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# Vitamin D modulates adipose tissue biology: possible consequences for obesity?

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Cross-sectional studies depict an inverse relationship between vitamin D (VD) status reflected by plasma 25-hydroxy-vitamin D and obesity. Furthermore, recent studies *in vitro* and in animal models tend to demonstrate an impact of VD and VD receptor on adipose tissue and adipocyte biology, pointing to at least a part-causal role of VD insufficiency in obesity and associated physiopathological disorders such as adipose tissue inflammation and subsequent insulin resistance. However, clinical and genetic studies are far less convincing, with highly contrasted results ruling out solid conclusions for the moment. Nevertheless, prospective studies provide interesting data supporting the hypothesis of a preventive role of VD in onset of obesity. The aim of this review is to summarise the available data on relationships between VD, adipose tissue/adipocyte physiology, and obesity in order to reveal the next key points that need to be addressed before we can gain deeper insight into the controversial VD–obesity relationship.

**Adipose tissue: Vitamin D: Obesity: Inflammation: Adipocytes: Nutrients: Nutrition**

## Vitamin D: a brief overview

Vitamin D (VD; calciferol) is a hormone mainly described for its role as a regulator of phosphate and calcium homeostasis[1]. It can be obtained through animal ($VD_3$, cholecalciferol) or plant ($VD_2$, ergocalciferol) food sources. Only a few foodstuffs contain significant amounts of VD, the main sources being fish liver oils, fatty fish (sardines, herring and mackerel) and egg yolk[2,3], but small quantities are also found in fortified milk, orange juice, bread and cereals. Alternatively, $VD_3$ is produced endogenously in the skin after UVB irradiation from the precursor 7-dehydrocholesterol to give pre-$VD_3$, which is further isomerised to $VD_3$ before being released into the circulation[4]. Classical estimates have assigned a majority (70–90 %) of VD supply to dermal synthesis, but a recent paper revised this figure down to just 10–25 % of VD supply[5] and posited that dietary intake of 25-hydroxy-vitamin D (25(OH)D) is a significant contributor to total VD input.

## Adipose tissue is a major storage site for vitamin D

Despite limited data, it is widely accepted that adipose tissue is a reservoir for VD in human subjects and rats[6–10]. Interestingly, visceral fat was found to contain 20 % more VD than subcutaneous fat[11]. Heaney *et al.*[12] calculated that 65 % of total VD in the body is in the form of $D_3$, for which adipose tissue and skeletal muscle appear to be the main body stores (accounting for 73 and 16 %, respectively). Regarding 25(OH)D, 34 % of it is found in adipose tissue, 30 % in serum and 20 % in skeletal muscle. However, 25(OH)D was recently

**Abbreviations:** 25(OH)D, 25-hydroxy-vitamin D; $1,25(OH)_2D$, 1,25-dihydroxy-vitamin D; MCP, monocyte chemoattractant protein; CYP24A1, vitamin D 24-hydroxylase; DBP, vitamin D-binding protein; VD, vitamin D; VDR, vitamin D receptor.

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detected in human subcutaneous adipose tissue[13]. Fat tissue may thus contain about 60 % of total body VD, but the amount of VD present in fat tissue varies strongly between individuals and is not correlated to serum 25(OH)D levels[8], whereas 25(OH)D adipose tissue content seems to be correlated to 25(OH)D plasma levels[13]. Other factors such as VD status and amount of intake can also influence adipose tissue storage. Indeed, it was calculated that for low VD intakes and when serum 25(OH)D concentration is below 88 nM/l, almost all VD is converted to 25(OH)D in the liver with very little deposited in tissues[14], indicating that low 25(OH)D status is associated with limited tissue stores as well.

A recent pilot study using time-of-flight secondary ion mass spectrometry confirmed that both VD and 25(OH)D were present in human adipose tissue, and also reported for the first time that 1,25-dihydroxy-vitamin D ($1,25(OH)_2D$) was also detectable in fat tissue[15]. This pilot study also suggested that all these molecules were located in adipocyte lipid droplets and that VD and 25(OH)D concentrations in adipose tissue were lower in obese than lean subjects, although this last observation was only generated with a very limited number of samples[15].

## Parallel between systemic vitamin D metabolism and adipose tissue metabolism

### *Uptake of vitamin D*

VD from food is partially absorbed in the distal part of the small intestine, in emulsion with bile salts[16]. Its intestinal absorption occurs not only by passive diffusion but also via at least two cholesterol carriers[17,18]. VD and its metabolites are majorly transported in the plasma bound to vitamin D-binding protein (DBP), a globulin produced in the liver[19], but also to albumin, LDL and chylomicrons for dietary VD[20]. Plasma DBP is in large excess compared with VD and metabolites, thus leaving only a very limited amount of circulating unbound VD and metabolites[21]. Interestingly, only the unbound part of VD is considered biologically active and able to diffuse in any target cells[21], thus leading to the free-hormone hypothesis[22]. Indeed, despite having low plasma levels of the different forms of VD compared with wild-type animals, Dbp-null mice do not show any signs of disrupted calcium homeostasis, suggesting that free VD levels can cover the needs of physiological functions as long as diet is VD-sufficient[23]. Subsequent work showed that kidney content of $1,25(OH)_2D$ was not different from that of wild-type animals[24]. Taken together, these data suggest that tissues may uptake VD and metabolites from the free pool through a DBP-independent mechanism.

The molecular mechanisms involved in VD uptake/secretion by adipose tissue have not yet been investigated but may well involve the megalin/cubulin pathway (described later) as suggested by Abboud *et al.*[25] and/or cholesterol transporters as described in the intestine[17] or for other lipophilic micronutrients in adipose tissue[26].

### *25-hydroxylation*

Whatever its origin (endogenous or exogenous), calciferol is taken to the liver via the circulation where the VD 25-hydroxylase enzyme catalyses the synthesis of 25(OH)D. 25(OH)D is the major circulating form of VD and its serum concentration is classically used as a marker of VD status. 25(OH)D has a relatively long half-life (15 d), and mean plasma 25(OH)D concentration varies between 20 and 50 ng/ml (50–125 nM/l)[27]. Several enzymes can accomplish this first hydroxylation of 25(OH)D, but CYP2R1 seems to be the key one[28,29]. Interestingly, $Cyp2r1^{-/-}$ mice only display a 50 % reduction in serum 25(OH)D compared with wild-type or heterozygous animals, suggesting that other enzymes help maintain circulating 25(OH)D levels and/or compensate for CYP2R1 dysfunction[30].

In human subjects, other P450 cytochromes such as CYP3A4[31], CYP2J2[32] and CYP27A1[33] display 25-hydroxylase activity towards VD molecules, but less efficiently (i.e. with a high $K_M$ relative to physiological substrate concentration)[30]. CYP2J3[34], CYP2D25 and CYP2C11 also show VD 25-hydroxylase activity but are only expressed in pigs and male rats, respectively[35,36].

25-Hydroxylation seems to be functional in adipose tissue, as Zoico *et al.*[37] recently reported that 25(OH)D release in the cell culture medium increased after 24 h incubation of 3T3-L1 adipocytes with VD. This production of 25(OH)D could be due to the presence of Cyp27A1, which is up-regulated by VD treatment. Interestingly, human adipose tissue biopsies have confirmed the expression of CYP27A1, CYP2R1 and CYP2J2[38], suggesting that human adipose tissue and adipocytes are able to convert VD to 25(OH)D.

### *1α-hydroxylation*

In renal proximal tubule cells, urinary loss of DBP–25(OH)D complexes is prevented by uptake via the membrane receptors megalin (also known as low-density lipoprotein receptor-related protein 2) and cubilin[39,40]. After internalisation into vesicles, DBP is degraded into lysosomes and 25(OH)D is handled by intracellular DBP. Intracellular DBP have been identified in VD-resistant new-world primates (four isoforms have been reported so far), are related to the human heat-shock protein 70 family, and are thought to mediate 25(OH)D interactions with intracellular proteins[41]. An additional binding protein termed cytosolic DBP has also been isolated from human intestinal cells[42]. 25(OH)D is then either secreted into circulation or directed towards mitochondrial 1α-hydroxylase CYP27B1 to be metabolised into $1,25(OH)_2D$, the active form of VD. CYP27B1 is the key enzyme of 1α-hydroxylation and its activity is regulated by parathyroid hormone, fibroblast growth factor 23, calcium and phosphorus and self-regulated by $1,25(OH)_2D$ via a negative-feedback mechanism[1]. $1,25(OH)_2D$ has a very short half-life (about 4 h) and is 1000 times less concentrated than 25(OH)D in the plasma.

The ability of adipocytes to convert 25(OH)D into $1,25(OH)_2D$ was initially demonstrated in 3T3-L1 cells

via the activation of a gene reporter system and through the identification of radiolabelled $1,25(OH)_2D$ derived from radiolabelled 25(OH)D[43]. The production of $1,25(OH)_2D$ from 25(OH)D was then confirmed by Ching *et al.*[44] and Nimitphong *et al.*[45]. CYP27B1 expression has also been detected in murine adipocytes[43] and in human adipose tissue biopsies[38].

### *24-hydroxylation*

Finally, vitamin D 24-hydroxylase (CYP24A1) is in charge of inactivating $1,25(OH)_2D$. This inactivation is self-regulated, since $1,25(OH)_2D$ induces the expression of CYP24A1 that converts 25(OH)D and $1,25(OH)_2D$ into less-active metabolites (e.g. $24,25(OH)_2D$ and $1,24,25(OH)_3D$), which are further catabolised into inactive calcitroic acid[40].

In adipose tissue, CYP24A1 expression has been detected in murine and human adipocytes[43,45]. In addition, the mRNA levels of CYP24A1 are strongly induced by $1,25(OH)_2D$ incubation[43,45]. CYP24A1 expression has also been confirmed in human adipose tissue biopsies[38].

### *Vitamin D signalling*

Even if few VD receptor (VDR)-independent effects of $1,25(OH)_2D$ have been documented[46], most biological activities of VD are mediated by the VDR, a member of the nuclear receptor superfamily that is the only nuclear receptor that binds $1,25(OH)_2D$ with high affinity[47,48]. VDR expression has been demonstrated in almost all human tissues[49], which means that all cells are potential targets of $1,25(OH)_2D$ action. The VDR–$1,25(OH)_2D$ complex is associated with the retinoid X receptor[50], and the retinoid X receptor–VDR–$1,25(OH)_2D$ complex binds to the DNA of sites called VD response elements in the promoter region of genes whose expression is either activated or repressed[47]. There are more than 1000 genes that are directly or indirectly regulated by $1,25(OH)_2D$ and involved in various physiological processes such as cell proliferation, differentiation, apoptosis and angiogenesis[51].

The presence of VDR in adipose tissue was first reported in the early 1990s[52] and has since been widely confirmed. Interestingly, it was recently found that VDR expression is increased in obese compared with lean subjects[38,53], but the physiological relevance of this up-regulation has not yet been elucidated.

Another VD-dependent signalling pathway has been described that involves ERp57 (also known as GRP58 or 1,25D3-MARRS), a protein disulfide isomerase involved in stress response[54] that mediates rapid cellular responses (i.e. within seconds or minutes) to $1,25(OH)_2D$ stimulation[55,56]. ERp57–$1,25(OH)_2D$ complexes are internalised, which opens the possibility that ERp57 might also participate in $1,25(OH)_2D$ intracellular trafficking, especially since ERp57 has been found to participate in nuclear complexes, including heat-shock protein 70, one of the human intracellular DBP. However, it is not yet known whether this signalling pathway is active in other tissues, particularly adipose tissue.

Taken together, these data demonstrate that on top of being a major storage site for VD, adipose tissue also expresses enzymes involved in VD metabolism and signalling, which points to the hypothesis that adipose tissue could be a target tissue that is also able to synthesise 25(OH)D and $1,25(OH)_2D$ that could be locally active via paracrine, autocrine or even intracrine processes[57]. The regulation of this local metabolism has never been studied but certainly warrants future investigation. Nevertheless, there is increasing evidence of the impact of VD and its active metabolites on adipose tissue, notably in terms of adipogenesis control, adipokine expression and a host of other metabolic regulations.

## *In vitro* and *in vivo* effects of vitamin D on adipose tissue and adipocyte biology

### *Regulation of adipogenesis*

Many studies have examined the role of $1,25(OH)_2D$ in the proliferation and differentiation of murine 3T3-L1 pre-adipocytes[52,58–61]. Low $1,25(OH)_2D$ concentrations were associated with an inhibition of adipogenesis and a reduction of TAG accumulation in 3T3-L1 cells, even if the opposite effects, i.e. induction of adipogenesis, have also been depicted in this cellular model[62]. The mechanism governing these effects implies $1,25(OH)_2D$-mediated down-regulation[59,60] of C/EBPα and PPARγ, the two master regulators of adipogenesis[63]. Other mechanisms such as antagonisation of PPARγ activity and stabilisation of the VDR protein are also components of this complex regulation[59]. Similar results, i.e. inhibited differentiation under $1,25(OH)_2D$, have also been reported in brown adipocytes[64].

However, these data have been recently challenged in human adipocytes where $1,25(OH)_2D$ enhanced adipocyte differentiation and lipid accumulation[45]. Interestingly, a similar activation of adipogenesis was found in primary mouse pre-adipocytes (albeit at a more advanced stage of differentiation compared with 3T3-L1 cells, suggesting that stage of differentiation is a key factor in the nature of the effect of $1,25(OH)_2D$ on adipogenesis). Similarly, $1,25(OH)_2D$ also increased adipogenesis in human adult stem cells derived from adipose tissue, as revealed by lipid accumulation and expression of adipogenic markers[65].

To summarise, the effects of $1,25(OH)_2D$ and VDR on adipogenesis are not fully consistent: VDR appears to act as a promoter of adipogenesis, but $1,25(OH)_2D$ has less clear effects. It is currently difficult to firmly conclude in favour of an anti- or pro-adipogenic effect, and further *in vivo* studies are required to clarify this point.

### *Regulation of gene expression linked to energy metabolism*

VD and particularly $1,25(OH)_2D$ may also influence adipose tissue and systemic biology. Indeed, $1,25(OH)_2D$ directly up-regulated leptin expression and secretion,


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independently of fat mass modifications[66]. 1,25(OH)$_2$D was found to promote glucose uptake by adipocytes[67], which could be related to the induction of GLUT4 protein expression and translocation observed in 3T3-L1 adipocytes[68]. We showed that VD supplementation in mice led to an increase of fatty oxidation (especially in brown adipose tissue) that could be responsible for a high-fat diet-induced limitation of body weight gain in VD-supplemented mice[69]. Note that similar weight gain limitations in response to VD supplementation have been reported in mice[70] while VD-deficient old rats showed fat mass gain[71]. Likewise, a global dietary vitamin restriction was associated with an increase of adiposity and a disruption of glucose homeostasis[72] in mice.

Taken together, these data suggest that VD regulates energy expenditure, notably via its impact on adipose tissue biology.

### *Regulation of inflammation*

Initial studies performed on human and mouse adipocytes (3T3-L1) found that 1,25(OH)$_2$D up-regulates several inflammatory cytokines and down-regulates anti-inflammatory cytokines in both cell types[73,74]. These results have since been challenged by several groups[67,75–77] who consistently report anti-inflammatory effects of 1,25(OH)$_2$D whatever the model studied, which fits better with the well-described anti-inflammatory effect of VD in many other cell types[78]. Indeed, it was shown that 1,25(OH)$_2$D significantly decreased the release of IL-8, monocyte chemoattractant protein (MCP)-1 and IL-6 by human preadipocytes[76] and MCP-1 by human adipocytes[75]. These anti-inflammatory effects were associated with inhibition of the NF-κB signalling pathway[77]. We also demonstrated the anti-inflammatory properties of 1,25(OH)$_2$D in murine and human adipocytes[67]. In these various models, 1,25(OH)$_2$D was able to decrease the expression of inflammatory markers such as IL-6, IL-1β and MCP-1 in both basal and TNFα-stimulated conditions[67]. Similarly, 1,25(OH)$_2$D reduced the expression of IL-6, IL-8 and MCP-1 in human adipose tissue biopsies submitted to IL-1β stimulation *in vitro*[79]. The molecular mechanisms have been investigated, and VDR and NF-κB signalling pathways and p38 mitogen-activated protein kinases were shown to be involved in 3T3-L1 adipocytes[67]. Interestingly, Zoico *et al.* recently demonstrated that VD, similarly to 1,25(OH)$_2$D, was able to blunt the lipopolysaccharide-mediated pro-inflammatory effect in human adipocytes[37]. Using a microarray approach, we recently demonstrated that 1,25(OH)$_2$D was able to down-regulate a large set of chemokines[80] induced by inflammatory stimulus[81] in human and murine adipocytes. This effect was accompanied by a reduction of macrophage migration mediated by an adipocyte-conditioned medium[80].

These anti-inflammatory properties of 1,25(OH)$_2$D have also been established in several types of immune cells found in the adipose tissue, including lymphocytes and macrophages[78]. Furthermore, 1,25(OH)$_2$D reduced macrophage-induced inflammatory response in human adipocytes via inhibition of NF-κB and mitogen-activated protein kinase activation together with monocyte migration mediated by the adipocyte-conditioned medium[82]. These data suggest that VD not only blunts adipocyte response to inflammatory stimulus, but also interferes with macrophage/adipocyte cross-talk, a key element of the propagation of metabolic inflammation in obesity[83].

The anti-inflammatory effect of VD in adipose tissue has also been observed *in vivo*. It was reported that dietary treatment with 1,25(OH)$_2$D-reduced IL6 protein content in the epididymal adipose tissue of obese mice[84], whereas feeding with a VD-deficient high-fat diet was found to increase Il-6 expression in rat adipose tissue[85]. In addition, we recently demonstrated that VD supplementation of high-fat diet reduced the expression of proinflammatory cytokines and chemokines and inhibited macrophage infiltration in the adipose tissue of obese mice[80]. Similar effects of VD supplementation were found in an acute inflammation model (intraperitoneal injection of LPS) where no modification of body weight was measured[80], which strongly suggests that the decreased inflammatory status of adipose tissue observed in obese mice is not only a consequence of reduced fat mass[69] but is also driven by an anti-inflammatory effect of VD *per se*.

To summarise, it has been demonstrated *in vitro* and *in vivo* that VD has a limiting effect on adipose tissue inflammation, acting on both inflammatory status in pre-adipocytes and adipocytes and on leucocyte infiltration.

## Energy metabolism in transgenic mice models impacting vitamin D metabolism

Several transgenic mice models generated over the last decade have been used to gain insight into the role of VD metabolism in body weight management and adipose tissue metabolism. Studies using transgenic mouse models have shown that Vdr$^{-/-}$ and Cyp27b1$^{-/-}$ mice (which are unable to synthesise 1,25(OH)$_2$D) are resistant to diet-induced obesity[86,87]. This phenotype was linked to the co-induction of fatty acid β-oxidation and uncoupling proteins in adipose tissue leading to increased energy expenditure in these mice. Conversely, overexpression of human VDR in mouse adipose tissue induced an obese phenotype characterised by increased weight and fat mass due to decreased energy expenditure, reduced fatty acid β-oxidation and lipolysis[88].

Taken together, these data strongly suggest that VDR or 1,25(OH)$_2$D has an impact on overall energy metabolism by acting on adipose tissue biology, but with a number of caveats. First of all, the use of global knockout models makes it difficult to attribute the observed phenotype to a specific tissue. In addition, these mice were fed a rescue diet containing large amounts of calcium and lactose, and calcium is strongly suspected to regulate energy homeostasis and well known to reduce intestinal lipid absorption[89]. Moreover, in wild-type mice, high-calcium rescue diet[86] has been shown to reduce 1,25(OH)$_2$D to extremely low levels similar to Cyp27b1$^{-/-}$ mice[90], making it unlikely that the observed effect on body weight is attributable to 1,25(OH)$_2$D.


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In all these animal models ($Vdr^{-/-}$, $Cyp27b1^{-/-}$ and human VDR overexpression), phenotype appears tightly linked to uncoupling protein-1 modulation[86–88]. However, we now know that unliganded VDR can down-regulate uncoupling protein-1[91], which means the VDR knockout could trigger an increase in uncoupling protein-1 leading to obesity resistance independently of plasma or adipose tissue levels of $1,25(OH)_2D$ or other VD metabolites. In this case, the resistance to diet-induced obesity observed in $Vdr^{-/-}$ mice would be only VDR-dependent and not mediated by its ligand[87]. This would also be the case of human VDR overexpression where a down-regulation of uncoupling protein-1 is associated with weight gain[88]. In the case of $Cyp27b1^{-/-}$, the decrease in $1,25(OH)_2D$ plasma levels likely results in a decrease of VDR, since VDR is able to induce its own expression[92], leading to the observed phenotype[86]. The phenotype of these mice models could stem from other mechanisms too, e.g. modification of the bile acid pool, as recently evoked[93].

Further research is clearly needed to provide an explanation (if any) that could reconcile data from transgenic mice and nutritional approaches on the impact of VD on energy metabolism regulation. An important aspect to investigate would be the concentrations of VD and its metabolites in adipose tissue in the different mice models (notably between lean and obese animals) and the regulation of VD metabolism in adipocytes, which remains largely unknown.

## Effects of vitamin D on obesity and associated disorders in human studies

Numerous cross-sectional studies have reported a correlation between VD deficiency and obesity. Indeed, serum 25(OH)D is consistently lower in obese than lean individuals[94]. A recent meta-analysis found that prevalence of VD deficiency was 35 % higher in obese and 25 % higher in overweight compared with lean subjects[95]. In addition, 25(OH)D plasma levels are inversely correlated to all the parameters of obesity, including BMI, fat mass and waist circumference[96,97], and increased dietary intake of VD, resulting in higher 25(OH)D plasma levels, is associated with a lower visceral adiposity[98].

The fact that adipose tissue is the main storage site for VD and/or its metabolites in the body has prompted the hypothesis that VD and/or its metabolites gets sequestered in the excess fat mass in obese persons[99]. However, the physiological mechanisms underlying this hypothesis have not been brought forward. Nevertheless, as pointed out in a recent study from Drincic *et al.*[100], it might just be that in individuals with a higher body mass, 25(OH)D is simply diluted in a higher volume, so they would require greater VD input than lean individuals to achieve a sufficient 25(OH)D status. Decreased plasma 25(OH)D levels could also result from a modification in VD metabolism occurring during obesity development. Indeed, modifications in the expression of genes encoding key enzymes of VD metabolism have been reported in the adipose tissue of obese people[38].

The relationship between obesity and $1,25(OH)_2D$ is less clear. Recent studies have reported an inverse relationship between $1,25(OH)_2D$ and BMI and fat mass[101,102] while an older study found a direct relationship[103]. The origin of these inconsistent results is unclear but could stem from methodological bias in calcitriol measurement or else indicate that serum $1,25(OH)_2D$ displays an inter-individual variability that is not adiposity-related. Also, no data are available on $1,25(OH)_2D$ concentration in adipose tissue, which could be the critical effector in relation to obesity.

Several recent prospective studies have reported that low 25(OH)D plasma levels were associated with higher prevalence of obesity in adults[104,105], children[106] and elderly women[107]. Low 25(OH)D was also associated with higher 5-year waist circumference[108]. Low VD intake has also been considered as predictor of obesity[109]. Mechanistic explanations to these prospective observations are scarce. Indeed, the impact of VD on the regulation of energy metabolism in human subjects is still unclear. Baseline 25(OH)D was positively correlated to diet-induced thermogenesis[110], which could at least partly explain why low 25(OH)D concentrations chronically modify energy balance. However, Boon *et al.* reported no effect of VD supplementation on energy expenditure and fat metabolism, but it should be noted that their supplementation regime was for 1 week only[111].

Intervention studies have been designed to study the causality between low plasma 25(OH)D levels and obesity. Except for Salehpour *et al.*[112] who reported that VD supplementation decreased body fat mass in healthy overweight and obese women, most randomised clinical trials have failed to demonstrate any benefit of VD supplementation in terms of weight loss[113–115]. These data were recently meta-analysed, and the lack of major effect of VD supplementation on weight loss was confirmed[116]. However, a well-designed randomised controlled trial combining a weight loss programme together with placebo or VD supplementation highlighted that VD supplementation was associated with a significantly higher reduction of BMI and waist circumference in subjects with 25(OH)D levels raised to 80 nM/l[117], suggesting that beneficial effects of the supplementation only kick in with elevated plasma 25(OH)D levels.

A recent study using Mendelian randomisation of several thousands of volunteers of different age, gender and geographical location demonstrated that an increase in BMI could cause a decrease in 25(OH)D status, whereas VD insufficiency would at most result in only very minor effects on obesity[118]. Note that the study only focused on genes related to 25(OH)D status (VDBP, DHCR7, CYP2R1 and CYP24A1) and chosen on the basis of a genome-wide association study[119] that explained 1–4 % of the variation in 25(OH)D concentrations, and so it cannot be ruled out that the use of polymorphisms present in other VD-related genes (such as VDR or CYP27B1) as instrumental variables of the Mendelian randomisation may lead to divergent results. Another large-scale study including Chinese women failed to show an association between obesity and genetic variants in genes in the pathway of VD metabolism[120], whereas

several other studies found associations, notably between VDR polymorphisms and adiposity[121]. The origin of these discrepancies has not been established but could stem from ethnic specificities, since it is well established that ethnicity is a significant determinant of plasma 25 (OH)D[122].

Taken together, these data suggest that VD may limit weight gain in human subjects even if it has no clear effect on weight reduction in obese or overweight people. However, clinical trials are needed to provide conclusive proof and to define the mechanisms governing this potential preventive effect of VD against obesity development. The question of the impact of VD supplementation and polymorphisms present in genes coding for key enzymes of VD metabolism remains unclear, and will require further investigations. Equally useful would be studies on the impact of VD supplementation on adipose tissue biology in well-designed randomised clinical trials that should follow several criteria, chiefly low baseline 25 (OH)D, use of doses necessary to raise 25(OH)D concentrations up to 75–80 nM/l, and genotyping subjects.

## Conclusions

Recent data from different research groups are converging to highlight the impacts of VD on adipose tissue/adipocyte biology. One of the best-documented effects is the ability of VD to limit the expression for inflammatory markers in adipose tissue and adipocytes. However, several key points urgently warrant further investigation, chiefly VD metabolism and its regulation in adipose tissue, which needs to be clarified, especially in the context of physiopathological disorders such as obesity. The last 5 years have seen some very interesting data in transgenic mice and rodents subjected to VD supplementation or restriction, but still without convergent findings. It is urgent to identify the origin of these discrepancies, where a key factor could be the quantification of VD metabolites in adipose tissue. Randomised clinical trials have been performed, but again the results remain contrasted, leaving persistent uncertainty over a beneficial role of VD supplementation on weight management. However, results from a recent intervention study suggest that a minimum level of plasma 25(OH)D has to be reached in order to elicit a beneficial effect from supplementation, since only subjects that became replete showed improvements in several parameters[116]. This observation is consistent with successful investigations in mice where plasma 25(OH)D levels were inflated. This same study also demonstrates that it is important to stratify the data according to 25(OH)D status in order to explore and interpret differential physiological responses at the end of the supplementation period, an approach that should be used in future clinical studies. Recent prospective studies have presented low plasma 25(OH)D levels as a predictor of body weight gain, suggesting that VD may limit the prevalence of obesity. If these observations are confirmed in dedicated well-designed clinical studies, it could pave the way to the use of VD in preventive nutrition to limit the development of obesity and associated disorders, notably by reducing the inflammatory status.

To conclude, even if preclinical studies have provided strong support for beneficial impacts of VD supplementation, well-designed clinical studies are urgently needed to demonstrate real valuable utility for limiting obesity in human subjects.

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## Conflict of Interest

None.

## Authorship

All authors participated in writing up this review.

## References

1. Holick MF (2007) Vitamin D deficiency. *N Engl J Med* **357**, 266–281.
2. Holick MF, Binkley NC, Bischoff-Ferrari HA *et al.* (2011) Evaluation, treatment, and prevention of vitamin D deficiency: an Endocrine Society clinical practice guideline. *J Clin Endocrinol Metab* **96**, 1911–1930.
3. Schmid A & Walther B (2013) Natural vitamin d content in animal products. *Adv Nutr* **4**, 453–462.
4. Holick MF (2011) Vitamin D: a D-lightful solution for health. *J Investig Med* **59**, 872–880.
5. Heaney RP, Armas LA & French C (2013) All-source basal vitamin d inputs are greater than previously thought and cutaneous inputs are smaller. *J Nutr* **143**, 571–575.
6. Mawer EB, Backhouse J, Holman CA *et al.* (1972) The distribution and storage of vitamin D and its metabolites in human tissues. *Clin Sci* **43**, 413–431.
7. Blum M, Dolnikowski G, Seyoum E *et al.* (2008) Vitamin $D_{(3)}$ in fat tissue. *Endocrine* **33**, 90–94.
8. Pramyothin P, Biancuzzo RM, Lu Z *et al.* (2011) Vitamin D in adipose tissue and serum 25-hydroxyvitamin D after roux-en-Y gastric bypass. *Obesity* (*Silver Spring*) **19**, 2228–2234.
9. Landrier JF, Marcotorchino J & Tourniaire F (2012) Lipophilic micronutrients and adipose tissue biology. *Nutrients* **4**, 1622–1649.
10. Marcotorchino J, Tourniaire F & Landrier JF (2013) Vitamin D, adipose tissue, and obesity. *Horm Mol Biol Clin Investig* **15**, 123–128.
11. Beckman LM, Earthman CP, Thomas W *et al.* (2013) Serum 25(OH) vitamin D concentration changes after Roux-en-Y gastric bypass surgery. Obesity *(Silver Spring)* **21**, E599–606.

12. Heaney RP, Horst RL, Cullen DM *et al.* (2009) Vitamin $D_3$ distribution and status in the body. *J Am Coll Nutr* **28**, 252–256.
13. Piccolo BD, Dolnikowski G, Seyoum E *et al.* (2013) Association between subcutaneous white adipose tissue and serum 25-hydroxyvitamin D in overweight and obese adults. *Nutrients* **5**, 3352–3366.
14. Heaney RP, Armas LA, Shary JR *et al.* (2008) 25-Hydroxylation of vitamin $D_3$: relation to circulating vitamin D3 under various input conditions. *Am J Clin Nutr* **87**, 1738–1742.
15. Malmberg P, Karlsson T, Svensson H *et al.* (2014) A new approach to measuring vitamin D in human adipose tissue using time-of-flight secondary ion mass spectrometry: a pilot study. *J Photochem Photobiol B* **138**, 295–301.
16. Borel P, Caillaud D & Cano NJ (2015) Vitamin d bioavailability: state of the art. *Crit Rev Food Sci Nutr* **55**, 1193–1205.
17. Reboul E, Goncalves A, Comera C *et al.* (2011) Vitamin D intestinal absorption is not a simple passive diffusion: evidences for involvement of cholesterol transporters. *Mol Nutr Food Res* **55**, 691–702.
18. Reboul E (2015) Intestinal absorption of vitamin D: from the meal to the enterocyte. *Food Funct* **6**, 356–362.
19. Daiger SP, Schanfield MS & Cavalli-Sforza LL (1975) Group-specific component (Gc) proteins bind vitamin D and 25-hydroxyvitamin D. *Proc Natl Acad Sci USA* **72**, 2076–2080.
20. Haddad JG, Jennings AS & Aw TC (1988) Vitamin D uptake and metabolism by perfused rat liver: influences of carrier proteins. *Endocrinology* **123**, 498–504.
21. Speeckaert M, Huang G, Delanghe JR *et al.* (2006) Biological and clinical aspects of the vitamin D binding protein (Gc-globulin) and its polymorphism. *Clin Chim Acta* **372**, 33–42.
22. Mendel CM (1989) The free hormone hypothesis: a physiologically based mathematical model. *Endocr Rev* **10**, 232–274.
23. Safadi FF, Thornton P, Magiera H *et al.* (1999) Osteopathy and resistance to vitamin D toxicity in mice null for vitamin D binding protein. *J Clin Invest* **103**, 239–251.
24. Zella LA, Shevde NK, Hollis BW *et al.* (2008) Vitamin D-binding protein influences total circulating levels of 1,25-dihydroxyvitamin $D_3$ but does not directly modulate the bioactive levels of the hormone *in vivo*. *Endocrinology* **149**, 3656–3667.
25. Abboud M, Gordon-Thomson C, Hoy AJ *et al.* (2013) Uptake of 25-hydroxyvitamin D by muscle and fat cells. *J Steroid Biochem Mol Biol* **144**, 232–236.
26. Moussa M, Gouranton E, Gleize B *et al.* (2011) CD36 is involved in lycopene and lutein uptake by adipocytes and adipose tissue cultures. *Mol Nutr Food Res* **55**, 578–584.
27. Jones KS, Schoenmakers I, Bluck LJ *et al.* (2012) Plasma appearance and disappearance of an oral dose of 25-hydroxyvitamin $D_2$ in healthy adults. *Br J Nutr* **107**, 1128–1137.
28. Cheng JB, Motola DL, Mangelsdorf DJ *et al.* (2003) De-orphanization of cytochrome P450 2R1: a microsomal vitamin D 25-hydroxilase. *J Biol Chem* **278**, 38084–38093.
29. Schuster I (2011) Cytochromes P450 are essential players in the vitamin D signaling system. *Biochim Biophys Acta* **1814**, 186–199.
30. Zhu J & DeLuca HF (2012) Vitamin D 25-hydroxylase - four decades of searching, are we there yet? *Arch Biochem Biophys* **523**, 30–36.
31. Gupta RP, Hollis BW, Patel SB *et al.* (2004) CYP3A4 is a human microsomal vitamin D 25-hydroxylase. *J Bone Miner Res* **19**, 680–688.
32. Aiba I, Yamasaki T, Shinki T *et al.* (2006) Characterization of rat and human CYP2J enzymes as vitamin D 25-hydroxylases. *Steroids* **71**, 849–856.
33. Guo YD, Strugnell S, Back DW *et al.* (1993) Transfected human liver cytochrome P-450 hydroxylates vitamin D analogs at different side-chain positions. *Proc Natl Acad Sci U S A* **90**, 8668–8672.
34. Yamasaki T, Izumi S, Ide H *et al.* (2004) Identification of a novel rat microsomal vitamin $D_3$ 25-hydroxylase. *J Biol Chem* **279**, 22848–22856.
35. Postlind H, Axen E, Bergman T *et al.* (1997) Cloning, structure, and expression of a cDNA encoding vitamin $D_3$ 25-hydroxylase. *Biochem Biophys Res Commun* **241**, 491–497.
36. Rahmaniyan M, Patrick K & Bell NH (2005) Characterization of recombinant CYP2C11: a vitamin D 25-hydroxylase and 24-hydroxylase. *Am J Physiol Endocrinol Metab* **288**, E753–E760.
37. Zoico E, Franceschetti G, Chirumbolo S *et al.* (2014) Phenotypic shift of adipocytes by cholecalciferol and 1alpha,25 dihydroxycholecalciferol in relation to inflammatory status and calcium content. *Endocrinology* **155**, 4178–4188.
38. Wamberg L, Christiansen T, Paulsen SK *et al.* (2012) Expression of vitamin D-metabolizing enzymes in human adipose tissue-the effect of obesity and diet-induced weight loss. *Int J Obes (Lond)* **37**, 651–657.
39. Nykjaer A, Dragun D, Walther D *et al.* (1999) An endocytic pathway essential for renal uptake and activation of the steroid 25-(OH) vitamin D3. *Cell* **96**, 507–515.
40. Dusso AS, Brown AJ, Slatopolsky E (2005) Vitamin D. *Am J Physiol Renal Physiol* **289**, F8–F28.
41. Gacad MA, Chen H, Arbelle JE *et al.* (1997) Functional characterization and purification of an intracellular vitamin D-binding protein in vitamin D-resistant new world primate cells. Amino acid sequence homology with proteins in the hsp-70 family. *J Biol Chem* **272**, 8433–8440.
42. Teegarden D, Nickel KP & Shi L (2000) Characterization of 25-hydroxyvitamin D binding protein from intestinal cells. *Biochem Biophys Res Commun* **275**, 845–849.
43. Li J, Byrne ME, Chang E *et al.* (2008) 1alpha,25-Dihydroxyvitamin D hydroxylase in adipocytes. *J Biochem Mol Biol* **112**, 122–126.
44. Ching S, Kashinkunti S, Niehaus MD *et al.* (2011) Mammary adipocytes bioactivate 25-hydroxyvitamin $D_{(3)}$ and signal via vitamin $D_{(3)}$ receptor, modulating mammary epithelial cell growth. *J Cell Biochem* **112**, 3393–3405.
45. Nimitphong H, Holick MF, Fried SK *et al.* (2012) 25-hydroxyvitamin d(3) and 1,25-dihydroxyvitamin d(3) promote the differentiation of human subcutaneous preadipocytes. *PLoS ONE* **7**, e52171.
46. Lips P (2006) Vitamin D physiology. *Prog Biophys Mol Biol* **92**, 4–8.
47. Carlberg C & Seuter S (2009) A genomic perspective on vitamin D signaling. *Anticancer Res* **29**, 3485–3493.
48. Bikle DD, Gee E & Pillai S (1993) Regulation of keratinocyte growth, differentiation, and vitamin D metabolism by analogs of 1,25-dihydroxyvitamin D. *J Invest Dermatol* **101**, 713–718.
49. Bouillon R, Carmeliet G, Verlinden L *et al.* (2008) Vitamin D and human health: lessons from vitamin D receptor null mice. *Endocr Rev* **29**, 726–776.
50. Issa LL, Leong GM & Eisman JA (1998) Molecular mechanism of vitamin D receptor action. *Inflamm Res* **47**, 451–475.

51. Plum LA & DeLuca HF (2010) Vitamin D, disease and therapeutic opportunities. *Nat Rev Drug Discov* **9**, 941–955.
52. Kamei Y, Kawada T, Kazuki R *et al.* (1993) Vitamin D receptor gene expression is up-regulated by 1, 25-dihydroxyvitamin $D_3$ in 3T3-L1 preadipocytes. *Biochem Biophys Res Commun* **193**, 948–955.
53. Clemente-Postigo M, Munoz-Garach A, Serrano M *et al.* (2015) Serum 25-hydroxyvitamin d and adipose tissue vitamin d receptor gene expression: relationship with obesity and type 2 diabetes. *J Clin Endocrinol Metab* **100**, E591–E595.
54. Turano C, Gaucci E, Grillo C *et al.* (2011) ERp57/GRP58: a protein with multiple functions. *Cell Mol Biol Lett* **16**, 539–563.
55. Nemere I, Safford SE, Rohe B *et al.* (2004) Identification and characterization of $1,25D_3$-membrane-associated rapid response, steroid ($1,25D_3$-MARRS) binding protein. *J Steroid Biochem Mol Biol* **89–90**, 281–285.
56. Nemere I & Hintze K (2008) Novel hormone 'receptors'. *J Cell Biochem* **103**, 401–407.
57. Lisse TS, Adams JS & Hewison M (2013) Vitamin D and microRNAs in bone. *Crit Rev Eukaryot Gene Expr* **23**, 195–214.
58. Ishida Y, Taniguchi H & Baba S (1988) Possible involvement of 1 alpha,25-dihydroxyvitamin $D_3$ in proliferation and differentiation of 3T3-L1 cells. *Biochem Biophys Res Commun* **151**, 1122–1127.
59. Kong J & Li YC (2006) Molecular mechanism of 1,25-dihydroxyvitamin $D_3$ inhibition of adipogenesis in 3T3-L1 cells. *Am J Physiol Endocrinol Metab* **290**, E916–E924.
60. Blumberg JM, Tzameli I, Astapova I *et al.* (2006) Complex role of the vitamin D receptor and its ligand in adipogenesis in 3T3-L1 cells. *J Biol Chem* **281**, 11205–11213.
61. Mutt SJ, Hypponen E, Saarnio J *et al.* (2014) Vitamin D and adipose tissue – more than storage. *Front Physiol* **5**, 228.
62. Vu D, Ong JM, Clemens TL *et al.* (1996) 1,25-Dihydroxyvitamin D induces lipoprotein lipase expression in 3T3-L1 cells in association with adipocyte differentiation. *Endocrinology* **137**, 1540–1544.
63. Farmer SR (2006) Transcriptional control of adipocyte formation. *Cell Metab* **4**, 263–273.
64. Ricciardi CJ, Bae J, Esposito D *et al.* (2014) 1,25-Dihydroxyvitamin D/vitamin D receptor suppresses brown adipocyte differentiation and mitochondrial respiration. *Eur J Nutr* **54**, 1001–1012.
65. Narvaez CJ, Simmons KM, Brunton J *et al.* (2013) Induction of STEAP4 correlates with 1,25-dihydroxyvitamin D3 stimulation of adipogenesis in mesenchymal progenitor cells derived from human adipose tissue. *J Cell Physiol* **228**, 2024–2036.
66. Kong J, Chen Y, Zhu G *et al.* (2013) 1,25-Dihydroxyvitamin $D_3$ upregulates leptin expression in mouse adipose tissue. *J Endocrinol* **216**, 265–271.
67. Marcotorchino J, Gouranton E, Romier B *et al.* (2012) Vitamin D reduces the inflammatory response and restores glucose uptake in adipocytes. *Mol Nutr Food Res* **56**, 1771–1782.
68. Manna P & Jain SK (2012) Vitamin D upregulates glucose transporter 4 (GLUT4) translocation and glucose utilization mediated by cystathionine-gamma-lyase (CSE) activation and $H_2S$ formation in 3T3L1 adipocytes. *J Biol Chem* **287**, 42324–42332.
69. Marcotorchino J, Tourniaire F, Astier J *et al.* (2014) Vitamin D protects against diet-induced obesity by enhancing fatty acid oxidation. *J Nutr Biochem* **25**, 1077–1083.
70. Sergeev IN & Song Q (2014) High vitamin D and calcium intakes reduce diet-induced obesity in mice by increasing adipose tissue apoptosis. *Mol Nutr Food Res* **58**, 1342–1348.
71. Domingues-Faria C, Chanet A, Salles J *et al.* (2014) Vitamin D deficiency down-regulates Notch pathway contributing to skeletal muscle atrophy in old Wistar rats. *Nutr Metab* (*Lond*) **11**, 47.
72. Amara NB, Marcotorchino J, Tourniaire F *et al.* (2014) Multivitamin restriction increases adiposity and disrupts glucose homeostasis in mice. *Genes Nutr* **9**, 410.
73. Sun X & Zemel MB (2007) Calcium and 1,25-dihydroxyvitamin $D_3$ regulation of adipokine expression. *Obesity* (*Silver Spring*) **15**, 340–348.
74. Sun X & Zemel MB (2008) Calcitriol and calcium regulate cytokine production and adipocyte-macrophage cross-talk. *J Nutr Biochem* **19**, 392–399.
75. Lorente-Cebrian S, Eriksson A, Dunlop T *et al.* (2012) Differential effects of 1alpha,25-dihydroxycholecalciferol on MCP-1 and adiponectin production in human white adipocytes. *Eur J Nutr* **51**, 335–342.
76. Gao D, Trayhurn P & Bing C (2012) 1,25-Dihydroxyvitamin $D_3$ inhibits the cytokine-induced secretion of MCP-1 and reduces monocyte recruitment by human preadipocytes. *Int J Obes* (*Lond*) **37**, 357–365.
77. Mutt SJ, Karhu T, Lehtonen S *et al.* (2012) Inhibition of cytokine secretion from adipocytes by 1,25-dihydroxyvitamin D(3) via the NF-kappaB pathway. *FASEB J* **26**, 4400–4407.
78. Guillot X, Semerano L, Saidenberg-Kermanac'h N *et al.* (2010) Vitamin D and inflammation. *Joint Bone Spine* **77**, 552–557.
79. Wamberg L, Cullberg KB, Rejnmark L *et al.* (2013) Investigations of the anti-inflammatory effects of vitamin D in adipose tissue: results from an *in vitro* study and a randomized controlled trial. *Horm Metab Res* **45**, 456–462.
80. Karkeni E, Marcotorchino J, Tourniaire F *et al.* (2015) Vitamin D limits chemokine expression in adipocytes and macrophage migration *in vitro* and in male mice. *Endocrinology* **156**, 1782–1793.
81. Tourniaire F, Romier-Crouzet B, Lee JH *et al.* (2013) Chemokine expression in inflamed adipose tissue is mainly mediated by NF-kappaB. *PLoS ONE* **8**, e66515.
82. Ding C, Wilding JP & Bing C (2013) 1,25-dihydroxyvitamin $D_3$ protects against macrophage-induced activation of NFkappaB and MAPK signalling and chemokine release in human adipocytes. *PLoS ONE* **8**, e61707.
83. Suganami T, Nishida J & Ogawa Y (2005) A paracrine loop between adipocytes and macrophages aggravates inflammatory changes: role of free fatty acids and tumor necrosis factor alpha. *Arterioscler Thromb Vasc Biol* **25**, 2062–2068.
84. Lira FS, Rosa JC, Cunha CA *et al.* (2011) Supplementing alpha-tocopherol (vitamin E) and vitamin $D_3$ in high fat diet decrease IL-6 production in murine epididymal adipose tissue and 3T3-L1 adipocytes following LPS stimulation. *Lipids Health Dis* **10**, 37.
85. Roth CL, Elfers CT, Figlewicz DP *et al.* (2012) Vitamin D deficiency in obese rats exacerbates nonalcoholic fatty liver disease and increases hepatic resistin and Toll-like receptor activation. *Hepatology* **55**, 1103–1111.
86. Narvaez CJ, Matthews D, Broun E *et al.* (2009) Lean phenotype and resistance to diet-induced obesity in vitamin D receptor knockout mice correlates with induction of uncoupling protein-1 in white adipose tissue. *Endocrinology* **150**, 651–661.
87. Wong KE, Szeto FL, Zhang W *et al.* (2009) Involvement of the vitamin D receptor in energy metabolism: regulation of

uncoupling proteins. *Am J Physiol Endocrinol Metab* **296**, E820–E828.
88. Wong KE, Kong J, Zhang W *et al.* (2011) Targeted expression of human vitamin D receptor in adipocytes decreases energy expenditure and induces obesity in mice. *J Biol Chem* **286**, 33804–33810.
89. Soares MJ, Murhadi LL, Kurpad AV *et al.* (2012) Mechanistic roles for calcium and vitamin D in the regulation of body weight. *Obes Rev* **13**, 592–605.
90. Rowling MJ, Gliniak C, Welsh J *et al.* (2007) High dietary vitamin D prevents hypocalcemia and osteomalacia in CYP27B1 knockout mice. *J Nutr* **137**, 2608–2615.
91. Malloy PJ & Feldman BJ (2013) Cell-autonomous regulation of brown fat identity gene UCP1 by unliganded vitamin D receptor. *Mol Endocrinol* **27**, 1632–1642.
92. Sun X & Zemel MB (2008) 1Alpha, 25-dihydroxyvitamin D and corticosteroid regulate adipocyte nuclear vitamin D receptor. *Int J Obes* (*Lond*) **32**, 1305–1311.
93. Bouillon R, Carmeliet G, Lieben L *et al.* (2014) Vitamin D and energy homeostasis-of mice and men. *Nat Rev Endocrinol* **10**, 79–87.
94. Gallagher JC, Yalamanchili V & Smith LM (2013) The effect of vitamin D supplementation on serum 25OHD in thin and obese women. *J Steroid Biochem Mol Biol* **136**, 195–200.
95. Pereira-Santos M, Costa PR, Assis AM *et al.* (2015) Obesity and vitamin D deficiency: a systematic review and meta-analysis. *Obes Rev* **16**, 341–349.
96. Garcia OP, Long KZ & Rosado JL (2009) Impact of micronutrient deficiencies on obesity. *Nutr Rev* **67**, 559–572.
97. Cheng S, Massaro JM, Fox CS *et al.* (2010) Adiposity, cardiometabolic risk, and vitamin D status: the Framingham Heart Study. *Diabetes* **59**, 242–248.
98. Caron-Jobin M, Morisset AS, Tremblay A *et al.* (2011) Elevated serum 25(OH)D concentrations, vitamin D, and calcium intakes are associated with reduced adipocyte size in women. *Obesity* (*Silver Spring*) **19**, 1335–1341.
99. Wortsman J, Matsuoka LY, Chen TC *et al.* (2000) Decreased bioavailability of vitamin D in obesity. *Am J Clin Nutr* **72**, 690–693.
100. Drincic AT, Armas LA, Van Diest EE *et al.* (2012) Volumetric dilution, rather than sequestration best explains the low vitamin d status of obesity. *Obesity* (*Silver Spring*) **20**, 1444–1448.
101. Parikh SJ, Edelman M, Uwaifo GI *et al.* (2004) The relationship between obesity and serum 1,25-dihydroxy vitamin D concentrations in healthy adults. *J Clin Endocrinol Metab* **89**, 1196–1199.
102. Konradsen S, Ag H, Lindberg F *et al.* (2008) Serum 1,25-dihydroxy vitamin D is inversely associated with body mass index. *Eur J Nutr* **47**, 87–91.
103. Bell NH (1985) Vitamin D-endocrine system. *J Clin Invest* **76**, 1–6.
104. Mai XM, Chen Y, Camargo CA Jr. *et al.* (2012) Cross-sectional and prospective cohort study of serum 25-hydroxyvitamin D level and obesity in adults: the HUNT study. *Am J Epidemiol* **175**, 1029–1036.
105. Gonzalez-Molero I, Rojo-Martinez G, Morcillo S *et al.* (2013) Hypovitaminosis D and incidence of obesity: a prospective study. *Eur J Clin Nutr* **67**, 680–682.
106. Gilbert-Diamond D, Baylin A, Mora-Plazas M *et al.* (2010) Vitamin D deficiency and anthropometric indicators of adiposity in school-age children: a prospective study. *Am J Clin Nutr* **92**, 1446–1451.
107. LeBlanc ES, Rizzo JH, Pedula KL *et al.* (2012) Associations between 25-hydroxyvitamin D and weight gain in elderly women. *J Womens Health* (*Larchmt*) **21**, 1066–1073.
108. Gagnon C, Lu ZX, Magliano DJ *et al.* (2012) Low serum 25-hydroxyvitamin D is associated with increased risk of the development of the metabolic syndrome at five years: results from a national, population-based prospective study (The Australian Diabetes, Obesity and Lifestyle Study: AusDiab). *J Clin Endocrinol Metab* **97**, 1953–1961.
109. Kamycheva E, Joakimsen RM & Jorde R (2003) Intakes of calcium and vitamin d predict body mass index in the population of Northern Norway. *J Nutr* **133**, 102–106.
110. Teegarden D, White KM, Lyle RM *et al.* (2008) Calcium and dairy product modulation of lipid utilization and energy expenditure. *Obesity* (*Silver Spring*) **16**, 1566–1572.
111. Boon N, Hul GB, Sicard A *et al.* (2006) The effects of increasing serum calcitriol on energy and fat metabolism and gene expression. *Obesity* (*Silver Spring*) **14**, 1739–1746.
112. Salehpour A, Hosseinpanah F, Shidfar F *et al.* (2012) A 12-week double-blind randomized clinical trial of vitamin $D_{(3)}$ supplementation on body fat mass in healthy overweight and obese women. *Nutr J* **11**, 78.
113. Zittermann A, Frisch S, Berthold HK *et al.* (2009) Vitamin D supplementation enhances the beneficial effects of weight loss on cardiovascular disease risk markers. *Am J Clin Nutr* **89**, 1321–1327.
114. Sneve M, Figenschau Y & Jorde R (2008) Supplementation with cholecalciferol does not result in weight reduction in overweight and obese subjects. *Eur J Endocrinol* **159**, 675–684.
115. Wamberg L, Kampmann U, Stodkilde-Jorgensen H *et al.* (2013) Effects of vitamin D supplementation on body fat accumulation, inflammation, and metabolic risk factors in obese adults with low vitamin D levels – results from a randomized trial. *Eur J Intern Med* **24**, 644–649.
116. Pathak K, Soares MJ, Calton EK *et al.* (2014) Vitamin D supplementation and body weight status: a systematic review and meta-analysis of randomized controlled trials. *Obes Rev* **15**, 528–537.
117. Mason C, Xiao L, Imayama I *et al.* (2014) Vitamin $D_3$ supplementation during weight loss: a double-blind randomized controlled trial. *Am J Clin Nutr* **99**, 1015–1025.
118. Vimaleswaran KS, Berry DJ, Lu C *et al.* (2013) Causal relationship between obesity and vitamin D status: bi-directional Mendelian randomization analysis of multiple cohorts. *PLoS Med* **10**, e1001383.
119. Wang TJ, Zhang F, Richards JB *et al.* (2010) Common genetic determinants of vitamin D insufficiency: a genome-wide association study. *Lancet* **376**, 180–188.
120. Dorjgochoo T, Shi J, Gao YT *et al.* (2012) Genetic variants in vitamin D metabolism-related genes and body mass index: analysis of genome-wide scan data of approximately 7000 Chinese women. *Int J Obes* (*Lond*) **36**, 1252–1255.
121. Ochs-Balcom HM, Chennamaneni R, Millen AE *et al.* (2011) Vitamin D receptor gene polymorphisms are associated with adiposity phenotypes. *Am J Clin Nutr* **93**, 5–10.
122. Sulistyoningrum DC, Green TJ, Lear SA *et al.* (2012) Ethnic-specific differences in vitamin D status is associated with adiposity. *PLoS ONE* **7**, e43159.