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Keloid Formation in Athletes: Pathophysiology, Biomechanical Risk Factors, Psychosocial Burden, and Current Therapeutic Approaches

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1. Abstract

Keloids represent a chronic dermatological condition resulting from abnormal wound healing and excessive proliferation of fibrotic tissue. These lesions may lead not only to physical symptoms such as pain, pruritus, and restricted mobility, but also to significant psychosocial consequences that adversely affect patients' quality of life. In recent years, increasing attention has been directed toward the molecular mechanisms underlying keloid formation, including dysregulation of fibroblast activity, abnormal signaling pathway modulation, and the influence of genetic and biomechanical factors.

Athletes constitute a particularly vulnerable group with regard to the development of pathological scars. Intense physical activity, frequent skin injuries, repetitive microtrauma, and surgical procedures commonly performed in sports medicine may increase the risk of keloid formation. Furthermore, scar

lesions may negatively affect tissue function, training comfort, physical performance, and the psychological well-being of athletes.

The aim of this paper is to present current knowledge regarding the molecular mechanisms involved in keloid formation, biomechanical risk factors observed in athletes, contemporary therapeutic approaches, and the psychosocial consequences of these lesions in the context of sports medicine.

Keywords

keloids, scar formation, sports medicine, fibroblasts, wound healing, psychosocial impact

2. Introduction

Keloids are a pathological form of scarring resulting from abnormal wound healing, characterized by excessive fibroblast proliferation and increased synthesis of extracellular matrix components (1). Unlike normal scars, keloid tissue extends beyond the boundaries of the original skin injury and demonstrates a tendency for continuous growth over time. Clinically, keloids present as firm, elevated skin lesions with variable pigmentation, ranging from erythematous to brown or violaceous in color (2,3)).

Despite their benign histopathological nature, keloids represent a significant clinical problem. These lesions are frequently associated with symptoms such as pain, pruritus, and skin tightness, which may substantially impair patients' daily functioning (4,5). Furthermore, keloids may lead to aesthetic concerns and functional limitations, particularly when located in areas exposed to increased mechanical tension or movement(6).

Data regarding the prevalence of keloids vary depending on the literature source. It is estimated that the prevalence in the Caucasian population is below 1%, whereas in African and Asian populations it ranges from 4% to 16%. Furthermore, keloids occur with similar frequency in both women and men (7–9). Keloids most commonly develop in young individuals, particularly between the second and

third decades of life, which may be associated with increased skin regenerative activity and hormonal changes occurring during this period(10).

Numerous studies have demonstrated that the presence of keloids may significantly reduce patients' quality of life, leading to physical discomfort as well as psychosocial problems such as decreased self-esteem and psychological distress (5,11).Additionally, this condition is characterized by a high recurrence rate despite the use of various therapeutic approaches, which constitutes a significant challenge in clinical practice (12). For this reason, keloids are considered a chronic dermatological condition that may significantly affect both patients' physical health and psychological well-being (4).

Keloids may pose a particular challenge in the athletic population due to the specific nature of injuries and wound-healing processes associated with physical activity. Skin injuries such as abrasions, lacerations, and traumatic wounds are relatively common during sports participation, as are surgical procedures performed in sports medicine, including ligament reconstructions, fracture treatment, and other orthopedic interventions. Any disruption of skin integrity initiates a wound-healing process that, in predisposed individuals, may lead to the development of pathological scars, including keloids(13,14).

An important factor contributing to keloid formation is mechanical skin tension, which plays a significant role in the pathogenesis of these lesions. Studies have shown that keloids develop more frequently in areas exposed to greater mechanical forces, such as the chest, shoulders, and upper back (15). These regions are also particularly stressed during many sports disciplines, especially in strength, contact, and activities requiring intensive shoulder girdle involvement. Repetitive microtrauma and chronic skin tension may disrupt the normal wound-healing process and promote excessive fibroblast proliferation as well as collagen deposition.

In athletes, it is particularly important that keloid formation following injuries or surgical procedures may affect not only skin appearance, but also tissue function and physical comfort during sports activity. These lesions may cause symptoms such as pain, pruritus, and a sensation of skin tightness, which in some cases may limit range of motion or lead to discomfort during training and competition (13). Visible scars may also affect athletes' self-esteem and psychological well-being, particularly in disciplines in which body appearance and skin exposure play an important role.

For this reason, appropriate scar prevention and early implementation of adequate treatment are of particular importance in physically active individuals. Understanding the mechanisms underlying keloid formation and the associated risk factors in the context of sports activity may contribute to improving prevention and treatment strategies for these lesions in sports medicine.

3. Methods

This study is a narrative literature review concerning the pathogenesis, biomechanical factors, treatment, and psychosocial aspects of keloids, with particular emphasis on athletes and issues related to sports medicine.

The literature review was conducted based on scientific publications retrieved from PubMed. Articles published after 2015 and available in peer-reviewed medical and dermatological journals were included. The search process involved the use of keywords including, but not limited to: “keloids”, “scar formation”, “fibroblasts”, “wound healing”, “sports medicine”, “psychosocial impact”, “mechanotransduction”, and “keloid treatment”.

The analysis included publications addressing the molecular mechanisms underlying keloid formation, biomechanical risk factors, conservative and invasive treatment methods, as well as the impact of keloids on quality of life and the functioning of physically active individuals. Articles were selected based on data relevance, methodological quality, and thematic consistency with the scope of the study.

4. Molecular Mechanisms of Keloid Formation

Keloid formation is the result of complex disturbances in the wound-healing process, involving excessive fibroblast proliferation, increased extracellular matrix synthesis, and abnormal activation of numerous signaling pathways regulating fibrosis. In contrast to normal wound healing, in which a balance is maintained between matrix synthesis and degradation, keloids are characterized by persistent activation of cells responsible for collagen production and a chronic inflammatory response leading to excessive deposition of fibrotic tissue (15,16).

4.1 Fibroblasts

Fibroblasts play a central role in the pathogenesis of keloids, as they are responsible for the production of collagen and other extracellular matrix components. Keloid tissue is characterized by increased

fibroblast proliferation and their transformation into myofibroblasts, which demonstrate enhanced collagen secretion and an increased capacity for extracellular matrix remodeling (17). Studies also indicate that keloid fibroblasts exhibit an altered response to signals regulating proliferation and apoptosis, leading to persistent activity of extracellular matrix–producing cells. As a result, excessive collagen production and the development of pathological scar tissue occur (4).

4.2 Extracellular Matrix Deposition

A characteristic feature of keloids is the excessive deposition of extracellular matrix components, particularly type I and type III collagen. In normal wound healing, matrix synthesis is regulated by a balance between fibroblast activity and collagen degradation mediated by matrix metalloproteinases (MMPs). In keloids, this balance is disrupted, leading to the accumulation of collagen and other structural proteins (18).The resulting tissue is characterized by a dense and abnormally organized collagen fiber structure, which may extend beyond the boundaries of the original skin injury (16).

Multiple interconnected signaling pathways are involved in the pathogenesis of keloids, regulating cell proliferation, collagen synthesis, and the inflammatory response. The most important of these include the TGF-β/Smad, MAPK, PI3K/AKT, and JAK/STAT pathways (19).

4.3 TGF-β/Smad Pathway

The transforming growth factor beta (TGF-β) pathway is one of the most important regulators of fibrotic processes in keloids. This cytokine stimulates fibroblast proliferation, enhances collagen synthesis, and inhibits extracellular matrix degradation (4,20). Its mechanism of action involves the activation of TGF-β receptors and phosphorylation of Smad2 and Smad3 proteins, which subsequently regulate the expression of genes responsible for the production of collagen and other extracellular matrix (ECM) components(4)

4.4 MAPK Pathway

The MAPK (mitogen-activated protein kinase) pathway plays an important role in the regulation of cell proliferation and the inflammatory response. Its activation leads to increased expression of genes responsible for fibroblast proliferation and collagen synthesis (19). Badania sugerują, że nieprawidłowa aktywacja tego szlaku może przyczyniać się do utrzymywania przewlekłego procesu włóknienia charakterystycznego dla keloidów.

4.5 PI3K/AKT/mTOR Pathway

The PI3K/AKT/mTOR pathway is another important mechanism regulating cell growth and fibroblast survival. Its excessive activation promotes increased cell proliferation and enhanced collagen synthesis, leading to the formation of scar tissue (21).

4.6 JAK/STAT Pathway

The JAK/STAT pathway plays an important role in the regulation of immune responses and inflammatory processes. Studies have demonstrated increased expression of the STAT3 protein in keloid tissue and keloid fibroblasts, indicating its involvement in the fibrotic process (22).

4.7 Genetic and Epigenetic Factors

In addition to abnormalities in signaling pathway regulation, genetic and epigenetic factors also play an important role in the development of keloids. Studies suggest that the predisposition to keloid formation may have a familial pattern, indicating the involvement of hereditary factors in the pathogenesis of these lesions (18).

In recent years, increasing attention has also been directed toward epigenetic mechanisms, such as the regulation of gene expression by microRNAs and histone modifications. These factors may influence fibroblast activity, collagen production, and the inflammatory response within keloid tissue (19).

5. Biomechanical Factors in Athletes

Biomechanical factors play a significant role in the pathogenesis of keloids, as the wound-healing process is highly dependent on the mechanical properties of the skin and the forces acting on tissues during regeneration. In recent years, increasing evidence has suggested that skin tension, microtrauma, and repetitive mechanical loading may influence fibroblast activation and enhance extracellular matrix synthesis. These factors are of particular importance in athletes, in whom skin injuries, intensive biomechanical stress, and surgical procedures occur more frequently than in the general population (15) (17).

5.1 Skin Tension and Mechanotransduction

One of the most important biomechanical factors influencing keloid formation is skin tension. Studies indicate that keloids most commonly develop in areas exposed to high mechanical forces, such as the chest, shoulders, and upper back. In these regions, skin tension may lead to excessive fibroblast activation (15).

This mechanism is associated with the process of mechanotransduction, defined as the ability of cells to convert mechanical stimuli into biochemical signals. In keloid fibroblasts, mechanical tension may activate multiple signaling pathways, including TGF-β and integrins, which regulate cell proliferation and extracellular matrix production (16,23).

Furthermore, studies have demonstrated that keloid fibroblasts respond more strongly to mechanical stimuli than fibroblasts derived from normal skin, leading to increased proliferative activity and excessive collagen synthesis (17).

5.2 Repetitive Injuries in Athletes

Sports activity is associated with the frequent occurrence of microtrauma and repetitive skin injuries, which may disrupt the normal wound-healing process. Abrasions, lacerations, and other minor skin injuries are particularly common in contact sports such as rugby, wrestling, and martial arts, as well as in disciplines requiring intensive physical activity (13). Repetitive microtrauma may lead to persistent inflammation, which promotes the development of pathological scars.

5.3 Postoperative Scars and Sports Injuries

Postoperative scars also constitute an important risk factor for keloid formation in athletes, as surgical procedures are relatively common in sports medicine (14). In individuals predisposed to keloid formation, postoperative wound healing may proceed abnormally. Such lesions may affect not only the appearance of the skin but also tissue function, causing skin tightness, pain, and restricted mobility (17).

In the context of sports medicine, appropriate prevention and early scar management are of particular importance, as they may reduce the risk of pathological scar formation and limit its impact on athletes' physical functioning.

6. Clinical Management of Keloids

The treatment of keloids remains a clinical challenge due to their high recurrence rate and complex molecular pathogenesis. In clinical practice, both conventional methods and novel therapeutic strategies targeting molecular mechanisms responsible for fibrosis are used. In many cases, the best outcomes are achieved through combination therapies, which help reduce fibroblast proliferation, decrease collagen production, and improve the appearance and function of scar tissue (13,15) (17).

6.1 Conventional Therapy

One of the most commonly used treatment methods for keloids is intralesional corticosteroid injection, primarily with triamcinolone. Corticosteroids act by inhibiting fibroblast proliferation, reducing collagen synthesis, and decreasing the inflammatory response within scar tissue. They have also been shown to reduce the expression of growth factors such as TGF-β, which play a key role in the fibrotic process(24,25).

6.2 Surgical Treatment

Surgical treatment involves excision of the scar lesion; however, the procedure itself is associated with a high risk of recurrence, which according to various studies may range from 45% to as high as 100%. For this reason, surgical removal of keloids is most commonly combined with additional therapeutic methods, such as radiotherapy, steroid injections, or pressure therapy (15).

6.3 Cryotherapy

Results indicate that intralesional cryotherapy may reduce keloid volume by an average of 51–63% and significantly alleviate symptoms such as pain and pruritus. However, this method does not provide complete scar removal, and recurrence has been observed in approximately 0–24% of cases. The most commonly reported adverse effect was skin hypopigmentation, particularly in patients with darker skin phototypes. The authors emphasize that although intralesional cryotherapy appears to be a promising treatment option for keloids, further high-quality studies are needed to confirm its efficacy and safety (26).

6.4 Laser Therapy

Based on the available studies, the effectiveness of laser therapy in the treatment of hypertrophic and keloid scars remains inconclusive. Some evidence suggests that pulsed dye laser (PDL) therapy may lead to greater improvement in scar appearance compared with no treatment; however, the overall quality of the available evidence is low or very low. At the same time, findings from certain analyses indicate that the combination of fractional CO_2 laser therapy with 5-fluorouracil may be one of the most effective approaches for reducing scar thickness, while fractional CO_2 (FCO_2) therapy may also improve scar elasticity. Despite these promising results, the available studies are highly heterogeneous, often involve small patient groups, and provide limited data regarding adverse effects (27,28).

6.5 Innovative Therapies

In recent years, advances in research on the molecular pathogenesis of keloids have led to the development of novel therapeutic strategies aimed at modulating signaling pathways responsible for fibroblast proliferation and collagen synthesis (4,16).

6.6 Biological therapies

Biological therapies focus on modulating the activity of cytokines and growth factors involved in the fibrotic process. Particular interest has been directed toward TGF-β inhibitors, as this pathway plays a key role in the pathogenesis of keloids(4). Inne badane strategie obejmują modulowanie aktywności interleukin oraz czynników zapalnych związanych z procesem włóknienia (10,18). Inhibitors of these pathways may reduce the fibrotic process and suppress keloid growth.

6.7 Molecularly Targeted Therapies

Novel therapeutic approaches also include the application of regenerative medicine, including stem cell therapy, biomaterials, and growth factors regulating the wound-healing process. The aim of these methods is to restore normal skin regeneration and prevent excessive fibrosis (4,16).

7. Psychosocial Consequences of Keloid Scars

Although keloids are classified as benign skin lesions, they may exert a significant impact on patients' psychological and social functioning as well as their quality of life. Physical symptoms such as pain and pruritus, together with the visible nature of scar lesions, may lead to psychological distress, reduced self-esteem, and difficulties in social relationships. Numerous studies have demonstrated that

keloids are associated with substantial psychosocial burden and impairment of quality of life comparable to that observed in other chronic dermatological diseases (29) (5).

7.1 Quality of Life

One of the most frequently analyzed aspects of the impact of keloids on patients is health-related quality of life (HRQoL). Various assessment tools are used in studies, including the Dermatology Life Quality Index (DLQI) and SCAR-Q, which allow evaluation of the effects of skin lesions on daily functioning, psychological well-being, and social relationships. In a study conducted by Bijlard et al., symptoms such as pain and pruritus were identified as some of the most important factors contributing to impaired quality of life in patients with keloids (29)

Similar findings were reported by Sitaniya et al., who demonstrated a significant correlation between the severity of keloid symptoms and deterioration in patients' quality of life (5).

7.2 Psychological Burden

Keloids constitute a significant psychological burden that extends beyond their physical symptoms. The literature emphasizes that they are not only a dermatological condition but also a problem with a substantial psychosocial dimension, leading to emotional disturbances, reduced quality of life, and difficulties in social functioning (30). One of the key aspects is the impact of keloids on body image. Studies have shown that the presence of visible skin lesions may significantly impair the perception of one's appearance, particularly when the lesions are located in exposed areas of the body. In a study conducted by Motoki et al., as many as 40% of patients demonstrated negative body image perceptions. Furthermore, meta-analyses concerning scars indicate that factors such as scar visibility, number, and size are strongly associated with impaired body image and increased symptoms of depression and anxiety (31).An important component of the psychological burden associated with keloids is the presence of emotional disturbances. Clinical studies have demonstrated that patients with keloids more frequently experience symptoms of anxiety and depression, which may result both from the chronic nature of the condition and from the visible appearance of the lesions (32)

7.3 Consequences for Athletes

Keloids may significantly affect athletes' functioning through both physical symptoms and psychosocial consequences. Pain and pruritus associated with keloids may hinder physical activity and negatively affect concentration during training and competition(29). Lesions located near joints may

restrict mobility and reduce tissue elasticity, which may negatively affect physical performance. The visibility of keloids may additionally lower self-esteem and influence body image, which is of particular importance in sports where physical appearance plays a significant role (33).

8. Implications for Sports Medicine

Keloids represent a significant challenge in sports medicine, as skin injuries and surgical procedures are common in this population, and abnormal scarring may affect both tissue function and return to physical activity. Therefore, early identification of patients at risk and the implementation of appropriate preventive strategies are of crucial importance (34).

8.1 Early Prevention Strategies

Prevention plays a crucial role in reducing the risk of keloid formation. The most commonly used methods include silicone dressings and pressure therapy, which are widely applied in both the prevention and treatment of pathological scars(35). Additionally, reducing skin tension within the wound area is of considerable importance, as mechanical forces play a key role in the pathogenesis of keloids.

8.2 Scar Management in Athletes

The treatment of keloids in athletes should take into account both functional aspects and the risk of recurrence, which may affect training continuity. In clinical practice, combination therapy integrating conservative and invasive methods is frequently used to improve treatment effectiveness. Systematic reviews on keloid treatment emphasize that monotherapy rarely provides long-term results, whereas combined therapeutic approaches are considered the standard of care.

Particular importance in athletes is placed on preserving tissue function and minimizing movement limitations. Scars may affect skin elasticity and cause discomfort during physical activity, especially when located in areas exposed to friction or stretching (6).

An important component of treatment is also the prevention of recurrence, which remains one of the greatest therapeutic challenges. Clinical studies have demonstrated that even after successful treatment, there is a high risk of lesion recurrence, necessitating long-term patient monitoring (2).

In athletes, it is also important to tailor therapy to individual needs and the specific type of sport practiced. Treatment should minimize time away from physical activity and reduce the risk of complications that could affect performance and return to sport. The literature emphasizes the importance of individualized treatment depending on scar location and clinical symptoms (30).

8.3 Multidisciplinary Approach

Due to the complex nature of keloids, their management requires an interdisciplinary approach. The therapeutic process should involve dermatologists, surgeons, and sports medicine specialists, as well as physiotherapists and psychologists when necessary. Such an approach not only enables more effective treatment of skin lesions but also facilitates optimization of return to physical activity and improvement of athletes' quality of life (11).

9. Conclusion

Keloids represent a complex clinical problem resulting from disturbances in the wound-healing process, including excessive fibroblast proliferation, abnormal extracellular matrix synthesis, and activation of numerous signaling pathways associated with fibrosis. Increasing attention has also been directed toward biomechanical, genetic, and epigenetic factors contributing to the development of pathological scars.

In the athletic population, the risk of keloid formation may be increased due to frequent skin injuries, repetitive microtrauma, and surgical procedures related to the treatment of sports injuries. These lesions may affect not only skin appearance but also tissue function, physical comfort, and the psychological well-being of athletes.

Despite the availability of multiple therapeutic approaches, the treatment of keloids remains a clinical challenge because of the high recurrence rate. The best therapeutic outcomes are generally achieved through combination therapy and individualized treatment strategies. The development of molecularly targeted therapies and regenerative medicine approaches may contribute to improved treatment efficacy in the future.

In sports medicine, early prevention strategies, reduction of skin tension, and a comprehensive multidisciplinary therapeutic approach are of particular importance. Early identification of high-risk

individuals and appropriate management may help limit the development of pathological scars and improve athletes' quality of life.

10. Disclosure

Author's Contribution

Conceptualization: Alicja Biskup, Agata Wnęk, Julia Smagowska, Ewa Kala - Kaziszyn

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