MEDICAL PROGRESS

Vitamin D Deficiency

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ONCE FOODS WERE FORTIFIED WITH VITAMIN D AND RICKETS APPEARED to have been conquered, many health care professionals thought the major health problems resulting from vitamin D deficiency had been resolved. However, rickets can be considered the tip of the vitamin D–deficiency iceberg. In fact, vitamin D deficiency remains common in children and adults. In utero and during childhood, vitamin D deficiency can cause growth retardation and skeletal deformities and may increase the risk of hip fracture later in life. Vitamin D deficiency in adults can precipitate or exacerbate osteopenia and osteoporosis, cause osteomalacia and muscle weakness, and increase the risk of fracture.

The discovery that most tissues and cells in the body have a vitamin D receptor and that several possess the enzymatic machinery to convert the primary circulating form of vitamin D, 25-hydroxyvitamin D, to the active form, 1,25-dihydroxyvitamin D, has provided new insights into the function of this vitamin. Of great interest is the role it can play in decreasing the risk of many chronic illnesses, including common cancers, autoimmune diseases, infectious diseases, and cardiovascular disease. In this review I consider the nature of vitamin D deficiency, discuss its role in skeletal and nonskeletal health, and suggest strategies for its prevention and treatment.

SOURCES AND METABOLISM OF VITAMIN D

Humans get vitamin D from exposure to sunlight, from their diet, and from dietary supplements (Table 1).[1-4] A diet high in oily fish prevents vitamin D deficiency.[3] Solar ultraviolet B radiation (wavelength, 290 to 315 nm) penetrates the skin and converts 7-dehydrocholesterol to previtamin D_3, which is rapidly converted to vitamin D_3 (Fig. 1).[1] Because any excess previtamin D_3 or vitamin D_3 is destroyed by sunlight (Fig. 1), excessive exposure to sunlight does not cause vitamin D_3 intoxication.[2]

Few foods naturally contain or are fortified with vitamin D. The "D" represents D_2 or D_3 (Fig. 1). Vitamin D_2 is manufactured through the ultraviolet irradiation of ergosterol from yeast, and vitamin D_3 through the ultraviolet irradiation of 7-dehydrocholesterol from lanolin. Both are used in over-the-counter vitamin D supplements, but the form available by prescription in the United States is vitamin D_2.

Vitamin D from the skin and diet is metabolized in the liver to 25-hydroxyvitamin D (Fig. 1), which is used to determine a patient's vitamin D status[1-4]; 25-hydroxyvitamin D is metabolized in the kidneys by the enzyme 25-hydroxyvitamin D-1α-hydroxylase (CYP27B1) to its active form, 1,25-dihydroxyvitamin D.[1-4] The renal production of 1,25-dihydroxyvitamin D is tightly regulated by plasma parathyroid hormone levels and serum calcium and phosphorus levels.[1-4] Fibroblast growth factor 23, secreted from the bone, causes the sodium–phosphate cotransporter to be internalized by the cells of the kidney and small intestine and also suppresses 1,25-dihydroxyvitamin D synthesis.[5] The efficiency of the absorption of renal calcium and of intestinal calcium and phosphorus is increased in the presence of 1,25-dihy-

droxyvitamin D (Fig. 1).[2,3,6] It also induces the expression of the enzyme 25-hydroxyvitamin D-24-hydroxylase (CYP24), which catabolizes both 25-hydroxyvitamin D and 1,25-dihydroxyvitamin D into biologically inactive, water-soluble calcitroic acid.[2-4]

DEFINITION AND PREVALENCE OF VITAMIN D DEFICIENCY

Although there is no consensus on optimal levels of 25-hydroxyvitamin D as measured in serum, vitamin D deficiency is defined by most experts as a 25-hydroxyvitamin D level of less than 20 ng per milliliter (50 nmol per liter).[7-10] 25-Hydroxyvitamin D levels are inversely associated with parathyroid hormone levels until the former reach 30 to 40 ng per milliliter (75 to 100 nmol per liter), at which point parathyroid hormone levels begin to level off (at their nadir).[10-12] Furthermore, intestinal calcium transport increased by 45 to 65% in women when 25-hydroxyvitamin D levels were increased from an average of 20 to 32 ng per milliliter (50 to 80 nmol per liter).[13] Given such data, a level of 25-hydroxyvitamin D of 21 to 29 ng per milliliter (52 to 72 nmol per liter) can be considered to indicate a relative insufficiency of vitamin D, and a level of 30 ng per milliliter or greater can be considered to indicate sufficient vitamin D.[14] Vitamin D intoxication is observed when serum levels of 25-hydroxyvitamin D are greater than 150 ng per milliliter (374 nmol per liter).

With the use of such definitions, it has been estimated that 1 billion people worldwide have vitamin D deficiency or insufficiency.[7-12,15-22] According to several studies, 40 to 100% of U.S. and European elderly men and women still living in the community (not in nursing homes) are deficient in vitamin D.[7-12,15-22] More than 50% of postmenopausal women taking medication for osteoporosis had suboptimal levels of 25-hydroxyvitamin D — below 30 ng per milliliter (75 nmol per liter).[12,22]

Children and young adults are also potentially at high risk for vitamin D deficiency. For example, 52% of Hispanic and black adolescents in a study in Boston[23] and 48% of white preadolescent girls in a study in Maine[24] had 25-hydroxyvitamin D levels below 20 ng per milliliter. In other studies, at the end of the winter, 42% of 15- to 49-year-old black girls and women throughout the United States had 25-hydroxyvitamin D levels below 20 ng per milliliter,[25] and 32% of healthy students, phy-sicians, and residents at a Boston hospital were found to be vitamin D–deficient, despite drinking a glass of milk and taking a multivitamin daily and eating salmon at least once a week.[26]

In Europe, where very few foods are fortified with vitamin D, children and adults would appear to be at especially high risk.[1,7,11,16-22] People living near the equator who are exposed to sunlight without sun protection have robust levels of 25-hydroxyvitamin D — above 30 ng per milliliter.[27,28] However, even in the sunniest areas, vitamin D deficiency is common when most of the skin is shielded from the sun. In studies in Saudi Arabia, the United Arab Emirates, Australia, Turkey, India, and Lebanon, 30 to 50% of children and adults had 25-hydroxyvitamin D levels under 20 ng per milliliter.[29-32] Also at risk were pregnant and lactating women who were thought to be immune to vitamin D deficiency since they took a daily prenatal multivitamin containing 400 IU of vitamin D (70% took a prenatal vitamin, 90% ate fish, and 93% drank approximately 2.3 glasses of milk per day)[33-35]; 73% of the women and 80% of their infants were vitamin D–deficient (25-hydroxyvitamin D level, <20 ng per milliliter) at the time of birth.[34]

CALCIUM, PHOSPHORUS, AND BONE METABOLISM

Without vitamin D, only 10 to 15% of dietary calcium and about 60% of phosphorus is absorbed.[2-4] The interaction of 1,25-dihydroxyvitamin D with the vitamin D receptor increases the efficiency of intestinal calcium absorption to 30 to 40% and phosphorus absorption to approximately 80% (Fig. 1).[2-4,13]

In one study, serum levels of 25-hydroxyvitamin D were directly related to bone mineral density in white, black, and Mexican-American men and women, with a maximum density achieved when the 25-hydroxyvitamin D level reached 40 ng per milliliter or more.[8] When the level was 30 ng per milliliter or less, there was a significant decrease in intestinal calcium absorption[13] that was associated with increased parathyroid hormone.[10-12] Parathyroid hormone enhances the tubular reabsorption of calcium and stimulates the kidneys to produce 1,25-dihydroxyvitamin D.[2-4,6] Parathyroid hormone also activates osteoblasts, which stimulate the transformation of preosteoclasts into mature osteoclasts (Fig. 1).[1-3] Osteoclasts dissolve the mineralized collagen matrix in bone, causing os-

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teopenia and osteoporosis and increasing the risk of fracture.[7,8,11,16-21]

Deficiencies of calcium and vitamin D in utero and in childhood may prevent the maximum deposition of calcium in the skeleton.[36] As vitamin D deficiency progresses, the parathyroid glands are maximally stimulated, causing secondary hyperparathyroidism.[7,9-12] Hypomagnesemia blunts this response, which means that parathyroid hormone levels are often normal when 25-hydroxyvitamin D levels fall below 20 ng per milliliter.[37] Parathyroid hormone increases the metabolism of 25-hydroxyvitamin D to 1,25-dihydroxyvitamin D, which further exacerbates the vitamin D deficiency. Parathyroid hormone also causes phosphaturia, resulting in a low-normal or low serum phosphorus level. Without an adequate calcium–phosphorus product (the value for calcium times the value for serum phosphorus), mineralization of the collagen matrix is diminished, leading to classic signs of rickets in children[1,28] and osteomalacia in adults.[7,38]

Whereas osteoporosis is unassociated with bone pain, osteomalacia has been associated with isolated or generalized bone pain.[39,40] The cause is thought to be hydration of the demineralized gelatin matrix beneath the periosteum; the hydrated matrix pushes outward on the periosteum, causing throbbing, aching pain.[7] Osteomalacia can often be diagnosed by using moderate force to press the thumb on the sternum or anterior tibia, which can elicit bone pain.[7,40] One study showed that 93% of persons 10 to 65 years of age who were admitted to a hospital emergency department with muscle aches and bone pain and who had a wide variety of diagnoses, including fibromyalgia, chronic fatigue syndrome, and depression, were deficient in vitamin D.[41]
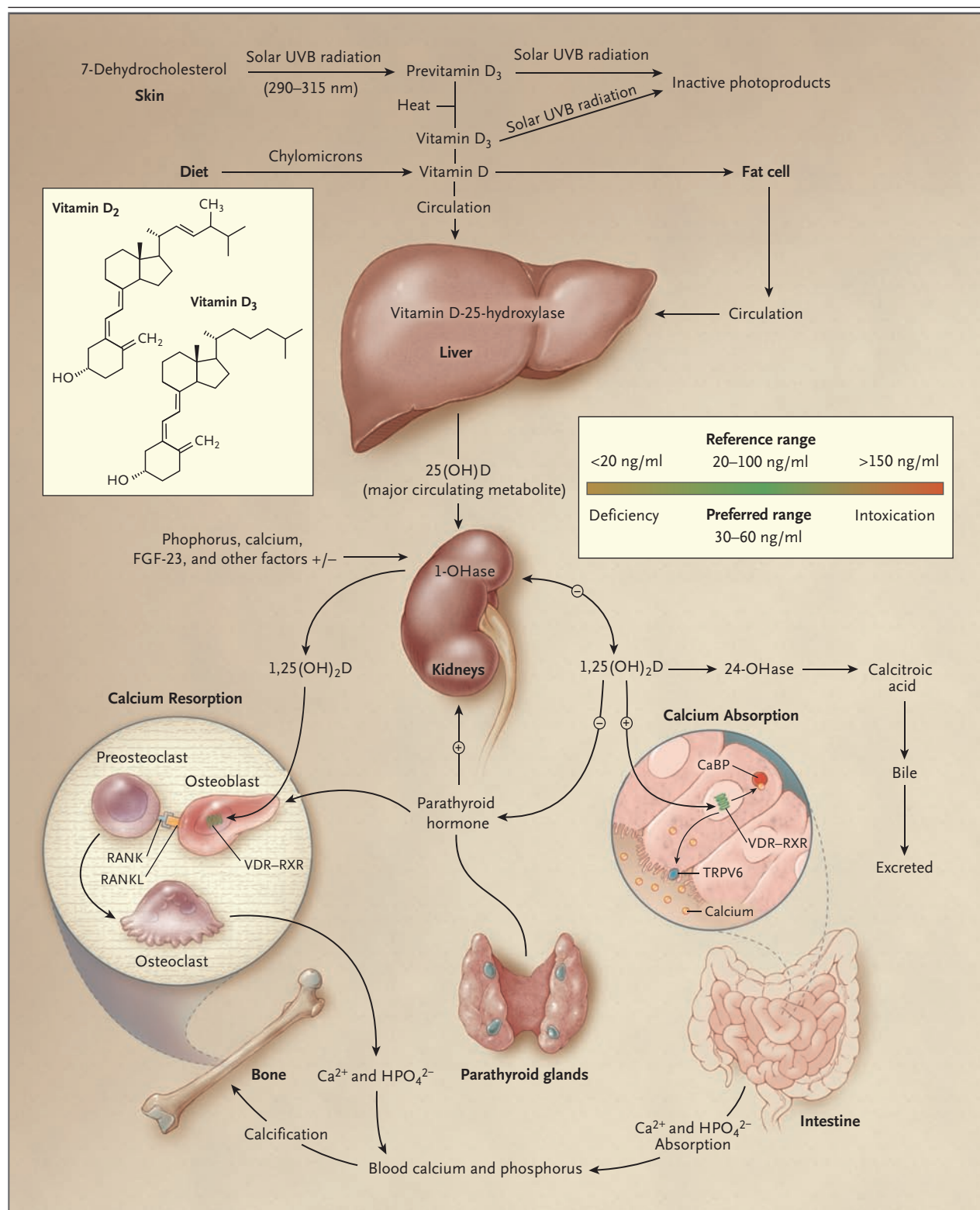
OSTEOPOROSIS AND FRACTURE

Approximately 33% of women 60 to 70 years of age and 66% of those 80 years of age or older have osteoporosis.[16,20] It is estimated that 47% of women and 22% of men 50 years of age or older will sustain an osteoporotic fracture in their remaining lifetime. Chapuy et al.[21] reported that among 3270 elderly French women given 1200 mg of calcium and 800 IU of vitamin D_3 daily for 3 years, the risk of hip fracture was reduced by 43%, and the risk of nonvertebral fracture by 32%. A 58%

Figure 1 (facing page). Synthesis and Metabolism of Vitamin D in the Regulation of Calcium, Phosphorus, and Bone Metabolism.

During exposure to solar ultraviolet B (UVB) radiation, 7-dehydrocholesterol in the skin is converted to previtamin D_3, which is immediately converted to vitamin D_3 in a heat-dependent process. Excessive exposure to sunlight degrades previtamin D_3 and vitamin D_3 into inactive photoproducts. Vitamin D_2 and vitamin D_3 from dietary sources are incorporated into chylomicrons and transported by the lymphatic system into the venous circulation. Vitamin D (hereafter "D" represents D_2 or D_3) made in the skin or ingested in the diet can be stored in and then released from fat cells. Vitamin D in the circulation is bound to the vitamin D–binding protein, which transports it to the liver, where vitamin D is converted by vitamin D-25-hydroxylase to 25-hydroxyvitamin D [25(OH)D]. This is the major circulating form of vitamin D that is used by clinicians to determine vitamin D status. (Although most laboratories report the normal range to be 20 to 100 ng per milliliter [50 to 250 nmol per liter], the preferred range is 30 to 60 ng per milliliter [75 to 150 nmol per liter].) This form of vitamin D is biologically inactive and must be converted in the kidneys by 25-hydroxyvitamin D-1α-hydroxylase (1-OHase) to the biologically active form — 1,25-dihydroxyvitamin D [1,25(OH)$_2$D]. Serum phosphorus, calcium, fibroblast growth factor 23 (FGF-23), and other factors can either increase (+) or decrease (−) the renal production of 1,25(OH)$_2$D. 1,25(OH)$_2$D decreases its own synthesis through negative feedback and decreases the synthesis and secretion of parathyroid hormone by the parathyroid glands. 1,25(OH)$_2$D increases the expression of 25-hydroxyvitamin D-24-hydroxylase (24-OHase) to catabolize 1,25(OH)$_2$D to the water-soluble, biologically inactive calcitroic acid, which is excreted in the bile. 1,25(OH)$_2$D enhances intestinal calcium absorption in the small intestine by interacting with the vitamin D receptor–retinoic acid x-receptor complex (VDR-RXR) to enhance the expression of the epithelial calcium channel (transient receptor potential cation channel, subfamily V, member 6 [TRPV6]) and calbindin 9K, a calcium-binding protein (CaBP). 1,25(OH)$_2$D is recognized by its receptor in osteoblasts, causing an increase in the expression of the receptor activator of nuclear factor-κB ligand (RANKL). RANK, the receptor for RANKL on preosteoclasts, binds RANKL, which induces preosteoclasts to become mature osteoclasts. Mature osteoclasts remove calcium and phosphorus from the bone, maintaining calcium and phosphorus levels in the blood. Adequate calcium (Ca^{2+}) and phosphorus (HPO_4^{2-}) levels promote the mineralization of the skeleton.

reduction in nonvertebral fractures was observed in 389 men and women over the age of 65 years who were receiving 700 IU of vitamin D_3 and 500 mg of calcium per day.[42]

A meta-analysis of seven randomized clinical

7-Dehydrocholesterol → Solar UVB radiation (290–315 nm) → Previtamin D_3 → Solar UVB radiation → Inactive photoproducts

Skin

Heat

Vitamin D_3 → Solar UVB radiation → Inactive photoproducts

Diet → Chylomicrons → Vitamin D → **Fat cell**

Circulation

Vitamin D_2

CH_3

Vitamin D_3

CH_2

HO

CH_2

HO

Vitamin D-25-hydroxylase

Liver

Circulation → Circulation

25(OH)D
(major circulating metabolite)

Reference range		
<20 ng/ml	20–100 ng/ml	>150 ng/ml
Deficiency	**Preferred range** 30–60 ng/ml	Intoxication

Phophorus, calcium, FGF-23, and other factors +/– →

1-OHase

Kidneys

1,25(OH)₂D → 24-OHase → Calcitroic acid → Bile → Excreted

1,25(OH)₂D

Calcium Resorption

Preosteoclast

Osteoblast

RANK
RANKL
VDR–RXR

Osteoclast

Calcium Absorption

CaBP

VDR–RXR

TRPV6

Calcium

Parathyroid hormone

Bone

Calcification

Ca^{2+} and HPO_4^{2-}

Parathyroid glands

Intestine

Ca^{2+} and HPO_4^{2-} Absorption

Blood calcium and phosphorus

Table 1. Dietary, Supplemental, and Pharmaceutical Sources of Vitamins D_2 and D_3.*

Source	Vitamin D Content
Natural sources	
Salmon	
Fresh, wild (3.5 oz)	About 600–1000 IU of vitamin D_3
Fresh, farmed (3.5 oz)	About 100–250 IU of vitamin D_3 or D_2
Canned (3.5 oz)	About 300–600 IU of vitamin D_3
Sardines, canned (3.5 oz)	About 300 IU of vitamin D_3
Mackerel, canned (3.5 oz)	About 250 IU of vitamin D_3
Tuna, canned (3.6 oz)	About 230 IU of vitamin D_3
Cod liver oil (1 tsp)	About 400–1000 IU of vitamin D_3
Shiitake mushrooms	
Fresh (3.5 oz)	About 100 IU of vitamin D_2
Sun-dried (3.5 oz)	About 1600 IU of vitamin D_2
Egg yolk	About 20 IU of vitamin D_3 or D_2
Exposure to sunlight, ultraviolet B radiation (0.5 minimal erythemal dose)†	About 3000 IU of vitamin D_3
Fortified foods	
Fortified milk	About 100 IU/8 oz, usually vitamin D_3
Fortified orange juice	About 100 IU/8 oz vitamin D_3
Infant formulas	About 100 IU/8 oz vitamin D_3
Fortified yogurts	About 100 IU/8 oz, usually vitamin D_3
Fortified butter	About 50 IU/3.5 oz, usually vitamin D_3
Fortified margarine	About 430 IU/3.5 oz, usually vitamin D_3
Fortified cheeses	About 100 IU/3 oz, usually vitamin D_3
Fortified breakfast cereals	About 100 IU/serving, usually vitamin D_3
Supplements	
Prescription	
Vitamin D_2 (ergocalciferol)	50,000 IU/capsule
Drisdol (vitamin D_2) liquid supplements	8000 IU/ml
Over the counter	
Multivitamin	400 IU vitamin D, D_2, or D_3‡
Vitamin D_3	400, 800, 1000, and 2000 IU

* IU denotes international unit, which equals 25 ng. To convert values from ounces to grams, multiply by 28.3. To convert values from ounces to milliliters, multiply by 29.6.
† About 0.5 minimal erythemal dose of ultraviolet B radiation would be absorbed after an average of 5 to 10 minutes of exposure (depending on the time of day, season, latitude, and skin sensitivity) of the arms and legs to direct sunlight.
‡ When the term used on the product label is vitamin D or calciferol, the product usually contains vitamin D_2; cholecalciferol or vitamin D_3 indicates that the product contains vitamin D_3.

trials that evaluated the risk of fracture in older persons given 400 IU of vitamin D_3 per day revealed little benefit with respect to the risk of either nonvertebral or hip fractures (pooled relative risk of hip fracture, 1.15; 95% confidence interval [CI], 0.88 to 1.50; pooled relative risk of nonvertebral fracture, 1.03; 95% CI, 0.86 to 1.24). In studies using doses of 700 to 800 IU of vitamin D_3 per day, the relative risk of hip fracture was reduced by 26% (pooled relative risk, 0.74; 95% CI, 0.61 to 0.88), and the relative risk of nonvertebral fracture by 23% (pooled relative risk, 0.77; 95% CI, 0.68 to 0.87) with vitamin D_3 as compared with calcium or placebo.[8] A Women's Health Initiative study that compared the effects of 400 IU of vitamin D_3 plus 1000 mg of calcium per day with placebo in more than 36,000 postmenopausal women confirmed these results, reporting an increased risk of kidney stones but no benefit with respect to the risk of hip fracture.

The Women's Health Initiative study also showed that serum levels of 25-hydroxyvitamin D had little effect on the risk of fracture when levels were 26 ng per milliliter (65 nmol per liter) or less. However, women who were most consistent in taking calcium and vitamin D_3 had a 29% reduction in hip fracture.[43] Optimal prevention of both nonvertebral and hip fracture occurred only in trials providing 700 to 800 IU of vitamin D_3 per day in patients whose baseline concentration of 25-hydroxyvitamin D was less than 17 ng per milliliter (42 nmol per liter) and whose mean concentration of 25-hydroxyvitamin D then rose to approximately 40 ng per milliliter.[8]

Evaluation of the exclusive use of calcium or vitamin D_3 (RECORD trial) showed no antifracture efficacy for patients receiving 800 IU of vitamin D_3 per day.[44] However, the mean concentration of 25-hydroxyvitamin D increased from 15.2 ng per milliliter to just 24.8 ng per milliliter (37.9 to 61.9 nmol per liter), which was below the threshold thought to provide antifracture efficacy.[8] Porthouse and colleagues,[45] who evaluated the effect of 800 IU of vitamin D_3 per day on fracture prevention, did not report concentrations of 25-hydroxyvitamin D. Their study had an open design in which participants could have been ingesting an adequate amount of calcium and vitamin D separate from the intervention. This called into question the conclusion that vitamin D supplementation had no antifracture benefit.[8]

MUSCLE STRENGTH AND FALLS

Vitamin D deficiency causes muscle weakness.[1,7,8,28] Skeletal muscles have a vitamin D receptor and may require vitamin D for maximum function.[1,8]

Performance speed and proximal muscle strength were markedly improved when 25-hydroxyvitamin D levels increased from 4 to 16 ng per milliliter (10 to 40 nmol per liter) and continued to improve as the levels increased to more than 40 ng per milliliter (100 nmol per liter).[8] A meta-analysis of five randomized clinical trials (with a total of 1237 subjects) revealed that increased vitamin D intake reduced the risk of falls by 22% (pooled corrected odds ratio, 0.78; 95% CI, 0.64 to 0.92) as compared with only calcium or placebo.[8] The same meta-analysis examined the frequency of falls and suggested that 400 IU of vitamin D_3 per day was not effective in preventing falls, whereas 800 IU of vitamin D_3 per day plus calcium reduced the risk of falls (corrected pooled odds ratio, 0.65; 95% CI, 0.4 to 1.0).[8] In a randomized controlled trial conducted over a 5-month period, nursing home residents receiving 800 IU of vitamin D_2 per day plus calcium had a 72% reduction in the risk of falls as compared with the placebo group (adjusted rate ratio, 0.28%; 95% CI, 0.11 to 0.75).[46]

NONSKELETAL ACTIONS OF VITAMIN D

Brain, prostate, breast, and colon tissues, among others, as well as immune cells have a vitamin D receptor and respond to 1,25-dihydroxyvitamin D, the active form of vitamin D.[1-4,6] In addition, some of these tissues and cells express the enzyme 25-hydroxyvitamin D-1α-hydroxylase.[1-3,6]

Directly or indirectly, 1,25-dihydroxyvitamin D controls more than 200 genes, including genes responsible for the regulation of cellular proliferation, differentiation, apoptosis, and angiogenesis.[1,2,47] It decreases cellular proliferation of both normal cells and cancer cells and induces their terminal differentiation.[1-3,6,47] One practical application is the use of 1,25-dihydroxyvitamin D_3 and its active analogues for the treatment of psoriasis.[48,49]

1,25-Dihydroxyvitamin D is also a potent immunomodulator.[2-4,6,50] Monocytes and macrophages exposed to a lipopolysaccharide or to *Mycobacterium tuberculosis* up-regulate the vitamin D receptor gene and the 25-hydroxyvitamin D-1α-hydroxylase gene. Increased production of 1,25-dihydroxyvitamin D_3 result in synthesis of cathelicidin, a peptide capable of destroying *M. tuberculosis* as well as other infectious agents. When serum levels of 25-hydroxyvitamin D fall below 20 ng per milliliter (50 nmol per liter), the monocyte or macrophage is prevented from initiating this innate immune response, which may explain why black Americans, who are often vitamin D–deficient, are more prone to contracting tuberculosis than are whites, and tend to have a more aggressive form of the disease.[51] 1,25-dihydroxyvitamin D_3 inhibits renin synthesis,[52] increases insulin production,[53] and increases myocardial contractility (Fig. 2).[54]

LATITUDE, VITAMIN D DEFICIENCY, AND CHRONIC DISEASES

### CANCER

People living at higher latitudes are at increased risk for Hodgkin's lymphoma as well as colon, pancreatic, prostate, ovarian, breast, and other cancers and are more likely to die from these cancers, as compared with people living at lower latitudes.[55-65] Both prospective and retrospective epidemiologic studies indicate that levels of 25-hydroxyvitamin D below 20 ng per milliliter are associated with a 30 to 50% increased risk of incident colon, prostate, and breast cancer, along with higher mortality from these cancers.[56,59-61,64] An analysis from the Nurses' Health Study cohort (32,826 subjects) showed that the odds ratios for colorectal cancer were inversely associated with median serum levels of 25-hydroxyvitamin D (the odds ratio at 16.2 ng per milliliter [40.4 nmol per liter] was 1.0, and the odds ratio at 39.9 ng per milliliter [99.6 nmol per liter] was 0.53; P≤0.01). Serum 1,25-dihydroxyvitamin D levels were not associated with colorectal cancer.[61] A prospective study of vitamin D intake and the risk of colorectal cancer in 1954 men showed a direct relationship (with a relative risk of 1.0 when vitamin D intake was 6 to 94 IU per day and a relative risk of 0.53 when the intake was 233 to 652 IU per day, P<0.05).[56] Participants in the Women's Health Initiative who at baseline had a 25-hydroxyvitamin D concentration of less than 12 ng per milliliter (30 nmol per liter) had a 253% increase in the risk of colorectal cancer over a follow-up period of 8 years.[62] In a study
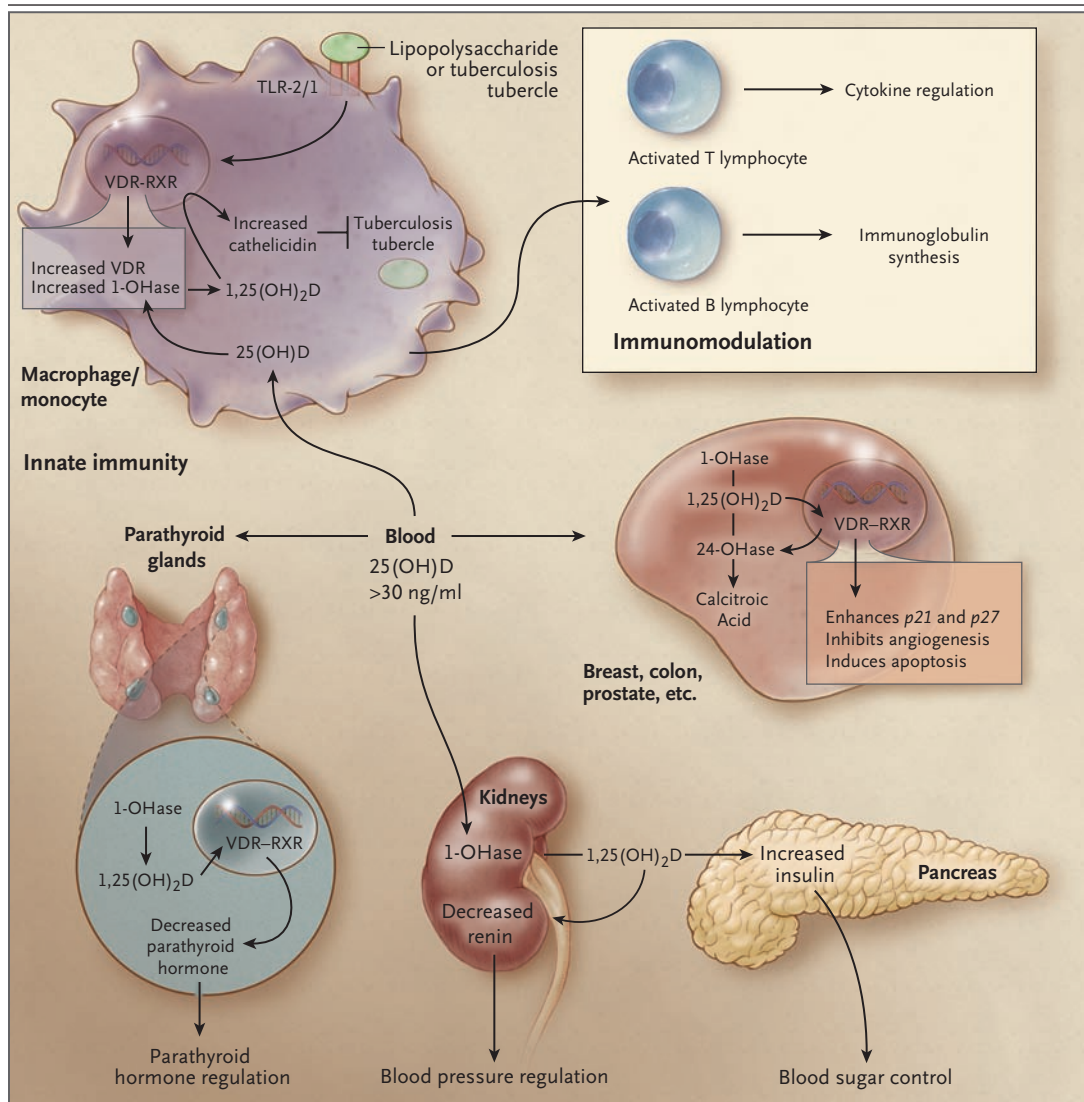
Figure 2. Metabolism of 25-Hydroxyvitamin D to 1,25-Dihydroxyvitamin D for Nonskeletal Functions.

When a macrophage or monocyte is stimulated through its toll-like receptor 2/1 (TLR2/1) by an infectious agent such as *Mycobacterium tuberculosis* or its lipopolysaccharide, the signal up-regulates the expression of vitamin D receptor (VDR) and 25-hydroxyvitamin D-1α-hydroxylase (1-OHase). A 25-hydroxyvitamin D [25(OH)D] level of 30 ng per milliliter (75 nmol per liter) or higher provides adequate substrate for 1-OHase to convert 25(OH)D to its active form, 1,25 dihydroxyvitamin D [1,25(OH)$_2$D]. 1,25(OH)$_2$D travels to the nucleus, where it increases the expression of cathelicidin, a peptide capable of promoting innate immunity and inducing the destruction of infectious agents such as *M. tuberculosis*. It is also likely that the 1,25(OH)$_2$D produced in monocytes or macrophages is released to act locally on activated T lymphocytes, which regulate cytokine synthesis, and activated B lymphocytes, which regulate immunoglobulin synthesis. When the 25(OH)D level is approximately 30 ng per milliliter, the risk of many common cancers is reduced. It is believed that the local production of 1,25(OH)$_2$D in the breast, colon, prostate, and other tissues regulates a variety of genes that control proliferation, including *p21* and *p27,* as well as genes that inhibit angiogenesis and induce differentiation and apoptosis. Once 1,25(OH)$_2$D completes the task of maintaining normal cellular proliferation and differentiation, it induces expression of the enzyme 25-hydroxyvitamin D-24-hydroxylase (24-OHase), which enhances the catabolism of 1,25(OH)$_2$D to the biologically inert calcitroic acid. Thus, locally produced 1,25(OH)$_2$D does not enter the circulation and has no influence on calcium metabolism. The parathyroid glands have 1-OHase activity, and the local production of 1,25(OH)$_2$D inhibits the expression and synthesis of parathyroid hormone. The 1,25(OH)$_2$D produced in the kidney enters the circulation and can down-regulate renin production in the kidney and stimulate insulin secretion in the beta islet cells of the pancreas.

of men with prostate cancer, the disease developed 3 to 5 years later in the men who worked outdoors than in those who worked indoors.[63] Pooled data for 980 women showed that the highest vitamin D intake, as compared with the lowest, correlated with a 50% lower risk of breast cancer.[64] Children and young adults who are exposed to the most sunlight have a 40% reduced risk of non-Hodgkin's lymphoma[65] and a reduced risk of death from malignant melanoma once it develops, as compared with those who have the least exposure to sunlight.[66]

The conundrum here is that since the kidneys tightly regulate the production of 1,25-dihydroxyvitamin D, serum levels do not rise in response to increased exposure to sunlight or increased intake of vitamin D.[1-3] Furthermore, in a vitamin D–insufficient state, 1,25-dihydroxyvitamin D levels are often normal or even elevated.[1,3,6,7] The likely explanation is that colon, prostate, breast, and other tissues express 25-hydroxyvitamin D-1α-hydroxylase and produce 1,25-dihydroxyvitamin D locally to control genes that help to prevent cancer by keeping cellular proliferation and differentiation in check.[1-3,47,56,58] It has been suggested that if a cell becomes malignant, 1,25-dihydroxyvitamin D can induce apoptosis and prevent angiogenesis, thereby reducing the potential for the malignant cell to survive.[2,3,7,67] Once 1,25-dihydroxyvitamin D completes these tasks, it initiates its own destruction by stimulating the *CYP24* gene to produce the inactive calcitroic acid. This guarantees that 1,25-dihydroxyvitamin D does not enter the circulation to influence calcium metabolism (Fig. 1).[1-4] This is a plausible explanation for why increased sun exposure and higher circulating levels of 25-hydroxyvitamin D are associated with a decreased risk of deadly cancers.[56-65]

AUTOIMMUNE DISEASES, OSTEOARTHRITIS, AND DIABETES

Living at higher latitudes increases the risk of type 1 diabetes, multiple sclerosis, and Crohn's disease.[68,69] Living below 35 degrees latitude for the first 10 years of life reduces the risk of multiple sclerosis by approximately 50%.[69,70] Among white men and women, the risk of multiple sclerosis decreased by 41% for every increase of 20 ng per milliliter in 25-hydroxyvitamin D above approximately 24 ng per milliliter (60 nmol per liter) (odds ratio, 0.59; 95% CI, 0.36 to 0.97; P=0.04).[71] Women who ingested more than 400 IU of vitamin D per day had a 42% reduced risk of developing multi-

ple sclerosis.[72] Similar observations have been made for rheumatoid arthritis[73] and osteoarthritis.[74]

Several studies suggest that vitamin D supplementation in children reduces the risk of type 1 diabetes. Increasing vitamin D intake during pregnancy reduces the development of islet autoantibodies in offspring.[53] For 10,366 children in Finland who were given 2000 IU of vitamin D_3 per day during their first year of life and were followed for 31 years, the risk of type 1 diabetes was reduced by approximately 80% (relative risk, 0.22; 95% CI, 0.05 to 0.89).[75] Among children with vitamin D deficiency the risk was increased by approximately 200% (relative risk, 3.0; 95% CI, 1.0 to 9.0). In another study, vitamin D deficiency increased insulin resistance, decreased insulin production, and was associated with the metabolic syndrome.[53] Another study showed that a combined daily intake of 1200 mg of calcium and 800 IU of vitamin D lowered the risk of type 2 diabetes by 33% (relative risk, 0.67; 95% CI, 0.49 to 0.90) as compared with a daily intake of less than 600 mg of calcium and less than 400 IU of vitamin D.[76]

CARDIOVASCULAR DISEASE

Living at higher latitudes increases the risk of hypertension and cardiovascular disease.[54,77] In a study of patients with hypertension who were exposed to ultraviolet B radiation three times a week for 3 months, 25-hydroxyvitamin D levels increased by approximately 180%, and blood pressure became normal (both systolic and diastolic blood pressure reduced by 6 mm Hg).[78] Vitamin D deficiency is associated with congestive heart failure[54] and blood levels of inflammatory factors, including C-reactive protein and interleukin-10.[54,79]

VITAMIN D DEFICIENCY AND OTHER DISORDERS

SCHIZOPHRENIA AND DEPRESSION

Vitamin D deficiency has been linked to an increased incidence of schizophrenia and depression.[80,81] Maintaining vitamin D sufficiency in utero and during early life, to satisfy the vitamin D receptor transcriptional activity in the brain, may be important for brain development as well as for maintenance of mental function later in life.[82]

LUNG FUNCTION AND WHEEZING ILLNESSES

Men and women with a 25-hydroxyvitamin D level above 35 ng per milliliter (87 nmol per liter) had

Table 2. Causes of Vitamin D Deficiency.*

Cause	Effect
Reduced skin synthesis	
Sunscreen use — absorption of UVB radiation by sunscreen[1-3,7,85]	Reduces vitamin D_3 synthesis — SPF 8 by 92.5%, SPF 15 by 99%
Skin pigment — absorption of UVB radiation by melanin[1-3,7,85]	Reduces vitamin D_3 synthesis by as much as 99%
Aging — reduction of 7-dehydrocholesterol in the skin[2,7,85]	Reduces vitamin D_3 synthesis by about 75% in a 70-year-old
Season, latitude, and time of day — number of solar UVB photons reaching the earth depending on zenith angle of the sun (the more oblique the angle, the fewer UVB photons reach the earth)[1-3,85]	Above about 35 degrees north latitude (Atlanta), little or no vitamin D_3 can be produced from November to February
Patients with skin grafts for burns — marked reduction of 7-dehydrocholesterol in the skin	Decreases the amount of vitamin D_3 the skin can produce
Decreased bioavailability	
Malabsorption — reduction in fat absorption, resulting from cystic fibrosis, celiac disease, Whipple's disease, Crohn's disease, bypass surgery, medications that reduce cholesterol absorption, and other causes[86,87]	Impairs the body's ability to absorb vitamin D
Obesity — sequestration of vitamin D in body fat†	Reduces availability of vitamin D
Increased catabolism	
Anticonvulsants, glucocorticoids, HAART (AIDS treatment), and antirejection medications — binding to the steroid and xenobiotic receptor or the pregnane X receptor[1-3,7,88]	Activates the destruction of 25-hydroxyvitamin D and 1,25-dihydroxyvitamin D to inactive calcitroic acid
Breast-feeding	
Poor vitamin D content in human milk[1,33,89]	Increases infant risk of vitamin D deficiency when breast milk is sole source of nutrition
Decreased synthesis of 25-hydroxyvitamin D	
Liver failure	
Mild-to-moderate dysfunction	Causes malabsorption of vitamin D, but production of 25-hydroxyvitamin D is possible[2,3,6,7,90]
Dysfunction of 90% or more	Results in inability to make sufficient 25-hydroxyvitamin D
Increased urinary loss of 25-hydroxyvitamin D	
Nephrotic syndrome — loss of 25-hydroxyvitamin D bound to vitamin D–binding protein in urine	Results in substantial loss of 25-hydroxyvitamin D to urine[2,3,6,91]
Decreased synthesis of 1,25-dihydroxyvitamin D	
Chronic kidney disease	
Stages 2 and 3 (estimated glomerular filtration rate, 31 to 89 ml/min/1.73 m²)	
Hyperphosphatemia increases fibroblast growth factor 23, which decreases 25-hydroxyvitamin D-1α-hydroxylase activity[5,6,91-94]	Causes decreased fractional excretion of phosphorus and decreased serum levels of 1,25-dihydroxyvitamin D
Stages 4 and 5 (estimated glomerular filtration rate <30 ml/min/1.73 m²)	
Inability to produce adequate amounts of 1,25-dihydroxyvitamin D[2,3,6,91-96]	Causes hypocalcemia, secondary hyperparathyroidism, and renal bone disease

a 176-ml increase in the forced expiratory volume in 1 second.[83] Children of women living in an inner city who had vitamin D deficiency during pregnancy are at increased risk for wheezing illnesses.[84]

CAUSES OF VITAMIN D DEFICIENCY

There are many causes of vitamin D deficiency, including reduced skin synthesis and absorption of vitamin D and acquired and heritable disorders of

Table 2. (Continued.)

Cause	Effect
Heritable disorders — rickets	
Pseudovitamin D deficiency rickets (vitamin D–dependent rickets type 1) — mutation of the renal 25-hydroxyvitamin D-1α-hydroxylase gene (CYP27B1)[1-3,97]	Causes reduced or no renal synthesis of 1,25-dihydroxyvitamin D
Vitamin D–resistant rickets (vitamin D–dependent rickets type 2) — mutation of the vitamin D receptor gene[1-3]	Causes partial or complete resistance to 1,25-dihydroxyvitamin D action, resulting in elevated levels of 1,25-dihydroxyvitamin D
Vitamin D–dependent rickets type 3 — overproduction of hormone-responsive-element binding proteins[98]	Prevents the action of 1,25-dihydroxyvitamin D in transcription, causing target-cell resistance and elevated levels of 1,25-dihydroxyvitamin D
Autosomal dominant hypophosphatemic rickets — mutation of the gene for fibroblast growth factor 23, preventing or reducing its breakdown[1-3,5,6,92]	Causes phosphaturia, decreased intestinal absorption of phosphorus, hypophosphatemia, and decreased renal 25-hydroxyvitamin D-1α-hydroxylase activity, resulting in low-normal or low levels of 1,25-dihydroxyvitamin D
X-linked hypophosphatemic rickets — mutation of the PHEX gene, leading to elevated levels of fibroblast growth factor 23 and other phosphatonins[1-3,5,6,92]	Causes phosphaturia, decreased intestinal absorption of phosphorus, hypophosphatemia, and decreased renal 25-hydroxyvitamin D-1α-hydroxylase activity, resulting in low-normal or low levels of 1,25-dihydroxyvitamin D
Acquired disorders	
Tumor-induced osteomalacia — tumor secretion of fibroblast growth factor 23 and possibly other phosphatonins[1-3,5,6,92,99]	Causes phosphaturia, decreased intestinal absorption of phosphorus, hypophosphatemia, and decreased renal 25-hydroxyvitamin D-1α-hydroxylase activity, resulting in low-normal or low levels of 1,25-dihydroxyvitamin D
Primary hyperparathyroidism — increase in levels of parathyroid hormone, causing increased metabolism of 25-hydroxyvitamin D to 1,25-hydroxyvitamin D[2,3,6]	Decreases 25-hydroxyvitamin D levels and increases 1,25-dihydroxyvitamin D levels that are high-normal or elevated
Granulomatous disorders, sarcoidosis, tuberculosis, and other conditions, including some lymphomas — conversion by macrophages of 25-hydroxyvitamin D to 1,25-dihydroxyvitamin D[100]	Decreases 25-hydroxyvitamin D levels and increases 1,25-dihydroxyvitamin D levels
Hyperthyroidism — enhanced metabolism of 25-hydroxyvitamin D	Reduces levels of 25-hydroxyvitamin D

* UVB denotes ultraviolet B, SPF sun protection factor, and HAART highly active antiretroviral therapy.
† There is an inverse relationship between the body-mass index and 25-hydroxyvitamin D levels.[2,7,85]

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vitamin D metabolism and responsiveness.[2,3,6] Table 2 lists causes and effects of vitamin D deficiency.

VITAMIN D REQUIREMENTS AND TREATMENT STRATEGIES

CHILDREN AND ADULTS

Recommendations from the Institute of Medicine for adequate daily intake of vitamin D are 200 IU for children and adults up to 50 years of age, 400 IU for adults 51 to 70 years of age, and 600 IU for adults 71 years of age or older.[101] However, most experts agree that without adequate sun exposure, children and adults require approximately 800 to 1000 IU per day.[1-3,8,15,16,20,102,103] Children with vitamin D deficiency should be aggressively treated to prevent rickets (Table 3).[1,28,105-107] Since vitamin D$_2$ is approximately 30% as effective as vitamin D$_3$ in maintaining serum 25-hydroxyvitamin

D levels,[117,118] up to three times as much vitamin D$_2$ may be required to maintain sufficient levels. A cost-effective method of correcting vitamin D deficiency and maintaining adequate levels is to give patients a 50,000-IU capsule of vitamin D$_2$ once a week for 8 weeks, followed by 50,000 IU of vitamin D$_2$ every 2 to 4 weeks thereafter (Table 3).[2,7,9] Alternatively, either 1000 IU of vitamin D$_3$ per day (available in most pharmacies) or 3000 IU of vitamin D$_2$ per day is effective.[2,7,102,103] Strategies such as having patients take 100,000 IU of vitamin D$_3$ once every 3 months have been shown to be effective in maintaining 25-hydroxyvitamin D levels at 20 ng per milliliter or higher and are also effective in reducing the risk of fracture.[119]

BREAST-FED INFANTS AND CHILDREN

Human milk contains little vitamin D (approximately 20 IU per liter), and women who are vitamin D–deficient provide even less to their breast-

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Table 3. Strategies to Prevent and Treat Vitamin D Deficiency.*

Cause of Deficiency†	Preventive and Maintenance Measures to Avoid Deficiency	Treatment of Deficiency
Children		
Breast-feeding without vitamin D supple-mentation[28,33,89,104] — up to 1 yr	400 IU of vitamin D_3/day,[1,28,104] sensible sun exposure,[1] 1000–2000 IU of vitamin D_3/day is safe,[1,2,27,75] maintenance dose is 400–1000 IU of vitamin D_3/day[1,2,104]	200,000 IU of vitamin D_3 every 3 mo,[1,105] 600,000 IU of vitamin D intramuscu-larly, repeat in 12 wk[106]; 1000–2000 IU of vitamin D_2 or vitamin D_3/day[1,107] with calcium supplementation
Inadequate sun exposure[24,29-31,108] or supplementation,[1,28,104-107] dark skin[23] — 1 through 18 yr	400–1000 IU vitamin D_3/day,[1,104,107] sensible sun exposure, 1000–2000 IU of vitamin D_3/day[1,108] is safe,[1,27,75,104,107] maintenance dose is 400–1000 IU of vitamin D/day[1,75]	50,000 IU of vitamin D_2 every wk for 8 wk[1,9]‡
Adults		
Inadequate sun exposure[7,15] or supple-mentation,[7-20] decreased 7-dehy-drocholesterol in skin because of aging (over 50 yr)[7]	800–1000 IU of vitamin D_3/day,[1-3,8,16,21,42] 50,000 IU of vitamin D_2 every 2 wk or every mo,[7,9] sensible sun exposure[7,15,109,110] or use of tanning bed or other UVB radiation device (e.g., portable Sperti lamp),[111-114] up to 10,000 IU of vitamin D_3/day is safe for 5 mo,[27] maintenance dose is 50,000 IU every 2 wk or every mo[7,9]‡	50,000 IU of vitamin D_2 every wk for 8 weeks[9]; repeat for another 8 wk if 25-hydroxyvitamin D <30 ng/ml‡
Pregnant or lactating (fetal utilization,[33] inadequate sun exposure[33,89] or supplementation[33,89])	1000–2000 IU of vitamin D_3/day,[33,89] 50,000 IU of vitamin D_2 every 2 wk, up to 4000 IU of vitamin D_3/day is safe for 5 mo,[33,89] maintenance dose is 50,000 IU of vitamin D_2 every 2 or 4 wk[9]‡	50,000 IU vitamin D_2 every wk for 8 wk[115]; repeat for another 8 wk if 25-hydroxyvita-min D <30 ng/ml‡
Malabsorption syndromes (malabsorp-tion of vitamin D,[2,3,86,87] inade-quate sun exposure[2,3,6,7] or sup-plementation[2,3,6,7])	Adequate exposure to sun or ultraviolet radia-tion,[7,113] 50,000 IU of vitamin D_2 every day, every other day, or every wk,† up to 10,000 IU of vitamin D_3/day is safe for 5 mo,[27] maintenance dose is 50,000 IU of vitamin D_2 every wk‡	UVB irradiation (tanning bed or portable UVB device, e.g., portable Sperti lamp),[111-114] 50,000 IU of vitamin D_2 every day or every other day‡
Drugs that activate steroid and xenobiotic receptor,[88] and drugs used in transplantation[116]	50,000 IU of vitamin D_2 every other day or ev-ery week, maintenance dose is 50,000 IU of vitamin D_2 every 1, 2, or 4 wk‡	50,000 IU of vitamin D_2 every 2 wk for 8–10 wk, or every wk if 25-hydroxyvita-min D <30 ng/ml‡
Obesity[2,7]	1000–2000 IU of vitamin D_3/day, 50,000 IU of vitamin D_2 every 1 or 2 wk, maintenance dose is 50,000 IU of vitamin D_2 every 1, 2, or 4 wk‡	50,000 IU of vitamin D_2 every wk for 8–12 wk; repeat for another 8–12 wk if 25-hydroxyvitamin D <30 ng/ml‡
Nephrotic syndrome[2,3,6,7,91-94]	1000–2000 IU of vitamin D_3/day, 50,000 IU of vitamin D_2 once or twice/wk,[2,94] maintenance dose is 50,000 IU of vitamin D_2 every 2 or 4 wk[2]‡	50,000 IU of vitamin D_2 twice/wk for 8–12 wk[2,94]; repeat for another 8–12 wk if 25-hydroxyvitamin D <30 ng/ml‡
Chronic kidney disease§		
Stages 2 and 3	Control serum phosphate,[6] 1000 IU of vitamin D_3/day, 50,000 IU of vitamin D_2 every 2 wk,[91,94] maintenance dose is 50,000 IU of vitamin D_2 every 2 or 4 wk; may also need to treat with an active vitamin D analog when vitamin D sufficiency is obtained‡	50,000 IU of vitamin D_2 once/wk for 8 wk[91,94]; repeat for another 8 wk if 25-hydroxyvitamin D <30 ng/ml‡
Stages 4 and 5	1000 IU of vitamin D_3/day,[51] 50,000 IU of vita-min D_2 every 2 wk, need to treat with 1,25-dihydroxyvitamin D_3 or active analogue‡	0.25–1.0 µg of 1,25-dihydroxyvitamin D_3 (calcitriol)[2,6,91,93,94] by mouth twice a day or one of the following: 1–2 µg of paricalcitriol IV every 3 days,[6,91,93,94] 0.04–0.1 µg/kg IV every other day ini-tially and can increase to 0.24 µg/kg, 2–4 µg by mouth three times/wk,[6,91,93,94] or doxecalciferol[6,91,93,94] 10–20 µg by mouth three times/wk or 2–6 µg IV three times/wk

Table 3. (Continued.)		
Cause of Deficiency† **Adults**	**Preventive and Maintenance Measures to Avoid Deficiency**	**Treatment of Deficiency**
Primary or tertiary hyperparathyroidism	800–1000 IU of vitamin D_3/day, 50,000 IU of vitamin D_2 every 2 wk (serum calcium levels will not increase),[115] maintenance dose is 50,000 IU of vitamin D_2 every 2 or 4 wk‡	50,000 IU of vitamin D_2 once a wk for 8 wk; repeat for another 8 wk if 25-hydroxyvitamin D <30 ng/ml
Granulomatous disorders and some lymphomas	400 IU of vitamin D_3/day, maintenance dose is 50,000 IU of vitamin D_2/mo‡	50,000 IU vitamin D_2 once a wk for 4 wk or every 2 to 4 wk, need to keep 25-hydroxyvitamin D between 20 and 30 ng/ml (level above 30 ng/ml can result in hypercalciuria and hypercalcemia)‡

* These recommendations are based on published literature and the author's personal experience. IV denotes intravenously. To convert the values for 25-hydroxyvitamin D to nanomoles per liter, multiply by 2.496.
† For the specific mechanism of deficiency, see Table 2.
‡ The goal is to achieve concentrations of 25-hydroxyvitamin D at about 30 to 60 ng per milliliter. Physicians should use these guidelines in combination with their clinical judgment according to the circumstances.
§ In stages 2 and 3 of chronic kidney disease, the estimated glomerular filtration rate is 31 to 89 ml per minute per 1.73 m²; in stages 4 and 5, the estimated rate is <30 ml per minute per 1.73 m².

fed infants.[33,89] Lactating women given 4000 IU of vitamin D_3 per day not only had an increase in the level of 25-hydroxyvitamin D to more than 30 ng per milliliter but were also able to transfer enough vitamin D_3 into their milk to satisfy an infant's requirement.[89]

In Canada, to prevent vitamin D deficiency, current guidelines recommend that all infants and children receive 400 IU of vitamin D_3 per day (Table 3).[104]

PATIENTS WITH CHRONIC KIDNEY DISEASE

In patients with any stage of chronic kidney disease, 25-hydroxyvitamin D should be measured annually, and the level should be maintained at 30 ng per milliliter or higher, as recommended in the Kidney Disease Outcomes Quality Initiative guidelines from the National Kidney Foundation.[6,91,93,94] It is a misconception to assume that patients taking an active vitamin D analogue have sufficient vitamin D; many do not. Levels of 25-hydroxyvitamin D are inversely associated with parathyroid hormone levels, regardless of the degree of chronic renal failure.[2,6,93-96] Parathyroid glands convert 25-hydroxyvitamin D to 1,25-dihydroxyvitamin D, which directly inhibits parathyroid hormone expression.[6,93-96,120] Patients with stage 4 or 5 chronic kidney disease and an estimated glomerular filtration rate of less than 30 ml per minute per 1.73 m² of body-surface area, as well as those requiring dialysis, are unable to make enough 1,25-dihydroxyvitamin D_3 or one of its less calcemic analogues to maintain calcium metabolism and to decrease parathyroid hormone levels and the risk of renal bone disease (Table 3).[6,91,93,94]

MALABSORPTION AND MEDICATION

Patients with mild or moderate hepatic failure or intestinal fat-malabsorption syndromes, as well as patients who are taking anticonvulsant medications, glucocorticoids, or other drugs that activate steroid and xenobiotic receptor, require higher doses of vitamin D (Table 3).[7,88] Exposure to sunlight or ultraviolet B radiation from a tanning bed or other ultraviolet B–emitting device is also effective.[7,113,115]

SUNLIGHT AND ARTIFICIAL ULTRAVIOLET B RADIATION

Sensible sun exposure can provide an adequate amount of vitamin D_3, which is stored in body fat and released during the winter, when vitamin D_3 cannot be produced.[7,15,85,108-110] Exposure of arms and legs for 5 to 30 minutes (depending on time of day, season, latitude, and skin pigmentation) between the hours of 10 a.m. and 3 p.m. twice a week is often adequate.[2,7,108-110] Exposure to one minimal erythemal dose while wearing only a bathing suit is equivalent to ingestion of approximately 20,000 IU of vitamin D_2.[1,2,7,85] The skin has a great capacity to make vitamin D_3, even in the elderly, to reduce the risk of fracture.[109-111] Most tanning beds

emit 2 to 6% ultraviolet B radiation and are a recommended source of vitamin D_3 when used in moderation.[111-113,115] Tanners had robust levels of 25-hydroxyvitamin D (approximately 45 ng per milliliter [112 nmol per liter]) at the end of the winter and higher bone density as compared with nontanners (with levels of approximately 18 ng per milliliter [45 nmol per liter]).[112] For patients with fat malabsorption, exposure to a tanning bed for 30 to 50% of the time recommended for tanning (with sunscreen on the face) is an excellent means of treating and preventing vitamin D deficiency (Table 3).[113] This reduces the risk of skin cancers associated with ultraviolet B radiation.

VITAMIN D INTOXICATION

Vitamin D intoxication is extremely rare but can be caused by inadvertent or intentional ingestion of excessively high doses. Doses of more than 50,000 IU per day raise levels of 25-hydroxyvitamin D to more than 150 ng per milliliter (374 nmol per liter) and are associated with hypercalcemia and hyperphosphatemia.[1-3,27,121,122] Doses of 10,000 IU of vitamin D_3 per day for up to 5 months, however, do not cause toxicity.[27] Patients with chronic granulomatous disorders are more sensitive to serum 25-hydroxyvitamin D levels above 30 ng per milliliter because of macrophage production of 1,25-dihydroxyvitamin D, which causes hypercalciuria and hypercalcemia.[1-3,100] In these patients, however, 25-hydroxyvitamin D levels need to be maintained at approximately 20 to 30 ng per milliliter to prevent vitamin D deficiency and secondary hyperparathyroidism (Table 3).[1-3,100]

CONCLUSIONS

Undiagnosed vitamin D deficiency is not uncommon,[1-3,6-20,123] and 25-hydroxyvitamin D is the barometer for vitamin D status. Serum 25-hydroxyvitamin D is not only a predictor of bone health[8] but is also an independent predictor of risk for cancer and other chronic diseases.[8,54,59-64,71-75,83-85]

The report that postmenopausal women who increased their vitamin D intake by 1100 IU of vitamin D_3 reduced their relative risk of cancer by 60 to 77% is a compelling reason to be vitamin D–sufficient.[124] Most commercial assays for 25-hydroxyvitamin D are good for detecting vitamin D deficiency. Radioimmunoassays measure total 25-hydroxyvitamin D, which includes levels of both 25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3. Some commercial laboratories measure 25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3 with liquid chromatography and tandem mass spectroscopy and report the values separately. As long as the combined total is 30 ng per milliliter or more, the patient has sufficient vitamin D.[7,14,27] The 1,25-dihydroxyvitamin D assay should never be used for detecting vitamin D deficiency because levels will be normal or even elevated as a result of secondary hyperparathyroidism. Because the 25-hydroxyvitamin D assay is costly and may not always be available, providing children and adults with approximately at least 800 IU of vitamin D_3 per day or its equivalent should guarantee vitamin D sufficiency unless there are mitigating circumstances (Table 2).

Much evidence suggests that the recommended adequate intakes are actually inadequate and need to be increased to at least 800 IU of vitamin D_3 per day. Unless a person eats oily fish frequently, it is very difficult to obtain that much vitamin D_3 on a daily basis from dietary sources. Excessive exposure to sunlight, especially sunlight that causes sunburn, will increase the risk of skin cancer.[125,126] Thus, sensible sun exposure (or ultraviolet B irradiation) and the use of supplements are needed to fulfill the body's vitamin D requirement.

REFERENCES

1. Holick MF. Resurrection of vitamin D deficiency and rickets. J Clin Invest 2006;116:2062-72.
2. Holick MF, Garabedian M. Vitamin D: photobiology, metabolism, mechanism of action, and clinical applications. In: Favus MJ, ed. Primer on the metabolic bone diseases and disorders of mineral metab-

olism. 6th ed. Washington, DC: American Society for Bone and Mineral Research, 2006:129-37.
3. Bouillon R. Vitamin D: from photosynthesis, metabolism, and action to clinical applications. In: DeGroot LJ, Jameson JL, eds. Endocrinology. Philadelphia: W.B. Saunders, 2001:1009-28.

4. DeLuca HF. Overview of general physiologic features and functions of vitamin D. Am J Clin Nutr 2004;80:Suppl:1689S-1696S.
5. Hruska KA. Hyperphosphatemia and hypophosphatemia. In: Favus, MJ, ed. Primer on the metabolic bone diseases and disorders of mineral metabolism. 6th

ed. Washington, DC: American Society for Bone and Mineral Research, 2006:233-42.

6. Dusso AS, Brown AJ, Slatopolsky E. Vitamin D. Am J Physiol Renal Physiol 2005;289:F8-F28.

7. Holick MF. High prevalence of vitamin D inadequacy and implications for health. Mayo Clin Proc 2006;81:353-73.

8. Bischoff-Ferrari HA, Giovannucci E, Willett WC, Dietrich T, Dawson-Hughes B. Estimation of optimal serum concentrations of 25-hydroxyvitamin D for multiple health outcomes. Am J Clin Nutr 2006;84:18-28. [Erratum, Am J Clin Nutr 2006;84:1253.]

9. Malabanan A, Veronikis IE, Holick MF. Redefining vitamin D insufficiency. Lancet 1998;351:805-6.

10. Thomas KK, Lloyd-Jones DM, Thadhani RI, et al. Hypovitaminosis D in medical inpatients. N Engl J Med 1998;338:777-83.

11. Chapuy MC, Preziosi P, Maamer M, et al. Prevalence of vitamin D insufficiency in an adult normal population. Osteoporos Int 1997;7:439-43.

12. Holick MF, Siris ES, Binkley N, et al. Prevalence of vitamin D inadequacy among postmenopausal North American women receiving osteoporosis therapy. J Clin Endocrinol Metab 2005;90:3215-24.

13. Heaney RP, Dowell MS, Hale CA, Bendich A. Calcium absorption varies within the reference range for serum 25-hydroxyvitamin D. J Am Coll Nutr 2003;22:142-6.

14. Dawson-Hughes B, Heaney RP, Holick MF, Lips P, Meunier PJ, Vieth R. Estimates of optimal vitamin D status. Osteoporos Int 2005;16:713-6.

15. Glerup H, Mikkelsen K, Poulsen L, et al. Commonly recommended daily intake of vitamin D is not sufficient if sunlight exposure is limited. J Intern Med 2000; 247:260-8.

16. Boonen S, Bischoff-Ferrari HA, Cooper C, et al. Addressing the musculoskeletal components of fracture risk with calcium and vitamin D: a review of the evidence. Calcif Tissue Int 2006;78:257-70.

17. Lips P. Vitamin D deficiency and secondary hyperparathyroidism in the elderly: consequences for bone loss and fractures and therapeutic implications. Endocr Rev 2001;22:477-501.

18. Bakhtiyarova S, Lesnyak O, Kyznesova N, Blankenstein MA, Lips P. Vitamin D status among patients with hip fracture and elderly control subjects in Yekaterinburg, Russia. Osteoporos Int 2006;17:441-6.

19. McKenna MJ. Differences in vitamin D status between countries in young adults and the elderly. Am J Med 1992;93:69-77.

20. Larsen ER, Mosekilde L, Foldspang A. Vitamin D and calcium supplementation prevents osteoporotic fractures in elderly community dwelling residents: a pragmatic population-based 3-year intervention study. J Bone Miner Res 2004;19:370-8.

21. Chapuy MC, Arlot ME, Duboeuf F, et al. Vitamin D₃ and calcium to prevent hip fractures in elderly women. N Engl J Med 1992;327:1637-42.

22. Lips P, Hosking D, Lippuner K, et al. The prevalence of vitamin D inadequacy amongst women with osteoporosis: an international epidemiological investigation. J Intern Med 2006;260:245-54.

23. Gordon CM, DePeter KC, Feldman HA, Grace E, Emans SJ. Prevalence of vitamin D deficiency among healthy adolescents. Arch Pediatr Adolesc Med 2004; 158:531-7.

24. Sullivan SS, Rosen CJ, Halteman WA, Chen TC, Holick MF. Adolescent girls in Maine at risk for vitamin D insufficiency. J Am Diet Assoc 2005;105:971-4.

25. Nesby-O'Dell S, Scanlon KS, Cogswell ME, et al. Hypovitaminosis D prevalence and determinants among African American and white women of reproductive age: Third National Health and Nutrition Examination Survey, 1988-1994. Am J Clin Nutr 2002;76:187-92.

26. Tangpricha V, Pearce EN, Chen TC, Holick MF. Vitamin D insufficiency among free-living healthy young adults. Am J Med 2002;112:659-62.

27. Vieth R. Why the optimal requirement for vitamin D₃ is probably much higher than what is officially recommended for adults. J Steroid Biochem Mol Biol 2004; 89-90:575-9.

28. Pettifor JM. Vitamin D deficiency and nutritional rickets in children in vitamin D. In: Feldman D, Pike JW, Glorieux FH, eds. Vitamin D. 2nd ed. Boston: Elsevier Academic Press, 2005:1065-84.

29. Sedrani SH. Low 25-hydroxyvitamin D and normal serum calcium concentrations in Saudi Arabia: Riyadh region. Ann Nutr Metab 1984;28:181-5.

30. Marwaha RK, Tandon N, Reddy D, et al. Vitamin D and bone mineral density status of healthy schoolchildren in northern India. Am J Clin Nutr 2005;82:477-82.

31. El-Hajj Fuleihan G, Nabulsi M, Choucair M, et al. Hypovitaminosis D in healthy schoolchildren. Pediatrics 2001;107:E53.

32. McGrath JJ, Kimlin MG, Saha S, Eyles DW, Parisi AV. Vitamin D insufficiency in south-east Queensland. Med J Aust 2001; 174:150-1.

33. Hollis BW, Wagner CL. Assessment of dietary vitamin D requirements during pregnancy and lactation. Am J Clin Nutr 2004;79:717-26.

34. Lee JM, Smith JR, Philipp BL, Chen TC, Mathieu J, Holick MF. Vitamin D deficiency in a healthy group of mothers and newborn infants. Clin Pediatr (Phila) 2007;46:42-4.

35. Bodnar LM, Simhan HN, Powers RW, Frank MP, Cooperstein E, Roberts JM. High prevalence of vitamin D insufficiency in black and white pregnant women residing in the northern United States and their neonates. J Nutr 2007;137:447-52.

36. Cooper C, Javaid K, Westlake S, Harvey N, Dennison E. Developmental origins of osteoporotic fracture: the role of maternal vitamin D insufficiency. J Nutr 2005;135:2728S-2734S.

37. Sahota O, Mundey MK, San P, Godber IM, Hosking DJ. Vitamin D insufficiency and the blunted PTH response in established osteoporosis: the role of magnesium deficiency. Osteoporos Int 2006;17: 1013-21. [Erratum, Osteoporos Int 2006;17: 1825-6.]

38. Aaron JE, Gallagher JC, Anderson J, et al. Frequency of osteomalacia and osteoporosis in fractures of the proximal femur. Lancet 1974;1:229-33.

39. Gloth FM III, Lindsay JM, Zelesnick LB, Greenough WB III. Can vitamin D deficiency produce an unusual pain syndrome? Arch Intern Med 1991;151:1662-4.

40. Malabanan AO, Turner AK, Holick MF. Severe generalized bone pain and osteoporosis in a premenopausal black female: effect of vitamin D replacement. J Clin Densitometr 1998;1:201-4.

41. Plotnikoff GA, Quigley JM. Prevalence of severe hypovitaminosis D in patients with persistent, nonspecific musculoskeletal pain. Mayo Clin Proc 2003;78:1463-70.

42. Dawson-Hughes B, Harris SS, Krall EA, Dallal GE. Effect of calcium and vitamin D supplementation on bone density in men and women 65 years of age or older. N Engl J Med 1997;337:670-6.

43. Jackson RD, LaCroix AZ, Gass M, et al. Calcium plus vitamin D supplementation and the risk of fractures. N Engl J Med 2006;354:669-83. [Erratum, N Engl J Med 2006;354:1102.]

44. Grant AM, Avenell A, Campbell MK, et al. Oral vitamin D₃ and calcium for secondary prevention of low trauma fractures in elderly people (Randomised Evaluation of Calcium Or Vitamin D, RECORD): a randomised placebo-controlled trial. Lancet 2005;365:1621-8.

45. Porthouse J, Cockayne S, King C, et al. Randomized controlled trial of supplementation with calcium and cholecalciferol (vitamin D₃) for prevention of fractures in primary care. BMJ 2005;330: 1003-6.

46. Broe KE, Chen TC, Weinberg J, Bischoff-Ferrari HA, Holick MF, Kiel DP. A higher dose of vitamin D reduces the risk of falls in nursing home residents: a randomized, multiple-dose study. J Am Geriatr Soc 2007;55:234-9.

47. Nagpal S, Na S, Rathnachalam R. Noncalcemic actions of vitamin D receptor ligands. Endocr Rev 2005;26:662-87.

48. Holick MF. Clinical efficacy of 1,25-dihydroxyvitamin D₃ and its analogues in the treatment of psoriasis. Retinoids 1998; 14:12-7.

49. Kragballe K, Barnes L, Hamberg KJ, et al. Calcipitriol cream with or without concurrent topical corticosteroid in psoriasis: tolerability and efficacy. Br J Dermatol 1998;139:649-54.

50. Penna G, Roncari A, Armuchastegui S, et al. Expression of the inhibitory receptor ILT3 on dendritic cells is dispensable for induction of CD4+Foxp3+ regulatory T cells by 1,25-dihydroxyvitamin D$_3$. Blood 2005; 106:3490-7.

51. Liu PT, Stenger S, Li H, et al. Toll-like receptor triggering of a vitamin D-mediated human antimicrobial response. Science 2006;311:1770-3.

52. Li YC. Vitamin D regulation of the renin-angiotensin system. J Cell Biochem 2003;88:327-31.

53. Chiu KC, Chu A, Go VLW, Saad MF. Hypovitaminosis D is associated with insulin resistance and β cell dysfunction. Am J Clin Nutr 2004;79:820-5.

54. Zittermann A. Vitamin D and disease prevention with special reference to cardiovascular disease. Prog Biophys Mol Biol 2006;92:39-48.

55. Apperly FL. The relation of solar radiation to cancer mortality in North America. Cancer 1941;1:191-5.

56. Gorham ED, Garland CF, Garland FC, et al. Vitamin D and prevention of colorectal cancer. J Steroid Biochem Mol Biol 2005; 97:179-94.

57. Hanchette CL, Schwartz GG. Geographic patterns of prostate cancer mortality: evidence for a protective effect of ultraviolet radiation. Cancer 1992;70: 2861-9.

58. Grant WB. An estimate of premature cancer mortality in the U.S. due to inadequate doses of solar ultraviolet-B radiation. Cancer 2002;94:1867-75.

59. Giovannucci E, Liu Y, Rimm EB, et al. Prospective study of predictors of vitamin D status and cancer incidence and mortality in men. J Natl Cancer Inst 2006;98: 451-9.

60. Ahonen MH, Tenkanen L, Teppo L, Hakama M, Tuohimaa P. Prostate cancer risk and prediagnostic serum 25-hydroxyvitamin D levels (Finland). Cancer Causes Control 2000;11:847-52.

61. Feskanich D, Ma J, Fuchs CS, et al. Plasma vitamin D metabolites and risk of colorectal cancer in women. Cancer Epidemiol Biomarkers Prev 2004;13:1502-8.

62. Holick MF. Calcium plus vitamin D and the risk of colorectal cancer. N Engl J Med 2006;354:2287-8.

63. Luscombe CJ, Fryer AA, French ME, et al. Exposure to ultraviolet radiation: association with susceptibility and age at presentation with prostate cancer. Lancet 2001;358:641-2.

64. Garland CF, Garland FC, Gorham ED, et al. The role of vitamin D in cancer prevention. Am J Public Health 2006;96:252-61.

65. Chang ET, Smedby KE, Hjalgrim H, et al. Family history of hematopoietic malignancy and risk of lymphoma. J Natl Cancer Inst 2005;97:1466-74.

66. Berwick M, Armstrong BK, Ben-Porat L, et al. Sun exposure and mortality from melanoma. J Natl Cancer Inst 2005;97:195-9.

67. Mantell DJ, Owens PE, Bundred NJ, Mawer EB, Canfield AE. 1α,25-dihydroxyvitamin D$_3$ inhibits angiogenesis in vitro and in vivo. Circ Res 2000;87:214-20.

68. Cantorna MT, Zhu Y, Froicu M, Wittke A. Vitamin D status, 1,25-dihydroxyvitamin D$_3$, and the immune system. Am J Clin Nutr 2004;80:Suppl 6:1717S-1720S.

69. Ponsonby A-L, McMichael A, van der Mei I. Ultraviolet radiation and autoimmune disease: insights from epidemiological research. Toxicology 2002;181-182:71-8.

70. VanAmerongen BM, Dijkstra CD, Lips P, Polman CH. Multiple sclerosis and vitamin D: an update. Eur J Clin Nutr 2004; 58:1095-109.

71. Munger KL, Levin LI, Hollis BW, Howard NS, Ascherio A. Serum 25-hydroxyvitamin D levels and risk of multiple sclerosis. JAMA 2006;296:2832-8.

72. Munger KL, Zhang SM, O'Reilly E, et al. Vitamin D intake and incidence of multiple sclerosis. Neurology 2004;62:60-5.

73. Merlino LA, Curtis J, Mikuls TR, Cerhan JR, Criswell LA, Saag KG. Vitamin D intake is inversely associated with rheumatoid arthritis: results from the Iowa Women's Health Study. Arthritis Rheum 2004;50:72-7.

74. McAlindon TE, Felson DT, Zhang Y, et al. Relation of dietary intake and serum levels of vitamin D to progression of osteoarthritis of the knee among participants in the Framingham Study. Ann Intern Med 1996;125:353-9.

75. Hypponen E, Laara E, Reunanen A, Jarvelin M-R, Virtanen SM. Intake of vitamin D and risk of type 1 diabetes: a birth-cohort study. Lancet 2001;358:1500-3.

76. Pittas AG, Dawson-Hughes B, Li T, et al. Vitamin D and calcium intake in relation to type 2 diabetes in women. Diabetes Care 2006;29:650-6.

77. Rostand SG. Ultraviolet light may contribute to geographic and racial blood pressure differences. Hypertension 1997;30: 150-6.

78. Krause R, Buhring M, Hopfenmuller W, Holick MF, Sharma AM. Ultraviolet B and blood pressure. Lancet 1998;352:709-10.

79. Zittermann A, Schleithoff SS, Tenderich G, Berthold HK, Körfre R, Stehle P. Low vitamin D status: a contributing factor in the pathogenesis of congestive heart failure? J Am Coll Cardiol 2003;41:105-12.

80. McGrath J, Selten JP, Chant D. Long-term trends in sunshine duration and its association with schizophrenia birth rates and age at first registration — data from Australia and the Netherlands. Schizophr Res 2002;54:199-212.

81. Gloth FM III, Alam W, Hollis B. Vitamin D vs. broad spectrum phototherapy in the treatment of seasonal effective disorder. J Nutr Health Aging 1999;3:5-7.

82. Eyles DW, Smith S, Kinobe R, Hewison M, McGrath JJ. Distribution of the vitamin D receptor and 1α-hydroxylase in human brain. J Chem Neuroanat 2005;29: 21-30.

83. Black PN, Scragg R. Relationship between serum 25-hydroxyvitamin D and pulmonary function in the Third National Health and Nutrition Examination Survey. Chest 2005;128:3792-8.

84. Camargo CA Jr, Rifas-Shiman SL, Litonjua AA, et al. Maternal intake of vitamin D during pregnancy and risk of recurrent wheeze in children at 3 y of age. Am J Clin Nutr 2007;85:788-95.

85. Holick MF. Vitamin D: importance in the prevention of cancers, type 1 diabetes, heart disease, and osteoporosis. Am J Clin Nutr 2004;79:362-71. [Erratum, Am J Clin Nutr 2004;79:890.]

86. Lo CW, Paris PW, Clemens TL, Nolan J, Holick MF. Vitamin D absorption in healthy subjects and in patients with intestinal malabsorption syndromes. Am J Clin Nutr 1985;42:644-9.

87. Aris RM, Merkel PA, Bachrach LK, et al. Guide to bone health and disease in cystic fibrosis. J Clin Endocrinol Metab 2005;90:1888-96.

88. Zhou C, Assem M, Tay JC, et al. Steroid and xenobiotic receptor and vitamin D receptor crosstalk mediates CYP24 expression and drug-induced osteomalacia. J Clin Invest 2006;116:1703-12.

89. Hollis BW, Wagner CL. Vitamin D requirements during lactation: high-dose maternal supplementation as therapy to prevent hypovitaminosis D for both the mother and the nursing infant. Am J Clin Nutr 2004;80:Suppl 6:1752S-1758S.

90. Gascon-Barre M. The vitamin D 25-hydroxylase. In: Feldman D, Pike JW, Glorieux FH, eds. Vitamin D. 2nd ed. Boston: Elsevier Academic Press, 2005:47-68.

91. K/DOQI clinical practice guidelines for bone metabolism and disease in chronic kidney disease. Am J Kidney Dis 2003; 42:Suppl 3:S1-S201.

92. Shimada T, Hasegawa H, Yamazaki Y, et al. FGF-23 is a potent regulator of vitamin D metabolism and phosphate homeostasis. J Bone Miner Res 2004;19:429-35.

93. Brown AJ. Therapeutic uses of vitamin D analogues. Am J Kidney Dis 2001; 38:Suppl5:S3-S19.

94. Holick MF. Vitamin D for health and in chronic kidney disease. Semin Dial 2005; 18:266-75.

95. Ritter CS, Armbrecht HJ, Slatopolsky E, Brown AJ. 25-Hydroxyvitamin D$_3$ suppresses PTH synthesis and secretion by bovine parathyroid cells. Kidney Int 2006; 70:654-9. [Erratum, Kidney Int 2006;70: 1190.]

96. Dusso AS, Sato T, Arcidiacono MV, et al. Pathogenic mechanisms for parathyroid hyperplasia. Kidney Int Suppl 2006;102: S8-S11.

97. Kitanaka S, Takeyama K, Murayama A, et al. Inactivating mutations in the human 25-hydroxyvitamin D_3 1α-hydroxylase gene in patients with pseudovitamin D–deficiency rickets. N Engl J Med 1998; 338:653-61.

98. Chen H, Hewison M, Hu B, Adams JS. Heterogeneous nuclear ribonucleoprotein (hnRNP) binding to hormone response elements: a cause of vitamin D resistance. Proc Natl Acad Sci U S A 2003;100:6109-14.

99. Ward LM, Rauch F, White KE, et al. Resolution of severe, adolescent-onset hypophosphatemic rickets following resection of an FGF-23-producing tumour of the distal ulna. Bone 2004;34:905-11.

100. Adams JS, Hewison M. Hypercalcemia caused by granuloma-forming disorders. In: Favus, MJ, ed, Primer on the metabolic bone diseases and disorders of mineral metabolism. 6th ed. Washington, DC: American Society for Bone and Mineral Research, 2006:200-2.

101. Standing Committee on the Scientific Evaluation of Dietary Reference Intakes Food and Nutrition Board, Institute of Medicine. Vitamin D. In: Dietary reference intakes for calcium, phosphorus, magnesium, vitamin D, and fluoride. Washington, DC: National Academy Press, 1999:250-87.

102. Tangpricha V, Koutkia P, Rieke SM, Chen TC, Perez AA, Holick MF. Fortification of orange juice with vitamin D: a novel approach for enhancing vitamin D nutritional health. Am J Clin Nutr 2003; 77:1478-83.

103. Heaney RP, Davies KM, Chen TC, Holick MF, Barger-Lux MJ. Human serum 25-hydroxycholecalciferol response to extended oral dosing with cholecalciferol. Am J Clin Nutr 2003;77:204-10. [Erratum, Am J Clin Nutr 2003;78:1047.]

104. Calvo MS, Whiting SJ, Barton CN. Vitamin D fortification in the United States and Canada: current status and data needs. Am J Clin Nutr 2004;80:Suppl 6:1710S-1716S.

105. Shah BR, Finberg L. Single-dose therapy for nutritional vitamin D-deficiency rickets: a preferred method. J Pediatr 1994; 125:487-90.

106. Thacher TD, Fischer PR, Pettifor JM, et al. A comparison of calcium, vitamin D, or both for nutritional rickets in Nigerian children. N Engl J Med 1999;341:563-8.

107. Markestad T, Halvorsen S, Halvorsen KS, Aksnes L, Aarskog D. Plasma concentrations of vitamin D metabolites before and during treatment of vitamin D deficiency rickets in children. Acta Padiatr Scand 1984;73:225-31.

108. Jones G, Dwyer T. Bone mass in prepubertal children: gender differences and the role of physical activity and sunlight exposure. J Clin Endocrinol Metab 1998; 83:4274-9.

109. Reid IR, Gallagher DJA, Bosworth J. Prophylaxis against vitamin D deficiency in the elderly by regular sunlight exposure. Age Ageing 1986;15:35-40.

110. Sato Y, Iwamoto J, Kanoko T, Satoh K. Amelioration of osteoporosis and hypovitaminosis D by sunlight exposure in hospitalized, elderly women with Alzheimer's disease: a randomized controlled trial. J Bone Miner Res 2005;20:1327-33.

111. Chel VGM, Ooms ME, Popp-Snijders C, et al. Ultraviolet irradiation corrects vitamin D deficiency and suppresses secondary hyperparathyroidism in the elderly. J Bone Miner Res 1998;13:1238-42.

112. Tangpricha V, Turner A, Spina C, Decastro S, Chen T, Holick MF. Tanning is associated with optimal vitamin D status (serum 25-hydroxyvitamin D concentration) and higher bone mineral density. Am J Clin Nutr 2004;80:1645-9.

113. Koutkia P, Lu Z, Chen TC, Holick MF. Treatment of vitamin D deficiency due to Crohn's disease with tanning bed ultraviolet B radiation. Gastroenterology 2001;121:1485-8.

114. de Nijs RNJ, Jacobs JWG, Algra A, Lems WF, Bijlsma JWJ. Prevention and treatment of glucocorticoid-induced osteoporosis with active vitamin D_3 analogues: a review with meta-analysis of randomized controlled trials including organ transplantation studies. Osteoporos Int 2004;15: 589-602.

115. Holick EA, Lu Z, Holick MT, Chen TC, Sheperd J, Holick MF. Production of previtamin D_3 by a mercury arc lamp and a hybrid incandescent/mercury arc lamp. In: Holick MF, ed. Biologic effects of light 2001: proceedings of a symposium. Boston: Kluwer Academic, 2002:205-12.

116. Grey A, Lucas J, Horne A, Gamble G, Davidson JS, Reid IR. Vitamin D repletion in patients with primary hyperparathy-roidism and coexistent vitamin D insufficiency. J Clin Endocrinol Metab 2005;90: 2122-6.

117. Armas LAG, Hollis BW, Heaney RP. Vitamin D_2 is much less effective than vitamin D_3 in humans. J Clin Endocrinol Metab 2004;89:5387-91.

118. Trang HM, Cole DEC, Rubin LA, Pierratos A, Siu S, Vieth R. Evidence that vitamin D_3 increases serum 25-hydroxyvitamin D more efficiently than does vitamin D_2. Am J Clin Nutr 1998;68:854-8.

119. Trivedi DP, Doll R, Khaw KT. Effect of four monthly oral vitamin D_3 (cholecalciferol) supplementation on fractures and mortality in men and women living in the community: randomised double blind controlled trial. BMJ 2003;326:469-75.

120. Correa P, Segersten U, Hellman P, Akerstrom G, Westin G. Increased 25-hydroxyvitamin D_3 1α-hydroxylase and reduced 25-hydroxyvitamin D_3 24-hydroxylase expression in parathyroid tumors — new prospects for treatment of hyperparathyroidism with vitamin D. J Clin Endocrinol Metab 2002;87:5826-9.

121. Adams JS, Lee G. Gains in bone mineral denisty with resolution of vitamin D intoxication. Ann Intern Med 1997;127:203-6.

122. Koutkia P, Chen TC, Holick MF. Vitamin D intoxication associated with an over-the-counter supplement. N Engl J Med 2001; 345:66-7.

123. Kreiter SR, Schwartz RP, Kirkman HN Jr, Charlton PA, Calikoglu AS, Davenport M. Nutritional rickets in African American breast-fed infants. J Pediatr 2000;137:153-7.

124. Lappe JM, Travers-Gustafson D, Davies KM, Recker RR, Heaney RP. Vitamin D and calcium supplementation reduces cancer risk: results of a randomized trial. Am J Clin Nutr 2007;85:1586-91.

125. Kennedy C, Bajdik CD, Willemze R, De Gruijl FR, Bouwes Bavinck JN. The influence of painful sunburns and lifetime sun exposure on the risk of actinic keratoses, seborrheic warts, melanocytic nevi, atypical nevi, and skin cancer. J Invest Dermatol 2003;120:1087-93.

126. Wolpowitz D, Gilchrest BA. The vitamin D questions: how much do you need and how should you get it? J Am Acad Dermatol 2006;54:301-17.

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