* ≤ 107, 108–156, 157–215, 216–303, ≥304, *F* ≤ 153, 154–218, 219–288, 289–404, ≥405

[d] Quintiles: *M* ≤ 46.5, 46.6–88.6, 88.7–155, 156–256, ≥257, *F* ≤ 80.3, 80.4–156, 157–244, 245–382, ≥383

[e] Test for trend was performed by including the variable in quintiles in the model

[f] Quintiles: *M* ≤ 5.64, 5.65–8.93, 8.94–13.9, 14.0–20.4, ≥20.5, *F* ≤ 4.45, 4.46–8.39, 8.40–12.4, 12.5–20.0, ≥20.1

[g] Quintiles: *M* ≤ 0,22, 0,23–0.34, 0.35–0.49, 0.50–0.72, ≥0.73, *F* ≤ 0.31, 0.32–0.47, 0.48–0.68, 0.69–1.08, ≥1.09

[h] Quintiles: *M* ≤ 17.3, 17.4–29.1 29.2–55.8 55.9–95.2, ≥95.3, *F* ≤ 17.3, 17.4–30.1, 30.2–55.2, 55.3–60.1, ≥60.2

[i] Quintiles: *M* ≤ 0.76, 0.77–1.00, 1.01–1.24, 1.25–1.60, ≥1.61, *F* ≤ 0.69, 0.70–0.92, 0.93–1.13, 1.14–1.42, ≥1.43

[j] Quintiles: *M* ≤ 0.29, 0.30–0.35, 0.36–0.40, 0.41–0.46, ≥0.47, *F* ≤ 0.31, 0.32–0.37, 0.38–0.42, 0.43–0.48, ≥0.49

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