VITAMIN D
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Vitamin D deficiency, stress fractures and post-traumatic recovery

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Summary

Vitamin D is essential for intestinal absorption of calcium and phosphate, as well as for maintaining good muscle performance and optimal immune function. In fact, consistently low vitamin D levels impair skeletal mineralisation and increase the risk of bone fractures. Among these, stress fractures, caused by repeated mechanical stress, have been associated with vitamin D deficiency and are a common problem among athletes and military personnel. Correcting and maintaining adequate vitamin D levels, together with optimising calcium levels, is one of the most effective strategies for strengthening the skeleton and, consequently, preventing the risk of fractures. Therefore, this review offers an overview of the mechanisms by which vitamin D affects bone health and post-traumatic recovery, providing a solid basis for future research and clinical interventions.

INTRODUCTION

Vitamin D is an essential nutrient that plays a crucial role in maintaining bone health. Its importance is well documented not only for the prevention of bone diseases, but also for its role in the modulation of the immune system, muscle contraction and the prevention of chronic diseases. However, vitamin D deficiency is a widespread problem globally, influenced by various factors, including seasonality, latitude, obesity, malnutrition, as well as acute inflammation and infection that may reduce serum vitamin D levels [1].

Vitamin D deficiency has been associated with a higher incidence of bone fractures, including stress fractures, caused by repetitive loads and mechanical stress, which are common among athletes, military personnel and individuals who engage in strenuous physical activity. The ability of bone to repair these micro-damages depends largely on the availability of essential nutrients, including vitamin D. Numerous evidences suggest that vitamin D deficiency may impair bone mineralisation, increasing susceptibility to fractures caused by stress. Furthermore, post-traumatic recovery from stress fractures is a complex process that requires adequate nutritional support to ensure effective healing. Vitamin D plays a key role in bone regeneration and fracture healing, accelerating the recovery process, improving the quality of bone callus and reducing immobilisation time [2].

In a context where the prevalence of vitamin D deficiency is increasing, it is essential to fully understand its implications on bone health and to identify the best practices for its management. Therefore, our review aims to explore the role of vitamin D in stress fracture prevention and post-traumatic recovery by analysing the association between vitamin D deficiency and increased incidence of fractures, as well as the benefits of vitamin D supplementation in the healing process.

ROLE OF VITAMIN D IN BONE HEALTH

Vitamin D is a fat-soluble vitamin crucial for regulating calcium and phosphorous metabolism. Vitamin D can be obtained through exposure to sun, which induces skin synthesis of vitamin D_3 or cholecalciferol, and through the intake of foods and supplements containing vitamin D_2 or ergocalciferol, and vitamin D_3. In the organism, vitamin D is converted in the liver to 25-hydroxyvita-

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Conflict of interest
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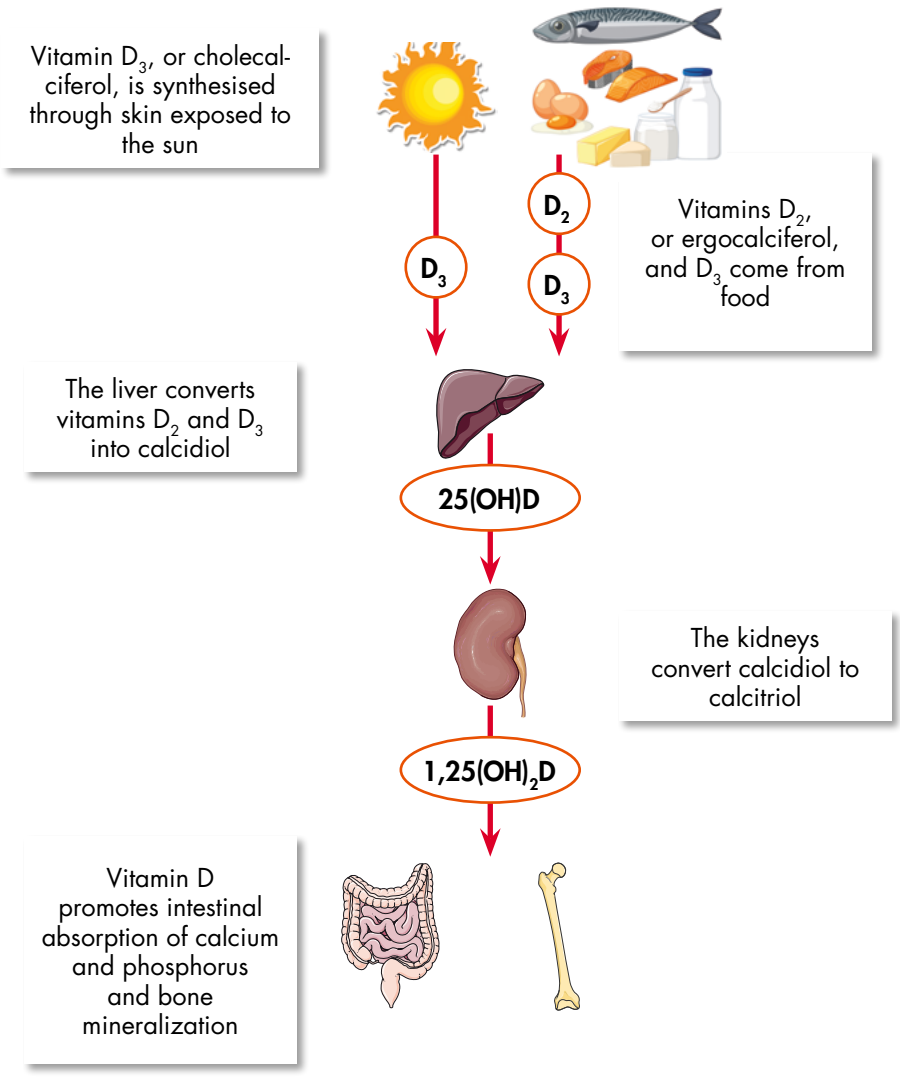

FIGURE 1.
Vitamin D synthesis and metabolism.

min D [25(OH)D] or calcidiol, the main circulating form. In the kidneys, 25(OH)D is converted into its active form, 1,25-dihydroxyvitamin D [$1,25(OH)_2D$], known as calcitriol, which acts on specific receptors in various tissues, contributing to the maintenance of homeostasis [3] (Fig. 1).
Numerous studies have shown that adequate levels of vitamin D are associated with increased bone mineral density, a key indicator of strength and endurance of the bones. It promotes the intestinal absorption of calcium and phosphorus, which are necessary for the mineralisation of the bone matrix. However, under conditions of vitamin D deficiency, calcium absorption is inefficient, causing hypocalcaemia. This condition stimulates the secretion of parathormone (PTH), which mobilises calcium from the bones to maintain serum calcium levels, causing bone demineralisation and increasing the risk of fractures [4].
Vitamin D increases the expression of calcium-binding proteins in the gut, facilitating the trans-cellular transport of calcium into the bloodstream. Furthermore, it acts directly on bone cells, stimulating the activity of osteoblasts and reducing the activity of osteoclasts. These actions are associated with the presence of the vitamin D receptor (VDR), a nuclear receptor that, by binding to calcitriol, regulates the expression of genes involved in calcium metabolism, cell growth and immune function. In fact, VDR dysfunction can alter tissue homeostasis, contributing to the onset of musculoskeletal disorders, including osteoporosis and sarcopenia [5]. In addition, severe vitamin D deficiency can cause rickets in children, a condition characterised by defects in bone mineralisation leading to skeletal deformities, while in adults it can cause osteomalacia, a condition in which the mineralisation of newly-formed bone is inadequate, causing muscle weakness and widespread bone pain [6].
Numerous epidemiological and clinical studies support the role of vitamin D in fracture prevention. In particular, a meta-analysis of randomised clinical trials showed that vitamin D supplementation, especially when combined with calcium, significantly reduces the risk of fractures in the elderly suffering from vitamin D deficiency [7]. Another study showed that patients with stress fractures frequently have insufficient vitamin D levels, suggesting that proper supplementation could prevent such injuries [8]. Overall, this evidence confirms the role of vitamin D in maintaining optimal bone mass and suggests the need to monitor and maintain adequate vitamin D levels, especially in individuals at risk, through adequate sun exposure, a balanced diet and, if necessary, vitamin D supplementation.

STRESS FRACTURES AND POST-TRAUMATIC RECOVERY: THE ROLE OF VITAMIN D

Stress fractures are injuries caused by repeated micro-trauma that exceeds the repair capacity of bone tissue. Vitamin D deficiency is a significant risk factor for the development of these fractures, as this vitamin is crucial for the health and adaptation of bones to mechanical stresses. This type of fracture is common in the lower limbs, where the bones bear the weight of the body and repeated impacts during activities such as running and jumping [9].
Several studies have shown that individuals with low vitamin D levels have an increased risk of stress fractures, especially among athletes, because they are exposed to repeated loads, and military personnel, subjected to intense physical activities. In particular, it has been shown that changes in training protocol, equipment used or the start of a new sport, especially in non-professional athletes, are frequent causes of stress injuries, suggesting the importance of vitamin D supplementation during periods of intense training or service [10].
Post-traumatic recovery from bone fractures

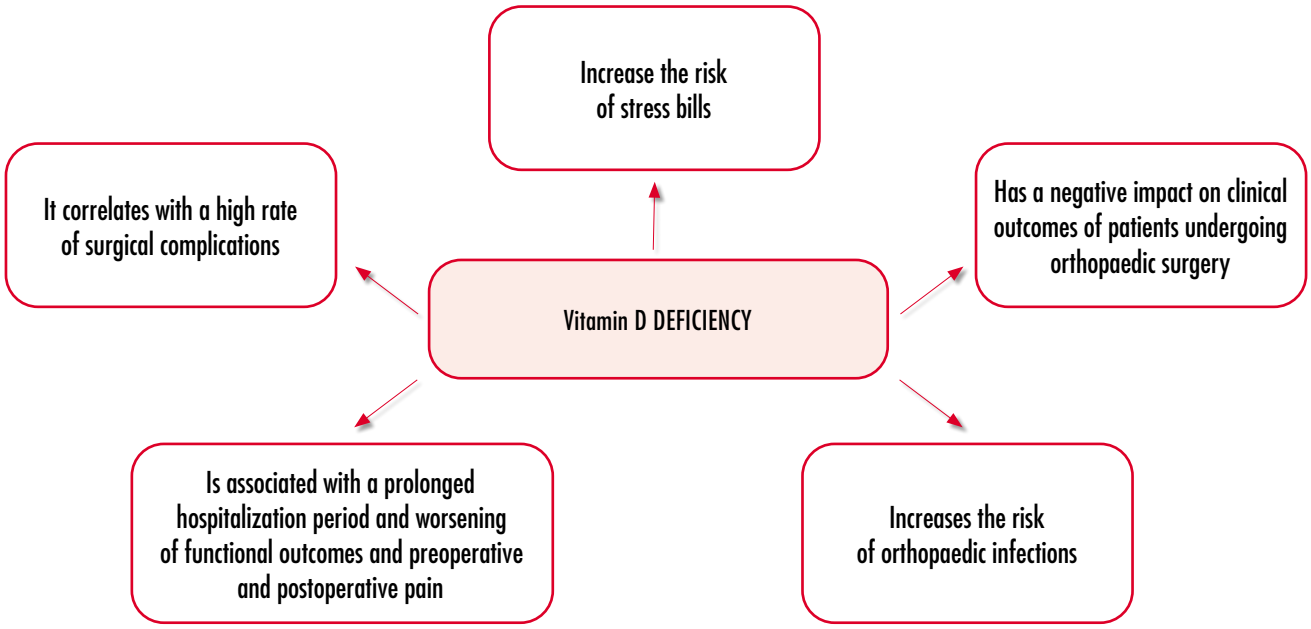

FIGURE 2.
Vitamin D deficiency: consequences in the orthopaedic field.

is also a complex process that requires adequate nutritional support to ensure effective healing. In this context, vitamin D plays a crucial role due to its ability to modulate the activity of osteoblasts and osteoclasts, ensuring an essential dynamic balance for bone repair. Several evidences have shown that adequate levels of vitamin D accelerate bone callus formation and improve the quality of bone regeneration [11]. Therefore, vitamin D deficiency can significantly impair the fracture healing process, causing poor bone callus formation, prolonging healing time and increasing the risk of complications, such as *non-union* (Fig. 2). In this respect, vitamin D-deficient patients with fractures show faster healing and better quality of bone callus if they receive vitamin D supplementation compared to deficient subjects [12]. Another study showed that patients with femur fractures treated with vitamin D and calcium had significantly reduced healing times compared to the control group without supplementation [13]. Therefore, the physiological action of vitamin D is a key element in the post-traumatic healing process, essential both in the inflammatory phase, due to its immuno-modulating properties, and for the formation, mineralisation and remodelling of bone callus.

PREVENTION AND MANAGEMENT OF VITAMIN D DEFICIENCY

Prevention and management of vitamin D deficiency are crucial to maintain bone health and prevent consequences such as stress fractures. In this context, skin synthesis of vitamin D through exposure to sunlight is the main source of vitamin D for many people. It is advisable to expose oneself to the sun for about 15 to 30 minutes a day, although factors such as latitude, season and skin pigmentation may influence the amount of vitamin D produced. In addition, a diet rich in foods containing vitamin D is essential. Some good sources of vitamin D include fish, such as salmon, mackerel and tuna, cod liver oil, egg yolks, beef liver and fortified foods such as milk, orange juice and cereals. Incorporating these foods into the daily diet can help maintain adequate levels of vitamin D [14]. Nevertheless, in many cases, vitamin D supplementation is necessary, especially for people at risk of deficiency, such as the elderly, individuals with limited sun exposure and those with absorption problems. In these individuals, regular monitoring of blood calcidiol levels is important to control and manage vitamin D levels. Blood tests can help determine whether supplementation doses are adequate or whether adjustments are needed. Overall, the prevention of vitamin D deficiency and its adequate supplementation require a multifactorial approach that must include sun exposure, a balanced diet and, when necessary, supplementation [15].

CONCLUSIONS

Vitamin D is essential for bone health, preventing stress fractures and improving post-traumatic recovery. This is especially true for individuals at risk of stress fractures, such as athletes and military personnel, whose intense physical activity subjects the bone tissue to continuous stress and overloads that could favour the development of micro-damage and, consequently, stress fractures. A deficiency of this vitamin impairs bone mineralisation and prolongs healing time. In order to prevent and manage this deficiency, adequate sun exposure, a vitamin D-rich diet and, if necessary, supplementation are recommended. For individuals at risk of deficiency, regular monitoring of vitamin D levels is essential to maintain bone health and reduce the risk of stress fractures.

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