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Vitamin D Deficiency – A Multifaceted Impact on Bone Health and Chronic Disease Risk

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Abstract
Vitamin D is a crucial micronutrient traditionally linked to skeletal health through calcium and phosphate metabolism. However, emerging research highlights its broader physiological significance, including roles in muscle function, immune regulation, and chronic disease prevention. Despite endogenous synthesis via UVB exposure, deficiency remains a global concern due to limited sun exposure, dietary insufficiency, and certain health conditions. This review explores vitamin D metabolism, physiological functions, and clinical implications of deficiency. Evidence shows its deficiency contributes to skeletal disorders such as rickets, osteomalacia, and osteoporosis. Additionally, low vitamin D levels are associated with increased risks of autoimmune diseases (e.g., multiple sclerosis, rheumatoid arthritis, type 1 diabetes), cardiovascular diseases, metabolic disorders (e.g., type 2 diabetes), and colorectal cancer. Calcitriol, the active form of vitamin D, exhibits neuroprotective properties, suggesting potential benefits in neurodegenerative diseases like Alzheimer's and Parkinson's. Supplementation studies indicate improvements in bone density, muscle strength, and immune function, particularly in at-risk populations. Beyond bone health, vitamin D is integral to overall physiological function. Addressing deficiency through responsible sun exposure and tailored supplementation may mitigate chronic disease risk. Further research is essential to refine supplementation guidelines, elucidate molecular mechanisms, and integrate findings into public health strategies.

Keywords: vitamin D; bone density; autoimmune diseases; cardiovascular disease; skin neoplasms

Introduction and purpose of the work

Vitamin D is one of the most versatile micronutrients, playing a significant role both in maintaining the health of the skeletal system and in regulating the functions of many other body systems. Its active form, calcitriol, acts through the vitamin D receptor (VDR), present in most body cells, which emphasizes its importance in numerous physiological processes. Vitamin D deficiency, which is a very common phenomenon in many countries around the world, has been associated with the development of many diseases, such as osteoporosis, diabetes, cardiovascular diseases, some cancers and autoimmune diseases [1, 2]. Statistics indicate that up to 40% of the European population has vitamin D deficiency, and 13% suffer from its severe form [26]. This is due to both insufficient exposure to UVB radiation and low consumption of foods that are a source of vitamin D [21]. This paper attempts to analyze the latest research on the metabolism, biological functions and clinical significance of vitamin D, focusing on its impact on bone and systemic health.

State of knowledge

Vitamin D and its importance

Vitamin D comprises a group of almost 50 fat-soluble chemical compounds that ensure the proper structure and function of the human skeletal system. There are two main forms of this vitamin: ergocalciferol (vit. D2), which occurs only exogenously, and cholecalciferol (vit. D3), synthesized in the human body under the influence of UV light.

Vitamins D2 and D3 are found in many food products, such as fish, cod liver oil and egg yolks. The diet provides only 10–20% of the human requirement for vitamin D [6].
Some researchers question the validity of vitamin D supplementation, suggesting that it does not bring sufficient health benefits. The reason for this opinion was the fact that the control group of the study included only people who did not have vitamin D deficiency [6, 7].

The role of vitamin D in bone metabolism

Vitamin D supports the absorption of calcium and phosphorus in the intestines, and its deficiency leads to secondary hyperparathyroidism, which results in bone demineralization. In the case of deficiency, the bone remodeling process is disturbed, which weakens their structure and increases the risk of fractures [3, 4]. Data from meta-analyses indicate that vitamin D supplementation reduces the risk of hip fractures and other osteoporotic fractures in the elderly [3, 8]. In studies conducted by Chapuy et al. and Dawson-Hughes et al., it was found that vitamin D supplementation with calcium improves bone mineral density and reduces the risk of fractures [4, 5].

Biochemical metabolism of vitamin D

The biochemical metabolism of vitamin D involves several steps, starting from skin synthesis under the influence of UVB radiation, through metabolic transformations in the liver and kidneys, to the action in target tissues:

1. **Skin synthesis**: Vitamin D3 is formed in the skin from 7-dehydrocholesterol under the influence of UVB radiation. This process depends on latitude, season, skin pigmentation and the use of sunscreens [4]. To prevent skin cancer and vitamin D deficiency at the same time, it is recommended to use sunscreen with caution. Studies suggest that short-term sun exposure (about 10–15 minutes per day) in the morning or late afternoon on exposed skin areas (such as the forearms or face) may be sufficient to synthesize an adequate amount of vitamin D. At the same time, in case of longer exposure to UV radiation, sunscreen with an SPF of 30 or higher should be used to prevent skin damage and the risk of developing skin cancers [21, 22]. People who are particularly susceptible to vitamin D deficiency, such as the elderly, should take supplements, especially during periods of reduced sunlight.
2. **Liver conversion**: In the liver, vitamin D3 (cholecalciferol) and vitamin D2 (ergocalciferol) undergo enzymatic hydroxylation with the participation of cytochrome P450, leading to the formation of 25-hydroxycholecalciferol (25(OH)D). This process takes place mainly in hepatocytes, where the enzyme 25-hydroxylase (CYP2R1) plays a key role in the first stage of vitamin D activation [8, 12]. The resulting 25(OH)D is the main storage form of vitamin D in the body and is transported in the bloodstream in a form bound to vitamin D binding protein (DBP) [12].

Serum 25(OH)D concentration is commonly used as a marker for assessing vitamin D status because its half-life is about 2-3 weeks, which allows it to reflect vitamin D status [19]. Cumulative data suggest, in the process of hydroxylation, the liver acts as a regulator of vitamin D storage, allowing for an adequate supply of its active forms to the body as needed [8].

Irregularities in the hepatic metabolism of vitamin D, such as enzymatic defects or liver failure, can lead to a decrease in 25(OH)D levels, resulting in vitamin D deficiency and related health consequences, including in the skeletal and immune systems [30].

3. **Activation in the kidneys**: In the kidneys, the process of vitamin D activation involves the conversion of 25-hydroxycholecalciferol (25(OH)D) into 1α,25-dihydroxycholecalciferol (calcitriol), which is the biologically active form of vitamin D. This reaction takes place in the cells of the proximal renal tubule with the participation of the enzyme 1α-hydroxylase (CYP27B1) [4, 12].

1α-hydroxylase activity is regulated by several factors that reflect the body's needs in terms of calcium and phosphate metabolism. Parathyroid hormone (PTH) is of key importance, stimulating the enzyme's activity in response to reduced blood calcium levels [4, 12]. In turn, high plasma phosphate levels inhibit 1α-hydroxylase activity, ensuring mineral homeostasis [8]. Calcitriol affects the absorption of calcium and phosphate in the gastrointestinal tract and reduces their excretion in urine, which promotes bone mineralization. Additionally, calcitriol, acting through the vitamin D receptor (VDR), which is found in many tissues, regulates the expression of genes involved in various physiological processes, such as immune response, control of proliferation and cell differentiation [8, 12].

Abnormalities in kidney function, such as chronic renal failure, can lead to reduced 1α-hydroxylase activity, which results in reduced calcitriol production. In such cases, secondary hyperparathyroidism and skeletal disorders, such as renal osteodystrophy, are often observed [12].

4. **Calcitriol's action in target tissues**: Calcitriol causes absorption of calcium and phosphorus in the intestines, reduces their excretion in urine and stimulates bone mineralization. It also acts on other tissues, including the immune system, muscles and skin.

Immune system

Calcitriol modulates the immune response by acting on various types of immune system cells, such as: T lymphocytes, B lymphocytes, macrophages and dendritic cells. It affects these cells via the vitamin D receptor (VDR), the expression of which has been confirmed in most cells of the immune system. Calcitriol promotes the balance between pro-inflammatory and anti-inflammatory responses, supporting the development of regulatory T lymphocytes (Treg) and inhibiting the proliferation of Th1 and Th17 lymphocytes, which are involved in autoimmune processes. Due to these properties, calcitriol may be useful in alleviating inflammation and autoimmune diseases such as rheumatoid arthritis or multiple sclerosis (10, 8, 11).

Muscles

In muscle tissue, calcitriol improves muscle function, which may reduce the risk of falls, especially in the elderly. The vitamin D receptor present in skeletal muscle regulates the expression of genes involved in the differentiation and regeneration of muscle fibers (3, 14). Calcitriol increases muscle protein synthesis and supports the preservation of muscle mass, which is crucial for the prevention of sarcopenia.

In addition, vitamin D deficiency is associated with weakened muscle strength, an increased risk of fractures, and reduced physical performance (5, 8).

Skin

In the skin, calcitriol plays a regulatory role in the processes of keratinocyte proliferation and differentiation, which is crucial for maintaining the integrity of the epidermal barrier (20, 19). Calcitriol has been shown to have a protective effect against UVB-induced skin damage and to support repair processes in skin injuries. It also has anti-inflammatory properties, which are useful in treating dermatological conditions such as psoriasis (9, 8). The skin also synthesizes vitamin D precursors in response to sunlight, which is crucial for its systemic effects (22, 21).

Health consequences of vitamin D deficiency

Vitamin D deficiency leads to a number of serious health consequences, including not only the skeletal system, but also other body systems:

1. Weakening of the skeletal system:

Rickets in children

Rickets is a disease resulting from disturbances in the mineralization of growing bones in children. Vitamin D deficiency leads to reduced absorption of calcium and phosphorus in the intestines, which results in hypocalcaemia and secondary hyperparathyroidism. Increased secretion of parathyroid hormone (PTH) causes the release of calcium from the bones in order to maintain an appropriate concentration of calcium in the serum, which causes a weakening of the bone structure [8, 19]. In the bones of growing children, disorders occur in the growth zones, which leads to skeletal deformities, such as limb curvatures (e.g. clubfoot or valgus knees), as well as muscle pain and weakness [10, 19].

Osteomalacia in adults

Osteomalacia is a disturbance in the mineralization of the bone matrix in adults resulting from vitamin D deficiency. This process results in the deposition of unmineralized bone matrix, which leads to bone softening and increased susceptibility to fractures [12, 19]. Unlike rickets, osteomalacia does not cause bone deformation, but manifests itself with bone pain, muscle weakness, and increased fracture frequency, especially in the pelvic and spine regions [10, 19]. Persistent vitamin D deficiency in adults can also lead to secondary hyperparathyroidism, which further increases bone demineralization [2, 19]. Osteoporosis in adults

Vitamin D deficiency leads to decreased absorption of calcium and phosphorus in the intestines, resulting in hypocalcaemia and secondary hyperparathyroidism. Parathyroid hormone (PTH), released in response to low blood calcium levels, causes bone demineralization by increasing bone resorption. This leads to reduced bone mineral density (BMD), which is a major risk factor for osteoporosis [2, 19]. Vitamin D deficiency also impairs osteoblast function, which further impedes bone remodeling processes [8, 19].

Mechanisms leading to increased risk of bone fractures

The weakening of bone structure associated with vitamin D deficiency increases their susceptibility to fractures, especially in predisposed areas such as the femoral neck, spine, or wrist [5, 13]. Calcitriol deficiency (1α,25-dihydroxycholecalciferol) reduces the efficiency of bone matrix mineralization, leading to bone fragility [12, 19]. In addition, vitamin D deficiency is associated with muscle weakness, which increases the risk of falls and therefore fractures, especially in the elderly [8, 14]. o The importance of vitamin D supplementation in preventing osteoporosis

Studies have shown that vitamin D supplementation, especially in combination with calcium, effectively reduces the risk of fractures in people with vitamin D deficiency [4, 13]. It improves bone mineral density and reduces the risk of falls by improving muscle function [5, 14]. Serum 25(OH)D levels ranging from 20 to 30 ng/ml, generally considered optimal, are crucial for maintaining bone health and minimizing the risk of fractures [18, 19].

2. Muscle weakness:

Vitamin D deficiency negatively affects muscle function by reducing the availability of calcitriol (1α,25-dihydroxycholecalciferol), which acts on vitamin D receptors (VDR) present in skeletal muscles. These receptors regulate the expression of genes invol ved in muscle protein synthesis and muscle repair and regeneration processes [8, 19]. Vitamin D deficiency leads to muscle weakness, which is manifested by reduced muscle strength and, consequently, limited mobility [19]. In elderly people, whose vitamin D levels are often low, sarcopenia occurs, i.e. loss of muscle mass and function, which significantly increases the risk of falls [8]. Additionally, vitamin D deficiency affects the function of the nervous system, which can impair balance and motor coordination [8]. Studies have shown that appropriate vitamin D supplementation improves muscle function and reduces the risk of falls in elderly people by approximately 20–30% [6, 13].

3. Increased susceptibility to infections:

Vitamin D modulates the immune system, supporting antiviral and antibacterial responses [10]. Vitamin D, especially its active form, calcitriol (1α,25-dihydroxycholecalciferol), affects immune cells such as macrophages, monocytes, dendritic cells, and T and B lymphocytes that express the vitamin D receptor (VDR). As a result, vitamin D influences the mechanisms of the immune response, supporting both innate and acquired immunity [10, 19].

Impact on the antimicrobial response

Vitamin D supports the antimicrobial response by inducing the expression of defensins and cathelicidins – natural antibacterial peptides. Calcitriol activates the CAMP (cathelicidin antimicrobial peptide) gene, encoding cathelicidin LL-37, which has bactericidal, antiviral and antifungal effects [19, 8]. LL-37 acts by damaging microbial cell membranes and modulating the inflammatory response, limiting the development of infection [10].

Regulation of innate immunity
Calcitriol activates macrophages and monocytes, increasing their ability to phagocytose and destroy microorganisms. At the same time, vitamin D inhibits excessive inflammatory reactions by inhibiting the production of proinflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor alpha (TNF-α) [10, 19]. This protects tissues from damage caused by excessive inflammatory response.

Supporting acquired immunity
Vitamin D promotes the differentiation of regulatory T lymphocytes (Treg), which inhibit excessive activation of Th1 and Th17 helper T lymphocytes. This has anti-inflammatory effects and prevents the development of autoimmune diseases [19]. Vitamin D also affects B lymphocytes, inhibiting their proliferation and differentiation, which limits the production of autoantibodies [10].

Clinical significance
Vitamin D deficiency has been associated with increased susceptibility to viral and bacterial infections, such as influenza, respiratory infections, and tuberculosis [10, 8]. Vitamin D supplementation can support the prevention and treatment of these diseases by strengthening the body's defense mechanisms.

4. Autoimmune diseases:
Vitamin D deficiency is associated with the development of diseases such as multiple sclerosis, rheumatoid arthritis (RA), and type 1 diabetes [11].

Vitamin D deficiency and its impact on the development of multiple sclerosis
Multiple sclerosis (MS) is a chronic autoimmune disease in which the immune system attacks the myelin sheaths of nerve fibers in the central nervous system (CNS), leading to neuronal damage, impaired nerve impulse conduction, and progression of disability. Vitamin D deficiency plays a significant role in increasing the risk of MS by affecting the regulation of the immune system and neuronal function [31, 33]. In MS, vitamin D limits the excessive activation of T helper lymphocytes type 1 (Th1) and type 17 (Th17), which are the main mediators of autoimmune myelin damage [8, 19]. Cytokines produced by these lymphocytes, such as interleukin-17 (IL-17) and interferon gamma (IFN-γ), enhance the inflammatory process and recruitment of other immune cells to the CNS [11, 19, 34]. Additionally, calcitriol supports the differentiation of regulatory T cells (Treg), which inhibit the autoimmune response by limiting the activity of pro-inflammatory lymphocytes [11, 19, 32]. Vitamin D deficiency leads to a weakening of Treg function, which promotes the prevalence of pro-inflammatory mechanisms.

Effect on the blood-brain barrier
Vitamin D participates in maintaining the integrity of the blood-brain barrier, which plays a key role in protecting the CNS from the penetration of harmful cells and substances. Vitamin D deficiency may weaken the functions of this barrier, which allows the migration of lymphocytes and monocytes to the nervous tissue, intensifying the demyelination process [8, 19].

Effect on nerve cells

Calcitriol has a neuroprotective effect by increasing the expression of neurotrophic growth factors, such as brain-derived neurotrophic factor (BDNF). Vitamin D deficiency may limit the ability of neurons to regenerate and adapt in response to damage, which accelerates the progression of the disease [19]. Epidemiological studies indicate a significant association between low serum vitamin D levels and a higher risk of MS. A growing body of evidence indicates that higher sun exposure (and thus higher cutaneous synthesis of vitamin D) is associated with a lower incidence of MS in populations with a similar genetic risk. [8, 11]. Vitamin D supplementation plays an important role in the prevention and treatment of MS. Vitamin D supplementation has been shown to reduce the severity of MS flares and improve clinical indicators associated with disability progression in people with MS [8, 19].

The impact of vitamin D deficiency on the development of RA

Autoantibodies, such as rheumatoid factor (RF) and anti-citrullinated peptide antibodies (ACPA), play a key role in the pathogenesis of RA. Vitamin D can inhibit the activation of B lymphocytes, which limits the production of autoantibodies and disease severity [11]. Calcitriol inhibits the production of pro-inflammatory cytokines (such as TNF-α, IL-6) and promotes the secretion of anti-inflammatory cytokines, such as interleukin-10 (IL-10). As a result, vitamin D alleviates the inflammatory process in the synovium of joints, limiting tissue damage [19]. Vitamin D deficiency increases osteoclastogenesis, which leads to accelerated bone resorption in the area of inflamed joints [8]. In addition, vitamin D supports the activity of chondrocytes, which are responsible for maintaining the integrity of joint cartilage. Its deficiency may accelerate cartilage degradation and the development of destructive changes in joints [12]. Studies have shown that people with RA often have lower serum vitamin D levels compared to the healthy population. In addition, vitamin D supplementation may reduce the severity of RA symptoms, such as joint pain, swelling and morning stiffness, and limit disease progression [8, 19].

Vitamin D and its impact on the development of type I diabetes

Vitamin D inhibits the activation of B lymphocytes and the production of autoantibodies, such as antibodies against insulin (IAA), glutamic acid decarboxylase (GADA) or tyrosine phosphatase (IA-2A), which are markers of autoimmune destruction of beta cells [8, 11].

Epidemiological studies show a correlation between vitamin D deficiency in early childhood and an increased risk of developing T1D. Higher levels of vitamin D in serum and appropriate supplementation in childhood may reduce the risk of the disease [8, 19]. There is substantial evidence from geographical observations that populations living in regions with less sunlight (resulting in lower vitamin D synthesis) exhibit a higher incidence of T1D [15]. In addition, vitamin D has protective mechanisms, including neuroprotection of pancreatic beta cells and stabilization of the pancreatic microenvironment. Calcitriol supports the protection and regeneration of beta cells by reducing oxidative stress and preventing their apoptosis and reduces local inflammation in the pancreatic islets, protecting beta cells from damage [12, 19].

Long-term vitamin D supplementation may reduce the risk of T1D, especially in high-risk groups such as children with genetic predisposition (HLA DR3/DR4) [8, 15]. The optimal serum 25(OH)D level for T1D prevention is 20–30 ng/ml [19].

5. Cardiovascular diseases and cancer:

Vitamin D deficiency has been associated with an increased risk of cardiovascular diseases such as hypertension, atherosclerosis, heart failure, and myocardial infarction. Calcitriol affects cardiovascular function by regulating blood pressure, acting anti-inflammatory, and protecting the endothelium of blood vessels [12, 19].

Blood pressure regulation

Vitamin D inhibits the activity of the renin-angiotensin-aldosterone system (RAAS), which plays a key role in regulating blood pressure. Vitamin D deficiency increases renin levels, leading to excessive vasoconstriction and increased blood pressure [12].

Anti-inflammatory effects

Calcitriol reduces the production of pro-inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor alpha (TNF-α), which are associated with the development of atherosclerotic processes. Vitamin D also protects against damage to the vascular endothelium, which reduces the risk of atherosclerotic plaque formation [13, 19].

Effects on glucose and lipid metabolism

Vitamin D improves glucose and lipid metabolism, which reduces the risk of type 2 diabetes and dyslipidemia – major risk factors for cardiovascular disease [12, 13].

Cancer, especially colon cancer

Vitamin D deficiency has also been associated with an increased risk of some cancers, including colon cancer. Calcitriol has anti-cancer effects by modulating cell proliferation, apoptosis and angiogenesis [19].

Inhibition of cancer cell proliferation

Calcitriol binds to VDR receptors present in cancer cells, regulating the expression of genes responsible for the cell cycle. This increases cell cycle arrest in the G1 phase and inhibits uncontrolled cell division [12, 19]. Vitamin D stimulates the process of programmed cancer cell death, which reduces the risk of cancer progression [19]. Calcitriol limits the formation of new blood vessels that supply nutrients to tumors, which slows down the development of tumors [13]. Epidemiological studies have shown that people with higher serum levels of vitamin D have a lower risk of developing colon cancer. In addition, adequate vitamin D supplementation may reduce the risk of developing this cancer, especially in populations at risk of vitamin D deficiency [12, 19].

6. Metabolic problems:

Vitamin D deficiency may contribute to insulin resistance and the development of type 2 diabetes [15]. Type 2 diabetes (T2D) is a chronic metabolic disease characterized by insulin resistance and progressive insulin deficiency. Vitamin D deficiency has been associated with an increased risk of developing T2D, mainly through its effects on glucose metabolism, anti-inflammatory effects, and protection of pancreatic beta cells.

Vitamin D acts on metabolic pathways involved in the regulation of glucose metabolism. It binds to VDR receptors present in skeletal muscle and adipose tissue, which improves peripheral tissue sensitivity to insulin [15, 19]. In addition, it indirectly increases insulin receptor activity and phosphorylation of proteins associated with insulin signaling, which promotes better glucose uptake by tissues [15].

As previously mentioned, it inhibits the activity of pro-inflammatory cytokines such as interleukin-1β (IL-1β) and TNF-α, which are involved in the destruction of beta cells [12, 19]. It reduces the amount of reactive oxygen species (ROS) in beta cells, which protects them from apoptosis [15].

Chronic low-grade inflammation is a key pathogenic factor in insulin resistance. Vitamin D reduces macrophage infiltration in adipose tissue, limiting the secretion of pro-inflammatory cytokines such as IL-6 and TNF-α [15, 19]. Vitamin D deficiency can disturb the balance of the gut microbiota, leading to increased intestinal barrier permeability and chronic inflammation [19].

Population studies have shown that individuals with vitamin D deficiency are more likely to develop insulin resistance and T2D compared to those with optimal serum vitamin D levels [15]. Interventional clinical trials suggest that vitamin D supplementation may improve insulin sensitivity and glycemic control, particularly in individuals with vitamin D deficiency [12, 19].

7. Neurological disorders:

A link has been shown between low vitamin D levels and an increased risk of neurodegenerative diseases such as Alzheimer's and Parkinson's disease [18]. Vitamin D deficiency affects the development of these diseases through several biological mechanisms.

Alzheimer's disease

In the case of Alzheimer's disease, vitamin D deficiency may contribute to pathological changes in the brain, such as the accumulation of beta-amyloid (Aβ) peptides and the development of neuroinflammatory processes [19, 8]. Calcitriol, the active form of vitamin D, affects the removal of beta-amyloid by stimulating macrophages, which is crucial for reducing its toxic effects in brain tissue [19]. In addition, vitamin D has a neuroprotective effect by regulating the level of neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), which support synaptic plasticity and neuronal regeneration [8]. Vitamin D deficiency also correlates with blood-brain barrier dysfunction, which increases the risk of damage caused by toxins and inflammation [18].

Parkinson's disease

In Parkinson's disease, vitamin D deficiency is associated with damage to dopaminergic neurons in the substantia nigra, which leads to the movement disorders characteristic of this disease [19]. Calcitriol modulates the activity of the immune system, reducing the intensity of inflammatory processes in the central nervous system, which may contribute to the degeneration of dopaminergic neurons [19, 8]. Vitamin D also regulates calcium metabolism in neurons, which is important for their survival and function. In addition, its deficiency is associated with a weakening of the protective capacity of mitochondria, which increases oxidative stress - one of the key mechanisms leading to neurodegeneration [19].

In summary, vitamin D deficiency has a negative effect on the nervous system by increasing inflammatory processes, disturbing the calcium balance in neurons and reducing the protective capacity of the brain against toxins and oxidative stress. Maintaining an optimal level of vitamin D may therefore be an important element in the prevention and treatment of neurodegenerative diseases.

Conclusions

Vitamin D, although widely known for its role in regulating calcium-phosphate metabolism and bone health, is equally important in the functioning of other body systems. Its deficiency leads to secondary hyperparathyroidism, impaired bone mineralization, and an increased risk of osteoporosis and fractures [5, 13]. Contemporary studies also indicate its key role in the prevention of cardiovascular, neoplastic, and autoimmune diseases [23, 15].

Interventional clinical trials clearly confirm the benefits of vitamin D supplementation, especially in the elderly and those at high risk of deficiency. These effects include a reduced risk of fractures, improved muscle function, and protection against chronic diseases [4, 7]. It is also worth emphasizing the need for an individualized approach to supplementation, taking into account variables such as age, place of residence, and lifestyle [11].

In summary, vitamin D is a key element of public health strategies aimed at reducing the global burden of bone diseases and chronic systemic diseases. Further research into its mechanisms of action and optimization of supplementation is essential to improving the health of the global population.

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Disclosure

Author contributions:

All Authors contributed to the article.

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