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). A diet high in oily fish prevents vitamin D deficiency. 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). 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.

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; 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. The renal production of 1,25-dihydroxyvitamin D is tightly regulated by plasma parathyroid hormone levels and serum calcium and phosphorus levels. 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. The efficiency of the absorption of renal calcium and of intestinal calcium and phosphorus is increased in the presence of 1,25-dihy-
25-hydroxyvitamin D (Fig. 1). 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 calcitriolic acid.

**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). 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). 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). 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.

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. 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. 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).

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 and 48% of white preadolescent girls in a study in Maine 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, and 32% of healthy students, physicians, 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.

In Europe, where very few foods are fortified with vitamin D, children and adults would appear to be at especially high risk. 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. 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. 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); 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.

**Calcium, Phosphorus, and Bone Metabolism**

Without vitamin D, only 10 to 15% of dietary calcium and about 60% of phosphorus is absorbed. 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).

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. When the level was 30 ng per milliliter or less, there was a significant decrease in intestinal calcium absorption that was associated with increased parathyroid hormone.

Parathyroid hormone enhances the tubular reabsorption of calcium and stimulates the kidneys to produce 1,25-dihydroxyvitamin D. Parathyroid hormone also activates osteoblasts, which stimulate the transformation of preosteoclasts into mature osteoclasts. Osteoclasts dissolve the mineralized collagen matrix in bone, causing os-
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-hydroxvitamin D to 1,25-dihydroxvitamin 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 children1,28 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.10,20 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 D₃ daily for 3 years, the risk of hip fracture was reduced by 43%, and the risk of nonvertebral fracture by 32%. A 58% reduction in nonvertebral fractures was observed in 389 men and women over the age of 65 years who were receiving 700 IU of vitamin D₃ and 500 mg of calcium per day.42

A meta-analysis of seven randomized clinical
Vitamin D Deficiency

- 7-Dehydrocholesterol (Skin)
- Solar UVB radiation (290–315 nm)
- Heat
- Vitamin D
- Chylomicrons
- Dietary Vitamin D
- Solar UVB radiation
- Inactive photoproducts
- Fat cell
- Circulation

Vitamin D-25-hydroxylase (Liver)

- 25(OH)D (major circulating metabolite)
- Phosphorus, calcium, FGF-23, and other factors +/-
- 1-OHase (Kidneys)

- 1,25(OH)_2D (Calcitriol)
- 24-OHase (Kidneys)
- Calcium Resorption
- Bone
- Parathyroid glands
- Intestine

Calcium Absorption
- Bile
- Excreted

Blood calcium and phosphorus

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholesterol

Vitamin D_2

Vitamin D_3

Solar UVB radiation

Previtamin D_3

Heat

Vitamin D_1

Circulation

Vitamin D_25-hydroxylase

Liver

25(OH)D

1-OHase

Kidneys

1,25(OH)_2D

24-OHase

Calcitriol acid

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

Vitamin D

Vitamin D_3

Chylomicrons

Diet

Fat cell

Circulation

Reference range

<20 ng/ml

20–100 ng/ml

>150 ng/ml

Deficiency

Preferred range

30–60 ng/ml

Intoxication

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholesterol

Vitamin D_2

Vitamin D_3

Solar UVB radiation

Previtamin D_3

Heat

Vitamin D_1

Circulation

Vitamin D_25-hydroxylase

Liver

25(OH)D

1-OHase

Kidneys

1,25(OH)_2D

24-OHase

Calcitriol acid

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

Vitamin D

Vitamin D_3

Chylomicrons

Diet

Fat cell

Circulation

Reference range

<20 ng/ml

20–100 ng/ml

>150 ng/ml

Deficiency

Preferred range

30–60 ng/ml

Intoxication

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholesterol

Vitamin D_2

Vitamin D_3

Solar UVB radiation

Previtamin D_3

Heat

Vitamin D_1

Circulation

Vitamin D_25-hydroxylase

Liver

25(OH)D

1-OHase

Kidneys

1,25(OH)_2D

24-OHase

Calcitriol acid

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholesterol

Vitamin D_2

Vitamin D_3

Solar UVB radiation

Previtamin D_3

Heat

Vitamin D_1

Circulation

Vitamin D_25-hydroxylase

Liver

25(OH)D

1-OHase

Kidneys

1,25(OH)_2D

24-OHase

Calcitriol acid

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholesterol

Vitamin D_2

Vitamin D_3

Solar UVB radiation

Previtamin D_3

Heat

Vitamin D_1

Circulation

Vitamin D_25-hydroxylase

Liver

25(OH)D

1-OHase

Kidneys

1,25(OH)_2D

24-OHase

Calcitriol acid

Calcium/Resorption

Calcium/Absorption

Bone

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

Calcification

Vitamin/uni0020D

CH_3

HO

CH_2

CH_2

HO

7-Dehydrocholester
Table 1. Dietary, Supplemental, and Pharmaceutical Sources of Vitamins D<sub>2</sub> and D<sub>3</sub>*

<table>
<thead>
<tr>
<th>Source</th>
<th>Vitamin D Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural sources</strong></td>
<td></td>
</tr>
<tr>
<td>Salmon</td>
<td></td>
</tr>
<tr>
<td>Fresh, wild (3.5 oz)</td>
<td>About 600–1000 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fresh, farmed (3.5 oz)</td>
<td>About 100–250 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt; or D&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Canned (3.5 oz)</td>
<td>About 300–600 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Sardines, canned (3.5 oz)</td>
<td>About 300 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Mackerel, canned (3.5 oz)</td>
<td>About 250 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Tuna, canned (3.6 oz)</td>
<td>About 230 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Cod liver oil (1 tsp)</td>
<td>About 400–1000 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Shiitake mushrooms</td>
<td></td>
</tr>
<tr>
<td>Fresh (3.5 oz)</td>
<td>About 100 IU of vitamin D&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Sun-dried (3.5 oz)</td>
<td>About 1600 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Egg yolk</td>
<td>About 20 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt; or D&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td><strong>Exposure to sunlight, ultraviolet B radiation (0.5 minimal erythemal dose)†</strong></td>
<td>About 3000 IU of vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td><strong>Fortified foods</strong></td>
<td></td>
</tr>
<tr>
<td>Fortified milk</td>
<td>About 100 IU/8 oz, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified orange juice</td>
<td>About 100 IU/8 oz vitamin D&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Infant formulas</td>
<td>About 100 IU/8 oz vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified yogurts</td>
<td>About 100 IU/8 oz, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified butter</td>
<td>About 50 IU/3.5 oz, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified margarine</td>
<td>About 430 IU/3.5 oz, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified cheeses</td>
<td>About 100 IU/3 oz, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Fortified breakfast cereals</td>
<td>About 100 IU/serving, usually vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td><strong>Supplements</strong></td>
<td></td>
</tr>
<tr>
<td>Prescription</td>
<td></td>
</tr>
<tr>
<td>Vitamin D&lt;sub&gt;2&lt;/sub&gt; (ergocalciferol)</td>
<td>50,000 IU/capsule</td>
</tr>
<tr>
<td>Drisdol (vitamin D&lt;sub&gt;3&lt;/sub&gt;) liquid supplements</td>
<td>8000 IU/ml</td>
</tr>
<tr>
<td><strong>Over the counter</strong></td>
<td></td>
</tr>
<tr>
<td>Multivitamin</td>
<td>400 IU vitamin D&lt;sub&gt;2&lt;/sub&gt;, D&lt;sub&gt;3&lt;/sub&gt;, or D&lt;sub&gt;3&lt;/sub&gt;‡</td>
</tr>
<tr>
<td>Vitamin D&lt;sub&gt;3&lt;/sub&gt;</td>
<td>400, 800, 1000, and 2000 IU</td>
</tr>
</tbody>
</table>

* 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<sub>2</sub>; cholecalciferol or vitamin D<sub>3</sub> indicates that the product contains vitamin D<sub>3</sub>.

trials that evaluated the risk of fracture in older persons given 400 IU of vitamin D<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub> as compared with calcium or placebo. A Women’s Health Initiative study that compared the effects of 400 IU of vitamin D<sub>3</sub> 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<sub>3</sub> had a 29% reduction in hip fracture. Optimal prevention of both nonvertebral and hip fracture occurred only in trials providing 700 to 800 IU of vitamin D<sub>3</sub> 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.

Evolution of the exclusive use of calcium or vitamin D<sub>3</sub> (RECORD trial) showed no antifracture efficacy for patients receiving 800 IU of vitamin D<sub>3</sub> per day. 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. Porthouse and colleagues, who evaluated the effect of 800 IU of vitamin D<sub>3</sub> per day on hip 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 separately from the intervention. This called into question the conclusion that vitamin D supplementation had no antifracture benefit.
MUSCLE STRENGTH AND FALLS

Vitamin D deficiency causes muscle weakness.\textsuperscript{1,7,8,28} Skeletal muscles have a vitamin D receptor and may require vitamin D for maximum function.\textsuperscript{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).\textsuperscript{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.\textsuperscript{8} The same meta-analysis examined the frequency of falls and suggested that 400 IU of vitamin D\textsubscript{3} per day was not effective in preventing falls, whereas 800 IU of vitamin D\textsubscript{3} per day plus calcium reduced the risk of falls (corrected pooled odds ratio, 0.65; 95\% CI, 0.4 to 1.0).\textsuperscript{8} In a randomized controlled trial conducted over a 5-month period, nursing home residents receiving 800 IU of vitamin D\textsubscript{3} 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).\textsuperscript{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.\textsuperscript{1-4,6} In addition, some of these tissues and cells express the enzyme 25-hydroxyvitamin D-1α-hydroxylase.\textsuperscript{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.\textsuperscript{1-2,47} It decreases cellular proliferation of both normal cells and cancer cells and induces their terminal differentiation.\textsuperscript{1-5,6,47} One practical application is the use of 1,25-dihydroxyvitamin D\textsubscript{3} and its active analogues for the treatment of psoriasis.\textsuperscript{48,49}

1,25-Dihydroxyvitamin D is also a potent immunomodulator.\textsuperscript{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\textsubscript{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.\textsuperscript{51} 1,25-dihydroxyvitamin D\textsubscript{3} inhibits renin synthesis,\textsuperscript{52} increases insulin production,\textsuperscript{53} and increases myocardial contractility (Fig. 2).\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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).\textsuperscript{50} 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.\textsuperscript{52} 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)₂D]. 1,25(OH)₂D 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)₂D 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)₂D 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)₂D 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)₂D to the biologically inert calcitroic acid. Thus, locally produced 1,25(OH)₂D 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)₂D inhibits the expression and synthesis of parathyroid hormone. The 1,25(OH)₂D produced in the kidney enters the circulation and can down-regulate renin 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 lymphoma65 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.1,3,4 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.1,3,4,7,56,58 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 calcitriol. 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.56,69 Living below 35 degrees latitude for the first 10 years of life reduces the risk of multiple sclerosis by approximately 50%.59,70 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 multiple sclerosis.72 Similar observations have been made for rheumatoid arthritis73 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 D3 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 failure74 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
Children of women living in an inner city who had vitamin D deficiency during pregnancy are at increased risk for wheezing illnesses.\textsuperscript{84}

### Causes of Vitamin D Deficiency\textsuperscript{85}

<table>
<thead>
<tr>
<th>Cause</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced skin synthesis</td>
<td>Reduces vitamin D\textsubscript{3} synthesis — SPF 8 by 92.5%, SPF 15 by 99%</td>
</tr>
<tr>
<td>Reduced skin synthesis</td>
<td>Reduces vitamin D\textsubscript{3} synthesis by as much as 99%</td>
</tr>
<tr>
<td>Reduced skin synthesis</td>
<td>Reduces vitamin D\textsubscript{3} synthesis by about 75% in a 70-year-old</td>
</tr>
<tr>
<td>Reduced skin synthesis</td>
<td>Above about 35 degrees north latitude (Atlanta), little or no vitamin D\textsubscript{3} can be produced from November to February</td>
</tr>
<tr>
<td>Decreased bioavailability</td>
<td>Decreases the amount of vitamin D the skin can produce</td>
</tr>
<tr>
<td>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</td>
<td>Impairs the body’s ability to absorb vitamin D</td>
</tr>
<tr>
<td>Obesity — sequestration of vitamin D in body fat†</td>
<td>Reduces availability of vitamin D</td>
</tr>
<tr>
<td>Increased catabolism</td>
<td>Activates the destruction of 25-hydroxyvitamin D and 1,25-dihydroxyvitamin D to inactive calcitroic acid</td>
</tr>
<tr>
<td>Breast-feeding</td>
<td>Increases infant risk of vitamin D deficiency when breast milk is sole source of nutrition</td>
</tr>
<tr>
<td>Decreased synthesis of 25-hydroxyvitamin D</td>
<td>Causes malabsorption of vitamin D, but production of 25-hydroxyvitamin D is possible.\textsuperscript{3,8,90}</td>
</tr>
<tr>
<td>Decreased synthesis of 25-hydroxyvitamin D</td>
<td>Results in inability to make sufficient 25-hydroxyvitamin D</td>
</tr>
<tr>
<td>Decreased synthesis of 1,25-dihydroxyvitamin D</td>
<td>Results in substantial loss of 25-hydroxyvitamin D to urine.\textsuperscript{2,3,6,91}</td>
</tr>
<tr>
<td>Chronic kidney disease</td>
<td>Causes hypocalcemia, secondary hyperparathyroidism, and renal bone disease</td>
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</table>

There are many causes of vitamin D deficiency, including reduced skin synthesis and absorption of vitamin D and acquired and heritable disorders of...
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. However, most experts agree that without adequate sun exposure, children and adults require approximately 800 to 1000 IU per day. Children with vitamin D deficiency should be aggressively treated to prevent rickets (Table 3). Since vitamin D2 is approximately 30% as effective as vitamin D3 in maintaining serum 25-hydroxyvitamin D levels, up to three times as much vitamin D2 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 D2 once a week for 8 weeks, followed by 50,000 IU of vitamin D2 every 2 to 4 weeks thereafter (Table 3). Alternatively, either 1000 IU of vitamin D3 per day (available in most pharmacies) or 3000 IU of vitamin D2 per day is effective. Strategies such as having patients take 100,000 IU of vitamin D2 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.

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-fed infants. However, breast-fed infants and children require 400 IU of vitamin D per day.
Table 3. Strategies to Prevent and Treat Vitamin D Deficiency.\textsuperscript{27}

<table>
<thead>
<tr>
<th>Cause of Deficiency</th>
<th>Preventive and Maintenance Measures to Avoid Deficiency</th>
<th>Treatment of Deficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Children</strong></td>
<td></td>
<td></td>
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<tr>
<td>Breast-feeding</td>
<td>400 IU of vitamin D\textsubscript{2} every 1, 2, 3, 6, 10 wk, 50,000 IU of vitamin D\textsubscript{2} every 2 wk or every 4 wk\textsuperscript{17}</td>
<td>200,000 IU of vitamin D\textsubscript{2} every 3 mo\textsuperscript{1,105}</td>
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<td>without vitamin D</td>
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<td>600,000 IU of vitamin D intramuscularly, repeat in 12 wk\textsuperscript{106}; 1000–2000 IU of vitamin D\textsubscript{2} or vitamin D\textsubscript{3} every day\textsuperscript{1,107} with calcium supplementation</td>
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<td>supplementation\textsuperscript{28,33,89,104}</td>
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<tr>
<td><strong>Adults</strong></td>
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<tr>
<td>Inadequate sun</td>
<td>800–1000 IU of vitamin D\textsubscript{2} every 1 wk or every 4 wk;\textsuperscript{7,15,109,110} or use of tanning bed or other UVB radiation device (e.g., portable Sperti lamp);\textsuperscript{111–114} up to 10,000 IU of vitamin D\textsubscript{2} every day is safe for 5 mo;\textsuperscript{27} maintenance dose is 50,000 IU every 2 wk or every 4 wk\textsuperscript{7}</td>
<td>50,000 IU of vitamin D\textsubscript{2} every wk for 8 wk\textsuperscript{11}; repeat for another 8 wk if 25-hydroxyvitamin D &lt;30 ng/ml\textsuperscript{12}</td>
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<tr>
<td>exposure\textsuperscript{7–15} or</td>
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<tr>
<td>supplementation\textsuperscript{7–15}</td>
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<tr>
<td>or malabsorption</td>
<td>Adequate exposure to sun or ultraviolet radiation;\textsuperscript{7,113} 50,000 IU of vitamin D\textsubscript{2} every day, every other day, or every wk\textsuperscript{1} up to 10,000 IU of vitamin D\textsubscript{2} every day is safe for 5 mo;\textsuperscript{33,89} maintenance dose is 50,000 IU of vitamin D\textsubscript{2} every wk\textsuperscript{7}; UVB irradiation (tanning bed or portable UVB device, e.g., portable Sperti lamp);\textsuperscript{111–114} 50,000 IU of vitamin D\textsubscript{2} every day or every other day\textsuperscript{7}</td>
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<td>syndrome (malabsorp-</td>
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<td>tion of vitamin D\textsubscript{2,3,36,87} inade-</td>
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<tr>
<td>quate sun exposure\textsuperscript{3,36,87} or</td>
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<tr>
<td>supplementation\textsuperscript{2,3,6,7}</td>
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<tr>
<td><strong>Drugs that activate</strong></td>
<td>50,000 IU of vitamin D\textsubscript{2} every day or every</td>
<td>50,000 IU of vitamin D\textsubscript{2} every 2 wk for 8–10 wk, or every wk if 25-hydroxyvita-</td>
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<tr>
<td>steroid and xenobiotic</td>
<td>week, maintenance dose is 50,000 IU of vitamin D\textsubscript{2} every 1, 2, or 4 wk\textsuperscript{7}</td>
<td>min D &lt;30 ng/ml\textsuperscript{12}</td>
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<td>receptor\textsuperscript{16} and drugs used in</td>
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<tr>
<td>transplantation\textsuperscript{156}</td>
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<tr>
<td><strong>Obesity</strong></td>
<td>1000–2000 IU of vitamin D\textsubscript{2} every day, 50,000 IU of vitamin D\textsubscript{2} every 1 or 2 wk, maintenance dose is 50,000 IU of vitamin D\textsubscript{2} every 1, 2, or 4 wk\textsuperscript{7}</td>
<td>50,000 IU of vitamin D\textsubscript{2} every 2 wk for 8–12 wk; repeat for another 8–12 wk if 25-hydroxyvitamin D &lt;30 ng/ml\textsuperscript{12}</td>
</tr>
<tr>
<td><strong>Nephrotic syndrome</strong></td>
<td>1000–2000 IU of vitamin D\textsubscript{2} every day, 50,000 IU of vitamin D\textsubscript{2} once or twice/wk\textsuperscript{2,44}; maintenance dose is 50,000 IU of vitamin D\textsubscript{2} every 2 or 4 wk\textsuperscript{2,4}</td>
<td>50,000 IU of vitamin D\textsubscript{2} twice/wk for 8–12 wk; repeat for another 8–12 wk if 25-hydroxyvitamin D &lt;30 ng/ml\textsuperscript{2,44}</td>
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<tr>
<td><strong>Chronic kidney disease</strong></td>
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<tr>
<td>Stages 2 and 3</td>
<td>Control serum phosphate;\textsuperscript{6} 1000 IU of vitamin D\textsubscript{2} every day, 50,000 IU of vitamin D\textsubscript{2} every 1 wk;\textsuperscript{105} maintenance dose is 50,000 IU of vitamin D\textsubscript{2} every 2 or 4 wk; may also need to treat with an active vitamin D analog when vitamin D sufficiency is obtained;\textsuperscript{7}</td>
<td>50,000 IU of vitamin D\textsubscript{2} once/wk for 8 wk\textsuperscript{91,93,94}; repeat for another 8 wk if 25-hydroxyvitamin D &lt;30 ng/ml\textsuperscript{12}</td>
</tr>
<tr>
<td>Stages 4 and 5</td>
<td>1000 IU of vitamin D\textsubscript{2} every day\textsuperscript{11}; 50,000 IU of vitamin D\textsubscript{2} every 2 wk, need to treat with 1,25-dihydroxyvitamin D\textsubscript{2} or active analogue\textsuperscript{7}; 0.25–1.0 μg of 1,25-dihydroxyvitamin D\textsubscript{2} (calcitriol)\textsuperscript{2,6,91,93,94} by mouth twice a day or one of the following: 1–2 μg of paricalcitol IV every 3 days\textsuperscript{6,91,93,94} 0.04–0.1 μg/kg IV every other day initially and can increase to 0.24 μg/kg, 2–4 μg by mouth three times/wk\textsuperscript{6,91,93,94} or doxercalciferol\textsuperscript{6,91,93,94} 10–20 μg by mouth three times/wk or 2–6 μg IV three times/wk</td>
<td>50,000 IU of vitamin D\textsubscript{2} once/wk for 8 wk\textsuperscript{91,94,93}; repeat for another 8 wk if 25-hydroxyvitamin D &lt;30 ng/ml\textsuperscript{12}</td>
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</tbody>
</table>
The 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.

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.

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 but were also able to transfer enough vitamin D₃ into their milk to satisfy an infant’s requirement.

In Canada, to prevent vitamin D deficiency, current guidelines recommend that all infants and children receive 400 IU of vitamin D₃ per day. Sensible sun exposure can provide an adequate amount of vitamin D₃, which is stored in body fat and released during the winter, when vitamin D₃ cannot be produced. Exposure to sunlight or ultraviolet B radiation from a tanning bed or other ultraviolet B–emitting device is also effective.

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). 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. Most tanning beds
emit 2 to 6% ultraviolet B radiation and are a recommended source of vitamin D₃ when used in moderation. 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 non-tanners (with levels of approximately 18 ng per milliliter [45 nmol per liter]). 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). 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 hypercalcaemia and hyperphosphataemia. Doses of 10,000 IU of vitamin D₃ per day for up to 5 months, however, do not cause toxicity. 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 hypercalcaemia. 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).

**Conclusions**

Undiagnosed vitamin D deficiency is not uncommon and 25-hydroxyvitamin D is the barometer for vitamin D status. Serum 25-hydroxyvitamin D is not only a predictor of bone health but is also an independent predictor of risk for cancer and other chronic diseases. The report that postmenopausal women who increased their vitamin D intake by 1100 IU of vitamin D₃ reduced their relative risk of cancer by 60 to 77% is a compelling reason to be vitamin D–sufficient. Most commercial assays for 25-hydroxyvitamin D are good for detecting vitamin D deficiency. Radioimmunossays measure total 25-hydroxyvitamin D, which includes levels of both 25-hydroxyvitamin D₂ and 25-hydroxyvitamin D₃. Some commercial laboratories measure 25-hydroxyvitamin D₂ and 25-hydroxyvitamin D₃ 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. 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 D₃ 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 D₃ per day. Unless a person eats oily fish frequently, it is very difficult to obtain that much vitamin D. Adequate intakes are actually inadequate and need to be increased to at least 800 IU of vitamin D₃ per day or its equivalent should guarantee vitamin D sufficiency unless there are mitigating circumstances (Table 2).

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