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The epidemic scourge of rickets in the 19th century was caused by vitamin D deficiency due to inadequate sun exposure and resulted in growth retardation, muscle weakness, skeletal deformities, hypocalcemia, tetany, and seizures. The encouragement of sensible sun exposure and the fortification of milk with vitamin D resulted in almost complete eradication of the disease. Vitamin D (where D represents D₂ or D₃) is biologically inert and metabolized in the liver to 25-hydroxyvitamin D [25(OH)D], the major circulating form of vitamin D that is used to determine vitamin D status. 25(OH)D is activated in the kidneys to 1,25-dihydroxyvitamin D [1,25(OH)₂D], which regulates calcium, phosphorus, and bone metabolism. Vitamin D deficiency has again become an epidemic in children, and rickets has become a global health issue. In addition to vitamin D deficiency, calcium deficiency and acquired and inherited disorders of vitamin D, calcium, and phosphorus metabolism cause rickets. This review summarizes the role of vitamin D in the prevention of rickets and its importance in the overall health and welfare of infants and children.

Nonstandard abbreviations used: 1-OHase, 25-hydroxyvitamin D-1α-hydroxylase; 1,25(OH)₂D, 1,25-dihydroxyvitamin D; 25(OH)D, 25-hydroxyvitamin D; DBP, vitamin D–binding protein; FGF23, fibroblast growth factor 23; PHEX, phosphate-regulating endopeptidase homolog, X-linked; PTH, parathyroid hormone; RANKL, receptor activator of NF-κB ligand; RXR, retinoic acid X receptor; SPⅡ, sun protection factor; UVB, ultraviolet B; VDR, vitamin D receptor; VDRE, vitamin D–responsive element.

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Resurrection of vitamin D deficiency and rickets
25(OH)D is the major circulating form of vitamin D that is measured to determine a person’s vitamin D status because it has a half-life in the circulation of 2 weeks and it is released and is converted in the mitochondria by the 25-hydroxyvitamin D-1α-hydroxylase [1-OHase; also known as CYP27B1] to form 1,25-dihydroxyvitamin D [1,25(OH)2D]. 1,25(OH)2D is the biologically active form of vitamin D responsible for maintaining calcium and phosphorus homeostasis. It accomplishes this by interacting with its nuclear receptor, the vitamin D receptor (VDR) in the small intestinal cells (22, 25). The 1,25(OH)2D–VDR structure complexes with retinoic acid X receptor (RXR) in the nucleus. The 1,25(OH)2D–VDR–RXR complex binds to the vitamin D–responsive element (VDRE) for the epithelial calcium channel (22, 25). The increased expression of the calcium channel permits more calcium to enter the cell, where the vitamin D–dependent calcium-binding protein calbindin 9K helps calcium’s translocation into the bloodstream. 1,25(OH)2D also enhances phosphorus absorption in the small intestine (1, 22, 25).

When dietary calcium is inadequate, vitamin D helps maintain calcium homeostasis by interacting with the VDR in osteoblasts to induce the expression of the plasma membrane protein receptor activator of NF-κB ligand (RANKL). The RANK on the plasma membrane of preosteoclasts binds RANKL, which induces the preosteoclast to become a mature osteoclast (20, 22, 26). The mature osteoclast releases hydrochloric acid and collagenases to dissolve bone and release its precious calcium and phosphorus stores into the circulation. Thus, the major physiologic function of vitamin D is to maintain serum calcium and phosphorus levels within the normal physiologic range to support most metabolic functions, neuromuscular transmission, and bone mineralization (1, 20, 22, 24) (Figure 3).

Vitamin D and calcium deficiencies as a cause of rickets
Vitamin D deficiency prevents the efficient absorption of dietary calcium and phosphorus. In a vitamin D–deficient state, only 10–15% of dietary calcium and 50–60% of dietary phosphorus are absorbed. The poor absorption of calcium causes a decrease in serum-ionized calcium levels. This is immediately recognized by the calcium sensor in the parathyroid glands, resulting in an increase in the expression, synthesis, and secretion of parathyroid hormone (PTH) (1, 20, 22, 27). PTH conserves calcium by increasing tubular reabsorption of calcium in both the proximal and distal convoluted tubules. PTH, like 1,25(OH)2D, enhances the expression of RANKL on osteoblasts to increase the production of mature osteoclasts to mobilize calcium stores from the skeleton. PTH also decreases phosphorus reabsorption in the kidney, causing loss of phosphorus into the urine (Figure 4). The serum calcium level is usually normal in a vitamin D–deficient infant or child. However, the serum phosphorus level is low, and thus there is inadequate calcium-phosphorus product, which is necessary to mineralize the osteoid laid down by osteoblasts (1, 20, 22, 24, 28) (Figure 4). Thus, typically, infants with vitamin D–deficiency rickets have a normal serum calcium level, low normal or low fasting serum phosphorus levels, elevated alkaline phosphatase levels, and low 25(OH)2D levels (<15 ng/ml) (23, 28–31) (Table 2). The secondary hyperparathyroidism stimulates the kidneys to produce 1,25(OH)2D, and thus, 1,25(OH)2D levels are normal or often elevated, which is why the measurement of 1,25(OH)2D is of no value in determining a state of vitamin D deficiency (24). Only when the calcium stores in the skeleton are totally depleted will the infant or child become hypocalemic.

Vitamin D deficiency causes global poor mineralization of the skeleton. Clinical and radiological bone manifestations predominate in areas of rapid bone growth, including the long bone epiphyses and the costochondral junctions (5, 6, 12–14, 30–32). This is why rickets is mostly observed before 18 months of age, with maximum frequency between the ages of 4 and 12 months. Skeletal deformities are usually a result of long-standing rickets.

Figure 1
Skeletal deformities observed in rickets. (A) Photograph from the 1930s of a sister (left) and brother (right), aged 10 months and 2.5 years, respectively, showing enlargement of the ends of the bones at the wrist, carpalped spasm, and a typical “Taylorwise” posture of rickets. (B) The same brother and sister 4 years later, with classic knock-knees and bow legs, growth retardation, and other skeletal deformities. Reproduced from ref. 14.

~35° latitude), very little, if any, vitamin D3 is produced in the skin from November through March (19, 20).

Vitamin D metabolism and its role in calcium and phosphorus metabolism
Vitamin D3 and vitamin D2 (D represents either D2 or D3) derived from supplements, fortified foods, and fish ingested from the diet (Table 1) are incorporated into chylomicrons and absorbed into the lymphatic system. From here they enter the circulation, where they are bound to the DBP and lipoproteins (1, 20–22). Vitamin D is released from DBP to the liver and undergoes a hydroxylation on C-25 by the vitamin D-25-hydroxylases (25-OHase; also known as CYP27A1, CYP3A4, CYP2R1, CYP2J3) to 25-hydroxyvitamin D [25(OH)D] (20–22) (Figure 3). 25(OH)D is the major circulating form of vitamin D that is measured to determine a person’s vitamin D status because it has a half-life in the circulation of 2 weeks and it correlates with secondary hyperparathyroidism, rickets, and osteomalacia (20, 22–24). 25(OH)D is bound to DBP, and this complex binds to megalin on the plasma membrane of the renal tubule cell and is transported into the cell (20, 22). Once inside, 25(OH)D is released and is converted in the mitochondria by the 25-hydroxyvitamin D-1α-hydroxylase [1-OHase; also known as CYP27B1] to form 1,25-dihydroxyvitamin D [1,25(OH)2D]. 1,25(OH)2D is the biologically active form of vitamin D responsible for maintaining calcium and phosphorus homeostasis. It accomplishes this by interacting with its nuclear receptor, the vitamin D receptor (VDR) in the small intestinal cells (22, 25). The 1,25(OH)2D–VDR structure complexes with retinoic acid X receptor (RXR) in the nucleus. The 1,25(OH)2D–VDR–RXR complex binds to the vitamin D–responsive element (VDRE) for the epithelial calcium channel (22, 25). The increased expression of the calcium channel permits more calcium to enter the cell, where the vitamin D–dependent calcium-binding protein calbindin 9K helps calcium’s translocation into the bloodstream. 1,25(OH)2D also enhances phosphorus absorption in the small intestine (1, 22, 25).

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Hypertrophy of the costochondral junctions leads to beading and the classic rachitic rosary that progresses with involution of the ribs and protrusion of the sternum (pigeon chest) and recession of the costochondral junctions and traverse depressions causing Harrison’s groove. Once the child begins to stand, gravity pushing on the lower limbs results in either inward (genu valgum) or outward (genu varum) tibial and femoral bowing. Muscle pull can also cause bone deformities in both upper and lower limbs even before the infant begins to walk. Muscle traction on the softened ribcage is responsible for the chest deformation, leading to pectus carinatum, thoracic asymmetry, and widening of the thoracic base. Softening of the occipital area (rachitic craniotabes), enlarged sutures and...
Inadequate calcium intake during the 3rd trimester of pregnancy can cause a serious calcium deficit in the fetal skeleton that is rapidly being mineralized during the last 7 weeks in utero. Typically at 28 weeks, 100 mg/d of calcium is being deposited in the skeleton, whereas at 35 weeks 350 mg/d is being deposited (30, 31, 36). Therefore, mother's milk containing 240–340 mg/l of calcium is unable to meet the demands of postnatal accretion rates of a preterm infant (30, 31).

Young children and adolescents, especially non-white individuals, on a strict vegetarian diet or a diet that is high in phytate, which binds calcium, can also be calcium deficient, which leads to rickets (33–35). This, in combination with vitamin D deficiency, is often the precipitating cause of rickets in children of Middle Eastern descent living in Great Britain and African American children in the United States (32–35).

The calcium deficiency and associated secondary hyperparathyroidism increase the requirement for vitamin D, since the vitamin D is rapidly metabolized to 1,25(OH)_{2}D. The combination of calcium deficiency and vitamin D deficiency accelerates and makes more severe the skeletal abnormalities and hypocalemia.

### Prevalence of subclinical vitamin D deficiency

Severe chronic vitamin D deficiency [25(OH)D level less than 15 ng/ml] leads to overt skeletal abnormalities in children that is typically defined as rickets (23, 30–32). However, there is a large number of infants, children, and adolescents who are vitamin D insufficient but have no apparent skeletal or calcium metabolism abnormalities (Table 2). We observed that of 40 “healthy” mother-infant pairs that were predominantly non-white, 73% of mothers and 80% infants had 25(OH)D levels of less than 20 ng/ml despite the fact that 80% of the mothers took a daily prenatal multivitamin that contained 400 IU of vitamin D (37). Sullivan et al. (38) reported that 48% of white girls aged 9–11 years in Maine had 25(OH)D levels less than 20 ng/ml at the end of the winter and 17% remained vitamin D deficient at the end of the summer due either to avoiding sun exposure or always wearing sun protection. Forty-two percent of adolescent African American and Hispanic children had 25(OH)D levels less than 20 ng/ml in Boston (39), which is consistent with the observation by the Centers for Disease Control that 48% of African American women aged 15–49 years throughout the entire United States had 25(OH)D levels of less than 15 ng/ml at the end of the winter (40). Similar observations have been made in Canada and Europe, where few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45). Remarkably, in the sunniest areas of the world, rickets is a major health problem. Because of the practice of purdah or wearing a burka (45, 46), avoidance of exposure of any skin to sunlight, and the fact that few foods are fortified with vitamin D and the high latitude limits vitamin D production in the skin (41–45).

### Inherited causes of rickets

Once it was recognized that vitamin D must be metabolized in the liver and kidneys before it can carry out its biologic effects on calcium, phosphorus, and bone metabolism, it was hypothesized that a defect in the hepatic 25-hydroxylation or renal 1α-hydroxylation steps would lead to an inability to activate vitamin D, thus causing...
a vitamin D deficiency–like state that was resistant to physiologic doses of vitamin D (Figure 4). There is only one documented case of 25-OHase–deficiency rickets (62). The most likely reason why more cases are not reported is that there are at least 4 different enzymes that have the ability to convert vitamin D to 25(OH)D (63). Since vitamin D undergoes its final activation in the kidneys, several studies of individuals with “vitamin D–resistant” diseases causing rickets in which patients were evaluated for a defect in the metabolism of 25(OH)D to 1,25(OH)₂D have been reported. Pseudovitamin D–deficiency rickets (also known as hereditary, vitamin D–dependent rickets type 1), a rare hereditary disorder, was found to be associated with very low or undetectable levels of 1,25(OH)₂D in the circulation (64). These children responded to orally administered 1,25(OH)₂D₃ (64). The cloning of the renal 1-OHase enzyme led to the identification of a multitude of point mutations of the CYP27B1 gene, which result in either a poorly functional 1-OHase or the complete absence of 1-OHase activity (65).

Several investigators reported children with severe rickets who often had alopecia and extremely elevated levels of 1,25(OH)₂D (65, 66). Some children with this disease, vitamin D–resistant rickets (hereditary, vitamin D–dependent rickets type 2), responded to pharmacologic doses of vitamin D or 1,25(OH)₂D₃, while others did not (66, 67). Point mutations in the VDR gene are responsible for the vitamin D resistance. Chen et al. (68) reported a new form of vitamin D resistance, hereditary vitamin D–dependent rickets type 3, caused by the abnormal expression of a hormone response element–binding protein (HRBP) that binds to the VDRE and therefore prevents the 1,25(OH)₂D–VDR–RXR complex from binding to its responsive element. This patient had normal VDR expression and was completely resistant to 1,25(OH)₂D₃ action. Children with these vitamin D–resistance syndromes often suffer from severe bone deformities and more marked hypocalcemia than children with vitamin D–deficiency rickets. Treatment depends on the cause and severity of the vitamin D resistance. Children have responded to pharmacologic doses of vitamin D, physiologic and pharmacologic doses of 1,25(OH)₂D₃, and its analog 1α-hydroxyvitamin D₃, as well as intravenous infusions of calcium and phosphorus (30, 64, 66–69).

![Figure 4](http://www.jci.org)
Inherited and acquired hypophosphatemic rickets

These disorders are characterized by hypophosphatemia, decreased reabsorption of phosphorus by the renal tubule, decreased absorption of calcium and phosphorus from the gastrointestinal tract, and varying degrees of rickets or osteomalacia (70, 71). Patients often have normal or reduced serum levels of 1,25(OH)2D, which is considered to be abnormal, since hypophosphatemia causes an increase in serum 1,25(OH)2D levels because it enhances the renal production of 1,25(OH)2D (70, 72). Originally, it was thought that hypophosphatemic disorders were caused by a defect in a renal phosphate transport protein. However, recent evidence suggests that other factors of bone origin participate in maintaining phosphorus homeostasis, including fibroblast growth factor 23 (FGF23), matrix extracellular phosphoglycoprotein, and frizzled-related protein 4. These factors are collectively known as phosphatonin (73). When FGF23 is elevated, it causes an internalization of the sodium phosphate cotransporter in both the kidneys and intestine, thereby causing phosphaturia and decreased intestinal phosphate absorption (74). It also inhibits CYP27B1 activity. Patients with autosomal dominant hypophosphatemic rickets (ADHR) have a mutation in the FGF23 gene that prevents or reduces FGF23 metabolic breakdown, leading to elevated FGF23 levels (70, 75). Tumor-induced osteomalacia is caused by a small tumor that is often benign and secretes FGF23 (70, 71, 73, 74). The exact cause of X-linked hypophosphatemic rickets is less well understood. It has been linked to a mutation of phosphatase regulating endopeptidase homolog, X-linked (PHEX) gene. Loss of its expression causes overexpression of FGF23 and possibly other phosphatonin in bone, leading to increased levels of circulating FGF23 (74).

Thus, hypophosphatemic rickets is caused by an inability to metabolize FGF23 or the excessive production of FGF23 (70, 71, 73, 74) (Figure 4). Intravenous phosphate delivery has been effective in treating rickets and osteomalacia (70, 71, 76), and removal of the tumor is curative (77, 78). Treatment includes frequent oral phosphate administration, typically 250–500 mg up to 5 times a day, as well as twice daily oral delivery of 0.5–1.0 μg of 1,25(OH)2D3 (70, 71, 76). Less frequent administration of higher doses of phosphate is to be discouraged, since the transient increase in serum phosphate causes a decrease in ionized calcium and an increase in PTH level and causes parathyroid glands to become hyperplastic and autonomous, which leads to tertiary hyperparathyroidism.

Prevention and treatment of vitamin D– and calcium-deficiency rickets

In the 1940s, the recommended intake of vitamin D for infants was 100 IU/day to prevent rickets (14). However, the current accepted recommendation to prevent rickets is a daily 400 IU dose of vitamin D and adequate calcium intake (32–35, 79). Clinical trials in preterm infants (16 days of age) were randomized to daily vitamin D intakes of 200 IU (90 IU/kg), 400 IU (180 IU/kg), or 800 IU (360 IU/kg) for up to one month. No radiological differences were observed between groups (80). The 25(OH)D levels in the group receiving 200 IU vitamin D for 24–29 days did not change, whereas the groups receiving 400 IU and 800 IU for the same period of time showed an increase in 25(OH)D levels of approximately 30%. Similar studies also suggested that preterm infants’ plasma 25(OH)D levels were maintained from early neonatal life to 3 months with administration of supplemental vitamin D of 400 IU/day. No benefit in vitamin D status or forearm bone mineral density was observed at a higher dose of 900 IU/day (30, 81). In Europe, the Nutrition Committee for the European Society of Pediatric Gastroenterology, Hepatology and Nutrition recommended a vitamin D intake of 800–1,600 IU/day (36). Mawer et al. (36) gave either 1,000 or 3,000 IU of vitamin D2 daily to low-birth-weight infants with a mean weight of 1.36 kg and found that the 25(OH)D level increased from a baseline of 6–10 ng/ml to a mean of 33 ng/ml in both dose groups after 7 weeks. They also observed that the 25(OH)D levels rapidly rose during the first week and began to plateau at 7 weeks at approximately 33 ng/ml. Markestad et al. (23) treated children with 1,700–4,000 IU vitamin D3/day for up to 10 weeks and showed an average 25(OH)D level of approximately 30 ng/ml and correction of their biochemical and skeletal abnormalities. Premature neonates treated with 1,200 IU vitamin D3/day for 7 days raised their 25(OH)D level from 8 ng/ml to 18 ng/ml (81). Although it is not known what the minimum normal level of 25(OH)D should be for infants and neonates based on these observations, it is not unreasonable for the blood level to be at least 20 ng/ml. However, since those studies showed that 25(OH)D levels reached a plateau at approximately 33 ng/ml, this is likely the ideal healthy level for infants and children and is similar for adults (23, 24, 30, 36, 81–84). To achieve a healthy 25(OH)D level of greater than 30 ng/ml, infants require at least 400–1,000 IU of vitamin D3/day depending on their 25(OH)D levels at birth.

Infants who are vitamin D deficient should not simply receive what is the recommended US adequate intake (200 IU/day) (85) or...

Table 2

<table>
<thead>
<tr>
<th>Vitamin D deficiency</th>
<th>25(OH)D, ng/ml</th>
<th>1,25(OH)2D</th>
<th>Ca</th>
<th>HPO2−</th>
<th>Alk. phos.</th>
<th>PTH</th>
<th>FGF23</th>
<th>Skeletal disease</th>
</tr>
</thead>
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<td>Vitamin D insufficiency</td>
<td>&lt;20</td>
<td>↑ or NL</td>
<td>↓ NL</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>NL</td>
<td>Rickets/osteomalacia</td>
</tr>
<tr>
<td>Vitamin D deficiency</td>
<td>21–29</td>
<td>↑ or NL</td>
<td>NL</td>
<td>↑ or NL</td>
<td>↑ or NL</td>
<td>↑</td>
<td>NL</td>
<td>None</td>
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<td>XLH</td>
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<td>Rickets</td>
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The upward-pointing arrows (↑ and ↑↑) indicate that the level is moderately or markedly above the normal range, respectively, and the downward-pointing arrows (↓ and ↓↓) indicate that the level is moderately or markedly below the normal range, respectively. NL represents levels within the normal range. BMD, bone mineral density; XLH, X-linked hypophosphatemic rickets; ADHR, autosomal dominant hypophosphatemic rickets; TIO, tumor-induced osteomalacia.
even 400 IU/d but rather should be aggressively treated with pharmacologic doses of vitamin D in order to build up the body stores of vitamin D and quickly correct the vitamin D deficiency. The best method to effectively treat and cure rickets is to give a total of 5–15 mg (200,000–600,000 IU) of vitamin D3 or vitamin D3 orally with adequate dietary calcium (86). These doses can be given safely either as a single-day therapy or as daily doses of 2,000–4,000 IU/d (50–100 μg/d) for 3–6 months (30, 86, 87). Typically there is rapid correction of both serum calcium and phosphorus levels within 6–10 days and normalization of PTH levels within 1–2 months. Alkaline phosphatase decline and healing of radiologic signs of rickets are observed within 3–6 months depending on the severity of the deficiency (30, 86). For those who may not comply with this regime, it is recommended that 5 mg (200,000 IU) of vitamin D be given as a single oral dose, with a follow-up dose of 5 mg 3 months later.

It is imperative to initiate therapy with large doses of vitamin D, since giving small daily doses of 200–400 IU/d will not restore adequate stores of vitamin D as rapidly as either a single large dose or daily doses that are 10–to 20-fold higher than the recommended adequate intake (AI) (30, 85, 86, 87). For infants and children who have fat malabsorption, including cystic fibrosis patients (88), it is recommended that subcutaneous or intramuscular administration be used. Alternatively, controlled exposure to sunlight or UV radiation from a commercial lamp is advisable (5, 6, 12–14, 30, 33, 88).

**Sunlight, UV irradiation, and neonatal and maternal vitamin D supplementation**

Regular and sensible sun exposure during the months of the year when vitamin D production is promoted is still the most physiological way to prevent vitamin D deficiency in infants and young children (1, 24, 80, 89). Seasonal variations in serum 25(OH)D in children and adults is well documented, with levels reaching a peak in the middle of the summer and nadir at the end of the winter in both the Northern and Southern Hemispheres (1, 19, 24, 57, 89). Since breast milk has very little, if any, vitamin D (usually no more than 25 IU/L), it is usually inadequate in satisfying the infant’s requirement (85, 87, 90). Thus, if the infant is receiving nutrition solely from breast-feeding and if the mother is vitamin D deficient, the infant will become vitamin D deficient and will likely develop rickets (30, 37, 90).

Neonates and young children who do not receive adequate vitamin D from their diet respond well to oral doses of 1,000–1,500 IU/d all year up to the age of 2 and during the winter up to age 5 years without any sign of vitamin D intoxication (30). This prevention scheme has been very effective in Europe for at-risk infants who are exclusively breast-fed or who are too old to take formula (30). Prevention with lower daily doses of 400–500 IU/d is recommended for other breast-fed infants and for at-risk neonates and young infants receiving formula. The effect of providing mother or infant during lactation with supplements of 400 IU of vitamin D showed that it is most effective to give the infant vitamin D supplementation daily. However, Hollis et al. (90) reported that giving lactating females 4,000 IU vitamin D3 daily provides adequate vitamin D in breast milk to satisfy the infant’s requirement.

**Noncalcemic and nonskeletal consequences of vitamin D deficiency in children**

Children with vitamin D deficiency often suffer from severe muscle weakness with toneless and flabby legs (1, 2, 12–14, 30–32). It is now recognized that skeletal muscle has a VDR and that 1,25(OH)2D improves muscle function (91). Serum 25(OH)D levels above 30 ng/ml maximize proximal muscle leg function in adults (92). It was observed in healthy adults that if the serum 25(OH)D was greater than 20 ng/ml, there was a significant increase in lung function, with an average increase in forced expiratory volume of 176 ml (93).

Camargo et al. (94) reported a prospective study of maternal intake of vitamin D during pregnancy and observed that vitamin D deficiency was highly predictive of increased risk for asthma.

The VDR is present not only in tissues that regulate serum calcium, including the small intestine, bone cells, and kidney, but also in essentially all tissues and cells in the body, including brain, colon, breast, prostate, pancreas, heart, skin, skeletal muscle, monocytes, and activated T and B lymphocytes (1, 20–22, 24, 25). The first insight into the noncalcemic role of 1,25(OH)2D was observed when 1,25(OH)2D was incubated with mouse and human leukemic cells. 1,25(OH)2D inhibited leukemic cell proliferation and induced the cells to mature (20–22, 95, 96). Many cancer cell lines and primary cancer cell cultures that possess a VDR demonstrate marked inhibition of growth and induction of maturation when exposed to 1,25(OH)2D or its active analogues (1, 20–22, 24, 96) (Figure 5). 1,25(OH)2D does this by inducing cellular maturation, regulating the expression of p21 and p27 and apoptosis, and acting as an antiangiogenic factor (20–22, 24, 95, 96).

Living at higher latitudes and being prone to vitamin D deficiency increase risk of cancers of the colon, prostate, breast, ovary, esophagus, and several other tissues (1, 24, 97–99). It has been suggested that maintenance of a 25(OH)D level greater than 20 ng/ml reduces risk of colon, prostate, breast, and ovarian cancer by as much as 30–50% (24, 97–99). Although it is unknown whether vitamin D deficiency in utero and during infancy and childhood would imprint on the child for the rest of his or her life an increased risk of these deadly cancers, the recent observation that children exposed to the most sunlight had a 40% reduced risk of developing non-Hodgkin lymphoma (100) and increased survival from malignant melanoma (101) suggests that maintenance of adequate 25(OH)D levels throughout life may help reduce risk of many deadly cancers (24, 97–99, 102).

Living above the 35° latitude for the first 10 years of life imprints on a child for the rest of his or her life a 100% increased risk of developing multiple sclerosis no matter where they live thereafter (24, 103, 104). Living at higher latitude and being prone to vitamin D deficiency increases risk of several other autoimmune diseases including type 1 diabetes and Crohn disease (105, 106). Children in Finland in the 1960s who received the recommended 2,000 IU of vitamin D/day at least during the first year of life and followed for the next 31 years demonstrated a reduced risk of developing type 1 diabetes by 80% (105). Furthermore, children from the same cohort who were vitamin D deficient at one year of age had a 2.4-fold increased risk of developing type 1 diabetes. Vitamin D deficiency in utero and during the first year of life has also been linked to increased risk of type 1 diabetes (107), 1,25(OH)2D affects the immune system (106, 108), and, as pancreatic islet β cells have a VDR, it also stimulates insulin secretion (20–22, 24) (Figure 5). Thus, hypovitaminosis D in children may increase their risk not only of type 2 diabetes but also insulin resistance and islet β cell dysfunction (109).

Living at higher latitude and vitamin D deficiency are also associated with hypertension and cardiovascular heart disease (24, 110, 111). Li et al. (112) reported that 1,25(OH)2D is an effective regulator of renin production, which controls blood pressure. A
study in hypertensive adults exposed to simulated sunlight 3 times a week for 3 months resulted in an increase in their 25(OH)D levels by more than 150% and a significant (6 mmHg) reduction in both systolic and diastolic blood pressure (113).

**Autocrine production and function of 1,25(OH)₂D**

Circulating levels of 1,25(OH)₂D are very low or undetectable in patients with chronic kidney disease (114). It has been assumed that the kidneys are the sole source of 1,25(OH)₂D. However, just as most tissues and cells in the body have a VDR, so too do these tissues and cells possess the ability to express CYP27B1. Thus, the skin, prostate, breast, colon, lung, brain, and placenta not only express the VDR but also have the capacity to produce 1,25(OH)₂D as part of the autocrine production of 1,25(OH)₂D. It is believed that the autocrine production of 1,25(OH)₂D is important for regulating cell growth and maturation, which decreases risk of the cell becoming malignant. 25(OH)D also is metabolized in macrophages by the 1-OHase to produce 1,25(OH)₂D. The expression of the VDR and 1-OHase is upregulated when TLR2/1 is stimulated by LPS. This results in an increase in the expression of the VDR and the 1-OHase. The increase production of 1,25(OH)₂D increases the nuclear expression of cathelicidin (CD) in the macrophage, which is a cationic peptide that causes the destruction of infective agents including *M. tuberculosis*.

Figure 5

Noncalcemic functions of 1,25(OH)₂D. Vitamin D coming from the photoproduction of previtamin D or coming from the diet is converted in the liver to 25(OH)D by the vitamin 25-OHase. 25(OH)D is converted in the kidneys by 1-OHase. 1,25(OH)₂D not only regulates calcium and phosphorus metabolism but can stimulate the pancreas to produce insulin and to downregulate the renal production of renin. 1,25(OH)₂D also interacts with its nuclear receptor (VDR) in a wide variety of tissues and cells and helps maintain normal cell proliferation and differentiation. 25(OH)D can also be converted to 1,25(OH)₂D in a wide variety of cells, including colon, prostate, and breast, for the autocrine production of 1,25(OH)₂D. It is believed that the autocrine production of 1,25(OH)₂D is important for regulating cell growth and maturation, which decreases risk of the cell becoming malignant. 25(OH)D also is metabolized in macrophages by the 1-OHase to produce 1,25(OH)₂D. The expression of the VDR and 1-OHase is upregulated when TLR2/1 is stimulated by LPS. This results in an increase in the expression of the VDR and the 1-OHase. The increase production of 1,25(OH)₂D increases the nuclear expression of cathelicidin (CD) in the macrophage, which is a cationic peptide that causes the destruction of infective agents including *M. tuberculosis*.

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Conclusion
Vitamin D–deficiency rickets is a sunlight deficiency disease. The inability to appreciate the beneficial effect of sunlight for health had devastating consequences for both children and adults for more than 300 years. When it was finally realized that exposure to sunlight could prevent and treat rickets, this led to the recommendation that all children be exposed to sensible sunlight to maximize bone health. The fortification of milk with vitamin D eradicated rickets as a major health problem, and, therefore, it was thought to have been conquered.

Rickets has, however, made an unfortunate comeback (120). The major cause of rickets in the United States is a lack of appreciation that human milk contains very little if any vitamin D to satisfy the infant’s requirement. African American women are often vitamin D deficient, and women who always wear sun protection and only provide breast milk to their infant as the sole source of nutrition, the infant will become vitamin D deficient. If the infant is not exposed to sunlight or does not receive a vitamin D supplement, the infant will inevitably develop rickets. However, the skeletal manifestations of rickets represent only the tip of the vitamin D efficiency iceberg. Vitamin D deficiency in utero and during the first year of life has devastating consequences and may imprint on the child’s life chronic diseases that will shorten his/her life span (24, 57). In utero, vitamin D deficiency results in reduced intrauterine long bone growth and slightly shorter gestation (121). This has been linked to increased risk of osteoporosis and fractures later in life (24, 60, 61, 82, 122). Children born and raised at latitudes below 35° for the first 10 years have a 50% reduced risk of developing rickets as a major health problem, and, therefore, it was thought to have been conquered.