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ORIGINAL ARTICLE

Associations of vitamin D with novel and traditional anthropometric indices according to age and sex: a cross-sectional study in central southern China

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Abstract

Purpose Vitamin D insufficiency and obesity are recognized as worldwide concerns and have been linked with each other. New anthropometric indices reflect visceral obesity better than traditional anthropometric indices. Our aim was to identify the specific correlations of novel and traditional anthropometric indices with 25-hydroxyvitamin D (25(OH)D) concentrations by sex and age.

Methods Cross-sectional data on sociodemographic characteristics, lifestyle factors, clinical characteristics and biochemical measurements were collected for 12,617 Chinese adults. Four traditional anthropometric indices, body mass index (BMI), waist circumference (WC), waist-to-hip ratio (WHR) and waist-to-height ratio (WHtR), and two novel anthropometric indices, body roundness index (BRI) and body shape index (ABSI), were calculated.

Results In both sexes, the mean values of BMI, WC, WHtR and BRI tended to increase with 25(OH)D insufficiency, regardless of adjustment (all $P < 0.05$). Males with insufficient 25(OH)D had increased odds of obesity (assessed by BMI, WC, WHtR, BRI and ABSI) compared to the odds of males with sufficient 25(OH)D. Females with insufficient 25(OH)D had a higher chance of general obesity (assessed by BMI). Low 25(OH)D status was associated with indicators of obesity only in participants aged 45–64 years in both sexes.

Conclusion A inverse association between obesity and lower vitamin D levels was found. Moreover, in addition to BMI, novel indicators of visceral adiposity, such as BRI and ABSI, were associated with lower 25(OH)D serum concentrations in males. The effects of optimizing vitamin D levels in obese Chinese adults need further examination, particularly in middle-aged males.

Level of evidence Level V, cross-sectional descriptive study.

Keywords Serum 25(OH)D · Obesity · Anthropometric indices · Sex · Age

Introduction

Vitamin D, beyond its function in maintaining bone health, is increasingly recognized as an important steroidal hormone in nonskeletal complications [1]. Studies have shown that low vitamin D levels play a pivotal role in the development of cardiovascular disease (CVD), type 2 diabetes (T2D) and autoimmune disease [2, 3]. Vitamin D deficiency/insufficiency in China has shown a high prevalence and has been confirmed as a serious modifiable public health risk because of a decrease in outdoor activities, the popularity of sun avoidance, air pollution, the scarcity of natural foods rich in vitamin D and reduced micronutrient intake [4].

In recent decades, obesity has emerged as a global public health problem, as well as a clinical dilemma in China [5].

Xiao-Ling Zhu and Zhi-Heng Chen contributed equally to this work.

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Evidence of an association between vitamin D deficiency and obesity has been mounting in recent years [6, 7]. However, the findings are conflicting. Some studies have shown an inverse association between serum 25(OH)D concentrations and obesity [8, 9]. In contrast, others found only a weak inverse correlation [10]. While most previous studies have established a link between traditional anthropometric indices, such as BMI and WC [11, 12], and 25(OH)D status, very little is known about the relationship of 25(OH)D with novel anthropometric indices, such as the body roundness index (BRI) and a body shape index (ABSI). Only one small ($N = 1447$) cross-sectional study among elderly adults found that lower 25(OH)D levels were associated with increased BRI and ABSI [13]. ABSI and BRI were developed because traditional general obesity (BMI) and abdominal obesity (WC) indicators fail to accurately reflect abdominal visceral fat. Thus, we hypothesized that these novel indices may be associated with 25(OH)D levels, as higher values may denote worse 25(OH)D status. In addition, few studies have focused on the age and sex differences in metabolic aberrations of obesity and 25(OH)D deficiency. More insight into the specific contributions of age and sex on this relationship may clarify mechanisms and reveal which individuals are at the highest risk. Therefore, we aimed to explore the association between 25(OH)D concentrations and both traditional and novel obesity parameters among a large sample of Chinese adults stratified by sex and age.

Materials and methods

Study participants

The sample was comprised of participants in a physical examination institution-based cross-sectional study in the Third Xiangya Hospital, Changsha, China, which offers primary health services [14]. All individuals attended a routine health check-up in the Health Management Center between January 2017 and December 2018. The exclusion criteria for the present analysis included history of chronic corticosteroid use ($n = 11$), vitamin D supplementation ($n = 39$), history of malabsorption disorder ($n = 7$), current cancer ($n = 46$), and missing data ($n = 341$). A total of 12,617 subjects aged 18 or older (range 18–93) were included in the final data analysis. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the institutional review board at the Third Xiangya Hospital (No. 2015-S164, 2018-S393). Informed written consent was obtained from all study subjects.

Anthropometric measurements

Anthropometric measurements were performed by trained recruiters following a standard protocol. Body weight (BW) and height were measured to the nearest 0.1 kg and 0.1 cm, respectively, using a weight and height measurement device (Solo® Eye-Level Clinical Scale; Detecto, Webb City, MO, USA) with the participants wearing light clothing without shoes. Body mass index (BMI) was calculated by dividing BW (kg) by the square of the height (m). Waist circumference (WC) and hip circumference (HC) were measured by a standard tape to the nearest 0.1 cm. WC was measured parallel to the midline between the lowest border of rib cage and the iliac crest after a gentle breath expiration, while participants were in standing position and spreading their feet 25–30 cm apart. HC was measured parallel to the convex part of the hip with the participants in a natural standing position. Blood pressure (BP) was the average of two right-arm readings (HEM-7230; Omron, Tokyo, Japan); the participant sat down for at least 5 min before the measurement.

Dietary assessment

Some information about the consumption frequency of food items was collected. These questions were about the frequency of fruit (rarely, < 1–2 times/week, 3–4 times/week, > 4 times/week), vegetable (< 100 g/day, 101–200 g/day, 201–500 g/day, > 500 g/day), meat (< 50 g/day, 51–100 g/day, 101–250 g/day, > 250 g/day), whole-grain food (0–100 g/meal, 101–200 g/meal, 201–300 g/meal, > 300 g/meal) and sugary juice intake (rarely, 1–2 times/week, 3–5 times/week, ≥ 6 times/week). To include dietary intake based on the four responses in the logistic multivariate analysis, we considered the first two categories of answers as "low intake" and the last two categories of answers as "adequate intake".

Biochemical measurements

Venous blood samples were collected in the morning after an overnight (≥ 12 h) fasting period. We used standard methods to measure fasting plasma glucose (FPG), liver enzyme levels, serum lipid profiles and biochemical parameters related to the kidney. Serum 25(OH)D levels were measured by electrochemiluminescence immunoassay (ECLIA) (Modular Analytics E170 analyzers, Roche Diagnostics, Mannheim, Germany). The intra-assay and inter-assay coefficients of variation (CVs) were < 6.8% and < 7.6%, respectively.

Definition of obesity and vitamin D deficiency

General obesity was defined as BMI ≥ 28 kg/m^2, and abdominal obesity was defined as WC ≥ 90 cm in males or

WC ≥ 85 cm in females, according to the Asian-Pacific Guidelines [15, 16]. WHR was calculated by dividing WC by HC. High WHR was defined as > 0.9 for males and > 0.85 for females [17]. The waist-to-height ratio (WHtR) was calculated by dividing WC by height. High WHtR was defined as > 0.5 [18]. BRI was calculated based on WC (m) and height (m): $BRI = 364.2 - 365.5 \times \sqrt{1 - \left(\frac{\left(\frac{WC}{2\pi}\right)^2}{(0.5\,\text{height})^2} \right)}$ [19]. ABSI was calculated according to the following formula based on WC (m), BMI (kg/m^2) and height (m): $ABSI = \frac{WC}{(BMI^{2/3} \times height^{1/2})}$ [20]. Since there are no clinical cutoff values for BRI or ABSI, high BRI and ABSI were defined as those within the highest quartile group (Q4). A 25(OH)D concentration < 30 ng/mL was defined as an insufficient status [21].

Covariates

All subjects completed an identical structured questionnaire examining sociodemographic and lifestyle characteristics and medical history by trained interviewers. Educational level was classified into three groups according to the number of years of schooling. Cigarette smoking was defined as having smoked ≥ 100 cigarettes in one's lifetime and a current smoking habit. Alcohol consumption was defined as the consumption of ≥ 30 g of alcohol per week for ≥ 1 year. Regular leisure-time physical activity was defined as participation in ≥ 30 min of moderate or vigorous activity per day for ≥ 3 days/week [22]. Hypertension was defined as SBP/DBP ≥ 140/90 mmHg, self-reported hypertension history or use of BP medication [23]. Diabetes mellitus was defined as fasting glucose ≥ 126 mg/dL, glycated hemoglobin (HbA1c) ≥ 6.5%, a medical history of diabetes or current use of diabetes medication, including insulin or oral hypoglycemic agents [24]. Dyslipidemia was defined as total cholesterol ≥ 6.22 mmol/L (≥ 240 mg/dL), LDL cholesterol ≥ 4.14 mmol/L (≥ 160 mg/dL), HDL cholesterol < 1.04 mmol/L (< 40 mg/dL), and/or the use of lipid-lowering medications [22].

Statistical analysis

All analyses were performed using SPSS software version 22.0 (SPSS Inc., Chicago, IL, USA). Continuous variables are expressed as median and inter-quartile range (IQR). Dichotomous data are expressed as percentages. The differences in demographic characteristics, laboratory results and anthropometric measurements between males and females were analyzed using an independent *t* test or the Kruskal–Wallis test for continuous variables, and the Chi-square test for dichotomized variables. For standardization, the *Z*-score for ABSI was calculated, as reported by Krakauer et al. [25]. The *Z*-score was calculated from measurement values, predicted means and SDs as follows: (measurement value − predicted mean)/predicted SD. A 25(OH)D concentration ≥ 30 ng/mL was defined as a clinically normal value. All analyses were performed for males and females separately. The general linear model was employed to compare the means of traditional and novel anthropometric indices in relation to abnormal 25(OH)D concentrations. Multivariable logistic regression analysis was used to estimate the risk for obesity (BMI ≥ 28 kg/m^2, WC ≥ 90 cm in males and ≥ 85 cm in females, WHR > 0.9 in males and > 0.85 in females, WHtR > 0.5, BRI and ABSI within the fourth quartile values) based on the comparison of abnormal versus normal 25(OH)D concentrations. In model 1, odds ratios (ORs) and 95% confidence intervals (CIs) were determined after adjusting for age and visit season. In model 2, smoking status, alcohol intake, physical activity, education, chronic diseases (hypertension, diabetes, dyslipidemia) and dietary intake (fruits, vegetables, meat, whole-grain foods and sugary juice) were additionally adjusted. To determine age differences in the relationship, we proceeded to quantify the association according to age with model 2 described above. The significance level was set at $P < 0.05$ (two-tailed).

Results

Among 12,617 subjects, 64.1% were men, and the median age was 47 years for males and 46 years for females. Table 1 shows the demographic characteristics and clinical and anthropometric data of the study population. Overall, the median 25(OH)D was 23.6 ng/mL. The percentage of participants with vitamin D insufficiency (< 30 ng/mL) was 78.2% and was higher in females (85.8%) than in males (73.9%). In males, the values of each anthropometric measurement, including BMI, WC, WHR, WHtR, BRI, and ABSI, were significantly higher than those of females.

Comparisons of various anthropometric measurement levels in relation to abnormal 25(OH)D levels after adjusting for covariables are shown in Fig. 1. In males, except for WHR, the means of all anthropometric measurements tended to increase with abnormal serum 25(OH)D concentrations. In females, except for WHR and ABSI, all other means showed significant differences with a similar trend.

Table 2 presents the ORs (95% CIs) of obesity based on an abnormal serum 25(OH)D concentrations. In model 1, males with a low 25(OH)D level had a higher risk of obesity, as assessed by BMI, WC, WHtR, BRI and ABSI, than those with normal 25(OH)D levels. These associations persisted after adjusting for various covariates (model 2) (BMI: OR 1.72, 95% CI 1.01–1.37; WC: OR 1.16, 95% CI 1.04–1.30; WHtR: OR 1.13, 95% CI 1.01–1.26; BRI: OR 1.14, 95% CI 1.01–1.29; ABSI: OR 1.17, 95% CI 1.04–1.24). Females

Table 1 Lifestyle and clinical characteristics of population by gender

Variables	All ($n=12,617$)	Men ($n=8083$)	Women ($n=4534$)	P value
Age, years	47.0 (37.0–55.0)	47.0 (38.0–55.0)	46.0 (37.0–54.0)	< 0.001
Education level, *n* (%)				< 0.001
Elementary or middle school	1970 (15.6)	880 (10.9)	1090 (24.0)	
High school	1770 (14.0)	943 (11.7)	827 (18.2)	
College or higher school	8877 (70.4)	6260 (77.4)	2617 (57.7)	
Lifestyle				
Current smoking, *n* (%)	3184 (25.2)	3107 (38.4)	77 (1.70)	< 0.001
Alcohol drinking, *n* (%)	1327 (10.5)	1251 (15.5)	76 (1.68)	< 0.001
Regular leisure-time physical activity, *n* (%)	5909 (46.8)	3996 (49.4)	1913 (42.2)	< 0.001
Fruits ≥ 3 times/week intake, *n* (%)	6472 (51.3)	3547 (43.8)	2925 (64.5)	0.002
Vegetables > 200 g/day intake, *n* (%)	2801 (22.2)	1725 (21.3)	1076 (23.7)	< 0.001
Meat ≤ 100 g/day intake, *n* (%)	10,350 (82.0)	6356 (78.6)	3994 (88.1)	< 0.001
Whole-grain foods ≤ 200 g/meal, *n* (%) (%)intake, %	10,581 (83.9)	6817 (84.3)	3764 (83.0)	0.053
Sugar juice < 3 times/week intake, *n* (%)	12,130 (96.1)	7701 (95.3)	4429 (97.7)	< 0.001
Chronic diseases				
Hypertension, no. (%)	1316 (10.4)	1015 (12.6)	301 (6.64)	< 0.001
Diabetes, no. (%)	561 (4.45)	465 (5.75)	96 (2.12)	< 0.001
Dyslipidemia, no. (%)	3165 (25.1)	2447 (30.3)	718 (15.8)	< 0.001
Systolic BP, mmHg	123.0 (113.0–134.0)	127.0 (117–136)	116.0 (107.0–129.0)	< 0.001
Diastolic BP, mmHg	75.0 (68.0–83.0)	78.0 (71.0–85.0)	70.0 (63.0–78.0)	< 0.001
Fasting glucose, mmol/L	5.35 (5.00–5.79)	5.43 (5.07–5.91)	5.22 (4.89–5.59)	< 0.001
Total cholesterol, mmol/L	4.94 (4.34–5.59)	4.96 (4.36– 5.60)	4.90 (4.30–5.56)	0.018
LDL-C, mmol/L	2.81 (2.30–3.36)	2.82 (2.30–3.37)	2.80 (2.30–3.35)	0.116
HDL-C, mmol/L	1.30 (1.13–1.52)	1.22 (1.08–1.39)	1.49 (1.30–1.70)	< 0.001
Triglyceride, mmol/L	1.38 (0.96–2.07)	1.60 (1.11–2.36)	1.09 (0.79–1.56)	< 0.001
25(OH)D status				
25(OH)D, ng/ml	23.6 (19.1–29.1)	24.8 (20.3–30.3)	21.6 (17.5–26.8)	< 0.001
25(OH)D insufficiency (< 30 ng/mL), *n* (%)	9861 (78.2)	5970 (73.9)	3891 (85.8)	< 0.001
Obesity measurements				
BW, kg	65.6 (57.0–74.1)	71.0 (64.7–77.7)	55.5 (51.0–60.7)	< 0.001
Height, cm	164.7 (158.6–170.2)	168.5 (164.4–172.5)	157.1 (153.5–160.8)	< 0.001
HC, cm	94.0 (90.0–98.0)	95.0 (92.0–99.0)	91.0 (88.0–94.0)	< 0.001
BMI, kg/m^2	24.2 (22.1–26.4)	25.1 (23.2–27.1)	22.5 (20.8–24.5)	< 0.001
WC, cm	83.0 (76.0–90.0)	87.0 (82.0–92.0)	75.0 (70.0–81.0)	< 0.001
WHR	0.89 (0.83–0.93)	0.91 (0.87–0.94)	0.83 (0.79–0.88)	< 0.001
WHtR	0.50 (0.47–0.54)	0.52 (0.48–0.55)	0.48 (0.44–0.52)	< 0.001
BRI	3.44 (2.77–4.14)	3.65 (3.05–4.29)	2.99 (2.38–3.74)	< 0.001
ABSI	0.077 (0.074–0.080)	0.078 (0.075–0.080)	0.075 (0.073–0.078)	< 0.001

Data presented as: % for categorical variables, median and inter-quartile range (IQR) for continuous variables

p values obtained by using analysis of independent *t* tests or Kruskal–Wallis for continuous variables, Chi-square tests for categorical variables

BP blood pressure, *LDL-C* low density lipoprotein cholesterol, *HDL-C* high-density lipoprotein cholesterol, *BW* body weight, *HC* hip circumference, *BMI* body mass index, *WC* waist circumference, *WHR* waist-to-hip ratio, *WHtR* waist-to-height ratio, *BRI* the body roundness index, *ABSI* a body shape index

with a low 25(OH)D level exhibited a higher risk for obesity as assessed by only BMI after controlling for covariates (OR 1.81, 95% CI 1.18–2.77). There was no significant association with WHR in males or WC, WHR, WHtR, BRI and ABSI in females.

Characteristics of the 25(OH)D levels and obesity indices stratified by age are listed in the Supplement (sTable 1 and sFigure 1). There was a strong age difference in 25(OH)D levels in both sexes. The 25(OH)D levels in participants aged 45–64 and ≥ 65 years were significantly higher than

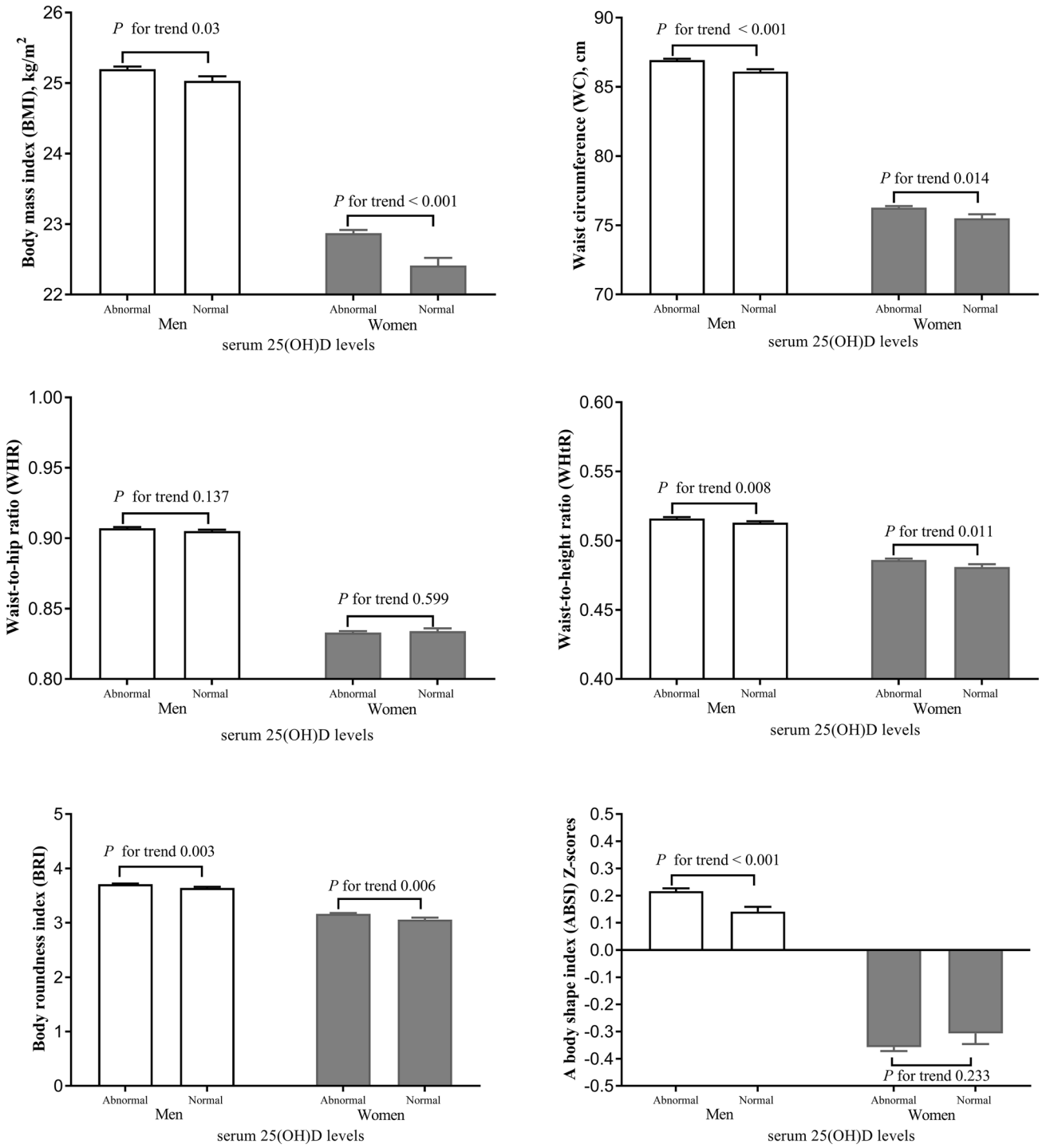

Fig. 1 Comparison of anthropometric indices levels in relation to vitamin D abnormality. General linear model analysis displayed the means of traditional and novel anthropometric measurements in relation to 25(OH)D levels after adjustment for covariates of age, season, smoking status, physical activity, alcohol intake, educational level, chronic diseases (hypertension, diabetes, dyslipidemia), and dietary assessments (fruits, vegetables, meat, whole-grain foods, sugar juice intake). Abnormal 25(OH) D concentration was defined as < 30 ng/mL. Data were expressed as mean ± SEM. *P* for trend was obtained from general linear model

those in participants aged 18–44 years. The age differences in obesity indices were slightly different for male and female participants. Among females, older participants (≥65 years) generally had higher obesity measurement levels than younger and middle-aged participants. In males, the prevalence of general obesity and abdominal obesity was

Table 2 Odds ratios and 95% CIs of obesity in relation to an abnormal serum 25(OH) D concentration according to gender

	Model 1			Model 2		
	Odds ratio	95% CI	*P*	Odds ratio	95% CI	*P*
Men						
BMI ≥ 28 kg/m^2	1.178	1.023–1.358	0.023	1.717	1.012–1.365	0.034
WC ≥ 90 cm	1.173	1.055–1.304	0.003	1.163	1.042–1.298	0.007
WHR > 0.9	1.078	0.971–1.197	0.157	1.065	0.956–1.187	0.254
WHtR > 0.5	1.123	1.010–1.249	0.031	1.125	1.007–1.255	0.037
BRI Q4	1.115	1.009–1.277	0.034	1.144	1.012–1.293	0.031
ABSI Q4	1.192	1.056–1.345	0.004	1.173	1.038–1.236	0.010
Women						
BMI ≥ 28 kg/m^2	1.678	1.105–2.551	0.015	1.809	1.180–2.773	0.007
WC ≥ 85 cm	1.061	0.884–1.333	0.612	1.125	0.890–1.422	0.324
WHR > 0.85	0.861	0.716–1.037	0.115	0.933	0.770–1.131	0.483
WHtR > 0.5	1.049	0.870–1.266	0.615	1.150	0.947–1.397	0.160
BRI Q4	1.121	0.917–1.370	0.265	1.142	0.930–1.403	0.205
ABSI Q4	0.896	0.737–1.089	0.269	0.952	0.781–1.161	0.627

Obesity was defined as BMI ≥ 28 kg/m^2, WC ≥ 90 cm in men or WC ≥ 85 cm in women, WHR > 0.9 for men and > 0.85 for women, WHtR > 0.5, BRI and ABSI within the highest quartile (Q4), respectively. An abnormal serum 25(OH)D concentration was defined as < 30 ng/mL. Data were obtained using binary logistic regression analysis

Model 1 was adjusted for age and visiting season

Model 2 was adjusted for model 1 plus, smoking status, physical activity, alcohol intake, educational level and chronic diseases (hypertension, diabetes, dyslipidemia) and dietary assessments (fruits intake, vegetables, meat, whole-grain foods and sugar juice)

BMI body mass index, *WC* waist circumference, *WHR* waist-to-hip ratio, *WHtR* waist-to-height ratio, *BRI* the body roundness index, *ABSI* a body shape index

significantly higher in the middle-age group; the prevalence of visceral obesity was significantly higher in the old-age group.

Figure 2 shows the results of the binary logic regression with the ORs for obesity and abnormal 25(OH)D levels according to age subgroups after controlling for covariates. Obesity was negatively correlated with 25(OH)D level only in the age group of participants 45–64 years old. Males with low 25(OH)D levels had an increased risk of obesity as assessed by BMI, WC, WHtR, BRI and ABSI. Females with low 25(OH)D levels had an increased risk of obesity as assessed by BMI. There was no significant association in the age groups < 45 years or ≥ 65 years in either sex.

Discussion

This cross-sectional study compared the association of both traditional and novel anthropometric indices with 25(OH) D level in the general population according to sex and age. We observed that the relationship between various obesity measurements and 25(OH)D concentrations was different for males and females. In males, except for WHR, all other indices, BMI, WC, WHtR, BRI and ABSI, were inversely related to 25(OH)D concentrations. In females, only BMI was related to 25(OH)D concentrations. In both sexes, associations of obesity parameters with 25(OH)D concentrations were observed only in the 45- to 64-year-old age group.

Our results revealed that 25(OH)D insufficiency (< 30 ng/mL) was very common and showed a slight female predominance. Similarly, in a multicenter study conducted in five representative geographical cities in China, the prevalence of vitamin D insufficiency (< 30 ng/mL) was 91.6% for males and 97.6% for females, which were higher than our findings (78.2%) [26]. However, the high prevalence of hypovitaminosis D could be overestimated due to different methods of measurement, cutoff values, climate and lifestyles; therefore, the result should be interpreted with caution. The higher prevalence in females may be attributed to reduced sunlight exposure from the use of sunscreen or the lack of involvement in sports. Among all age groups, young adults tend to have a higher percentage of low 25(OH)D levels than middle-aged and old adults, which is also in line with the findings of previous health surveys in China [27, 28]. Several factors could explain the results. First, young adults tend to be under pressure from school or work, which occupy a large amount of time that could be used for outdoor activities. Second, the majority of young adults tend not to visit the health department regularly or treat vitamin D deficiency in a timely manner. In contrast, elderly Chinese

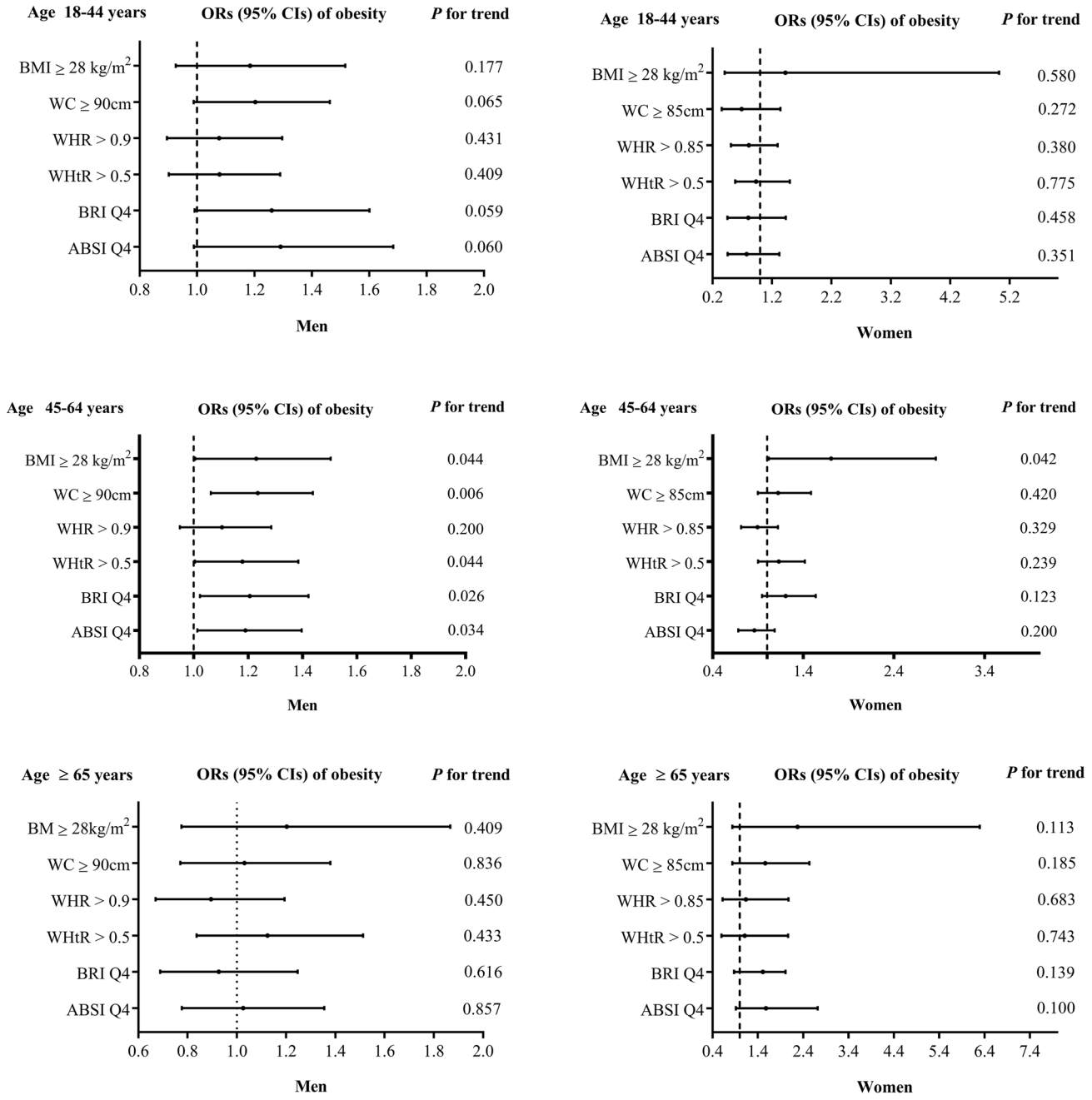

Fig. 2 Odds ratio (95% confidence interval) for obesity according to vitamin D levels stratify by age and gender. An abnormal serum 25(OH)D concentration was defined as < 30 ng/mL. Results were derived from regression coefficients with 95% confidence intervals from binary regression analyses. All analyses were adjusted for visiting season, educational level, smoking status, physical activity, alcohol intake, and chronic diseases (hypertension, diabetes, dyslipidemia) and dietary assessments (fruits intake, vegetables, meat, whole-grain foods and sugar juice)

individuals are more mindful of their health and often exercise. In addition, the results might vary due to social and cultural differences.

Obesity has been confirmed to be a strong risk factor that contributes to CVD [29]. Traditional anthropometric indices, such as BMI, WC, WHR and WHtR, have long been considered practical and valuable tools to diagnose obesity [30]. BMI is the most commonly used general obesity index, although it cannot perfectly distinguish body weight increase caused by fat or muscle accumulation. WC, WHR and WHtR are traditionally chosen as indicators of abdominal obesity. ABSI and BRI have recently been proposed as novel anthropometric measurements, were positively correlated with visceral adiposity [20, 25]. In our study, males had much higher

levels of obesity parameters than females, and accordingly, males were more likely to have a worse cardiovascular health status with a higher prevalence of chronic diseases and increased levels of blood glucose and lipids compared to females. Moreover, the study revealed that obesity phenotypes differed by sex and age. Females reached their highest prevalence of all obesity phenotypes at ≥ 65 years of age; whereas in males, the prevalence of general and abdominal obesity peaked at 45–64 years and that of visceral obesity at ≥ 65 years. Several possible factors could explain the discrepancy. First, sex steroid hormones that change during the menopausal transition could accelerate the development of obesity in older women [31]. Second, young females more care about their body shape, so they often use diet, exercise or other interventions to control weight. Third, older individuals tend to lose muscle mass and have more visceral fat distribution than those in the younger group [32]. Lastly, cigarette smoking and alcohol consumption may contribute to general and abdominal obesity in middle-aged males.

The current study found sex differences in the effect of 25(OH)D on traditional and novel obesity indices. Abnormal 25(OH)D seemed to foster general obesity in both females and males but to a greater extent in males. Similarly, in a cohort of older persons, BMI was associated with 25(OH)D concentrations in both male and female participants, and the association was stronger in females [33]. In addition, our data showed a negative correlation between low vitamin D status and markers of abdominal adipose tissue (WC, WHtR) and visceral adipose tissue (BRI, ABSI) in males. Our finding is consistent with previous literature showing an inverse association of abdominal fat and visceral fat with 25(OH)D concentrations. A cross-sectional study found that the highest categories of WC and BRI were directly associated with lower 25(OH)D levels in older male and female adults [13]. In the Netherlands Epidemiology of Obesity study, after correction for total body fat, visceral adipose tissue was associated with serum 25(OH)D in both males and females using magnetic resonance imaging (MRI) as a measurement technique [34]. Similarly, the Framingham study showed that variations in abdominal subcutaneous and visceral adiposity were inversely related to 25(OH) D status measured by computed tomography (CT) [35]. However, the sex-related differences found in our study could be explained by a difference in body fat distribution [36]. In general, females have a higher percentage of total body fat than males, which could potentially explain why females showed stronger associations between a general obesity indicator (BMI) and 25(OH)D [37]. Additionally, males tended to store more fat in the visceral (abdominal) region, whereas females stored more fat in the gluteal–femoral region, which could explain why central obesity (WC and WHtR) and visceral obesity (BRI and ABSI) were related to 25(OH)D concentrations only in males in our study. Additionally, our study demonstrated that BMI, as an indicator of general obesity, showed a stronger association with 25(OH)D than did the abdominal and visceral adiposity indices. Although the strength of the relationship varied by race and age group, most studies found that visceral adipose tissue showed the strongest association with 25(OH)D among those of different body fat deposits [34, 38, 39]. These inconsistent results could be largely due to the difference in methods of fat distribution measurements. Our study used calculations based on body weight, waist circumference and hip circumference as crude evaluation tools, while others use bioimpedance, CT or MRI as precise evaluation tools.

Notably, the negative correlations between vitamin D levels and obesity were demonstrated only in participants aged 45–64 years but not in those aged 18–44 years or ≥ 65 years. Limited studies with inconsistent results have explored this relationship according to age. Similarly, an obesity study conducted with 6671 males and females aged between 45 and 65 years showed that visceral adipose tissue (assessed by MRI) was inversely related to 25(OH)D concentrations in both sexes [34]. A study of women in young and middle adulthood (25–60 years) also found BMI to be negatively associated with 25OHD levels [40]. In contrast, another recent study including 380 Malay adults found that 25(OH)D deficiency (< 20 ng/mL) and BMI status were independently associated in younger females [11]. In a Swedish study, among female anorexia nervosa subjects (20–36 years), vitamin D parameters were correlated with BMI [41]. Moreover, Ana Rita Sousa-Santos et al. found that indicators of obesity, such as BMI, WC, BRI and ABSI, were associated with lower 25(OH)D serum concentrations in participants 65 years or older [13]. In a randomized, placebo-controlled study, BMI was negatively associated with the change in 25(OH)D levels following 25(OH)D supplementation in older adults (≥ 64 years) but not in younger adults (20–40 years) [42]. These inconsistent findings may have resulted from differences in age, sex, race, diet, and skin pigmentation in the various study populations.

The negative correlation of low vitamin D status with obesity might have been caused by multiple possible mechanisms. First, because vitamin D is fat soluble, a larger amount of vitamin D could be sequestered by adipose tissue in a stored form and volumetrically diluted by the large fat mass in obese individuals [35]. Second, experimental studies have revealed that vitamin D deficiency could promote greater adiposity by increasing parathyroid hormone, which may stimulate calcium influx into adipocytes and enhance adipogenesis [33]. Moreover, the expression of vitamin D-dependent receptors is decreased in obese individuals, and these receptors are involved in vitamin D metabolism [43]. Third, vitamin D-related gene

variants have been associated with obesity in some studies [44]. In addition, some clinical investigations have suggested that improvements in 25(OH)D levels could help weight control [45, 46].

There are some limitations to the current study that must be considered. First, this was a cross-sectional study; therefore, the possibility of reverse causation should not be excluded. Second, these results may not be readily generalized to other races or age groups since our sample represented southern Chinese adults engaged in mostly indoor-based occupations. Third, although most young people in China do not supplement 25(OH)D, we did not obtain data on subjects' sun exposure levels or vitamin D intake from the diet. Finally, participants' body fat percentage by body composition analysis, or abdominal subcutaneous adipose tissue and visceral adipose tissue by MRI or CT were not estimated in this study; such measurements can be used to explore the specific contribution of different fat deposits.

In contrast, important strengths of our study include the large study population and the availability of both traditional and novel anthropometric indices. This enabled us to investigate the individual contributions of the different fat deposits to the relationship with 25(OH)D concentrations. To our knowledge, this is one of the few studies among Asian participants to address the association between serum vitamin D status and risk of obesity. This study revealed that the association differed by gender and age. In addition, a large amount of data was available for our study cohort, which allowed for the adjustment of potential confounding factors.

In conclusion, this study showed that in females, general obesity (BMI) and in males, general obesity (BMI), central obesity (WC and WHtR) and visceral obesity (BRI and ABSI) were inversely related to 25(OH)D concentrations. The current study adds support to a growing body of literature implicating low 25(OH)D status in the development of obesity. Correcting 25(OH)D insufficiency through diet, lifestyle change or supplementation may potentially help prevent obesity, especially in males in China. However, our study demonstrated the association only in participants aged 45–64 years. The finding suggests that 25(OH)D may differentially affect obesity in participants of different ages based on race/ethnicity. Well-designed, large-scale prospective studies are required to elucidate which mechanisms underlie the contribution of low 25(OH)D concentrations to obesity.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Ethical approval All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all subjects included in the study.

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