



Review

Vitamin D, obesity, and obesity-related chronic disease among ethnic minorities: A systematic review

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ABSTRACT

Objective: To assess the association between 25-hydroxyvitamin D (25[OH]D) status and obesity, cardiovascular diseases (CVDs), the metabolic syndrome, and type 2 diabetes mellitus (T2DM) in ethnic minorities.

Methods: Databases searched were CINAHL with full text, Global Health, MEDLINE with full text, and PsycINFO from 1980 through 2010 (February). Studies were included if they 1) targeted immigrants from low- to high-income countries or ethnic minorities, 2) focused primarily on 25(OH)D and its relation to obesity, T2DM, and/or CVDs, and 3) were published in peer-reviewed journals. The influences of key confounders such as age, gender, and ethnicity on any observed relations were also assessed. Due to the heterogeneity of study characteristics, only a narrative synthesis was undertaken.

Results: Ethnic minorities had significantly higher rates of vitamin D insufficiency (25[OH]D <50 nmol/L; children 43.6–48.7% versus 10%; adults 30.3–53% versus 13.7–26%) than their white counterparts. None of the studies reported a prevalence of obesity stratified by ethnicity. There was evidence supporting links between vitamin D deficiency and obesity-related chronic diseases, with 14 of 14 studies reporting a statistically significant result with a measurement of obesity, four of five for T2DM, four of five for CVDs, and one of one for the metabolic syndrome. However, the strength of the association varied across ethnic groups depending on the index used to measure adiposity, T2DM, and CVDs. Because most of the included studies were cross-sectional and there were variations in outcome measurements, it was not possible to determine the relative contributions of obesity or vitamin D insufficiency to CVD risk and risk of T2DM or which is the initial driver. It is possible both have a role to play.

Conclusion: Further research specific to migrant populations using randomized controlled trials are required to establish whether causal links between 25(OH)D and obesity-related chronic disease exist, and whether vitamin D supplementation could be valuable in the prevention or treatment of obesity-related diseases.

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Introduction

Migration from low- to high-income countries has been shown to be associated with an increased risk for obesity and other lifestyle-related chronic diseases such as type 2 diabetes (T2DM) and cardiovascular diseases (CVD) in adults and children [1–3]. Factors predisposing migrants to obesity and chronic diseases are well documented and include lifestyle changes, environmental factors, cultural perceptions, and level of

acculturation [2,4]. However, there is emerging evidence linking vitamin D insufficiency/deficiency (VDI/VDD) to obesity-related chronic diseases [5].

American, European, and Australian studies have demonstrated that migrants and ethnic minorities with dark skin exhibit low serum 25-hydroxyvitamin D (25[OH]D) concentrations [6,7]. In Australia, the prevalence of VDI/VDD (25[OH]D <50 nmol/L) [8] in migrant populations of an African background has been estimated to be 87% in children [9] and 92% in adults [6]. High levels of VDI/VDD have also been reported in Hispanic, African American, and Asian migrants in the United States [10, 11], and Turkish, Moroccan, Indian and sub-Saharan African

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populations in Europe [12]. Data from these studies have suggested that the risk factors for VDI/VDD include being of female gender, longer residency in a host country (>2 y), and being mostly covered while outdoors

For migrants with dark skin relocating to Western countries, not only are their 25(OH)D levels lower than their white counterparts, they tend to be lower than that of native populations in their country of origin [12]. Humans derive vitamin D primarily from exposure to sunlight, and only small amounts are derived from dietary sources, unless dietary supplements are used [5]. There are few natural sources of vitamin D in food and the main source for humans is the conversion of provitamin D (7-dehydrocholesterol) in the skin to previtamin D₃ after sun exposure to ultraviolet-B radiation, which is subsequently converted to vitamin D₃ through a heat-dependent process [13]. Because most people meet their vitamin D needs through exposure to sunlight [13], the synthesis of vitamin D varies by the color of the skin (determined by the amount and type of melanin). The darker the skin, the higher the amount of sunlight required to produce vitamin D [14]. The application of sunscreen decreases the synthesis of vitamin D₃ [15], and complete cloud-cover and shade can decrease ultraviolet energy by 50% and 60%, respectively [16]. Similarly, the skin is unable to make vitamin D from the sun at latitudes above 37°N and below 37°S [17,18]. Thus, when migrants of skin color relocate to Western and cooler climate countries, with high northern (e.g., European) or low southern (e.g., Australian) latitudes, their risk for VDI/VDD increases exponentially.

It is worth noting that the increased risk for obesity, T2DM, and CVD in migrants with dark skin relocating to Western and cooler climate countries [1] occurs simultaneously with the increased risk of VDI/VDD. Data from epidemiologic and experimental studies in non-migrant populations, especially those living at higher latitudes, have found that low levels of 25(OH)D are associated with the risk of hypertension, CVDs, T2DM, cancers, and cancer-related mortality [5,19].

Several factors have been proposed to explain the VDI/VDD association with obesity [20–22]: 1) obese people may not get enough sun exposure due to limited mobility or clothing habits; 2) their bodies cannot be easily release vitamin D because it is stored in the body fat compartments; 3) the obese have an increased need for vitamin D for stronger bones to support their greater weight but are unable to meet such needs due to a decreased bioavailability of 25(OH)D; and 4) increased levels of the active vitamin D metabolite decreases serum 25(OH)D by exerting negative feedback control on the hepatic synthesis of 25(OH)D. However, the inverse relation between body mass index (BMI) and 25(OH)D levels is not consistent across ethnic groups. For example, Nesby-O'Dell et al. [23] examined determinants of hypovitaminosis D in 1546 African American women and 1426 white women 15 to 49 y old using data from the Third National Health and Nutrition Examination Survey. They found that VDI/VDD was significantly associated with a BMI of at least 30.0 kg/m² in white women, but not in African American women. Similarly, in New Zealand Scragg et al. [24] examined the relation between vitamin D status and major cardiovascular risk factors in 390 New Zealand residents 40 to 64 y old (95 Pacific Islanders, 74 Maori, and 221 others mostly of European descent). The investigators found that in residents of mixed ethnicity, serum 25(OH)D concentrations were unrelated to BMI. There is emerging evidence that vitamin D status is only modestly associated with parameters of disturbed glucose and lipid metabolism [25]; hence, the impact of VDI/VDD on this type of cardiovascular risk factors cannot be evaluated with certainty.

Furthermore, Wu et al. [26] found no associations between lower 25(OH)D levels and typical cardiovascular risk factors when respective correlations were adjusted for BMI.

Notwithstanding these findings, among migrant populations the links between vitamin D and obesity and obesity-related chronic disease are less clear and not yet completely understood. Understanding this link will help health planners to decrease health inequalities and the burden of obesity and chronic diseases in migrant populations in receiving countries. The aim of this systematic review was to assess the association between vitamin D status as measured by 25(OH)D and CVDs, obesity, and T2DM in migrant and ethnic minority population groups.

Materials and methods

Search strategy

A search for relevant publications was conducted using CINAHL with full text, Global Health, MEDLINE with full text, and PsycINFO. Additional articles were located from the reference lists of relevant papers. The search strategy can be viewed in Table 1.

Selection and data extraction

All potentially relevant studies had their abstracts screened by one of the authors (J. A. H.) for eligibility using the following criteria: 1) the study included targeted immigrants from low- to high-income countries or skin-colored populations from ethnic minorities; 2) the focus of the study was primarily on 25(OH)D and its relation to obesity, T2DM, and/or CVDs; and 3) the study was published in a peer-reviewed journal in English from 1980 through 2010 (February). Publications selected for inclusion were then independently reviewed by an author (J. A. H.) and independently verified by another author (A. M. N. R.). Studies that did not include human participants, were review articles, or focused on diabetes other than T2DM (e.g., gestational diabetes or type 1 diabetes mellitus) were excluded from the review. Because of the scarcity of intervention studies examining the effect of vitamin D supplementation on obesity and cardiovascular outcomes in migrants and/or ethnic minorities, this review focused on cross-sectional and longitudinal studies. Case reports ($n = 2$) were also excluded from analysis as a form of quality control, because these studies are not representative of a population. Two articles that matched participants and compared mean values but did not examine the relation between 25(OH)D and the variable of interest were also excluded from the review. In total, 20 studies were included in the systematic review. This process is described in Figure 1.

In extracting the data, the limitations of each study were assessed using the following questions: Were the selection criteria, study setting, study design, aims/hypothesis, spectrum of participants, results, and analysis described clearly with sufficient detail? Was there any evidence that a study protocol had been developed before the study commenced? Was the execution of the index test described in sufficient detail to permit replication of the test? Did all participants receive the same reference standard regardless of the index test result? Was the cutoff value prespecified or acceptable in light of previous research? Was the reference standard chosen appropriate to verify test results? Did the study

Table 1

Search strategy—keywords

Search 1	lipoproteins, HDL/high density lipoprotein/cholesterol, HDL/glucose intolerance/blood glucose/blood sugar/insulin resistance/impaired fasting glucose/type 2 diabetes/diabetes mellitus, non-insulin-dependent/diabetes mellitus, type 2/diabetes/metabolic syndrome/syndrome X/metabolic syndrome X/weight gain/obesity/high blood pressure/hypertension/triglyceride*/triacylglycerol*/dislipidemia*/cardiovascular diseases/cardiovascular disorders/death/death and dying/mortality
Search 2	25(OH)D/cholecalciferol/calcitriol/25-hydroxy, 25(OH)D/1,25-dihydroxycalciferol/(ergocalciferol and deficient*)/hypovitaminosis D/25(OH)D deficient*
Search 3	migrant*/migrate*/ethnic group/(transients and migrants)/race/ethnicity
Search 4	searches 1 and 2 and 3

Virgule indicates or

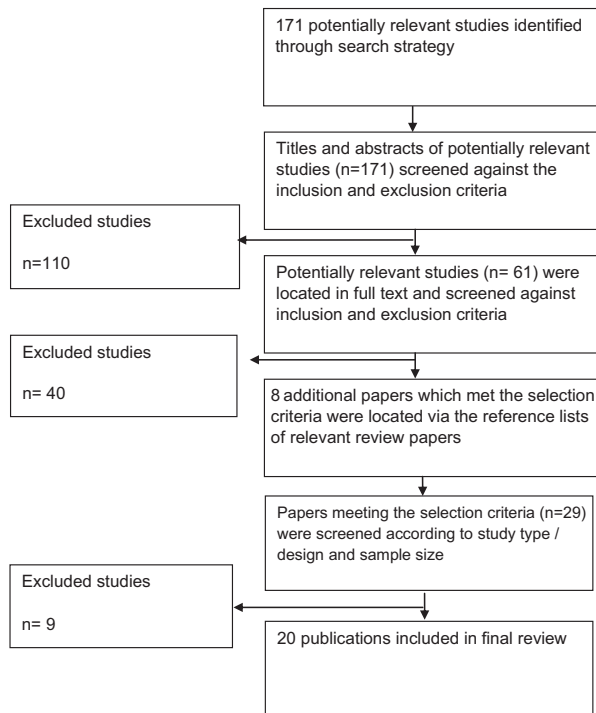


Fig. 1. Search strategy—included and excluded articles.

consider, measure, and adjust for the relevant confounding variables? Was the sample size adequate? [27].

Considered indicators

A 25(OH)D concentration level no higher than 50 nmol/L was used as the cutoff for VDI/VDD [28]. For obesity, studies were selected that included the following measurements of adiposity: BMI, waist-to-hip ratio, waist circumference, body fat mass/total body fat, total percentage body fat (%BF), weight, visceral adipose tissue, subcutaneous adipose tissue, or visceral adipose tissue/subcutaneous adipose tissue ratio. For T2DM, measurements included diagnosed T2DM or insulin sensitivity (IS), insulin resistance, fasting insulin, plasma glucose, β -cell function (β cf), and glycosylated hemoglobin. For CVDs, measurements included congestive heart failure, myocardial infarction, stroke, angina, coronary heart disease, heart failure, peripheral arterial disease, hypertensive diseases, ischemic heart disease, arrhythmia, cerebrovascular disease, atherosclerosis, coronary artery calcification, and other diseases of the arteries. Also included were studies that measured the metabolic syndrome.

Data synthesis

Due to the heterogeneity in study design and measurements of the diseases of interest, undertaking a meta-analysis was not appropriate. The analysis focused on the narrative, describing the study design, target population, the setting, and the relation between vitamin D and outcomes of interest.

Results

Characteristics of studies

In total 20 studies were included in this review, of which 18 were conducted in the United States and two were conducted in New Zealand (Table 2). Sixty-five percent of the studies ($n = 13$) were in adults only (age ≥ 18 y), 25% ($n = 5$) included adults and children/adolescents (age < 18 y), and 10% ($n = 2$) were in children/adolescents. All reviewed studies included multiethnic groups including migrants and/or ethnic minorities. Seventeen of the reviewed studies were cross-sectional and three were longitudinal.

Vitamin D status

All reviewed studies reported on vitamin D status and 13 of the studies reported mean 25(OH)D concentrations stratified by race. VDI/VDD (defined as mean serum 25(OH)D ≤ 50 nmol/L) was reported for black/African American/non-Hispanic black (participants had VDI/VDD in 9 of 11 studies reporting mean serum 25(OH)D concentrations), white/Caucasian/non-Hispanic white (1 of 10), Hispanic/Mexican American (two of nine), Asian American (one of one), Maori (two of two), and Pacific (two of two). Mean 25(OH)D was significantly lower in migrants and/or ethnic minorities (range 23.7–60.1 nmol/L) than in their white counterparts (range 65.4–79.6 nmol/L). Overall, participants with dark skin (e.g., African Americans 37.2–52.2 nmol/L or Pacific Islanders or Maori 34–43 nmol/L) had significantly lower 25(OH)D levels than those with light-colored skin (e.g., Mexican Americans 49.0–60.1 nmol/L and whites 53–79.6 nmol/L). Although few studies (only 7 of 20) reported the prevalence of VDI/VDD by ethnicity, the available data suggested that migrants or ethnic minorities are more affected than their white counterparts. In children, the prevalence of VDI/VDD (25(OH)D < 50 nmol/L) was significantly lower in white children (10%) than in children of ethnic minority background (range 43.6–48.7%). This pattern was also true in adults (13.7–26% in white versus 30.3–53% in migrant or ethnic minorities, except for the Chinese in whom the prevalence of 20.4% was comparable to that reported in whites).

Vitamin D status and adiposity

Fifteen of 20 studies investigated the relation between vitamin D status and adiposity, but only 14 of these studies used multilevel analysis. None of the studies reported the prevalence of obesity stratified by ethnicity. In the USA sample the prevalence of overweight or obesity varied from 45% to 64.7% in those at least 15 y old, whereas in the New Zealand studies the prevalence was 45% in those 5 to 14 y old. In terms of vitamin D status and adiposity, the two studies that focused on children only showed consistent results. That is, children and adolescents with low levels of 25(OH)D had significantly higher BMI or body fat mass, with overweight and obese children/adolescents displaying lower mean 25(OH)D levels compared with children/adolescents of a normal weight (Table 2) [10,29]. Of the remaining 13 studies that focused on adults or subjects with mixed age (adults and children/adolescents), the findings highlighted the increased risk of VDI/VDD in overweight or obese participants, but with ethnic differences dependent on the index used to measure adiposity. For instance, %BF was found to be significantly inversely associated with 25(OH)D in three of three studies; however, Looker [30] found that the relation with %BF was stronger and significant in white women of all ages and significant in black women younger than 50 y. Other ethnic differences were observed in six of seven (85.7%) studies that measured BMI and all studies measuring the waist-to-hip ratio or the prevalence of overweight/obesity. For example, in a longitudinal study involving a large sample of 1356 participants, Young et al. [31] found that adiposity measured by BMI, visceral adipose tissue, and subcutaneous adipose tissue was inversely associated with 25(OH)D in Hispanics and African Americans; but when adiposity was measured by visceral adipose tissue/subcutaneous adipose tissue ratio the relation was marginally significant in African Americans and not significant in Hispanics. Similarly, Rockell et al. [32] undertook a cross-sectional study involving 2946 participants and found

Table 2
Summary of reviewed studies

Reference, design, and country	Population/sample size	Measurements	Results	Limitations
Alemzadeh et al. 2008 [10], cross-sectional, USA	obese Caucasian, Mexican American, or African American children or adolescents 6–17.9 y old/ <i>n</i> = 127	IS, HbA _{1c} , FM	VDI/VDD prevalence 43.6% for Hispanics, 48.7% for African Americans, 10.2% for Caucasians (<i>P</i> < 0.001) VDI/VDD inversely associated with BFM (<i>r</i> = −0.40, <i>P</i> < 0.001) and HbA _{1c} (<i>r</i> = −0.23, <i>P</i> < 0.01), positively associated with IS (<i>r</i> = 0.24, <i>P</i> < 0.01) multiple regressions: model 1 adjusting for ethnicity, age, gender, season; model 2 adding FM to the model; in model 1 25(OH)D was associated with FM (β = −0.27, <i>P</i> < 0.001), IS (β not reported), and HbA _{1c} (β not reported); in model 2 25(OH)D remained associated with IS but not with HbA _{1c} (β = −0.13, <i>P</i> = 0.30), suggesting FM is a mediator in the latter; stratified analyses by ethnicity found that 25(OH)D was associated with HbA _{1c} in Caucasians but not African Americans or Hispanics	results not well presented and reported (tables of multiple regressions not provided and many other coefficients not reported in text); also did not stratify analysis by season OGTTs were not performed, thus glucose homeostasis and β cf were not measured inadequate measurement of body composition (larger error in individual estimates, used BIA rather than DEXA) only some of the analysis was clustered by ethnicity (e.g., analysis for HbA _{1c})
Arunabh et al. 2003 [33], cross-sectional, USA	healthy black and white women 20–80 y old/ <i>n</i> = 410	BMI, %BF	inverse relation between %TBF and 25(OH)D concentration (<i>r</i> = −0.13, <i>P</i> = 0.0013), adjusted for race, season, age and dietary vitamin D; no relation between 25(OH)D and BMI (<i>r</i> = −0.08, <i>P</i> > 0.05) in stepwise regression the variance in 25(OH)D was explained by ethnicity (<i>r</i> ² = 0.24, <i>P</i> < 0.001), season (<i>r</i> ² = 0.10, <i>P</i> < 0.001), %BF (<i>r</i> ² = 0.02, <i>P</i> = 0.011), and age (<i>r</i> ² = 0.01, <i>P</i> = 0.027)	ethnicity was defined as black or white; not clear whether black people encompassed all people of color no measurement of vitamin D supplementation only some of the analysis was clustered by ethnicity (not stepwise regression)
Chiu et al. 2004 [34], cross-sectional, USA	healthy, glucose-tolerant African American, Asian American, white, and Mexican American adults 20–32 y old/ <i>n</i> = 126	BMI, WHR, IS, PG, β cf (measured by first and second insulin responses)	VDI/VDD prevalence 47% for Asian Americans, 54% for African Americans, 26% for whites, 41% for Mexican Americans 25(OH)D was inversely associated with components of metabolic syndrome (with participants with VDI/VDD having a prevalence of metabolic syndrome of 30% versus 11% in participants with adequate vitamin D status (<i>P</i> = 0.008) after adjusting for potential confounders (age, sex, ethnicity, season, systolic and diastolic blood pressures, BMI, WHR), 25(OH)D was negatively associated with BMI (β = −0.04, <i>P</i> = 0.029) and PG concentration at fasting (β = 0.11, <i>P</i> = 0.026), and during OGTTs after overnight fasting at 60 min (β = −0.70, <i>P</i> < 0.001), 90 min (β = −0.61, <i>P</i> = 0.001), and 120 min (β = −0.52, <i>P</i> < 0.001); also 25(OH)D was positively associated with IS (β = 0.25, <i>P</i> < 0.001); 25(OH)D was not associated with WHR or PG at 30 min (after overnight fast)	narrow age range of participants (\pm 6 y) no measurement of vitamin D supplementation or sun exposure; study deduced a negative impact of VDD on β cf despite NS results for IR (which they used to measure β cf) analysis not clustered by ethnicity
de Boer et al. 2009 [35], longitudinal, USA	white, Chinese, black, and Hispanic adults with no history of CVD 45–84 y old/ <i>n</i> = 1370	prevalent CAC, incident CAC (development after 3 y)	prevalence of 25(OH)D concentration <15 ng/mL (37.4nmol/L) 47.3% for blacks, 30.3% for Hispanics, 20.4% for Chinese, 13.7% for whites lower 25(OH)D concentration associated with non-white race/ethnicity, higher BMI, diabetes (values not reported) 25(OH)D concentration not associated with prevalent CAC (<i>P</i> = 0.28) after full adjustment (for age, gender, race/ethnicity, site, season, measurement batch, physical activity, BMI, smoking, diabetes, blood pressure, CRP, total cholesterol, HDL cholesterol, and triacylglycerols after full adjustment (as above) incident CAC was marginally associated with lower 25(OH)D concentration—10-ng/mL (25-nmol/L) decrease in 25(OH)D concentration resulted in 23% increased risk of CAC development (RR 1.23, 95% CI 1.00–1.52, <i>P</i> = 0.049); association did not vary by race/ethnicity	single measurement of 25(OH)D was collected (does not encapsulate cumulative vitamin D exposure) results not well reported in parts— <i>P</i> values for baseline characteristic associations were not included

(continued on next page)

Table 2 (continued)

Reference, design, and country	Population/sample size	Measurements	Results	Limitations
Florez et al. 2007 [36], cross-sectional, USA	obese and non-obese Hispanic and non-Hispanic white adults 48–75 y old/ <i>n</i> = 291	BMI	VDI/VDD prevalence 17% for Hispanics, 12.6% for white non-Hispanics 25(OH)D levels progressively decreased as BMI increased ($r = -0.21$, $P = 0.0003$) obese participants had > 2 times the risk of 25(OH)D <75 nmol/L (P not reported) after adjusting for age, gender, and ethnicity	did not measure or control for many confounders, especially vitamin supplementation RESULTS section lacked detail in reporting various cutoff points for 25(OH)D concentrations because it was measured at different clinical laboratories
Kim et al. 2008 [37], cross-sectional, USA	black, Hispanic, and white adults ≥ 20 y old/ <i>n</i> = 8351	CHD, HF, PAD, stroke	prevalence 25(OH)D <30 ng/mL (74.9 nmol/L) 68% for whites, 97% for blacks, 88% for Hispanics significant inverse dose–response relation between 25(OH)D concentration and prevalence of CHD ($P = 0.003$), HF ($P = 0.005$), and PAD ($P < 0.001$) but not stroke ($P = 0.400$) after adjustment for age, race, gender after full adjustment for age, race, gender, current smoking, leisure time physical activity, vitamin D supplement use, regular milk drinking, BMI, chronic kidney disease, hypertension, and diabetes mellitus, only the relation with PAD remained significant with decreasing 25(OH)D tertile (OR 1, 1.23, 95% CI 0.85–1.79; OR 1.52, 95% CI 1.03–2.25, $P = 0.009$)	tests and analysis not described in adequate detail clustered sampling may have resulted in false-positive associations and there were small numbers of participants in certain clusters
Kendrick et al. 2009 [38], cross-sectional, USA	non-Hispanic black, Mexican American, non-Hispanic white, and other adults ≥ 18 y old/ <i>n</i> = 16 603	CVD	mean \pm SD serum 25(OH)D concentration 19.4 \pm 5.4 ng/mL (48.4 \pm 13.5 nmol/L) for non-Hispanic blacks, 25.2 \pm 4.1 ng/mL (62.9 \pm 10.2 nmol/L) for Mexican Americans, 31.8 \pm 16.1 ng/mL (79.4 \pm 40.2 nmol/L) for non-Hispanic whites, 24.8 \pm 12.9 ng/mL (61.9 \pm 32.2 nmol/L) for others participants with CVD had significantly ($P = 0.0001$) lower mean 25(OH)D concentrations (27.1 \pm 9.7 ng/mL [67.6 \pm 24.2 nmol/L]) than those without CVD (29.8 \pm 12.2 ng/mL [74.4 \pm 30.5 nmol/L]) age-adjusted linear inverse relation between increasing CVD prevalence and decreasing 25(OH)D concentration ($F = 8.14$, $P < 0.0001$) VDI/VDD participants at increased risk of CVD (OR 1.20, 95% CI 1.01–1.36, $P = 0.03$) after adjustment for age, gender, race/ethnicity, season of measurement, physical activity score, BMI, smoking status, hypertension, diabetes, dyslipidemia, chronic kidney disease, vitamin D use	CVD was measured by self-report and did not account for date of diagnosis or subsequent lifestyle changes
Liu et al. 2007 [39], cross-sectional, USA	Caucasian, African American, Mexican American women ≥ 65 y old/ <i>n</i> = 3998	CHF	mean \pm SD serum 25(OH)D concentrations 28.2 \pm 10.3 ng/mL (70.4 \pm 25.7 nmol/L) for Caucasians, 20.9 \pm 9.9 ng/mL (52.5 \pm 24.7 nmol/L) for African Americans, 24.1 \pm 9.8 ng/mL (60.2 \pm 24.5) for Mexican Americans significantly lower 25(OH)D concentrations in participants with CHF (24.3 ng/mL [60.7 nmol/L] for men, 19.3 ng/mL [48.2 nmol/L] for women) compared with those without CHF (26.1 ng/mL [65.1 nmol/L] for men, 22.7 ng/mL [56.7 nmol/L] for women) logistic regression analysis adjusted for age, sex, BMI, glomerular filtration rate, γ -glutamyltranspeptidase level found a decrease of 10 ng/mL (25 nmol/L) in serum 25(OH)D associated with increased relative risk (RR 1.22, 95% CI 1.08–1.36) for CHF; relation present in participants with and without coexisting metabolic syndrome	self-report used to measure CHF analysis not clustered by ethnicity

Looker 2005 [30], cross-sectional, USA	non-Hispanic white and non-Hispanic black women ≥12 y old/n = 6402	%BF	mean 25(OH)D concentrations higher in non-Hispanic white women compared with non-Hispanic black women before (1.4–1.9 times higher depending on age) and after adjusting for %BF (1.3–1.9 times higher depending on age) regression analysis adjusting for age, physical activity, month of blood collection, smoking, oral contraceptive or hormone use, daily dietary vitamin D intake, frequency of milk or cereal consumption, vitamin–mineral supplement use showed significant negative relation between %BF and 25(OH)D concentration for all age tertiles in non-Hispanic white women ($\beta = -0.3192, -0.3721, -0.1854, P < 0.001$), but in non-Hispanic black women the relation was weaker and significant only in the 12–29-y and 30–49-y tertiles ($\beta = -0.1117, -0.1326, P < 0.001$), not the ≥50-y tertile ($\beta = 0.0273, P = 0.7721$)	measurements of vitamin D consumption based on single 24-h recall test used to measure %BF did not directly measure BF; rather %BF was predicted after measurement of body water also, no measurement of sun exposure; this was estimated by physical activity and different tests for physical activity were applied to different age groups more black participants had blood tests in winter (secondary analyses were run to overcome these limitations)
McKinney et al. 2008 [40], cross-sectional, USA	Hispanic (mostly Mexican), non-Hispanic white, non-Hispanic black women 16–33 y old/n = 800	%TBF, TBF, BMI	mean 25(OH)D concentration 47.9 nmol/L for Hispanics, 37.7 nmol/L for non-Hispanic black participants, 71.8 nmol/L for non-Hispanic white participants negative correlations between 25(OH)D levels and %TBF, TBF, and BMI ($r = -0.28, -0.33, -0.36, P < 0.001$) relation between 25(OH)D and % TBF was significant after controlling for age, race, dietary vitamin D, season, smoking ($r = -0.29, P < 0.0001$) during stepwise multivariate analysis, %BF, race, and season remained in the final statistical model as predictors for 25(OH)D levels ($P < 0.05$), explaining 36% of variance prevalence of 25(OH)D <17.8 ng/mL (44.4 nmol/L) 50.3% for non-Hispanic blacks, 9.5% for non-Hispanic whites, 23.4% for Mexican Americans, 24.6% for others inverse relation between 25(OH)D quartile and diabetes prevalence and mean BMI ($P < 0.001$) multivariate analysis (adjusted for age, sex, race/ethnicity, diabetes, CVD history, BMI, hypertension, total cholesterol, HDL cholesterol, cholesterol-lowering medication use, former and current smoking, season, estimated glomerular filtration rate, log albuminuria/creatinine, log CRP, serum albumin, low SES, vitamin D supplement use, and physical activity level) found non-white ethnicity to be independently associated with 25(OH)D concentration <17.8ng/mL (OR 10.17, 95% CI 8.13–12.72, for non-Hispanic blacks, 2.45, 1.96–3.06, for Mexican Americans, and 3.03, 2.18–4.20, for other, $P < 0.01$) in same multilevel analysis, 25(OH)D <17.8 ng/mL was also independently associated with diabetes (OR 1.46, 1.16–1.84, $P = 0.02$) and higher BMI (OR 1.04, 1.02–1.06, $P < 0.01$) increased risk of CVD mortality in participants with 25(OH) D <17.8 ng/mL (RR 1.20, 0.87–1.64, $P > 0.05$) in fully adjusted (as above) model	did not measure vitamin D supplementation stepwise analysis may have slightly over-fit the data analysis not clustered by ethnicity
Melamed et al. 2008 [41], longitudinal, USA	non-Hispanic black, non-Hispanic white, Mexican American, and other adults ≥20 y old/n = 13 331	diabetes, BMI, CVD history	obese participants displayed significantly lower ($P < 0.0001$) mean serum concentrations of 25(OH)D than non-obese participants (23.5 ± 12.2 ng/mL [58.7 ± 30.5 nmol/L] and 31.0 ± 14.4 ng/mL [77.4 ± 35.9 nmol/L], respectively) negative associations between 25(OH)D and BMI ($r = -0.4, P < 0.0001$) and FM ($r = -0.4, P < 0.0001$); inverse relation between BMI and 25(OH)D present in African American ($r = -0.37, P < 0.0006$) and Caucasian ($r = -0.428, P < 0.0001$) ethnic groups	participants who had blood tests in the afternoon or evening fasted for shorter period than those who were tested in the morning because non-Hispanic blacks had much lower vitamin D concentrations than non-Hispanic whites, subgroup analysis was conducted with ethnicity-based cutoffs (i.e., non-Hispanic black participants had different vitamin D cutoffs than other participants) analysis not clustered by ethnicity
Parikh et al. 2004 [42], cross-sectional, USA	healthy obese and non-obese adults classified as Caucasian, African American, or other ethnicity 18–71 y old/n = 302	BMI, FM	obese participants displayed significantly lower ($P < 0.0001$) mean serum concentrations of 25(OH)D than non-obese participants (23.5 ± 12.2 ng/mL [58.7 ± 30.5 nmol/L] and 31.0 ± 14.4 ng/mL [77.4 ± 35.9 nmol/L], respectively) negative associations between 25(OH)D and BMI ($r = -0.4, P < 0.0001$) and FM ($r = -0.4, P < 0.0001$); inverse relation between BMI and 25(OH)D present in African American ($r = -0.37, P < 0.0006$) and Caucasian ($r = -0.428, P < 0.0001$) ethnic groups	analysis and results were described briefly, e.g., did not compare mean 25(OH)D concentrations or prevalence of VDI/VDD by race study reported multiple regression analysis only for 1,25(OH) ₂ D, not for 25(OH)D

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Table 2 (continued)

Reference, design, and country	Population/sample size	Measurements	Results	Limitations
Reis et al. 2009 [43], cross-sectional, USA	adolescents without diagnosed diabetes 12–19 y old/ <i>n</i> = 3577	BMI (\geq 95th percentile), WC (\geq 90th percentile, metabolic syndrome, HbA _{1c} , PG	adolescent mean 25(OH)D concentrations 28.0 ng/mL (69.9 nmol/L) for whites, 21.5 ng/mL (53.7 nmol/L) for Mexican Americans, 15.5 ng/mL (38.7 nmol/L) for blacks mean 25(OH)D lower in adolescents who were obese or abdominally obese and those with the metabolic syndrome ($P < 0.01$) inverse association between 25(OH)D quartile and BMI and WC ($P < 0.001$) and inverse trend with fasting PG ($P = 0.010$) after adjustment for age, gender, ethnicity, poverty-to-income ratio, and physical activity; also, HbA _{1c} concentrations not associated with 25(OH)D ($P = 0.020$) as 25(OH)D quartile decreased, OR for obesity (BMI), abdominal obesity (WC), and the metabolic syndrome increased significantly ($P < 0.001$) in multivariate logistic regression analysis adjusted for age, gender, ethnicity, poverty-to-income ratio, physical activity, and BMI (metabolic syndrome only)	did not measure dietary intake, season or sun exposure, residential geographic location or season of blood collection analysis not clustered by ethnicity
Rock et al. 1999 [44], cross-sectional, USA	white, Hispanic, African American, and other adults \geq 18 y old/ <i>n</i> = 1042	BMI	mean or prevalence of 25(OH)D concentration stratified by race was not reported multivariate analysis showed significant ($P < 0.05$) inverse association between 25(OH)D concentration and BMI per 10% increase (–6.0, –7.4 to –4.5) after adjustment for age, sex, race/ethnicity, dietary intake, supplements, serum cholesterol, serum triacylglycerols, smoking, alcohol, physical activity, sun exposure; Also, in the same model, ethnicity was the strongest independent determinant of 25(OH)D status, with non-white ethnicity predicting 25(OH)D concentration (–44.3, –48.9 to –39.2, $P < 0.05$)	only small proportion (22.6%) of sample consisted of ethnic minorities (African American, Hispanic, or other) analysis not clustered by ethnicity
Rockell et al. 2005 [29], cross-sectional, New Zealand	Maori, Pacific, and NZEO children 5–14 y old/ <i>n</i> = 2946	obesity	children's mean 25(OH)D concentrations NZEO (53nmol/L), Maori (43nmol/L), Pacific (36nmol/L) obese children had lower mean 25(OH)D levels compared with normal-weight children (99% CI, adjusted mean difference 6 nmol/L, 1–11) in multiple regression analysis adjusted for age, sex, ethnicity, season, region 25(OH)D $<$ 37.5 nmol/L predicted by ethnicity ($P < 0.01$) but not by obesity ($P > 0.01$) in logistic regression analysis adjusted for age, sex, ethnicity, season, region, and obesity	results may have underestimated mean 25(OH)D status due to time of year when blood was collected analysis not clustered by ethnicity
Rockell et al. 2006 [32], cross-sectional, New Zealand	Maori, Pacific, and NZEO-descent participants \geq 15 y old/ <i>n</i> = 2946	obesity	mean 25(OH)D concentrations in NZEO (53 nmol/L, 51–56), Pacific (34 nmol/L, 29–40) participants ($P < 0.05$); this result remained significant after adjustment for age, season, and region in multiple linear regression prevalence of VDI/VDD was 46% (52–50)% for NZEO, 61% (51–72%) for Maori, 69% (56–82%) for Pacific also, obesity (BMI) was significantly inversely related to 25(OH)D concentration in women (25 [OH]D was 6 nmol/L lower in obese than in normal-weight women, 99% CI 3–10, $P < 0.001$) but not in men ($P = 0.045$) adjusted for ethnicity, age, season, region in multiple linear regression	analysis not clustered by ethnicity vitamin D intake was not measured

Saintonge et al. 2009 [45], cross-sectional, USA	non-Hispanic black, non-Hispanic white, Mexican, and other adolescents 12–19 y old/ <i>n</i> = 2955	overweight (≥95th percentile)	mean ± SE 25(OH)D concentrations 36.1 ± 0.86 ng/mL (90.1 ± 2.1 nmol/L) for non-Hispanic whites, 27.2 ± 0.48 ng/mL (67.9 ± 1.2 nmol/L) for Mexican Americans, 21.0 ± 0.55 ng/mL (52.4 ± 1.4 nmol/L) for non-Hispanic blacks, and 26.4 ± 1.03 ng/mL (65.9 ± 2.6 nmol/L) for others; in multiple regression models, ethnicity was a statistically significant predictor of 25(OH)D <27.5 nmol/L after adjustment for gender, age, region, metropolitan area, income, education simple linear regression showed that as BMI percentile increased by 1%, 25(OH)D level decreased by 5% overweight adolescents had almost double the odds of VDD than adolescents of a normal weight (OR 1.97, 95% CI 1.26–3.08, <i>P</i> < 0.001) in multiple regression model adjusted for race/ethnicity, gender, age, region, metropolitan area, income, education	did not measure diet, supplementation, season, latitude, or sun exposure analysis not clustered by ethnicity
Scragg et al. 2004 [46], cross-sectional survey, USA	non-Hispanic black, Mexican American, and non-Hispanic white adults ≥20 y old/ <i>n</i> = 6228	BMI, T2DM, FG, 2hG, HOMA-IR, FI, HOMA-βcf	mean 25(OH)D concentration 79.6 ± 0.7 nmol/L for non-Hispanic whites, 66 ± 1 nmol/L for Mexican Americans, 49.1 ± 0.9 nmol/L for non-Hispanic blacks BMI quartile and diabetes significantly and inversely associated with 25(OH)D concentration (<i>P</i> < 0.05) after adjustment for age, sex, BMI, leisure time physical activity, and season; odds of diabetes (FG ≥7.0mmol/L) showed linear trend with 25(OH)D in non-Hispanic whites and Mexican Americans but not in non-Hispanic blacks in multiple linear regression adjusted for age, sex, BMI, leisure time physical activity, season, HOMA IR, and HOMA-βcf not associated with 25(OH)D concentration in any ethnic group (<i>P</i> > 0.05) multiple linear regression analysis adjusted for age, sex, BMI, leisure time physical activity, and season showed inverse association between 25(OH)D and FG (β = -0.009 [0.009]), 2hG (β = -0.0135 [0.067]), FI (β = -0.012 [0.005]), and HOMA-IR (β = -0.016 [0.005]) in Mexican Americans (<i>P</i> < 0.05) but not in other ethnic groups (<i>P</i> > 0.05)	no direct test for βcf or IR (calculated by FG and FI measurements) there may have been random variation in data influenced by weighting variable
Winters et al. 2009 [47], cross-sectional, USA	white and African American women 18–44 y old/ <i>n</i> = 88	BMI	mean 25(OH)D concentrations 9.5 ± 7.8 ng/mL (23.7 ± 19.5 nmol/L) for African American women, 15.4 ± 13.5 ng/mL (38.4 ± 33.7 nmol/L) for white women (<i>P</i> < 0.01) 25(OH)D levels were lower (<i>P</i> < 0.05) in white obese women compared with white normal-weight women, NS in African American women BMI associated with 25(OH)D in white women only (<i>r</i> ² = 0.10, <i>P</i> = 0.02) in multiple regression analysis adjusting for age	not all tests were standardized; blood was taken at various times of day and had no relation with mealtimes tests may have over- or underestimated 25(OH)D concentrations did not measure vitamin D intake, supplementation, sun exposure

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Table 2 (continued)

Reference, design, and country	Population/sample size	Measurements	Results	Limitations
Young et al. 2009 [31], longitudinal, USA	Hispanic and African American 25–63 y old/n = 1356 at baseline, 946 at follow-up	BMI, VAT, SAT, VSR	mean 25(OH)D concentration at baseline 16.6 ng/mL (41.4 nmol/L) for Hispanics, 11.0 ng/mL (27.5 nmol/L) for African Americans multivariate regression analysis adjusting for age, sex, smoking, marital status, clinic site (Hispanics only), and energy expenditure from physical activity showed, in Hispanics and African Americans, respectively, inverse associations between 25(OH)D and BMI (-0.006 ± 0.0009 , -0.006 ± 0.002), VAT (-0.06 ± 0.19 , -0.09 ± 0.02), and SAT (-0.13 ± 0.02 , -0.11 ± 0.04 , $P < 0.001$); also, inverse association between 25(OH)D and VSR in African Americans only (-0.007 ± 0.004 , $P = 0.049$) 5-y change in adiposity not significantly associated with 25(OH)D concentration at baseline after adjustment for age, age squared, gender, corresponding adiposity phenotype at baseline, and clinic site (Hispanics only) in multivariable regression analysis	did not measure sun exposure, vitamin D dietary intake, or supplementation did not measure 25(OH)D concentration at follow-up

%BF, percentage of body fat; 25(OH)D, 25-hydroxyvitamin D; 2hG, 2-h glucose; BFM, body fat mass; BIA, bioimpedance analysis; BMI, body mass index; CAC, coronary artery calcification; CHD, coronary heart disease; CHF, congestive heart failure; CI, confidence interval; CRP, C-reactive protein; CVD, cardiovascular disease; DEXA, dual x-ray absorptiometry; Fg, fasting glucose; Fi, fasting insulin; FM, fat mass; HbA_{1c}, glycosylated hemoglobin; HDL, high-density lipoprotein; HF, heart failure; HOMA, homeostasis model assessment; IR, insulin resistance; IS, insulin sensitivity; MI, myocardial infarction; NZEO, New Zealand European/other; OGTT, oral glucose tolerance test; OR, odds ratio; PAD, peripheral arterial disease; PG, plasma glucose; RR, risk ratio; SAT, subcutaneous adipose tissue; SES, socioeconomic status; T2DM, type 2 diabetes mellitus; TBF, total body fat; VAT, visceral adipose tissue; VDD, vitamin D deficiency; VDI, vitamin D insufficiency; VSR, ratio of visceral to subcutaneous adipose tissue; WC, waist circumference; WHR, waist-to-hip ratio; β cf, β -cell function

that the inverse relation between obesity and 25(OH)D was only significant in female subjects. Ethnicity, gender, and age may play a role in mediating the relation between 25(OH)D and weight status, which requires further investigation.

Vitamin D status and T2DM

Five studies (one included child participants only, one included children and adults, and three included adults only) investigated the associations between vitamin D and diagnosed diabetes or its risk markers (i.e., IS, insulin resistance, plasma glucose, fasting insulin, β cf, and glycolated hemoglobin; Table 2) [10,41,43,46,48]. All these studies were from the USA and included male and female participants and participants from non-Hispanic black, Hispanic, and non-Hispanic white or equivalent ethnicities. Less commonly included ethnicities were Asian American and other. Findings from these studies suggested a link between vitamin D status and risk of diabetes regardless of age, but these findings varied depending on the measurement used for ascertaining diabetes status. One study in adults observed that the odds of 25(OH)D deficiency increased for diabetics (defined by physician diagnosis, use of diabetes medications, fasting glucose >7.0 mmol/L [>126 mg/dL], or non-fasting glucose >11.1 mmol/L [>200 mg/dL]) [41]. In a study that used a slightly lower cutoff point for fasting glucose as a risk marker for diabetes (fasting glucose >5.6 mmol/L [>100 mg/dL]) [49], the relation was non-significant. In two studies that measured glucose levels over a period of 2 h, one observed significant results at fasting and 60, 90, and 120 min and non-significant results at 30 min in a racially diverse sample [34], whereas the other study observed significant results at fasting and 120 min in Mexican Americans only (not significant in non-Hispanic white and non-Hispanic black participants) [46]. In two studies that used glycosylated hemoglobin as a risk marker for diabetes, one study found an inverse association between 25(OH)D concentration and glycosylated hemoglobin [10]. However, once the analysis was stratified by race, this trend was significant only in Caucasians, not in Hispanics or African Americans. The other study did not find any relation between the two variables [43]. In two studies that used IS as a risk marker of diabetes, there was a positive association with 25(OH)D and IS [10,34]. However, Alemzadeh et al. [10] found that this relation was mediated by fat mass. In a study by Scragg et al. [46], inverse associations were also observed between 25(OH)D and fasting insulin and insulin resistance; however, these two results were significant in Mexican American participants and not in non-Hispanic black or non-Hispanic white participants [46]. Two studies [34,46] investigated β cf and found no significant correlation with 25(OH)D. The other study [46] included diabetic and non-diabetic participants and found that β cf was not associated with 25(OH)D concentration in all ethnic groups examined.

Metabolic syndrome and vitamin D

Two studies, one in adults [34] and the other in adolescents [43], investigated the associations between vitamin D and the metabolic syndrome; however, only one of these studies used multilevel analysis to investigate the potential correlation between these two variables (Table 2). The studies used different definitions for the metabolic syndrome. In a study by Chiu et al. [34] VDD (25(OH)D <20 ng/mL [50 nmol/L]) was associated with an increased risk of the metabolic syndrome (30% of deficient participants and 11% of non-deficient participants were at risk, respectively, $P = 0.0097$); however, the investigators did not

adjust for confounding variables. Reis et al. [49] found vitamin D concentration after adjustment for age, gender, race/ethnicity, poverty-to-income ratio, physical activity, and BMI in multivariate analysis to be inversely associated with the metabolic syndrome (odds ratio 3.88, 95% confidence interval 1.57–9.58, for 25[OH]D <15 ng/mL [37.4 nmol/L] compared with >26 ng/mL [64.9 nmol/L], $P = 0.003$).

CVD and vitamin D

Five studies in adults only investigated the associations between vitamin D and CVD (Table 2). All the studies were sampled from the USA. Each study examined different aspects of CVD including congestive heart failure [50]; myocardial infarction, stroke, and angina [38]; coronary heart disease, heart failure, stroke, and peripheral arterial disease [37]; hypertensive diseases, ischemic heart disease, arrhythmia, heart failure, cerebrovascular disease, atherosclerosis, and other diseases of the arteries [41]; and coronary artery calcification [35]. Four of the studies used cross-sectional data to examine the relation between vitamin D concentration (25[OH]D) and the prevalence of at least one type of CVD (or in one case, coronary artery calcification). Of these studies, after adjustment, three found significant inverse associations between vitamin D and prevalence of the CVD measurements of interest [38,50], one study found significant and non-significant associations depending on the measurement [37], and in the other study the results were non-significant [35]. Two of these studies used a longitudinal study design or passive follow-up to examine the future development of coronary artery calcification or CVD mortality rates. In a study by Melamed et al. [41], after a median 8.7-y follow-up, a 25(OH)D level lower than 17.8 ng/mL (44.4 nmol/L) was associated with a 70% higher risk of CVD mortality. However, in the fully adjusted model (age, gender, race, season, hypertension, diabetes, smoking, high-density lipoprotein cholesterol, total cholesterol, CVD history, cholesterol-lowering medications, estimated glomerular filtration rate, serum albumin, log albumin-to-creatinine ratio, log C-reactive protein, BMI, low socioeconomic status, vitamin D supplementation, and physical activity), this was no longer significant (CVD mortality rate ratio 1.20, 95% confidence interval 0.87–1.64). In a study by de Boer et al. [35], the risk of developing incident coronary artery calcification was marginally significant ($P = 0.049$) and inversely associated with 25(OH)D concentration after full adjustment. The association did not vary by age, gender, or ethnicity. Only two of the mentioned studies examined their results according to race/ethnicity. Kim et al. [37] found that in participants with CVD, hypovitaminosis D prevalence was more common in black participants, followed by Hispanic and then white participants, and that there were no consistent patterns between people of different age or gender. Kendrick et al. [38] also observed a higher prevalence of VDD in non-Hispanic black, followed by Hispanic and then non-Hispanic white participants with CVD, adjusted for age.

Discussion

This is the first study to examine the relation between 25(OH)D and obesity and obesity-related chronic diseases in migrants and ethnic minorities. Twenty articles met our criteria for inclusion. Most of the studies included in this systematic review were cross-sectional and thus are placed low within the hierarchy of evidence provided by study designs compared with the “gold standard” randomized controlled trial. For this reason, this

review could not comment on the potential causality of VDD on the symptoms of obesity and lifestyle-related chronic disease, or vice versa, within the sample of interest. Nonetheless, this systematic review presents a body of evidence consisting of weaker and sometimes conflicting (in terms of statistical significance) data, which suggests that there may be a link between VDD and obesity, T2DM, CVD, and the metabolic syndrome. The links between 25(OH)D and ethnicity are evident, although the links with migration could not be established because of the scarcity of evidence specific to migrant populations. All reviewed studies were in ethnic minorities and there was no single study that focused on newly arrived migrants.

We found that ethnic minorities had significantly higher rates of VDI/VDD and obesity than their white counterparts. Because most included studies were cross-sectional and there were variations in outcome measurements, it was not possible to assess whether it is the level of obesity or VDD driving the risks for CVD and T2DM. It is possible both have a role to play. However, obesity is a known risk factor for T2DM and CVD, and obesity may also be linked with vitamin D status. Our review highlighted the increased risk of VDI/VDD in overweight or obese participants, but with ethnic differences dependent on the index used to measure adiposity. One suggested reason for this association is that decreased bioavailability can lead to VDD because of excess fat being stored in the body, which vitamin D sequesters to, making it less available [28]. We also observed ethnic, gender-, and age-related differences when the results were stratified. The complexities of these differences can be further explored when comparing the results of BMI with those of %BF. In this systematic review, six of seven studies observed a significant relation between BMI and 25(OH)D and three of three studies observed a significant relation with %BF after multilevel analysis. Two studies [33,40] measured BMI and %BF and explored the relation between obesity and 25(OH)D further in female samples by entering BMI and %BF. In these two studies, %BF but not BMI remained in the final model, suggesting that %BF is the main predictor of 25(OH)D status. However, because the correlation between BMI and %BF was greater than 0.7 [51], it was invalid to include the two parameters together in the same regression model. Nevertheless, race and season also remained in the final model in the two studies. In a study by Arunabh et al. [33] age also remained in the final model (participants 20–28 y of age), whereas in a study by McKinney et al. [40] age did not enter the model, perhaps because of the narrow age range of participants (participants 16–33 y of age).

For T2DM, our review found a link between vitamin D status and risk of T2DM regardless of age, with four of five studies reporting a significant finding between 25(OH)D and a measurement of T2DM (Table 2). However, these findings varied depending on the measurement used for ascertaining diabetes status; four of five studies also reported a non-significant finding between 25(OH)D and a measurement of T2DM. Two of the studies investigating measurements of T2DM stratified some of their results by ethnicity and found that the results were significant only in some ethnic groups; this may have contributed to the large proportion of non-significant results. Interestingly, in the two studies investigating markers of diabetes that stratified results by ethnicity [10,46] the results were consistently non-significant for African American/non-Hispanic black participants, whereas the results for the Caucasian/non-Hispanic white and Hispanic participants were more varied, showing significant results and non-significant results. Scragg et al. [46] commented that the

consistent non-significant results in non-Hispanic black participants were unexpected and require further investigation. They suggested that there may be a threshold effect of vitamin D that is influenced by ethnicity and that non-Hispanic blacks may be less sensitive to the effect of vitamin D compared with non-Hispanic whites and Mexicans. The mechanisms behind the potential association between T2DM and 25(OH)D are unclear; vitamin D status may have an impact on a number of factors including pancreatic β cf, impaired insulin action, and systemic inflammation [52]. Nonetheless, evidence is mounting that vitamin D may be useful in the prevention and treatment of T2DM. Studies have shown supplementation in participants with VDD to result in improved glucose tolerance, whereas supplementation in participants with sufficient vitamin D has yielded conflicting results [53].

Similarly, we saw evidence that there may be a link between 25(OH)D and CVD, with four of five studies reporting significant associations; however, there was some variation depending on the measurements used, gender, and ethnicity, with three studies also reporting non-significant results. The current evidence base regarding CVD and vitamin D status suggests that there is an association between these variables, but the mechanisms behind the association are still under investigation. Separate review studies have reported that the relation between vitamin D with CVD may be influenced by a link with diabetes or hypertension [41], and that the relation between CVD and vitamin D may be due to the effect of 1, 25(OH)D on cardiomyocytes and vascular smooth muscle cells [54]. Given time and further research, this could be an interesting development toward decreasing the morbidity and mortality associated with T2DM and CVD.

Limitations

This study has a number of limitations. First, due to the longitudinal and cross-sectional study design of the included studies, they cannot be used to establish causality. Rather, this review has reported the combined existing evidence, highlighting similarities, differences, and gaps within the current evidence. Second, although we set out to examine migrant and ethnic minority groups, all samples focused on ethnic minorities and included majority population groups and not all studies stratified by race. None of the studies focused specifically on migrant groups; this could be an interesting area of further research. Third, the studies included in this review varied in terms of the tests and measurements used and the confounding variables that were adjusted for. The extent to which confounders were explored by each study may have influenced the results, contributing to the mixed evidence reported in this review.

Conclusion

Notwithstanding the limitations of the reviewed studies, the emerging evidence is that low vitamin D levels are associated with obesity, T2MD, CVD, and the metabolic syndrome depending on which index was used to measure these diseases, and ethnic minorities are the most affected. This review provides further support toward the links between ethnicity and 25(OH)D status, although the links with migration are still unclear because of a paucity of evidence specific to migrant populations. Further research specific to migrant populations using randomized controlled trials are required to establish whether causal links between 25(OH)D and obesity-related chronic disease

exist, and whether vitamin D supplementation could be valuable in the prevention or treatment of obesity-related diseases. Such research will be necessary to establish a causal relation between VDI/VDD and obesity and obesity-related chronic disease within migrant groups. Establishing an understanding of whether there is a causal relation between vitamin D status and obesity, T2DM, CVD, and the metabolic syndrome and an understanding of the mechanisms behind these links will be valuable, because established vitamin levels could be used in food fortification for the prevention or treatment T2DM and CVD.

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