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The Role of Vitamin D and Calcium in type 2 diabetes. A systematic Review and Meta-Analysis*

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Abstract

Context—Altered vitamin D and calcium homeostasis may play a role in the development of type 2 diabetes (t2DM).

Evidence Acquisition and Analyses—MEDLINE review through January 2007 for observational studies and clinical trials in adults with outcomes related to glucose homeostasis. When data was available to combine, meta-analyses were performed and summary odds ratios (OR) are presented.

Evidence Synthesis—Observational studies show a relatively consistent association between low vitamin D status, calcium or dairy intake and *prevalent* t2DM or metabolic syndrome (OR [95% CI]: t2DM prevalence, 0.36 [0.16 – 0.80] among non-blacks for highest vs. lowest 25-OHD; metabolic syndrome prevalence, 0.71 [0.57 – 0.89] for highest vs. lowest dairy intake). There are also inverse associations with *incident* t2DM or metabolic syndrome (OR [95% CI]: t2DM incidence, 0.82 [0.72 – 0.93] for highest vs. lowest combined vitamin D and calcium intake; 0.86 [0.79 – 0.93] for highest vs. lowest dairy intake). Evidence from trials with vitamin D and/or calcium supplementation suggests that combined vitamin D and calcium supplementation may have a role in the prevention of t2DM only in populations at high risk (i.e. glucose intolerance). The available evidence is limited because most observational studies are cross-sectional and did not adjust for important confounders while intervention studies were short in duration, included few subjects, used a variety of formulations of vitamin D and calcium or did *post-hoc* analyses.

Conclusions—Vitamin D and calcium insufficiency may negatively influence glycemia while combined supplementation with both nutrients may be beneficial in optimizing glucose metabolism.

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Key terms

Vitamin D; calcium; type 2 diabetes

Introduction

The incidence of type 2 Diabetes Mellitus (t2DM) is increasing at an alarming rate both nationally and worldwide with more than 1 million new cases per year diagnosed in the US alone (1). Diabetes is the fifth leading cause of death in the US and it is also a major cause of significant morbidity. Although our current methods of treating t2DM and its complications have improved, prevention of the disease is preferable. Indeed, epidemiologic data suggest that 9 out of 10 cases of type 2 diabetes could be attributed to habits and forms of modifiable behavior (2). Potentially modifiable environmental risk factors for t2DM have been identified, the major one being obesity. Although weight-loss (achieved by any means) has been shown to be successful in delaying t2DM, it is difficult to achieve and maintain long-term. Therefore, identification of environmental and easily modified risk factors is urgently needed to prevent development of t2DM in the 41 million Americans who are at risk of the disease (3).

The major and most well known function of vitamin D is to maintain calcium and phosphorus homeostasis and promote bone mineralization. However, recent evidence suggests that vitamin D and calcium homeostasis may also be important for a variety of non-skeletal outcomes including neuromuscular function and falls, psoriasis, multiple sclerosis and colorectal and prostate cancer (4,5). Based on basic and animal studies, vitamin D and calcium have also been suspected as modifiers of diabetes risk. Vitamin D insufficiency has long been suspected as a risk factor for type 1 diabetes based on animal and human observational studies (6). More recently, there is accumulating evidence to suggest that altered vitamin D and calcium homeostasis may also play a role in the development of t2DM. The purpose of our systematic review was to examine: (1) the association between vitamin D and calcium status and risk of t2DM and (2) the effect of vitamin D and/or calcium supplementation on glucose metabolism.

Materials and Methods

We searched MEDLINE for English-language literature through January 2007 for observational studies on the association between vitamin D / calcium status (defined by serum 25-OHD concentration, and vitamin D, calcium, or dairy intake) and t2DM (prevalence or incidence) and for randomized controlled trials of the effect of vitamin D and/or calcium supplementation in non-pregnant adults on outcomes related to glucose homeostasis. We also examined metabolic syndrome (prevalence or incidence) as an outcome of interest, given that insulin resistance – a feature of t2DM – is considered to be a central mechanism underlying the metabolic syndrome. Search terms included *diabetes, hyperglycemia, glucose, glycohemoglobin, metabolic syndrome, insulin resistance, homa, homeostasis model assessment, beta cell function, insulin secretion, vitamin D, calcium, dairy, milk* and related terms. Additional publications were identified from citations from the recovered articles, review articles and personal reference lists. We excluded letters, abstracts, and conference proceedings that were not published in full in peer-reviewed journals (7). We excluded studies in children because insulin dynamics are evolving during childhood, especially during puberty (8,9). We excluded studies of type 1 diabetes (or insulin-requiring diabetes of unclear type), hemodialysis, hyperparathyroidism, and other conditions or medications that affect vitamin D metabolism (e.g. epilepsy). Qualitative synthesis of available data was performed due to the large heterogeneity in the methods for assessing outcomes among the studies. However, when data was available to combine, meta-analyses using a random-effects model (10) were performed and summary odds ratios (OR) are presented. For certain studies that reported a

confidence interval that was asymmetric around the mean, we used a conservative approach and included in the metaanalysis the widest confidence interval reported.

Potential Mechanisms for the Effects of Vitamin D and Calcium on t2DM

For glucose intolerance and t2DM to develop, defects in pancreatic beta-cell function, insulin sensitivity and systemic inflammation are often present (11,12). There is evidence to support that vitamin D and calcium influence these mechanisms, as summarized next and in Table 1.

Pancreatic Beta Cell Function

There are several lines of evidence supporting a role for vitamin D in pancreatic beta cell function, as shown in Table 1. Vitamin D appears to affect exclusively the insulin response to glucose stimulation while it does not appear to influence basal insulinemia (13,14). The direct effect of vitamin D may be mediated by binding of its circulating active from, 1,25-OHD, to the beta cell vitamin D receptor. Alternatively, activation of vitamin D may occur within the beta cell by the 1-alpha-hydroxylase enzyme, which was recently shown to be expressed in beta cells (15). The indirect effects of vitamin D may be mediated via its important and well-recognized role in regulating extracellular calcium and calcium flux through the beta cell (Table 1). Insulin secretion is a calcium dependent process (16) therefore, alterations in calcium flux can have adverse effects on beta cell secretory function. We speculate that inadequate calcium intake or vitamin D insufficiency may alter the balance between the extracellular and intracellular beta cell calcium pools, which may interfere with normal insulin release, especially in response to a glucose load. Some (17-21) but not all (22,23) studies in several cohorts with varied baseline vitamin D status have reported an association between vitamin D deficiency and impaired glucose-mediated insulin release. Vitamin D supplementation improved insulin release in some (17,21,23,24) but not all (21,23,25) small-scale short-term randomized trials.

Insulin Resistance

Vitamin D may have a beneficial effect on insulin action either directly, by stimulating the expression of insulin receptor thereby enhancing insulin responsiveness for glucose transport (26), or indirectly via its role in regulating extracellular calcium ensuring normal calcium influx through cell membranes and adequate intracellular cytosolic calcium $[Ca^{2+}]_i$ pool (Table 1). Calcium is essential for insulin-mediated intracellular processes in insulin-responsive tissues such as skeletal muscle and adipose tissue (27-29) with a very narrow range of $[Ca^{2+}]_i$ needed for optimal insulin-mediated functions (30). Changes in $[Ca^{2+}]_i$ in primary insulin target tissues may contribute to peripheral insulin resistance (30-37) via impaired insulin signal transduction (29,34) leading to decreased GLUT-4 activity (34,38). Associations between low vitamin D level and decreased insulin sensitivity have been reported in cross-sectional studies (18-23, 39,40). Some (19,40) but not all (23) observational studies have shown an inverse association between vitamin D or calcium status and insulin resistance. Results from randomized trials on the effect of vitamin D and/or calcium supplementation on insulin resistance show either no effect (23,41-45) or improvement(46-48) of insulin action with supplementation.

Inflammation

It is currently recognized that t2DM is associated with systemic inflammation (12,49,50). Systemic inflammation has been linked primarily to insulin resistance but elevated cytokines may also play a role in beta cell dysfunction by triggering beta cell apoptosis. Vitamin D may improve insulin sensitivity and promote beta-cell survival by directly modulating the generation and effects of cytokines (Table 1). There are very limited and conflicting data from human studies that have directly examined the relationship between vitamin D or calcium status and systemic inflammation in relation to t2DM (48,51-53).

Evidence from Observational Human Studies

What is the association between vitamin D status and *prevalent* t2DM or metabolic syndrome?

The role of vitamin D in t2DM is suggested by a seasonal variation in glycemic control reported in patients with t2DM being worse in the winter (54-56), which may, at least in part, be due to prevalent hypovitaminosis D in the winter. In cross-sectional studies (Table 2A), inverse associations between serum 25-OHD and measurements of glycemia or presence of t2DM have been reported in a variety of cohorts (18,19,40,57-59) but the relationship is not consistent (18,19,23,40,60,61). In the largest cross-sectional study to date from NHANES data, serum 25-OHD concentration (after multivariate adjustment) was inversely associated with diabetes prevalence in a dose-dependent pattern in non-Hispanic whites and Mexican-Americans (40, 57). In the same study, 25-OHD concentration also correlated with measures of insulin resistance (estimated by Homeostatic Model Assessment [HOMA-R] based on fasting glucose and insulin levels) but did not correlate with beta cell function (estimated by HOMA-beta). No correlation between 25-OHD and diabetes prevalence or measures of insulin resistance or beta-cell function was seen in non-Hispanic blacks. This lack of association may be explained by the observation that non-whites exhibit a different vitamin D, calcium and PTH homeostasis compared to whites (62).

Combining data from all studies that reported on the association between 25-OHD level and prevalent t2DM (40,60,61,63), the summary odds ratio (OR) was 0.54 (95% CI, 0.23 – 1.27) for the highest vs. the lowest 25-OHD concentration (25-38 ng/ml vs. 10-23 ng/ml, respectively), but with significant heterogeneity among studies. When we excluded the data on non-Hispanic blacks, there was a statistically significant inverse association between 25-OHD concentration and prevalent t2DM (OR 0.36 [95%CI, 0.16 – 0.80]).

Vitamin D intake and 25-OHD concentration have also been inversely associated with prevalence of metabolic syndrome (19,57). In the largest study using NHANES data, serum 25-OHD concentration (after multivariate adjustment, but not including calcium intake) was inversely associated with having the metabolic syndrome (57) among both sexes and all three major racial or ethnic groups (57). The components of the metabolic syndrome that were independently associated with low 25-OHD were abdominal obesity and hyperglycemia, therefore, the results of this study may simply reflect the inverse association between serum 25-OHD and body weight or fatness (40,64,65). In a recent cross-sectional analysis of the Women's Health Study, a large randomized trial designed to evaluate the effects of low-dose aspirin and vitamin E in cardiovascular disease, the inverse association between vitamin D intake and prevalence of metabolic syndrome was dissipated after adjustment for calcium intake (66).

In most (17,51,59,63,67-72) but not all (69,73,74) case-control studies, patients with t2DM or glucose intolerance are found to have lower serum 25-OHD concentration compared to controls without diabetes (Table 2B).

What is the association between vitamin D status and *incident* type 2 diabetes or metabolic syndrome?

Two prospective studies have examined the association of vitamin D intake with incident t2DM (Table 2C). In the Women's Health Study, an intake of 511 IU/day of vitamin D or more was associated with lower risk of incident t2DM compared to an intake of 159 IU/day or less (2.7 vs. 5.6% of the cohort developed t2DM respectively) (66). However, this analysis did not adjust for other risk factors of t2DM or calcium intake. Recently, our group examined the association between vitamin D and calcium intakes and incident t2DM among 83,806 women in the Nurses

Health Study, a large prospective observational cohort (52). After adjusting for age, BMI, and non-dietary covariates, we observed a significant inverse association between total (food + supplements) vitamin D intake and risk of t2DM. The association was attenuated after adjusting for dietary factors, in particular, magnesium and calcium.

What is the association between calcium intake and *prevalent* type 2 diabetes or metabolic syndrome?

A potentially important role for calcium status in the development of t2DM is suggested by case control studies where calcium intake was found to be lower in patients with diabetes compared to controls (72). In the analysis from the Women's Health Study, calcium intake (after adjustment for vitamin D intake) was inversely associated with prevalence of metabolic syndrome (66).

What is the association between calcium intake and *incident* type 2 diabetes or metabolic syndrome?

In prospective studies, low calcium intake is consistently found to be inversely associated with incident t2DM (52,66,75,76) or the metabolic syndrome (77). In the Nurses Health Study, total (food + supplements) calcium intake was inversely associated with incident t2DM after complete multivariate adjustment, including vitamin D intake (52). A similar inverse association was seen in the Black Women's Health Study, a prospective cohort of ~59,000 women aged 21-69 at baseline (76). In the latter study, there was no adjustment for vitamin D status, but the association was attenuated after adjustment for magnesium intake. After combining data from the latter 2 studies, the summary OR (95% CI) for incident t2DM was 0.82 [0.72 – 0.93] for the highest vs. the lowest calcium intake (661-1200 mg/day vs. 219-600 mg/day, respectively). The results of these studies highlight an important role for calcium intake.

What is the association between dairy intake and type 2 diabetes or metabolic syndrome?

The association between calcium and vitamin D status and t2DM can also be assessed from studies that report the effects of intake of dairy products on measurements of glycemia and metabolic syndrome. After combining data from cross-sectional studies, the summary OR for prevalence of metabolic syndrome was 0.71 [95% CI, 0.57 – 0.89] for the highest dairy intake (3-4 servings/day) vs. lowest (0.9-1.7 servings/day) (66,78,79), with no apparent heterogeneity among studies. In prospective studies, a moderate inverse association of dairy intake with incident t2DM (52,76,80,81) or metabolic syndrome (77) is consistently reported. The summary OR for incident t2DM was 0.86 [95% CI 0.79 – 0.93] for the highest vs. lowest dairy intake (3-5 vs. <1.5 servings/day, respectively) (52,76,80,81) with no apparent heterogeneity among studies. It is important to note that although calcium and vitamin D are important components of dairy products, their contribution to the measured outcomes cannot be separated from other components in dairy products.

Summary of evidence from human observational studies and future directions

The evidence from observational studies suggests an association between low vitamin D status and calcium intake (including low dairy intake) and risk of t2DM or metabolic syndrome. However, definite conclusions from these studies are limited for a variety of reasons: (1) In cross-sectional or case-control studies, vitamin D or calcium status was measured in patients with glucose intolerance or established diabetes, therefore these measures may not reflect vitamin D or calcium status prior to diagnosis and, as a result, the causative nature of the observed associations cannot be established. (2) There is considerable variability in studied cohorts (normal glucose tolerance vs. diabetes [newly diagnosed vs. established], ethnicity, latitude etc). (3) In most studies, there is lack of adjustment for important confounders, such

as adiposity, physical activity, and importantly, vitamin D or calcium status (for calcium or vitamin D studies respectively). To clarify the individual contribution of each nutrient to future t2DM risk, in the Nurses Health Study, our group examined the combined effects of total (food + supplements) vitamin D and calcium intake on risk of incident t2DM (Figure). We observed that, after multivariate adjustment, women with the highest calcium (>1200 mg/day) *and* vitamin D (>800 IU/day) intake (1.3% of the cohort) had a 33% lower risk of t2DM compared to women with the lowest calcium (<600 mg/day) and vitamin D (<400 IU/day) intakes. The lower risk seen with the combined intake was more than that seen with the highest intake of each nutrient separately, which highlights the importance of both nutrients as potential t2DM risk modifier and the need to take into consideration both nutrients in observational studies.

Evidence from Intervention Human Studies

What is the effect of vitamin D supplementation on t2DM?

There are four small-scale short-term and two long-term controlled trials that have examined the effect of supplementation with a variety of formulations of vitamin D on t2DM parameters. Among 18 young healthy men, supplementation with $1,25(OH)_2D_3$ for 7 days did not change fasting glycemia or insulin sensitivity (42). In another small study (n=14) in patients with t2DM, 2 mcg/day IU of $1OHD_3$ administration daily for 3 weeks enhanced insulin secretion but had no effect on post-load glucose tolerance (24). Ljunghall et al randomized 65 middle-aged men with impaired glucose tolerance or mild diabetes and sufficient vitamin D levels at baseline to 0.75 mcg/day of $1OHD_3$ or placebo for 3 months and found no effect in fasting or stimulated glucose tolerance (41). In that trial, participants had sufficient vitamin D levels at baseline (mean 25-OHD 38 ng/ml). In a cross-over trial, 20 patients with t2DM and vitamin D deficiency were treated for 4 days with 1 mcg/day of 1,25-OHD and no change was seen in fasting or stimulated glucose, insulin or C-peptide concentrations but an improvement in insulin and C-peptide secretion was seen in patients with diabetes of short duration (23). The intervention period in this trial was too short to draw definitive conclusions but it does suggest that vitamin D supplementation at an early stage in the development of diabetes (i.e. glucose intolerance) may be of benefit in delaying progression to clinical t2DM which is supported by more recent data described below (48). Lastly, in a *post-hoc* analyses of a 2-year trial designed for bone-related outcomes, supplementation with vitamin D_3 or $1OHD_3$ had no effect on fasting glycemia in postmenopausal non-diabetic women (82).

What is the effect of calcium or dairy supplementation on t2DM?

There is limited evidence of an effect of calcium supplementation on diabetes-related parameters from trials that have examined the effects of calcium either alone or as a component of dairy products (Table 3). In 20 non-diabetic patients with essential hypertension, supplementation with 1,500 mg/day of calcium vs. placebo for 8 weeks did not influence fasting glycemia but improved insulin sensitivity, as measured by euglycemic hyperinsulinemic clamp (46). Trials with small numbers of non-diabetic participants that have examined the effects of calcium supplementation as a component of dairy products in relation to glycemia or insulin resistance have shown conflicting results but most studies show a neutral effect (43-45,47, 83).

What is the effect of combined vitamin D and calcium supplementation on t2DM?

In a recent report from our group, *post-hoc* analyses of a trial designed for bone-related outcomes showed that combined supplementation with 700 IU of vitamin D_3 and 500 mg of calcium as calcium citrate malate had no effect on glycemia or insulin resistance in 221 adults over age 65 with normal glucose tolerance at baseline (48). However, among participants with impaired fasting glucose at baseline those who took combined vitamin D_3 and calcium supplements had a significantly lower rise in fasting glycemia and insulin resistance at 3 years

compared to those on placebo (0.4 vs. 6.1 mg/dl respectively) (48). The effect size with combined vitamin D and calcium supplementation seen in this high risk group was similar in magnitude to the progression of fasting glycemia seen in the Diabetes Prevention Program with intensive lifestyle or metformin (0.2 mg/dl in the lifestyle and 0.2 mg/dl in the metformin arm vs. 5.5 mg/dl in placebo)(84).

Summary of evidence from human intervention studies and future directions

It is difficult to draw definitive conclusions from the available intervention studies with vitamin D and/or calcium supplementation, because most studies were short in duration, included few subjects, used a variety of formulations and combinations of vitamin D and calcium among various cohorts or used *post-hoc* analyses. Furthermore, the contribution of vitamin D and/or calcium in studies with dairy are difficult to interpret because dairy may have additional components affecting glucose metabolism. However, the overall evidence suggests that vitamin D alone probably has no effect in healthy individuals, but combined vitamin D and calcium supplementation may have a role in the prevention of t2DM especially in populations at risk for t2DM such as those with glucose intolerance.

Optimal Intake of Vitamin D and Calcium in Relation to Type 2 Diabetes

Currently recommended intakes for calcium are 1,200 mg/day for adults aged >50 years and for vitamin D are 400 IU/day for those aged 51-70 years and 600 IU/day for those aged >70 years (85). However, there is growing consensus that vitamin D intakes above the current recommendations may be associated with better health outcomes. Optimal levels of 25-OHD have not been defined but for a variety of skeletal and non-skeletal outcomes, the most advantageous serum concentration of 25-OHD appears to be 30-40 ng/ml (4). In relation to t2DM, it is difficult to draw definitive conclusion about an optimal level is, because available studies were done in a variety of cohorts with a large range of 25-OHD levels (Table 2). However, the data suggest that serum 25-OHD concentration above 20 ng/ml are desirable, but those above 40 ng/ml may be better. To achieve such 25-OHD concentration, an intake of approximately 1000 IU/day of vitamin D is needed (4,86). In relation to calcium intake for type 2 diabetes, the evidence suggests that intakes above 600 mg/day are desirable but intakes above 1200 mg may be optimal (Tables 2and 3and Figure).

Data from NHANES III show that vitamin D insufficiency (25-OHD <25 ng/ml) may affect up to half of the non-institutionalized adolescent and adult population in the US, even in the southern latitudes during the winter (87). Additional studies have shown a prevalence of vitamin D insufficiency ranging from 36-100% in a variety of populations including healthy young adults to hospitalized elderly individuals (52,88-90). Insufficiency of calcium status is difficult to document biochemically, but there is concern that Americans are not meeting the recommended intake for calcium (91,92). Adjusted for day-to-day variation, the median reported intake of calcium in the US population declines with age (708 mg/day for men and 571 mg/day for women 51-70 years; 702 mg/day for men and 517 mg/day for women >70 years) (85,93). Combined insufficiency in vitamin D and calcium intake may be even more prevalent. In the Nurses Health Study, the group of female nurses with the highest intake of calcium (>1200 mg/day) and vitamin D (>800 IU/day) that was associated with the lowest risk of incidence t2DM was only 1.3% of the cohort (52).

Therefore, given the potential link between vitamin D, calcium and diabetes described above, it is plausible that the rising incidence of t2DM may, at least in part, be due to suboptimal vitamin D and calcium status of the US adult population. Furthermore, certain determinants of adequate Vitamin D and calcium status (aging, physical inactivity, dark skin and obesity) are also strong risk factors for type 2 Diabetes. Although this may simply reflect confounding, the

link between these risk factors and t2DM may, at least partially, be mediated by vitamin D and calcium insufficiency.

Conclusions and Future Directions

There appears to be a relationship between insufficient vitamin D and calcium status and t2DM. However, the available human data are limited because most observational studies are cross-sectional while prospective studies have not measured 25-OHD concentration and there is a paucity of randomized controlled trials with vitamin D and/or calcium supplementation specifically designed for outcomes related to t2DM. Although the evidence to date suggests that vitamin D and calcium deficiency influences post-prandial glycemia and insulin response while supplementation may be beneficial in optimizing these processes, our understanding of the exact mechanisms by which vitamin D and calcium may promote beta cell function, or ameliorate insulin resistance and systemic inflammation is incomplete. It is also not clear whether the effects are additive or synergistic.

Future research should focus on studies within prospective observational cohorts to clarify and quantify the association between calcium intake and 25-OHD concentration, rather than self-reported intake of vitamin D, and incident t2DM and define the individual contributions of each nutrient on t2DM risk. Additionally, there is a need for randomized trials to examine the effects of vitamin D and/or calcium supplementation with intermediary endpoints (glucose tolerance, insulin secretion, insulin sensitivity) and ultimately with incident t2DM. The results of future studies will define the clinical role of vitamin D and calcium as potential interventions for prevention and management of t2DM, which will have significant public health implications since vitamin D and calcium insufficiency is common in US adults and both interventions can be implemented easily and inexpensively in clinical practice.

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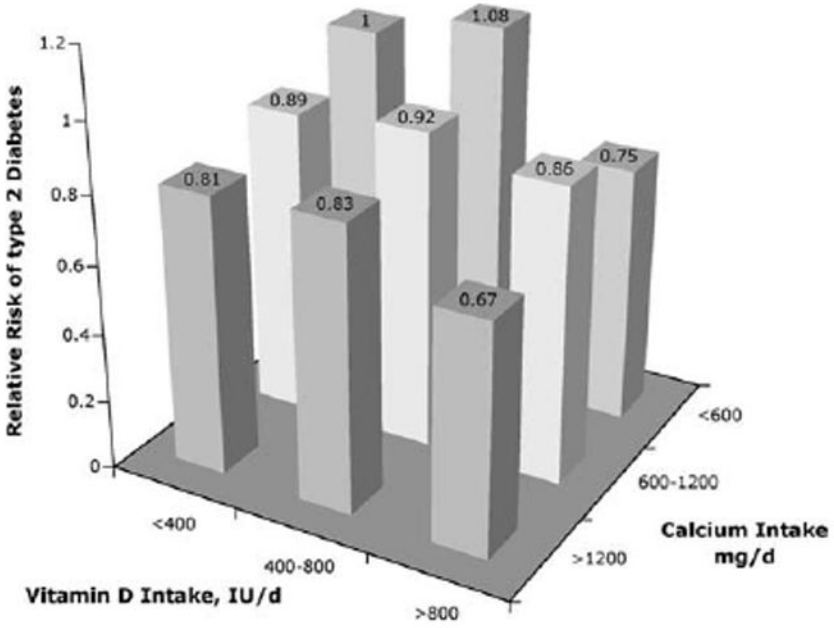

Figure.

Adjusted Relative risk of incident type 2 diabetes in the Nurses Health Study by calcium and vitamin D intake (52)

Table 1

Potential mechanisms and evidence to support a benefit for vitamin D and calcium in type 2 diabetes

Mechanisms	Evidence
Improvement in Pancreatic Beta Cell Function	
Direct effect of Vitamin D on insulin secretion	Presence of specific vitamin D receptors in pancreatic beta cells (94)
	Expression of 1-alpha-hydroxylase enzyme in pancreatic beta cells (15)
	Impaired insulin secretory response in mice lacking functional vitamin D receptors (14)
	Presence of the vitamin D response element in the human insulin gene promoter (95)
	Transcriptional activation of the human insulin gene by 1,25-OHD (96)
	Vitamin D deficiency impairs glucose-mediated insulin secretion from rat pancreatic beta cells in vitro (13,97-99) and in vivo (100,101)
	Supplementation with vitamin D restores insulin secretion in animals (13,97,99,100,102)
Indirect Effect of vitamin D on insulin secretion	Vitamin D contributes to normalization of extracellular calcium ensuring normal calcium flux through cell membranes and adequate intracellular cytosolic calcium $[Ca^{2+}]_i$ pool
	Regulation of calcium flux and $[Ca^{2+}]_i$ in the pancreatic beta cell via regulation of calbindin, a cytosolic calcium-binding protein (103)
Calcium effect on insulin secretion	Alterations in calcium flux can have adverse effects on insulin secretion, a calcium-dependent process (16)
	Calcium repletion alone normalized glucose tolerance and insulin secretion in vitamin D-depleted rats (104)
	In people without diabetes, hypocalcemia is associated with impairment of insulin release (105,106)
	In diabetes patients, an oral calcium load augments glucose-induced insulin secretion (107)
	Patients with resistance to 1,25-OHD were found to have abnormal insulin secretion only if they were hypocalcemic (108)
Improvement in Insulin Action	
Direct effect of Vitamin D on insulin action	Inverse association between 25-OHD levels and sarcopenia (109)
	Presence of vitamin D receptor in skeletal muscle (110)
	Vitamin D stimulates the expression of insulin receptor and enhances insulin responsiveness for glucose transport in vitro (26)
	Vitamin D directly activates peroxisome proliferator activator receptor-delta (111), a transcription factor implicated in the regulation of fatty acid metabolism in skeletal muscle and adipose tissue (112)
Indirect effect of Vitamin D on insulin action	Vitamin D contributes to normalization of extracellular calcium ensuring normal calcium influx through cell membranes and adequate intracellular cytosolic calcium $[Ca^{2+}]_i$ pool
Calcium effect on insulin action	Calcium is essential for insulin-mediated intracellular processes in insulin-responsive tissues such as skeletal muscle and adipose tissue (27-29) with a very narrow range of $[Ca^{2+}]_i$ needed for optimal insulin-mediated functions (30)
	Changes in $[Ca^{2+}]_i$ in primary insulin target tissues contributes to alterations in insulin action (30-37)
	Impairment of insulin receptor phosphorylation, a calcium-dependent process (113) leading to impaired insulin signal transduction (29,34) and decreased GLUT-4 activity (34,38)
	Changes in $[Ca^{2+}]_i$ modulate adipocyte metabolism which may promotes triglyceride accumulation via increased de novo lipogenesis and inability to suppress insulin-mediated lipolysis leading to fat ccumulation (114,115)
	Patients with type 2 diabetes exhibit impaired cellular calcium homeostasis including defects in skeletal muscle, adipocytes, and liver (116)
Improvement in Systemic Inflammation	
Effects of vitamin D on cytokines	Vitamin D interacts with vitamin D response elements in the promoter region of cytokine genes tointerfere with nuclear transcription factors implicated in cytokine generation and action (117-119)
	Vitamin D can down regulate activation of NF-kB (117,119,120), which is an important regulatorof genes encoding pro-inflammatory cytokines implicated in insulin resistance (121)
	Vitamin D interferes with cytokine generation by upregulating expression of calbindin (94,122,123), a cytosolic calcium-binding protein found in many tissues including pancreatic beta cells (94,123) Calbindin has been shown to protect against cytokine-induced apoptosis that may occur after a rise in cytosolic free calcium $[Ca^{2+}]_I$ (124)
Effects of calcium on cytokines	Changes in $[Ca^{2+}]_I$ may lead to cytokine-induced apoptosis (85)

Table 2A

Cross-sectional studies reporting an association between vitamin D status, calcium intake, dairy intake and prevalence of type 2 diabetes / metabolic syndrome in non-pregnant adults

Study, First author, Year	Sex, M/F	Age (mean or range), y	Cohort	Outcome (assessment)	Predictor, range or category	Main Study Results	Adjustments	Comments and Other Outcomes
Vitamin D status (25-OHD concentration or vitamin D intake)								
Orwoll et al, 1994 (23)	M/F	40-70	Non-insulin-treated-T2DM, N=20	FPG	25-OHD, NR	25-OHD not associated with FPG		25-OHD not associated with IR (fasting insulin)
Baynes et al, 1997 (18)	M	76	Non-diabetics, N=142	FPG, 2hPG	25-OHD, 1-75 ng/ml	25-OHD not associated with FPG or 2hPG	BMI, skinfold, exercise, smoking, alcohol	25-OHD inversely associated with 1hPG (r = -0.2), GLU_{AUC} (r = -0.3)
Wareham et al, 1997 (60)	M/F	40-65	Non-diabetics, N=1,057	IGT (2hPG)	25-OHD, <23 ng/ml >25 ng/ml	Odds Ratio 1.00 1.03 (1.01-1.05)		
Chiu et al, 2004 (19)	M/F	26	Non-diabetics, N=126	FPG, 2hPG	25-OHD, 5-75 ng/ml	25-OHD inversely associated with 1hPG, 2hPG 25-OHD not associated with FPG	Age, sex, race, BMI, WHR, blood pressure	25-OHD inversely associated with 1hPG, IR (clamp). 25-OHD not associated with Insulin Release
Scragg et al, 2004 (40)	M/F	>20	NHANES, N=2,766 Non-Hispanic whites	T2DM (FPG)	25-OHD, <18 ng/ml >32 ng/ml	Odds Ratio 1.00 0.25 (0.11-0.60)	Age, sex, race, BMI, exercise, season	25-OHD inversely associated with IR (HOMA)
	M/F	>20	NHANES, N=1,726 Mexican Americans	T2DM (FPG)	25-OHD, <18 ng/ml >32 ng/ml	Odds Ratio 1.00 0.17 (0.08-0.37)	Age, sex, race, BMI, exercise, season	25-OHD inversely associated with IR (HOMA)
	M/F	>20	NHANES, N=1,726 Non-Hispanic blacks	T2DM (FPG)	25-OHD, <18 ng/ml >32 ng/ml	Odds Ratio 1.00 3.40 (1.07-10.86)	Age, sex, race, BMI, exercise, season	
Ford et al, 2005 (57)	M/F	>20	NHANES, N=8,241	T2DM (FPG)	25-OHD, <19 ng/ml >38 ng/ml	Odds Ratio 1.00 0.17 (0.08-0.37)	Age, sex, race, exercise, smoking, alcohol, diet, vitamin use, cholesterol, CRP, education, season	
Need et al, 2005 (58)	F	63	Non-diabetics, N=753	FPG	25-OHD, NR	25-OHD (>16 ng/ml) inversely associated with FPG	Age, BMI	

Study, First author, Year	Sex, M/F	Age (mean or range), y	Cohort	Outcome (assessment)	Predictor, range or category	Main Study Results	Adjustments	Comments and Other Outcomes
Vitamin D status (25-OHD concentration or vitamin D intake)								
Snijder et al, 2006 (61)	M/F	75	N=1,235	T2DM (self-report)	25-OHD, <10 ng/ml ≥30 ng/ml	Odds Ratio 1.0 1.23 (0.50 – 3.02)	Age, sex, WHR exercise, smoking, alcohol, region, season	
Hypponen and Power, 2006	M/F	45	Caucasians, N=7,198	Hemoglobin A1c (%)	25-OHD, <10 ng/ml ≥30 ng/ml	Hemoglobin A1c Concentration 5.4% 5.1%	Sex, season	Association pronounced among obese
Chiu et al, 2004 (19)	M/F	26	Non-diabetics, N=126	Metabolic Syndrome	25-OHD, 5-75 ng/ml	25-OHD inversely associated with Metabolic Syndrome	Age, sex, race, BMI, WHR, blood pressure	
Ford et al, 2005 (57)	M/F	>20	NHANES, N=8,241	Metabolic Syndrome	25-OHD, <19 ng/ml >38 ng/ml	Odds Ratio 1.00 0.46 (0.32-0.67)	Age, sex, race, exercise, smoking, alcohol, diet, vitamin use, cholesterol, CRP, education, season	
Liu et al, 2005 (66)	F	>45	Women's Health Study, N=10,066	Metabolic Syndrome	Vitamin D intake, ≤159 IU/d ≥511 IU/d	Odds Ratio 1.00 1.05 (0.84-1.32)	Age, exercise, smoking, alcohol, vitamin use, history of myocardial infarction, calcium intake	
Calcium Intake								
Liu et al, 2005 (66)	F	>45	Women's Health Study, N=10,066	Metabolic Syndrome	Calcium intake, ≤ 610 mg/d ≥1284 mg/d	Odds ratio 1.00 0.68 (0.55 – 0.83)	Age, exercise, smoking, alcohol, vitamin use, history of myocardial infarction, vitamin D intake	
Dairy intake								
Mennen et al, 2000 (78)	M	30-64	N=2,439	FPG	≤ 1 servings/d > 4 servings/d	Dairy intake inversely associated with FPG	Age, WHR, energy intake	
Azadbakht et al, 2005 (79)	M/F	18-74	Tehranian adults, N=827	IGT (FPG>110 mg/dl)	<1.7 servings/d ≥3.1 servings/d	Odds Ratio 1.00 0.88 (0.73-1.09)	Age, sex, BMI, WHR, exercise, smoking, energy intake, calcium intake	
Mennen et al, 2000 (78)	F	30-64	N=2,537	Metabolic Syndrome	≤1 servings/d > 4 servings/d	Odds ratio 1.00 0.76 (0.47-2.66)	Age, WHR, energy intake	
Mennen et al, 2000 (78)	M	30-64	N=2,439	Metabolic Syndrome	≤ 1 servings/d > 4 servings/d	Odds ratio 1.00 0.63 (0.40-0.99)	Age, WHR, energy intake	Dairy intake inversely associated With FPG (OR not provided)
Azadbakht et al, 2005 (79)	M/F	18-74	Tehranian adults, N=827	Metabolic Syndrome	<1.7 servings/d ≥3.1 servings/d	Odds ratio 1.00 0.82 (0.64-0.98)	Age, sex, BMI, WHR, exercise, smoking, energy	

Study, First author, Year	Sex, M/F	Age (mean or range), y	Cohort	Outcome (assessment)	Predictor, range or category	Main Study Results	Adjustments	Comments and Other Outcomes
Vitamin D status (25-OHD concentration or vitamin D intake)								
Liu et al, 2005 (66)	F	>45	Women's Health Study, N=10,066	Metabolic Syndrome	<0.9 servings/d >3 servings/d	Odds Ratio 1.00 0.66 (0.55-0.80)	intake, calcium intake Age, exercise, smoking, alcohol, vitamin use, history of myocardial infarction	

Table 2B

Case-control studies reporting an association between vitamin D status, calcium intake and type 2 diabetes or metabolic syndrome in non-pregnant adults

Study, First author, Year	Sex, M/F	Age (mean or range), y	Cases/ Outcome Measure	Control group	Predictor	Main Study Results	Adjustments	Comments and Other Outcomes
Vitamin D status (25-OHD concentration or vitamin D intake)								
Heath et al, 1979 (74)	M/F	18-75	T2DM, N=82	N=40	25-OHD	↔ 25-OHD in T2DM vs. controls (35 vs. 38-44 ng/ml)		
Christiansen et al, 1982 (67)	M	36	Insulin-treated T2DM, N=26	Age-, sex-matched, N=14	25-OHD	↓ 25-OHD in T2DM vs. controls (17 vs. 22 ng/ml)		25-OHD not associated with C-peptide level
Stepan et al, 1982 (68)	M/F	40-70	Sulfonylurea-treated T2DM, N=22	Blood donors, N=30	25-OHD	↓ 25-OHD in T2DM vs. controls (9 vs. 14 ng/ml)		
Ishida et al, 1985 (73)	M/F	19-80	T2DM, N=168	N=78	25-OHD	↔ 25-OHD in T2DM vs. controls (30 vs. 28 ng/ml)		
Nyomba et al, 1986 (69)	M/F	34-60	Bantu insulin-treated T2DM, N=20	Bantu, N=36	25-OHD	↓ 25-OHD in T2DM vs. controls (26 vs. 35 ng/ml)		
	M/F	14-63	Caucasian diet- and insulin-treated T2DM, N=44	Caucasian, N=26	25-OHD	↔ 25-OHD in T2DM vs. controls (34 vs. 33 ng/ml)		
Pietschamann et al, 1988 (70)	M/F	62	T2DM, N=38	Age-, sex-matched, N=17	25-OHD	↓ 25-OHD in T2DM vs. controls (8 vs. 15 ng/ml)		
Boucher et al, 1995 (17)	M/F	40-57	IGT/T2DM, N=44	Age-, sex-matched, N=15	25-OHD	↓ 25-OHD in IGT/T2DM vs. controls (28 vs. 30 ng/ml)		
Scragg et al,1995 (63)	M/F	40-64	IGT/newly diagnosed T2DM, N=238	Age-, sex-, ethnicity-date-matched, N=238	25-OHD ≤24 >33	Odds Ratio 1.00 0.36 (0.19-0.71)	BMI, exercise, cholesterol, hypertension	Nested case-control study
Aksoy et al, 2000 (71)	M/F	57	T2DM with retinopathy, N=66	Season- matched, N=20	25-OHD	↓ 25-OHD in T2DM vs. controls (12 vs. 24 ng/ml)		
Isaia et al, 2001 (72)	F	NR	T2DM, N=66	N=66	25-OHD	↓ 25-OHD in T2DM vs. controls (9 vs. 11 ng/ml)	Age, time since menopause	
Cigolini et al, 2006 (51)	M/F	61	T2DM, N=459	Age-, sex-matched, N= 459	25-OHD	↓ 25-OHD in T2DM vs. controls (20 vs. 24 ng/ml)		
Hypponen and Power, 2006(59)	M/F	45	T2DM, N=125	Sex-, season-matched, N=7,073	25-OHD	↓ 25-OHD in T2DM vs. controls (15 vs. 21 ng/ml)		
Calcium Intake								
Isaia et al, 2001 (72)	F	NR	T2DM, N=66	N=66	Calcium intake	↓ Calcium intake in T2DM vs. controls (679 vs. 792 mg/d)	Age, time since menopause	

Table 2C

Prospective studies reporting an association between vitamin D status, calcium intake, dairy intake and incidence of type 2 diabetes / metabolic syndrome in non-pregnant adults

Study First author, Year	Sex, M/F	Age at baseline (mean or range), y	Cohort, Total N/No. of cases	Outcome (assessment)	Predictor, Lowest and highest category	Main Study Results	Adjustments	Comments
Vitamin D status (25-OHD concentration or vitamin D intake)								
Liu et al, 2005 (66)	F	>45	Women's Health Study, 10,066/NR	T2DM (validated self-report)	Vitamin D Intake ≤ 159 IU/d ≥ 511 IU/d	% of cohort with T2DM 5.6 2.7	Age	
Pittas et al, 2006 (52)	F	46	Nurses Health Study, 83,779/4,843	T2DM (validated self-report)	Vitamin D intake ≤ 200 IU/d > 800 IU/d	Relative Risk 1.00 0.87 (0.69-1.09)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee diet, hypertension, calcium intake	
Calcium Intake								
Liu et al, 2005 (66)	F	>45	Women's Health Study, 10,066/NR	T2DM (validated self-report)	Calcium Intake ≤ 610 mg/d ≥1284 mg/d	% of cohort with T2DM 5.6 2.7	Age	
Pittas et al, 2006 (52)	F	46	Nurses Health Study, 83,779/4,843	T2DM (validated self-report)	Calcium intake ≤ 600 mg/d >1200 mg/d	Relative Risk 1.00 0.79 (0.70-0.90)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee diet, hypertension, calcium intake	
Van Dam et al, 2006 (76)	F	39	BWHS, 41,186/1,964	T2DM (validated self-report)	Calcium intake 219 mg/d 661 mg/d	Relative Risk 1.00 0.86 (0.74-1.00)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee, diet, education	Association dissipated after adjustment for magnesium intake
Pereira et al, 2002 (77)	M/F	18-30	CARDIA, 3,157	Metabolic Syndrome (ATP-3 criteria)	Calcium intake < 600 mg/d >1200 mg/d	Relative Risk 1.00 0.79 (0.61-1.03) Among overweight (BMI >25) only	Age, sex, BMI, exercise, smoking, diet, vitamin use, energy intake,	Association dissipated after adjusting for dairy intake.
Combined vitamin D and calcium intake								
Pittas et al, 2006 (52)	F	46	Nurses Health Study, 83,779/4,843	T2DM (validated self-report)	Vitamin D and Calcium ≤ 400 IU/d and ≤ 600 mg/d > 800 IU/d and >1200 mg/d	Relative Risk 1.00 0.67 (0.49-0.90)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee diet, hypertension	
Dairy intake								
Choi et al, 2005 (80)	M	53	HPFS 41,254/1,243	T2DM (validated self-report)	0.5 servings/d 4.1 servings/d	Relative Risk 1.00 0.82 (0.67-0.1.00)	Age, BMI, exercise, diabetes family history, smoking, diet, cholesterol, hypertension	Adjustment for calcium intake reduced statistical significance of dairy intake

Study First author, Year	Sex, M/F	Age at baseline (mean or range), y	Cohort, Total N/No. of cases	Outcome (assessment)	Predictor, Lowest and highest category	Main Study Results	Adjustments	Comments
Vitamin D status (25-OHD concentration or vitamin D intake)								
Liu et al, 2006 (81)	W	55	Women's Health Study 37,183/1,603	T2DM (validated self-report)	Low-fat <0.9 servings/d ≥ 3 servings/d	Relative Risk 1.00 0.80 (0.67-0.95)	Age, BMI, exercise, diabetes family history, smoking, diet, hormone use, cholesterol, hypertension	Inverse association persisted after adjusting for calcium, vitamin D intake
Pittas et al, 2006 (52)	F	46	Nurses Health Study, 83,779/4,843	T2DM (validated self-report)	< 1 servings/d ≥ 3 servings/d	Relative Risk 1.00 0.89 (0.81-0.99)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee diet, hypertension	
Van Dam et al, 2006 (76)	F	39	Non-diabetics (black) 41,186/1,964	T2DM (validated self-report)	Low-fat 0 servings/d > 1 servings/d	Relative Risk 1.00 0.87 (0.76-1.00)	Age, BMI, exercise, diabetes family history, smoking, alcohol, coffee, diet, education	
Pereira et al, 2002 (77)	M/F	18-30	CARDIA, 3,157/909	Metabolic Syndrome (ATP-3 criteria)	< 1.5 servings/d ≥ 5 servings/d	Relative Risk 1.00 0.31 (0.14-0.70) Among overweight (BMI >25) only	Age, sex, BMI, exercise, smoking, diet, energy intake, vitamin use, calcium and vitamin D intake	

BMI, body mass index; NR, not reported; NGT, normal glucose tolerance (based on FPG or 2hPG); IGT, impaired glucose tolerance (based on FPG or 2hPG); T2DM, Type 2 Diabetes Mellitus (based on FPG, 2hPG or self-report); FPG, fasting plasma glucose; 1hPG, plasma glucose 1 hour after 75 gram glucose load; 2hPG, plasma glucose 2 hours after 75 gram glucose load; GLU_{AUC}, glucose area-under-the-curve after 75 gram glucose load; IR, insulin resistance; HOMA, Homeostasis Model Assessment; CRP, C-reactive protein; WHR, waist-hip-ratio; 25-OHD: 25-hydroxyvitamin D; ↓ decreased (statistically significant), ↑ increased (statistically significant), ↔ no difference (no statistical significance);NHANES, National Health and Nutrition Examination Survey; BWHS, Black Women's Health Study; CARDIA, Coronary Artery Risk Development in Young Adults study; HPFS, Health Professionals Follow-up Study;
To convert 25-OHD concentration to SI units, multiply by 2.459

Table 3

Randomized controlled trials of the effect of vitamin D and/or calcium supplementation on glucose tolerance

Study, First author, Year	Sex, M/F	Age (mean or range), y	Study Participants	25-OHD concentration and calcium intake at baseline	Intervention		Main Outcome (glycemia)	Comment and other outcomes
					Type and dose	Duration		
Vitamin D Alone								
Nilas et al, 1984 (82)	F	45-54	Non-diabetic; N=151	NR	Vitamin D_3 2,000 IU/d [N=25] vs. $1OHD_3$ 0.25 mcg/d [N=23] vs. Placebo [N=103] All received 500 mg/d calcium	104 w	↔FPG (change from baseline, [mg/dl]: +2.2 vs. -0.33 vs. +0.1269)	
Inomata et al, 1986 (24)	M/F	36-80	T2DM; N=14	NR	$1OHD_3$ 2 mcg/d [N=7] vs. Placebo [N=7]	3 w	↔GLU_{AUC} (change from baseline [mg/2h/dl]: -21.2 vs. - 2.3)	↑ INS_{AUC}
Ljunghall et al, 1987 (41)	M	61-65	IGT/mild t2DM; N=65	25-OHD 38 ng/ml	$1OHD_3$ 0.75 mcg/d [N=33] vs. Placebo [N=32]	12 w	↔FPG (baseline to end-of study [mg/dl]: 117 to 117 vs. 115 to 117) ↔A1c (baseline to end [%]: 6.46 to 5.90 vs. 6.28 to 5.70)	↔ IR_{IVGTT}
Orwoll et al, 1994 (23)	M/F	40-70	Non-insulin- treated T2DM; N=20	25-OHD 14 ng/ml	1,25-OHD 1 mcg/d vs. Placebo [Cross-over trial, N=20[	4 d	↔FPG (baseline to end-of- study [mg/dl]: 214 to 209 vs. 214 to 198) ↔ Meal-stimulated PG (data NR)	↔ IR_{FI}, ↔ INS_{AUC} ↑ INS_{AUC} if diabetes of short duration
Fliser et al, 1997 (42)	M	26	Healthy, non-diabetic; N=18	NR	$1,25(OH)_2D_3$ 1.5 mcg/d [N=9] vs. Placebo [N=9]	1 w	↔FPG (baseline to end-of study [mg/dl]: 84 to 86 vs. 86 to 88)	↔ IR_M
Calcium Alone or Dairy Supplementation								
Sanchez 1997 (46)	M/F	25-56	Non-diabetic with essential Hypertension; N=20	NR	Calcium 1500 mg/d [N=10] vs. Placebo [N=10]	8 w	↔FPG (baseline to end-of study [mg/dl]: 99 to 102 vs. 96 to 93)	↓IR_M
Barr et al, 2000 (43)	M/F	55-85	Non-diabetic; N=204	Calcium intake, 649-801 mg/d	Skim/low-fat milk (3 servings/d) [N=101] vs. Usual diet [N=100]	12 w	↑FPG (baseline to end-of study, [mg/dl] 94 to 94 vs. 95 to 95) ↔A1c (data NR)	↔IR_{FI}
Zemel et al, 2004 (47)	M/F	18-60	Non-diabetic, obese; N=32	NR	High dairy (calcium 1300 mg/d) [N =11] vs. High calcium (calcium 1300 mg/d) [N=11] or Low calcium (500 mg/d) [N =10] All received energy restriction (-500 kcal/d)	24 w	↔FPG (data NR) ↓GLU_{AUC} (change from baseline, [%] -27 vs. NR vs. NR)	↔INS_{AUC}, ↓ IR_{FI}, Not adjusted for weight loss
Bowen et al, 2005 (44)	M/F	25-64	Non-diabetic, overweight;	Calcium intake, 787-899 mg/d	High dairy protein (calcium 2400 mg/d)	16 w	↔FPG (data NR), ↔GLU_{AUC} (data given)	↔ IR_{FI}, INS_{AUC},

Study, First author, Year	Sex, M/F	Age (mean or range), y	Study Participants	25-OHD concentration and calcium intake at baseline	Intervention		Main Outcome (glycemia)	Comment and other outcomes
					Type and dose	Duration		
Vitamin D Alone								
			N=50		[N=25] vs. High mixed protein (calcium 500 mg/d) [N=25] All received energy restriction			Protein source was altered
Thompson et al, 2005 (45)	M/F	25-70	Non-diabetic obese; N=90	NR	Dairy, 2 servings/d [N =29] vs. Dairy, 4 servings/d [N =30] All received energy restriction (-500 kcal/ d)	48 w	↔FPG (change from baseline [mg/ dl]: -1.4 vs. -4.0) ↔2hPG (change from baseline [mg/dl]: 1.6 vs. -5.4)	↔INS_{120}, IR_{FI}
Combined Vitamin D plus Calcium Supplementation								
Pittas et al, 2006	M/F	71	Normal FastingGlucose; N=222	25-OHD, 30 ng/ ml; Calcium intake, 750 mg/d	D_3 700 IU/d + calcium citrate 500 mg/d [N=108] vs. Placebo [N=114]	3 y	↔FPG (change from baseline [mg/ dl]: 2.7 vs. 2.2)	↔ IR_{HOMA}
	M/F		Impaired Fasting Glucose; N=92	25-OHD, 30 ng/ ml; Calcium intake, 680 mg/d	D_3 700 IU/d + calcium citrate 500 mg/d [N=45] vs. Placebo [N=47]	3 y	↓FPG (change from baseline [mg/ dl]: 0.4 vs. 6.1	↓ IR_{HOMA}

NR, not reported; IGT, impaired glucose tolerance (based on FPG or 2hPG); T2DM, Type 2 Diabetes Mellitus (based on FPG, 2hPG or self-report); FPG, fasting plasma glucose; 2hPG, plasma glucose 2 hours after 75 gram glucose load; GLU_{AUC}, glucose area-under-the-curve after 75 gram glucose load; INS_{AUC}, insulin area-under-the-curve after 75 gram glucose load; INS_{120}, Insulin value at 120' after glucose load is given; IR, insulin resistance; 25-OHD: 25-hydroxyvitamin D; IR_{FI}, Insulin resistance by fasting insulin; IR_{HOMA}, Insulin resistance by homeostasis model assessment-; IR_M, Insulin resistance after euglycemic hyperinsulinemic clamp; IR_{IVGTT}, insulin resistance after intravenous glucose tolerance test.

↓ decreased (statistically significant), ↑ increased (statistically significant), ↔ no difference (no statistical significance);

To convert 25-OHD concentration to SI units, multiply by 2.459; to convert FPG to SI units, multiply by 0.0555