Vitamin D deficiency: a worldwide problem with health consequences[1–4]

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ABSTRACT

Vitamin D deficiency is now recognized as a pandemic. The major cause of vitamin D deficiency is the lack of appreciation that sun exposure in moderation is the major source of vitamin D for most humans. Very few foods naturally contain vitamin D, and foods that are fortified with vitamin D are often inadequate to satisfy either a child's or an adult's vitamin D requirement. Vitamin D deficiency causes rickets in children and will precipitate and exacerbate osteopenia, osteoporosis, and fractures in adults. Vitamin D deficiency has been associated with increased risk of common cancers, autoimmune diseases, hypertension, and infectious diseases. A circulating level of 25-hydroxyvitamin D of >75 nmol/L, or 30 ng/mL, is required to maximize vitamin D's beneficial effects for health. In the absence of adequate sun exposure, at least 800–1000 IU vitamin D_3/d may be needed to achieve this in children and adults. Vitamin D_2 may be equally effective for maintaining circulating concentrations of 25-hydroxyvitamin D when given in physiologic concentrations. *Am J Clin Nutr* 2008;87(suppl):1080S–6S.

HISTORICAL PERSPECTIVE

Some of the earliest phytoplankton life forms on earth that have existed unchanged in the Atlantic ocean for >750 y can make vitamin D when exposed to sunlight (1, 2). Most vertebrates, including amphibians, reptiles, birds, and lower primates, depend on sun exposure for their vitamin D requirement (2). The lack of sunlight and its association with the devastating bone-deforming disease rickets in children was first recognized by Sniadecki in 1822 (3). One hundred years would pass before it was observed that exposure to ultraviolet B radiation (UVB; 290–315 nm) from a mercury arc lamp or sunlight prevented and treated rickets (4). In the early 1930s, the US government set up an agency to provide recommendations to parents about the beneficial effect of sensible exposure to sunlight for the prevention of rickets (4-6).

The fortification of milk in the 1930s with 100 IU vitamin D_2 per 8 ounces was effective in eradicating rickets in the United States and Europe. The unfortunate outbreak of hypercalcemia in the 1950s in Great Britain was blamed on the overfortification of milk with vitamin D, even though there was little evidence for this (7). Because milk was scarce at the end of the war, many local stores that sold milk would add vitamin D to it if it was not purchased by the expiration date. This was thought to extend the shelf-life of the vitamin D–fortified milk. This rise in the incidence of hypercalcemia in infants in the 1950s resulted in Europe forbidding the fortification of dairy products with vitamin D. Only recently have Finland and Sweden begun fortifying milk with vitamin D.

SOURCES OF VITAMIN D

The major source of vitamin D for most humans is exposure to sunlight (1, 2, 4–6). As shown in **Figure 1**, seasonal variation is found in the major circulating form of vitamin D, 25-hydroxyvitamin D [25(OH)D] (8). Few foods naturally contain vitamin D, including oily fish such as salmon, mackerel, and herring and oils from fish, including cod liver oil. We recently conducted a study and observed that wild-caught salmon had on average 500–1000 IU vitamin D in 100 g (3.5 ounces), whereas farmed salmon contained ≈100–250 IU vitamin D per 100-g serving (9). The most likely reason is that vitamin D is plentiful in the food chain but is not plentiful in the pelleted diet fed to farmed salmon. In the United States, milk, some juice products, some breads, yogurts, and cheeses are fortified with vitamin D. Multivitamins that contain 400 IU vitamin D and supplements containing vitamin D only are now available in various amounts including 400, 1000, 2000, 4000, 5000 and 50 000 IU vitamin D_3. The pharmaceutical form of vitamin D in the United States is vitamin D_2 and is available as 50 000 IU vitamin D_2 in a capsule or 8000 IU vitamin D_2/mL (4, 10). In Canada, Europe, Japan, and India, vitamin D_3 is available as a pharmaceutical.

CONSEQUENCES OF VITAMIN D DEFICIENCY ON THE MUSCULOSKELETAL SYSTEM

Much debate has taken place over the definition of vitamin D deficiency. Most agree that a 25(OH)D concentration <50 nmol/L, or 20 ng/mL, is an indication of vitamin D deficiency, whereas a 25(OH)D concentration of 51–74 nmol/L, or 21–29 ng/mL, is considered to indicate insufficiency; concentrations

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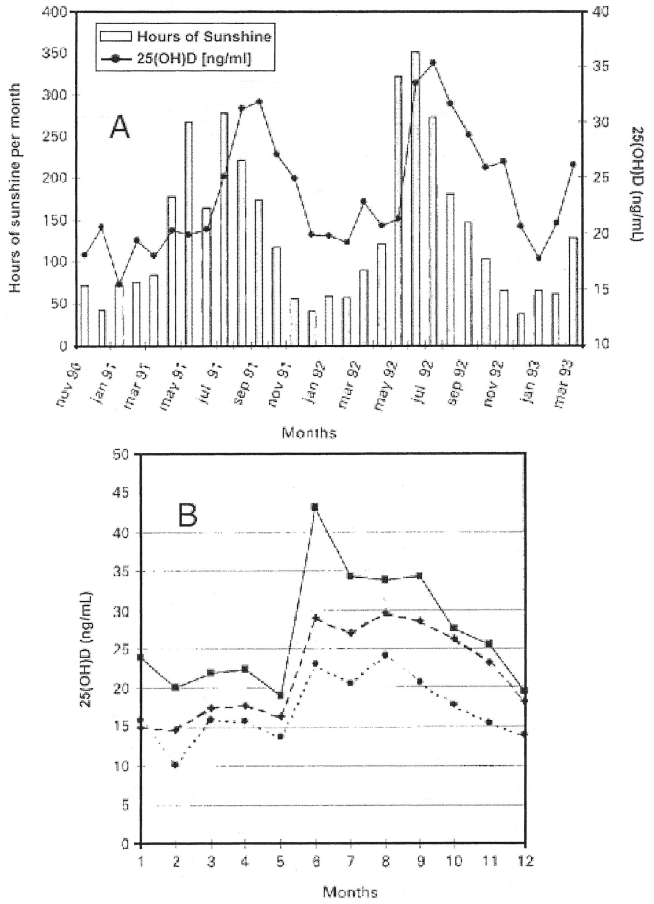

FIGURE 1. A: Relation between hours of sunshine and serum 25-hydroxyvitamin D [25(OH)D] concentrations. ■, hours of sunshine; ●, 25(OH)D. B: Seasonal fluctuation in serum 25(OH)D according to frequency of sun exposure. ■, regular sun exposure; ♦, occasional sun exposure; ●, avoiding direct sun exposure. Adapted from reference 8.

>30 ng/mL are considered to be sufficient (10–15; **Figure 2**) This is based on the observation that intestinal calcium absorption is maximized above 80 nmol/L, or 32 ng/mL, in postmenopausal women (16) and that parathyroid hormone (PTH) concentrations in adults continue to decline and reach their nadir at ≈75–100 nmol/L, or 30–40 ng/mL (11, 14, 15). It has been assumed that children have the same requirement as adults; however, no comparable studies have been carried out on intestinal calcium transport or PTH levels in children. Vitamin D intoxication typically does not occur until 25(OH)D concentrations are >375 nmol/L, or 150 ng/mL (10, 16, 17).

Vitamin D deficiency in children will cause growth retardation (5, 18) and classic signs and symptoms of rickets (4–6, 18). In adults, vitamin D deficiency will precipitate and exacerbate both osteopenia and osteoporosis and increase the risk of fracture (10, 11, 19, 20).

Muscle weakness has long been associated with vitamin D deficiency. A vitamin D receptor is present in skeletal muscle (21), and vitamin D deficiency has been associated with proximal muscle weakness, increase in body sway, and an increased risk of falling (22–24).

Vitamin D deficiency in adults can also cause a skeletal mineralization defect. The unmineralized osteoid provides little structural support for the periosteal covering. As a result, patients with osteomalacia often complain of isolated or global bone discomfort along with aches and pains in their joints and muscles (25–27). These patients may be misdiagnosed with fibromyalgia, dysthymia, degenerative joint disease, arthritis, chronic fatigue syndrome, and other diseases (10, 25, 28).

CAUSES OF VITAMIN D DEFICIENCY

The major source of vitamin D for humans is exposure to sunlight (4, 8, 10). Anything that diminishes the transmission of solar UVB radiation to the earth's surface or anything that interferes with the penetration of UVB radiation into the skin will affect the cutaneous synthesis of vitamin D_3 (2, 9; **Figure 3**) Melanin is extremely efficient in absorbing UVB radiation, and,

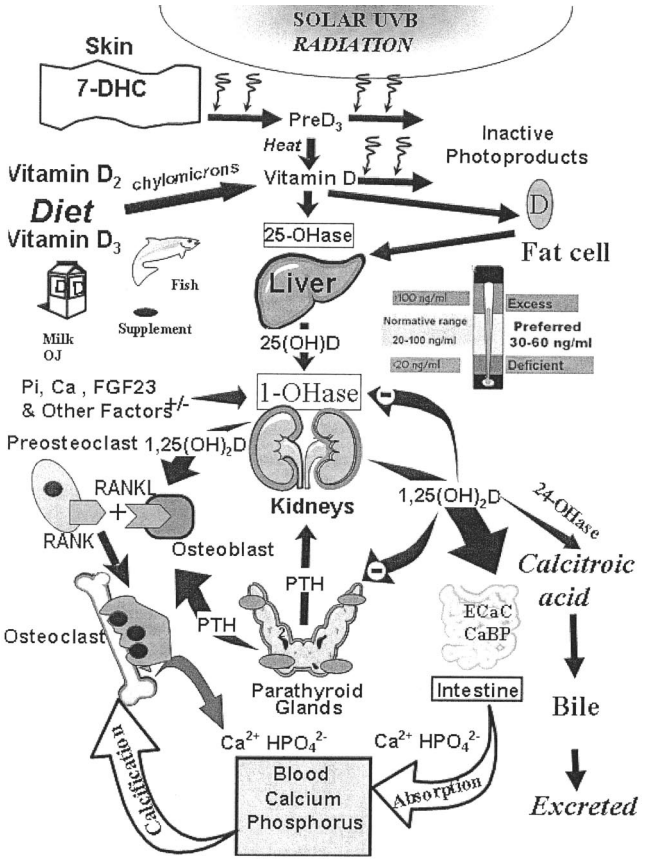

FIGURE 2. Schematic representation of the synthesis and metabolism of vitamin D for regulating calcium, phosphorus, and bone metabolism. During exposure to sunlight, 7-dehydrocholesterol (7-DHC) in the skin is converted to previtamin D_3 ($preD_3$) and then by a heat-dependent process to vitamin D_3. Vitamin D (D represents D_2 or D_3) made in the skin or ingested in the diet is converted by the vitamin D-25-hydroxylase (25-OHase) to 25-hydroxyvitamin D [25(OH)D]. 25(OH)D is converted in the kidneys by the 25-hydroxyvitamin D-1α-hydroxylase (1-OHase) to its biologically active form 1,25-dihydroxyvitamin D [$1,25(OH)_2D$]. $1,25(OH)_2D$ increases the expression of the 25-hydroxyvitamin D-24-hydroxylase (24-OHase) to catabolize $1,25(OH)_2D$ and 25(OH)D to the water-soluble biologically inactive calcitroic acid. $1,25(OH)_2D$ enhances intestinal calcium absorption in the small intestine. $1,25(OH)_2D$ is recognized by its receptor in osteoblasts, causing an increase in the expression of receptor activator of NFκB ligand (RANKL). CaBP, calcium binding protein; ECaC, epithelial channel calcium; FGF23, fibroblast growth factor 23; OJ, orange juice; Pi, inorganic phosphate; PTH, parathyroid hormone; UVB, ultraviolet B radiation.

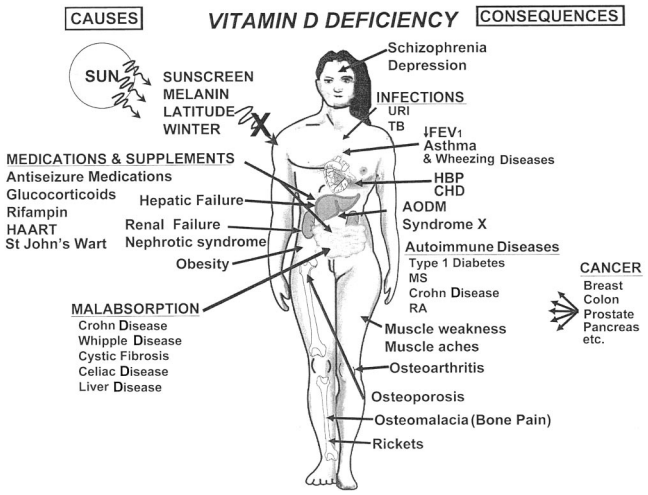

FIGURE 3. A schematic representation of the major causes of vitamin D deficiency and potential health consequences. AODM, adult onset diabetes mellitus; CHD, coronary heart disease; FEV_1, forced expiratory volume in 1 s; HAART, highly active antiretroviral therapy; HBP, high blood pressure; MS, multiple sclerosis; RA, rheumatoid arthritis; TB, tuberculosis; URI, urinary tract infection.

thus, increased skin pigmentation markedly reduces vitamin D_3 synthesis (29). Similarly, a sunscreen with a sun protection of 15 absorbs 99% of the incident UVB radiation, and, thus, when topically applied properly will decrease the synthesis of vitamin D_3 in the skin by 99% (30). African Americans with very dark skin have an SPF of 15, and, thus, their ability to make vitamin D in their skin is reduced by as much as 99% (9, 29). This along with decreased milk intake are the explanations for why most African Americans who live in a temperate climate are vitamin D deficient, whereas Africans living near the equator where vitamin D_3 synthesis is more efficient because of the higher flux of UVB photons are not (31, 32).

The angle at which the sun reaches the earth has a dramatic effect on the number of UVB photons that reach the earth's surface (2, 31). This is why when the zenith angle is increased during the wintertime and in the early morning and late afternoon, little if any vitamin D_3 synthesis occurs (2, 31). The practice of purdah, whereby all skin is covered and prevented from being exposed to sunlight places those who practice it at high risk of vitamin D deficiency and explains why in the sunniest areas of the world vitamin D deficiency is very common in both children and adults (33, 34). No one is immune from vitamin D deficiency. This includes both children and adults living in the United States, Europe, Middle East, India, Australia, and Asia. These studies suggest that upwards of 30–50% of children and adults are at risk of vitamin D deficiency (33–42).

Aging is associated with decreased concentrations of 7-dehydrocholesterol, the precursor of vitamin D_3 in the skin. A 70-y-old has ≈25% of the 7-dehydrocholesterol that a young adult does and thus has a 75% reduced capacity to make vitamin D_3 in the skin (43). Because vitamin D is fat soluble, it is readily taken up by fat cells. Obesity is associated with vitamin D deficiency, and it is believed to be due to the sequestration of vitamin D by the large body fat pool (44). Medications including antiseizure medications and glucocorticoids and fat malabsorption are also common causes of deficiency (45; Figure 3).

NONSKELETAL CONSEQUENCES OF VITAMIN D DEFICIENCY

More than 80 y ago, it was reported that living at higher latitudes in the United States correlated with an increased risk of dying of common cancers (46). In the 1980s and 1990s, several observations suggested that living at higher latitudes increased the risk of developing and dying of colon, prostate, breast, and several other cancers (47–52). Because living at higher latitudes diminishes vitamin D_3 production, it was suggested that an association may exist between vitamin D deficiency and cancer mortality. Both men and women exposed to the most sunlight throughout their lives were less likely to die of cancer (50–54). Several retrospective and prospective studies that evaluated circulating concentrations of 25(OH)D support the concept that vitamin D deficiency increases the risk of developing and dying from cancer (52, 53). It has been suggested that adults with 25(OH)D of <50 nmol/L who were then followed for up to 19 y had a 30–50% increased risk of developing colorectal, breast, prostate, and many other cancers (50, 52, 54, 55). A meta-analysis showed that increasing intake of vitamin D to 1000 IU vitamin D_3/d would be associated with a decreased risk of colorectal and breast cancer of as much as 50% (53). Men who ingested >400 IU vitamin D/d had a markedly reduced risk of developing several cancers, including those of the pancreas and esophagus and non-Hodgkin lymphoma (52). Lappe et al (56) reported that postmenopausal women who received 1100 IU vitamin D_3 and 1000 mg Ca daily for 4 y reduced their risk of developing cancer by 60%.

Living at higher latitudes is associated with an increased risk of type 1 diabetes (57), multiple sclerosis (58, 59), and hypertension (60). Children who received 2000 IU vitamin D/d during the first year of life and who were followed for 31 y were found to have a reduced risk of developing type 1 diabetes by 78% compared with children who were not supplemented with vitamin D (61). Women who received >400 IU vitamin D/d were found to have a >40% reduced risk of developing multiple sclerosis (62) and rheumatoid arthritis (63). Hypertensive patients who were exposed to a tanning bed raised their blood concentrations of 25(OH)D by >180% in 3 mo and became normotensive (64). Patients who live at higher latitudes and are at risk of vitamin D deficiency are also more prone to developing schizophrenia (65), and vitamin D deficiency has been associated with depression (66). Vitamin D deficiency in pregnancy has also been associated with an increased risk of preeclampsia (67).

African Americans are at higher risk of developing and having more severe cases of tuberculosis. It has been known for >100 y that exposure to sunlight helped in the treatment of tuberculosis (68). Liu et al (69) reported that the likely mechanism is that when a macrophage is infected with tuberculosis, it stimulates the cell to increase the production of 1,25-dihydroxyvitamin D_3 [$1,25(OH)_2D_3$] and increase the expression of the vitamin D receptor. In combination, they enhanced the gene expression of the bacteriocidal protein cathelicidin, which is known to kill tuberculosis and other infective agents (**Figure 4**).

MECHANISMS OF ACTION OF VITAMIN D

Vitamin D is metabolized in the liver to 25(OH)D and then in the kidneys to $1,25(OH)_2D$ (70, 71; Figure 2). It is also recognized that many other tissues in the body, including

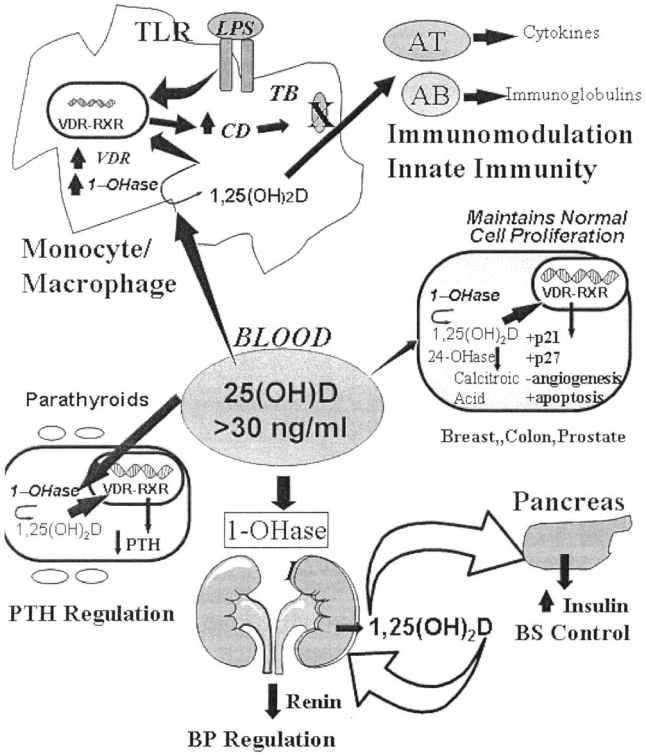

FIGURE 4. Metabolism of 25-hydroxyvitamin D [25(OH)D] to 1,25 dihydroxyvitamin D [1,25$(OH)_2$D] for nonskeletal functions. When a monocyte or macrophage is stimulated through its toll-like receptor 2/1 (TLR2/1) by an infective agent such as *Mycobacterium tuberculosis* (TB) or its lipopolysaccharide (LPS), the signal up-regulates the expression of vitamin D receptor (VDR) and the 25-hydroxyvitamin D-1-hydroxylase (1-OHase). 1,25$(OH)_2$D increases the expression of cathelicidin (CD). When 25(OH)D concentrations are ≈ 30 ng/mL, the risk of many common cancers is reduced. It is believed that the local production of 1,25$(OH)_2$D regulates genes that control proliferation and apoptosis. AB, B-lymphocytes; AT, T-lymphocytes; BP, blood pressure; BS, blood sugar; 24-OHase, 25-hydroxyvitamin D-24-hydroxylase; PTH, parathyroid hormone.

macrophages, brain, colon, prostate, breast, and others, have the enzymatic machinery to locally produce 1,25$(OH)_2$D (72–76; Figure 4). 1,25$(OH)_2$D produced by the kidneys enters the circulation and travels to its major target tissues the intestine and bone, where it interacts with its vitamin D receptor to enhance intestinal calcium absorption and mobilize osteoclastic activity (70; Figure 3).

The local production of 1,25$(OH)_2$D in non-calcium-regulating tissues such as the colon, prostate, and breast is thought to be for the purpose of regulating up to 200 genes, which helps to control cell growth and cellular differentiation and may be responsible for decreasing the risk of the cells being transformed into a malignant state (77). 1,25$(OH)_2D_3$ has been shown to inhibit cancer cell growth, induce cancer cell maturation, induce apoptosis, and decrease angiogenesis (77, 78; Figure 4). 1,25$(OH)_2$D inhibits renin production in the kidney (79) and has a immunomodulatory activity on monocytes and activated T and B lymphocytes (80-82; Figure 4).

PREVENTION AND TREATMENT OF VITAMIN D DEFICIENCY

The Institute of Medicine recommended that all children (also endorsed by the American Academy of Pediatrics) and adults up to the age of 50 y require 200 IU vitamin D/d and adults aged 51–70 and ≥71 y need 400 and 600 IU vitamin D/d (83). The National Osteoporosis Foundation recently recommended that all postmenopausal women take 800–1000 IU vitamin D/d (84). Cheng et al (85) reported an association of low 25(OH)D concentrations with elevated serum PTH concentrations and low cortical bone density in early pubertal and prepubertal Finnish girls. This confirmed the earlier observations of Outila et al (86), who noted elevated PTH concentrations and lower forearm bone density and vitamin D deficiency in the winter in adolescent females, and Guillemant et al (87), who observed seasonal variation in PTH concentrations in growing male adolescents. When 171 prepubertal girls were given 400 IU vitamin D_2/d from October to February and 500 mg Ca supplementation, their serum 25(OH)D concentrations did not change. When these girls received 800 IU vitamin D_2/d, their blood concentrations rose during the winter but did not reach concentrations observed during the summer (88). Thus, on the basis of these and other observations, many experts now agree that in the absence of adequate sun exposure, 800–1000 IU vitamin D/d is needed for children of all ages and adults of all ages (84, 88–91), although this is not the current recommendation of pediatric or governmental organizations. Higher doses may be required if fat malabsorption, obesity, or other causes exist that would enhance vitamin D catabolism and its destruction (10, 45; Figure 2).

As many as 4 different enzymes have been suggested to be capable of converting vitamin D to 25(OH)D (92). These enzymes most likely have different K_m values for vitamin D and have different levels of negative feedback regulation by the serum 25(OH)D concentration. Thus, circulating 25(OH)D concentrations in response to vitamin D may be influenced by the baseline 25(OH)D concentration. As can be seen in **Figure 5**, the baseline concentration of 25(OH)D is an important factor for how a person responds to a vitamin D dose. When serum 25(OH)D concentrations were <50 nmol/L (20 ng/mL) in nursing home patients, doses of 200, 400, and 600 IU vitamin D_2/d for 5 mo (23) raised serum 25(OH)D concentrations by ≈100% to ≈62 nmol/L (24 ng/mL). Only when the dose was increased to 800 IU/d for 5 mo did concentrations rise above 75 nmol/L, or 30 ng/mL (Figure 5). However, subjects who had starting mean 25(OH)D concentrations above 64 nmol/L (25 ng/mL) showed no significant change in their serum 25(OH)D concentrations when they took 200, 400, 600, or 800 IU/d. When the baseline 25(OH)D concentration was above 50 nmol/L (20 ng/mL), only 800 IU vitamin D_2/d for 5 mo was effective in raising the serum 25(OH)D level (Figure 5). This study evaluated vitamin D_2, which has been reported to be only 30% to 50% as effective as vitamin D_3 in maintaining serum 25(OH)D concentrations (93, 94). Our data suggest that vitamin D_2 was effective in raising blood concentrations of 25(OH)D by ≥1 ng/100 IU, as has been reported for vitamin D_3 (91, 95). These data are consistent with our recent observation that 1000 IU vitamin D_2/d was as effective as 1000 IU vitamin D_3/d in raising and maintaining serum 25(OH)D concentrations (91). Thus, physiologic doses of vitamin D_2 may be equally effective as vitamin D_3 in maintaining serum 25(OH)D concentrations.

To treat vitamin D deficiency in the United States, 50 000 IU vitamin D_2 (or vitamin D_3, which is available in Canada, Europe, Japan, and India) once a week for 8 wk often attains a 25(OH)D concentration of ≈75 nmol/L (13). To maintain vitamin D sufficiency, Holick (10) recommends that 50 000 IU vitamin D_2

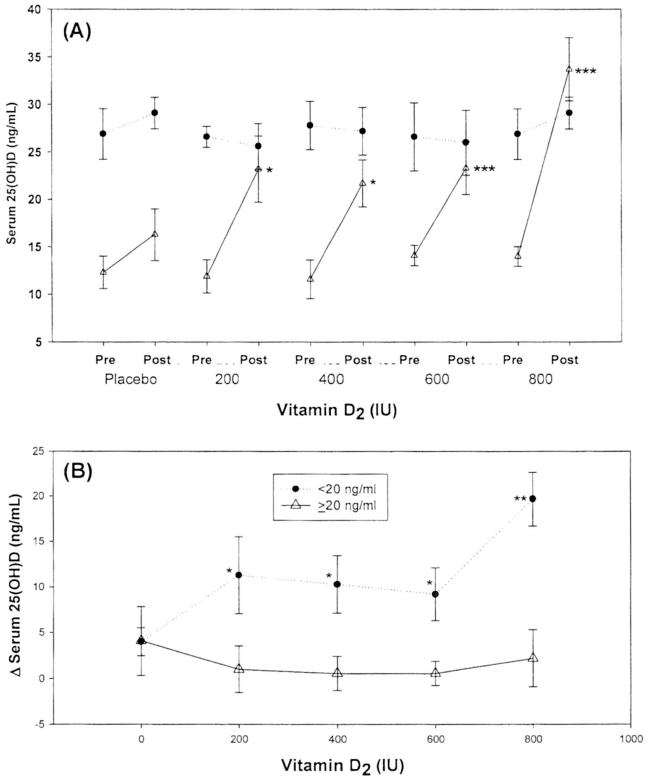

FIGURE 5. Mean (±SE) circulating concentrations (A) and changes (B) in 25-hydroxyvitamin D [25(OH)D] in nursing home residents with initial 25(OH)D serum concentrations of either <20 ng/mL (△ –△) or ≥20 ng/mL (● … ●) before and after receiving 0, 200, 400, 600, or 800 IU vitamin D_2/d for 5 mo from October through March. Data are from 6–16 individuals. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

every 2 wk or its equivalent will sustain 25(OH)D concentrations above 75 nmol/L.

CONCLUSION

Throughout evolution, humans have depended on the sun for their vitamin D requirement (1, 2). Indeed, a likely reason that melanin pigmentation devolved was to permit humans who migrated north and south of the equator to make enough vitamin D in their skin to satisfy their requirement (96). The recommendation for the avoidance of all sun exposure has put the world's population at risk of vitamin D deficiency (97). This has become apparent in Australia, where a dramatic increase in skin cancer rates resulted in the promotion of never exposing the skin to direct sunlight without sun protection, ie, clothing or sunscreen. The so-called sun-safe message has resulted in a marked increase in the risk of vitamin deficiency in Australia (40).

The best method for determining a person's vitamin D status is to measure a 25(OH)D concentration. Most commercial assays are reliable enough to determine a person's vitamin D status (10). These include various radioimmunoassays (98) and what is now considered to be the gold standard: liquid chromatography–tandem mass spectroscopy (14). There has been much discussion about vitamin D_2 being only ≈30–50% as effective as vitamin D_3 in maintaining serum concentrations of 25(OH)D (93, 94). This, however, did not mean that vitamin D_2 was less active than vitamin D_3 once it was metabolized to $1,25(OH)_2D_2$. It only meant that vitamin D_2 may need to be given in higher doses to raise the blood concentrations of 25(OH)D above 75 nmol/L, or 30 ng/mL. Our data (Figure 5), as well as our recent observation that vitamin D_2 was as effective as vitamin D_3 in raising the blood concentrations of 25(OH)D (91), however, calls into question whether this is really necessary.

A reevaluation needs to take place of what the adequate intakes of vitamin D should be for children and adults. The literature over the past decade suggests that the Institute of Medicine recommendations in 1997 (83) are inadequate, and some experts including us suggest that both children and adults should take ≥800–1000 IU vitamin D/d from dietary and supplemental sources (4, 9, 77) when sunlight is unable to provide it. This recommendation, however, has not yet been embraced either by official government or pediatric organizations in the United States, Canada, or Europe for either children or adults.

Neither of the authors had a conflict of interest.

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