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editorial-office@sciformat.ca

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FUTURE PROSPECTS FOR ACNE TREATMENT- ARTIFICIAL INTELLIGENCE, NANOMEDICINE AND PRECISION DERMATOLOGY: A COMPREHENSIVE REVIEW

Aleksandra Magdalena Skrzyniarz *(Corresponding Author, Email: askrzyniarzz03@gmail.com)*
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0003-0065-643X

Maria Kiełbus
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0003-1946-3013

Julia Oziębło
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0008-9794-9824

Magdalena Kijowska
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0004-1086-7086

Karolina Klusek
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0004-7006-0188

Michał Batory
No. 1 University Clinical Hospital in Lublin, Lublin, Poland
ORCID ID: 0009-0008-7018-7823

Jakub Jakubowski
Medical University of Warsaw, Warsaw, Poland
ORCID ID: 0009-0009-0269-1371

Karol Kraska
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0003-8113-2151

Nadzieja Krasucka
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0007-2777-892X

Aleksandra Zynkowska
Medical University of Lublin, Lublin, Poland
ORCID ID: 0009-0005-1759-5842

ABSTRACT

Acne vulgaris is one of the most common chronic inflammatory skin diseases with a complex and multifactorial pathogenesis, including keratinization disorders, excessive sebum production, skin microbiome dysbiosis, inflammatory processes, and hormonal and genetic factors. Despite the availability of numerous effective therapies, such as retinoids, antibiotics, and hormonal therapy, their use is still associated with limitations, including adverse effects, unsatisfactory results, the risk of antibiotic resistance, and disease recurrence. Consequently, contemporary dermatology is increasingly focusing on the development of personalized therapies and modern technologies supporting the diagnosis and treatment of acne.

The aim of this study was to review current trends in the diagnosis and treatment of acne vulgaris, which are aimed at combining digital and biotechnological tools and exploring new treatment alternatives to improve treatment effectiveness. Data were analyzed regarding the use of artificial intelligence algorithms in assessing skin lesions, the use of nanocarriers in drug delivery, and the importance of genetic, immunological, hormonal, and microbiological factors in the pathogenesis of acne. The complex and multifactorial nature of acne vulgaris pathogenesis suggests that effective future therapies will require a multifaceted approach that takes into account individual patient predispositions.

KEYWORDS

Acne, Acne Treatment, Nanomedicine, Artificial Intelligence, Precision Treatment

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1. Introduction

Acne vulgaris is one of the most common chronic inflammatory diseases worldwide (Kultu et al., 2023), affecting both adolescents and adults, and significantly impacting patients' quality of life. It affects approximately 9% of the global population – approximately 85% of those aged 12-24 and approximately 50% of those aged 20-29 (Eichenfield et al., 2021).

It is a multifactorial disorder clinically characterized by the presence of inflammatory and non-inflammatory lesions in areas rich in pilosebaceous units, such as the face, neck, back, arms, and upper chest. Acne vulgaris is classified based on the patient's age, lesion morphology, distribution, and severity (Eichenfield et al., 2021).

The pathogenesis is multifactorial and includes hyperkeratosis of hair follicles, increased sebum production, and complex inflammatory processes associated with both innate and adaptive immunity (Reynolds et al., 2024). In turn, the accumulation of necrotic keratinocytes and fatty acids contributes to the proliferation of Cutibacterium acnes, a Gram-positive, anaerobic bacillus, a commensal skin organism believed to play a pathogenic role in the development of acne (Alkhawaja et al., 2020). Neuroendocrine mechanisms, the action of androgens and their receptors, microfloral dysbiosis, and genetic predisposition also play a significant role. The risk of acne increases during adolescence, in individuals with a positive family history, and in patients with oily skin.

Despite the availability of numerous effective acne treatments, such as retinoids, antibiotics, and hormonal therapies, their use is still associated with numerous limitations, including adverse effects, increasing microbial resistance, and negative impact on the skin microbiome. Consequently, new therapeutic strategies aimed at restoring the skin's microbial balance, modulating the host's immune response, and improving treatment safety and tolerability are gaining increasing interest.

2. Materials and Methods

A literature review was conducted in PubMed in May 2026. Both original articles and reviews, primarily those published between 2017 and 2026, were analyzed to provide an overview of the current state of knowledge and treatment methods for acne. The search terms used were "acne vulgaris," "acne vulgaris treatment," "personalized acne treatment," "nanomedicine in dermatology," "microbiota of acne vulgaris," and "artificial intelligence in dermatology." Additionally, older publications, dating back to 2002, were used to elucidate the pathophysiological mechanisms of acne. Exclusion criteria included publications in languages other than English and studies focusing primarily on acne scars. After applying the inclusion and exclusion criteria, a total of 42 articles were selected for analysis.

3. Symptoms and Impact of Acne on Quality of Life

People with acne most commonly observe the presence of comedones, papules, and pustules (Heng & Chew, 2020). Comedones are divided into two types: open (black) comedones, which form as a result of blocked hair follicle openings and are exposed to air, leading to their oxidation, and closed (white) comedones, which remain beneath the skin's surface without a visible opening (Bhatt et al., 2026). Papules are small, raised inflammatory lesions less than 1 cm in diameter, while pustules resemble papules but contain pus and have a clear inflammatory basis. In more severe forms of acne, nodules and cysts—swollen, painful inflammatory lesions exceeding 5 mm in diameter—may also appear. Cysts are primarily formed as a result of the immune response against bacteria and the lipid content of comedones (Bhatt et al., 2026). Cysts are inflammatory lesions that are usually larger than 5 mm in size and often leave deep scars. Additionally, patients often experience sequelae of the disease, such as acne scarring, post-inflammatory redness, and skin discoloration.

It should be noted that acne, despite being a skin condition, has a significant impact on the mental health and social functioning of patients. Visible skin lesions, particularly those located on the face, can lead to lower self-esteem, loss of self-confidence, and a deterioration in body image. The chronic nature of the disease and therapeutic challenges can contribute to the development of stress, frustration, and social isolation (Morshed et al. 2023). Some patients experience avoidance of interpersonal contact, limited social activity, and difficulties in professional and personal relationships (Layton et al., 2021). Studies also indicate an increased risk of anxiety and depressive disorders in acne sufferers (Altunay et al. 2020; Misery et al. 2020; Lukaviciutate et al., 2020), especially in more severe forms of the disease or the presence of acne scars.

The increase in the number of cases observed in recent decades (Chen et al., 2022) indicates that this disease poses a significant challenge, both clinically and socially. The growing scale of the problem, as well as its significant impact on psychological aspects, emphasizes the need to seek new, more effective, and modern diagnostic methods and therapies that will allow for better control of the disease and limit its consequences.

4. Main Treatment Methods

Current treatment options, such as topical retinoids, antibiotics, and hormonal therapies, may not be sufficient to address the increasing incidence and severity of acne. Individual medications vary in their mechanism of action, efficacy, and safety profile. Characteristics of the most commonly used medications for acne treatment are presented in Table 1.

Table 1. The most commonly used drugs in the treatment of acne vulgaris, including their mechanism of action and the most frequently observed side effects based on the current EuroGuiDerm acne treatment guidelines (update 2025/2026) [Nast et al., 2026].

Drug / Drug class	Mechanism of action	Most common side effects
Tretinoin (topical retinoid)	Normalizes follicular keratinization, has anti-inflammatory effects, and reduces comedone formation	Skin irritation, redness, dryness, peeling, photosensitivity
Adapalene (topical retinoid)	Anti-inflammatory and comedolytic effects; regulates epidermal cell turnover	Dry skin, burning sensation, irritation, erythema
Benzoyl peroxide	Antibacterial action against *Cutibacterium acnes*, reduction of sebum production and prevention of antibiotic resistance.	Dryness, peeling, irritation, bleaching of fabrics
Azelaic acid	Antibacterial, anti-inflammatory, and depigmenting effect on post-acne hyperpigmentation	Burning sensation, itching, skin redness
Clindamycin (topical antibiotic)	Inhibits bacterial growth and reduces inflammation	Skin irritation, dryness, risk of bacterial resistance
Doxycycline (oral antibiotic)	Antibacterial and anti-inflammatory effects	Nausea, diarrhea, photosensitivity, gastrointestinal disturbances
Lymecycline / tetracyclines	Reduce bacterial proliferation and inflammation	Gastrointestinal upset, photosensitivity, dizziness
Isotretinoin (oral retinoid)	Strongly reduces sebum production, anti-inflammatory and indirect antibacterial effects	Severe dryness of skin and mucous membranes, muscle pain, hepatotoxicity, teratogenicity
Spironolactone	Anti-androgenic effect; reduces sebum production	Menstrual irregularities, breast tenderness, dizziness
Oral contraceptives	Regulate hormonal balance and reduce androgen influence	Nausea, headache, increased risk of thrombosis

5. Artificial Intelligence in Acne Diagnosis and Treatment

The dynamic development of artificial intelligence (AI) is contributing to the increasingly widespread use of modern technologies in dermatology, including the diagnosis and treatment of acne. The development of machine learning algorithms enables faster and more precise analysis of skin lesions. AI-based technologies are used in both diagnosis and disease monitoring, as well as supporting therapeutic decisions.

Many scales are currently used to classify the severity of the disease, but a single universal and fully standardized assessment tool is still lacking. One of the most commonly used scales is the Global Acne Grading System (GAGS), which is based on the number and location of skin lesions in various areas of the face and body. Another popular method is the Investigator's Global Assessment (IGA), which classifies acne severity based on a dermatologist's overall clinical assessment of lesions. In Europe, the Global Evaluation Acne (GEA) is also frequently used, enabling a simple assessment of the disease's severity (Seité et al., 2019, Bae et al. 2024). Scientific studies also utilize scales based on counting specific lesion types, such as comedones, papules, or pustules. Despite their widespread use, existing scales have numerous limitations. Primarily, many of them rely on the physician's subjective assessment, which can lead to differences in the interpretation of results between researchers. An additional problem is the time-consuming nature of manually counting skin lesions and the limited reproducibility of results. Consequently, modern technologies utilizing artificial intelligence, such as AI algorithms analyzing smartphone images, are gaining increasing interest. These technologies enable automatic assessment of acne severity, identification, and counting of skin lesions with an accuracy comparable to that of a dermatologist (Seité et al., 2019). Artificial intelligence algorithms, primarily based on deep neural networks (DNNs) and convolutional neural networks (CNNs), reduce subjectivity and interobserver variability through automatic lesion detection and segmentation. AI models are trained on thousands of anonymized clinical images, enabling them to accurately identify and count individual lesions: comedones (closed and open), papules, pustules, and nodules (Kim et al., 2023). They also demonstrate objective classification of disease severity by analyzing the density and type of lesions, automatically assigning the patient to the appropriate category on a disease severity scale. Modern systems also benefit from multispectral analysis, utilizing not only standard photographs but also fluorescence or hyperspectral imaging. This allows for the detection of porphyrins (metabolic products of the Cutibacterium acnes bacterium) and subsurface inflammation, invisible to the naked eye. Additionally, the algorithm used by Seité et al. employs geolocation to analyze the impact of environmental factors, such as air pollution or climatic conditions, on the course of the disease (Seité et al., 2019). The need for long-term treatment remains a significant challenge in acne therapy, and modern digital technologies can support monitoring of therapy effects, increase regularity of follow-up, and facilitate personalized treatment.

However, assessing acne severity based on clinical images poses a significant diagnostic challenge both in dermatological practice and in automated image analysis systems. This is due to the high morphological variability of skin lesions, their small size, and the difficulty in clearly differentiating them in images, which may contain artifacts related to lighting, image blurriness, or partial occlusion of lesions, e.g., by hair (Kim et al., 2023). Consequently, both manual and automated assessments may be subject to limited reproducibility. Early methods based on classic machine learning techniques were characterized by limited effectiveness in the detection and classification of acne lesions. Only the development of deep learning methods has significantly improved the capabilities of dermatological image analysis, enabling more precise detection and differentiation of lesion types. At the same time, the effectiveness of AI models remains dependent on the quality, size, and representativeness of training datasets, as well as the accuracy of expert annotations. An additional limitation is the difficulty in detecting very small lesions and the high heterogeneity of their appearance, which continues to pose a challenge for automated dermatological image analysis systems (Kim et al., 2023). An example of the use of artificial intelligence in dermatological diagnostics is a study that compared the diagnostic capabilities of AI models, such as ChatGPT-4 and Google Lens, in the assessment of skin diseases (T.P. et al., 2024). The authors pointed out that modern AI systems can support the diagnostic process by analyzing dermatological images and generating possible clinical diagnoses. Such technologies are particularly important in teledermatology and in situations where access to specialized dermatological care is limited. Because acne is a chronic condition requiring months of discipline, AI becomes a bridge between patient and doctor in remote care. Mobile applications based on AI would allow patients to regularly take self-photographs to monitor treatment progress, and the algorithm would assess whether inflammatory lesions are reducing, which could increase patient engagement in therapy.

Although AI's potential is enormous, it also has limitations, such as data bias, due to the fact that most algorithms are trained on Caucasian populations. AI's diagnostic accuracy can drop dramatically in Fitzpatrick skin phototypes IV-VI (dark skin), where inflammatory erythema masks itself differently. Another issue is the lack of standardized lighting, as images taken by patients under different lighting conditions and with different home cameras pose a challenge to the reproducibility of algorithm results. Despite promising results, AI cannot currently replace clinical assessment by a dermatologist. However, due to its extremely dynamic recent development, its high potential for medical applications, and the continuous improvement of deep learning algorithms, it may soon become an important diagnostic and disease monitoring tool.

6. Nanomedicine

Nanomedicine is one of the most promising advances in modern dermatology and is finding increasing application in acne treatment. The use of nanotechnology allows for the creation of nanosized carriers, including liposomes, nanoemulsions, and polymer nanoparticles, which transport therapeutic substances directly to hair follicles and sebaceous glands—key sites in the development of acne lesions. Many dermatological conditions are preferentially treated with topical preparations, but their penetration is limited by the presence of the stratum corneum, which limits the diffusion of small and lipophilic drugs (Cuip et al., 2021). The ability of topical preparations to effectively deliver active substances to the target site is uncertain. Therefore, nanoparticles, due to their unique size and surface chemistry, are increasingly being investigated as a method for increasing drug penetration into the deeper layers of the skin, improving absorption, and reducing side effects (Cui et al., 2021; Paiva- Santos et al., 2021). Nanomaterials are materials less than 100 nm in size, whose advantages include the ability to overcome microbial resistance and potentially induce immunomodulatory effects (Chakraborty et al. 2022). The size of nanoparticles is one of the most important factors influencing the effectiveness of dermatological therapies. Very small nanoparticles, with a diameter of less than 4 nm, can penetrate through successive layers of the epidermis and into the dermis, regardless of their electrical charge. Flexible liposomes, also known as deformable liposomes, more easily adapt to the skin's structure and penetrate its barrier more effectively than rigid liposomes. Cationic liposomes, on the other hand, possess a positive electrical charge, are characterized by increased skin penetration. The material from which nanocarriers are made is also important. For example, biodegradable polymer nanoparticles can gradually degrade in tissues, enabling controlled and sustained drug release (Cui et al., 2021). This allows for maintaining a stable concentration of the active substance over a longer period and reducing the frequency of drug applications. Metallic nanoparticles, such as gold nanoparticles, are used in acne therapy due to their ability to control the delivery of active substances and their activation under the influence of external stimuli, such as light, which allows for precise action on the sebaceous glands and acne lesions (Artounian et al., 2021)

An example of the effectiveness of nanotechnology is research on retinoids. Although topical tretinoin is an effective treatment, its use is limited by its low aqueous solubility and high instability in air and high temperatures. Therefore, attempts have been made to utilize nanocarriers to improve drug stability and therapeutic efficacy. One such approach was a study in which the efficacy and safety of tretinoin (NLC-TRE) was assessed using nanostructured lipid carriers (NLC) compared to a conventional cream containing 0.05% tretinoin (TRE) in the treatment of mild to moderate acne vulgaris (Samadi et al., 2022). Clinical trial results demonstrated significantly greater efficacy of NLC-TRE compared to the standard preparation – the rate of acne lesion reduction was higher with NLC-TRE, and a greater reduction in the size and intensity of porphyrin production in pilosebaceous follicles was observed.

Another example of efficacy is a study in which adapalene was encapsulated in tyrosine-derived nanospheres (TyroSphere™). In ex vivo hair follicle penetration studies, the thyrospheres significantly increased adapalene transport into the pilosebaceous unit, and in vitro studies also demonstrated reduced irritation potential (Ramezanli et al., 2017).

It is also worth emphasizing that despite the high therapeutic potential of nanoparticles in acne treatment, their safety profile has not yet been fully confirmed in long-term studies. This is due to the fact that nanomaterials may exhibit different biological activity depending on size, shape, coating type, and application method. Research is ongoing into their potential cellular toxicity, ability to accumulate in tissues, and potential impact on the immune system.

The dynamic development of nanotechnology and increasingly advanced testing methods mean that knowledge about their safety is steadily expanding. Consequently, nanomedicine has a real chance of becoming a key tool in the future for more effective and precise acne treatment.

7. Precision Dermatology

Precision dermatology is a modern approach to acne treatment that involves tailoring therapy to the individual patient, rather than using one-size-fits-all treatment regimens. Unlike traditional methods, it is based on the analysis of multiple factors influencing the development of the disease, such as hormonal profile, skin microbiome composition, genetic predisposition, individual immune system reactivity, and the nature of inflammatory lesions. Modern diagnostic tools, including genetic testing and microbiological analyses, play a key role in precision dermatology, allowing for a better understanding of the mechanisms underlying acne in a given patient. This allows for the selection of targeted therapy, which increases treatment effectiveness, can prevent relapses, and simultaneously reduces the risk of adverse effects.

7.1. Microbiome and Immunological Aspects

Conventional acne treatment methods, such as topical retinoids, benzoyl peroxide, and oral antibiotics, affect C. acnes and modulate the associated inflammatory pathways (Lam et al., 2022). However, these approaches often disrupt the skin microbiome, leading to microbial imbalances that favor opportunistic pathogens and undermine skin homeostasis. It is increasingly recognized that the problem lies not in the presence of C. acnes itself, but rather in the disruption of microbiome diversity and the predominance of pro-inflammatory strains (Dréno et al., 2020). Furthermore, overuse of antibiotics is associated with adverse effects, such as the development of resistance and further microbial disruption (Lee et al. 2019). This growing awareness has shifted treatment strategies from simply eradicating C. acnes to restoring microbiome balance and diversity, emphasizing the need for innovative therapeutic alternatives.

The growing understanding of the role of the microbiome in acne pathogenesis could significantly impact future therapeutic strategies. One of the main areas of development is microbiome-modulating therapies, such as probiotics, prebiotics, and postbiotics, which aim to support beneficial skin and gut bacteria and reduce inflammation. Particular importance is also attributed to the gut-skin axis, as intestinal dysbiosis may influence the activation of the immune system, increase oxidative stress and the production of inflammatory mediators, which may translate into the exacerbation of acne lesions (Dréno et al., 2020; Lee et al. 2019).

In this context, acne is increasingly being viewed as a systemic disease, not just a dermatological one, opening the door to dietary and microbiological interventions aimed at modulating the gut-cutaneous axis.

Disruptions in the skin's microbial balance affect not only the composition of the microbiome but also the activation of immune mechanisms responsible for the development of inflammatory lesions. Interactions between Cutibacterium acnes and cells of the skin's immune system lead to the activation of numerous proinflammatory pathways, which play a key role in the pathogenesis of acne. Keratinocytes constitute the main population of epidermal cells and play a crucial role in both the innate and adaptive immune responses of the skin. They are an active source of antimicrobial peptides and proinflammatory cytokines, which initiate an inflammatory response in response to contact with pathogen-associated molecular patterns (PAMPs) or threat-associated AMPs (DAMPs). In the context of acne, ligands of the Toll-like receptors TLR2 and TLR6, present in, among others, keratinocytes, are of particular importance. on the surface of Cutibacterium acnes. Activation of TLR2 receptors by C. acnes components leads to the initiation of signaling pathways, including NF-κB (Nuclear Factor kappa-light-chain-enhancer of activated B cells) - a transcription factor controlling the expression of inflammatory genes, and increased production of proinflammatory cytokines such as IL-1α, IL-6, IL-8, TNF-α (Tumor Necrosis Factor alpha) and GM-CSF (Granulocyte-Macrophage Colony-Stimulating Factor) (Graham et al., 2004). This process promotes the recruitment of immune cells, especially neutrophils and macrophages, which dominate in inflammatory acne lesions, and their activation may additionally intensify damage to the structure of the pilosebaceous follicle by releasing proteolytic and lysosomal enzymes. Early acne lesions are characterized by strong infiltration of inflammatory cells and increased expression of TLR2 within macrophages surrounding hair follicles. Concomitantly, deregulation of genes associated with the inflammatory response and extracellular matrix remodeling is observed, including genes encoding metalloproteinases (MMP1, MMP3), β-defensins, and neutrophil enzymes (Trivedi et al. 2006). Antimicrobial peptides (AMPs), such as β-defensins, cathelicidin LL-37, and S100 family proteins, also play a significant role in acne pathogenesis (Lesiak et al., 2024). These compounds exhibit both antibacterial and immunomodulatory effects, influencing inflammatory cell activity and cytokine production. Although some of these compounds are constitutively present in the skin, their expression is significantly increased in acne lesions under the influence of C. acnes. Currently, research is underway on synthetic AMPs that could selectively inhibit the development of pathogenic C. acnes strains while limiting inflammation (Graham et al., 2004).

The increasing understanding of the relationship between the skin microbiome, immune response, and environmental factors suggests that the future of acne treatment may rely on more selective microenvironment modulation, targeting specific C. acnes strains without compromising the entire skin microbiome. These include the use of bacteriophages, antimicrobial peptides, and acne vaccines targeting bacterial virulence factors (Dréno et al., 2020; O'Neil & Gallo, 2018).. The use of bacteriophages, viruses capable of selectively infecting and destroying specific bacterial strains, may enable the reduction of pro-inflammatory C. acnes strains without damaging other components of the skin microbiome, potentially reducing the risk of dysbiosis and the development of antibiotic resistance (Mohammadi, 2024). Intensive research is also underway on vaccines, which may in the future find application not only in the treatment of active inflammatory lesions but also in the prevention of severe forms of acne in individuals genetically or hormonally predisposed. Various vaccine formulations are currently being studied, including those based on inactivated whole bacterial cells and more precise recombinant vaccines targeting selected C. acnes antigens. However, vaccines targeting specific virulence factors, such as CAMP (Christie–Atkins–Munch–Petersen factor) proteins, sialidases, and other structures responsible for adhesion and induction of the inflammatory response, are of greatest interest (Goh et al., 2025). Simultaneously, modern methods based on mRNA technology are also being developed, allowing for the rapid design of an immune response against selected bacterial antigens. Clinically, such interventions could reduce the risk of disease progression to severe forms, including nodular-cystic lesions and those with a tendency to scarring, through prior modulation of the host's immune response.

7.2. Genetic Factors

Genetic factors play a significant role in the pathogenesis of acne, influencing both the susceptibility to its occurrence and the severity and clinical course of the disease. Acne is polygenic, meaning it is not determined by a single gene, but by the interaction of multiple genetic variants related to, among other things, the functioning of the sebaceous glands, the immune response, and the regulation of inflammatory processes. Bataille et al. conducted a study on a sample of 458 pairs of monozygotic twins and 1,099 pairs of dizygotic twins. The results indicated that a significant portion of the disease variability, specifically 81%, can be attributed to genetic factors, with the remainder to environmental factors (Bataille et al., 2002). To effectively identify, treat, and alleviate acne at an early stage, it is necessary to investigate the genetic factors that contribute to an individual's susceptibility to this disease. Currently, only a subset of genes associated with the genetic predisposition to acne have been identified, and their significance may vary depending on ethnicity, environmental factors, and individual susceptibility. Previous studies indicate a significant role for genes involved in the inflammatory response and sebaceous gland function, including genes encoding interleukins, TNF-α, resistin (RETN), cytochrome P450 enzymes (CYPs), and matrix metalloproteinases and their inhibitors (TIMPs) (Zhang & Zhang 2023). Most of these genes are involved in regulating sebum production, keratinization processes, and the intensity of the immune and inflammatory response, playing a significant role in acne pathogenesis. An example of this is a study showing that keratinocyte activation by C. acnes can induce the production of interleukin-1 alpha, which then influences hyperkeratinization of the infundibulum segments of hair follicles, which is considered an initial step in the development of comedogenesis (Thiboutot, 2014). Genetic factors may also influence individual response to treatment, including drug metabolism. Cytochrome P450 enzyme polymorphisms may determine the rate of metabolism of retinoids, antibiotics, or hormonal drugs, which translates into differences in treatment effectiveness and the risk of adverse effects.

A key area of development is the use of genetic markers to identify patients at risk for more severe disease, a tendency toward scarring, or resistance to standard treatments. Analysis of polymorphisms in genes related to proinflammatory cytokines (e.g., IL-1, IL-6, TNF-α), androgen receptors, and cytochrome P450 enzymes may, in the future, enable prediction of response to specific therapies.

Modern genetic studies, particularly genome-wide association analyses (GWAS), have significantly expanded our understanding of acne predisposition. These studies have revealed the existence of numerous susceptibility loci associated with, among other things, the regulation of pilosebaceous unit function and signaling pathways involved in skin tissue differentiation and remodeling. Mitchell's research revealed clear similarities between the effects of different allelic variants at the EDAR locus and the WNT10A locus, where genetic variation influences both the risk of acne and hair morphology, as well as the occurrence of ectodermal dysplasia (Mitchell et al., 2022). This study also demonstrated the involvement of neutrophilic inflammatory processes, confirming the association signal at the IL36RN locus, where rare loss-of-function variants are associated with various forms of pustular skin diseases.

In addition to genetic factors, epigenetic mechanisms, including microRNAs, which regulate the expression of genes associated with the skin's immune response, also play a significant role. Abnormalities in their profile can exacerbate inflammatory processes in sebocytes and keratinocytes, suggesting their potential role in the pathogenesis of acne and as future therapeutic targets (Gordon et al., 2024).

Understanding the genetic mechanisms of acne also paves the way for the development of molecularly targeted therapies. Instead of nonspecific anti-inflammatory effects, future drugs could be designed to modulate specific biological pathways disrupted in a given patient. Pharmacogenetics, or tailoring therapy to individual differences in drug metabolism, is also crucial. CYP enzyme polymorphisms could in the future provide the basis for personalized dosing of acne medications, increasing their efficacy and safety. In the long term, genetic panels could also be used in dermatological diagnostics. This would enable early identification of individuals particularly predisposed to developing acne and the implementation of preventive and therapeutic measures before serious skin lesions develop.

7.3. The Effects of Hormones

Androgens play a key role in the pathogenesis of acne by influencing the function of the sebaceous glands. Their action is mediated by androgen receptors (ARs) present in sebocytes. The main ligands of these receptors are testosterone and dihydrotestosterone (DHT), with DHT exhibiting a more potent biological effect. Activation of androgen receptors leads to increased sebum production and hyperkeratinization of hair follicles, which promotes the development of acne lesions. Circulating androgenic prohormones, such as dehydroepiandrosterone (DHEA), DHEA sulfate (DHEAS), and androstenedione, are converted in the skin into active androgens- testosterone and DHT -due to the presence of steroidogenic enzymes, particularly 5α-reductase, which is responsible for the conversion of testosterone to DHT (Jiang et al. 2022).

The influence of androgens on the development of acne is multifaceted. In addition to stimulating sebum production, androgens can enhance sebocyte lipogenesis by activating pathways associated with SREBP proteins and insulin-like growth factor IGF-1 (Smith et al., 2008). IGF-1 also influences androgen metabolism and increases the activity of androgen receptors. Androgens and ARs can also enhance the inflammatory response by activating macrophages and neutrophils, contributing to the progression of inflammatory lesions in acne.

Due to the significant role of androgens and ARs in the pathogenesis of the disease, antiandrogen therapy is an important therapeutic approach, particularly in patients with severe or treatment-resistant acne. However, traditional systemic therapies carry the risk of systemic side effects, which stimulates the development of topical endocrine modulation. A significant breakthrough in this area was the introduction of clascoterone, the first topical AR antagonist, which effectively inhibits hormonal stimulation of lipogenesis and the synthesis of proinflammatory cytokines directly in the pilosebaceous unit, without systemic impact on the patient's hormonal profile (Di Stefano et al., 2025). In addition to androgens, insulin and IGF-1 are important hormones influencing the function of the sebaceous glands. Individuals with insulin resistance or a predisposition to hyperinsulinemia exhibit increased activation of the IGF-1 axis, leading to increased lipogenesis in sebocytes, increased sebum production, and intensified inflammatory processes. At the same time, genetic differences, including those in the PI3K/AKT signaling pathway and FOXO1 (forkhead O1) expression, may modulate the degree of response to IGF-1 and androgens, which explains the varied clinical course of acne in patients with similar disease presentations (Melnik, 2015). Metabolic disorders and stimulation of the IGF-1 axis lead to excessive activation of the intracellular protein complex mTORC1 (mammalian target of rapamycin complex 1), which acts as a master biosensor that enhances lipid synthesis and the secretion of inflammatory proteins in skin cells (Lesiak et al., 2024). Contemporary skin neuroendocrinology also indicates a significant role of stress in the pathophysiology of acne. In response to psychological stimuli, skin cells are capable of locally synthesizing corticotropin-releasing hormone (CRH), which, by binding to CRH-R1 receptors on sebocytes, directly induces a rapid flare of inflammatory changes and seborrhea (Zhang H. et al., 2024).

In this context, acne should be viewed as a heterogeneous disease, with different pathogenetic mechanisms predominating in individual patients. To practically implement the principles of personalized medicine, implementing targeted laboratory panels is crucial, allowing the identification of patients with a dominant endocrine-metabolic basis. A basic diagnostic profile should include assessment of the androgen axis by measuring free testosterone, androstenedione, dehydroepiandrosterone sulfate, and sex hormone-binding globulin (SHBG), which allows for an estimate of the actual pool of ligands stimulating AR receptors in the skin. Equally important is the simultaneous verification of metabolic parameters, including fasting insulin and glucose levels (with calculation of the HOMA-IR index) and IGF-1 levels, as direct activators of the mTORC1 cascade. Such a structured diagnostic approach, supplemented in women with the assessment of gonadotropic hormones (LH and FSH) in the follicular phase, enables precise mapping of the heterogeneous pathogenic mechanisms of acne and lays the foundation for future, individualized therapeutic strategies.

Personalizing hormonal treatment would enable the selection of therapy tailored to the specific patient profile, which in practice would mean a shift from formulaic treatment to therapy directed at the dominant mechanism of the disease. Furthermore, the development of hormonal and molecular diagnostics could enable the identification of patients whose acne has a strong endocrine basis, allowing for earlier implementation of causal treatment. This approach could also limit the use of ineffective empirical therapies and reduce the risk of adverse effects caused by them.

8. Discussion

The presented data indicate that acne vulgaris is a disease with a complex pathophysiology influenced by numerous genetic, immunological, and hormonal factors. A growing understanding of its mechanisms is leading to a shift from an approach focused solely on symptomatic treatment toward strategies aimed at identifying and modifying the underlying processes. Individual patient assessment, encompassing, among other things, hormonal profile, genetic factors, and the nature of the inflammatory response, is crucial. This approach allows for a better understanding of the dominant disease mechanisms in a given individual and potentially for selecting more effective treatment. In parallel, new therapeutic strategies are developing rapidly, such as modulating the skin microbiome, using bacteriophages, and vaccines targeting selected bacterial virulence factors, which can selectively limit pathogenic strains without disrupting the physiological microbiome.

Technologies supporting diagnostics and treatment monitoring also remain an important direction of development. Artificial intelligence enables the objectification of skin lesion assessment, reducing the subjectivity of classic scales, and long-term monitoring of response to therapy. Nanomedicine, in turn, opens up opportunities to improve drug bioavailability, selectively deliver drugs to the pilosebaceous unit, and reduce adverse effects.

Despite the promising nature of the approaches described, significant limitations of the current state of knowledge should be emphasized. For many modern methods, such as bacteriophage therapy, acne vaccines, and advanced nanocarrier systems, clinical data are still limited and often come from preclinical studies or small research samples. Similarly, artificial intelligence-based solutions are characterized by limited standardization and potential bias resulting from insufficient representation of different skin phototypes. Furthermore, the availability of advanced hormonal, genetic, and microbiological diagnostics in everyday clinical practice remains a challenge for personalized approaches.

In summary, the integration of new technologies and biological approaches is a promising direction for the development of acne treatment, but their actual clinical application requires further, well-designed studies and validation of safety and efficacy.

9. Conclusions

Acne vulgaris is a multifactorial disease with a complex and heterogeneous pathogenesis, which justifies the need for an individualized therapeutic approach. Traditional treatment regimens, despite their proven effectiveness, do not always provide complete disease control, indicating the need for new, cause-specific strategies. The most promising development direction is personalized medicine, which integrates patient clinical, biological, and molecular data to optimize therapy. Modern AI-based technologies may also improve treatment precision and effectiveness; once refined, they could become an important diagnostic tool and be used for disease monitoring. However, the introduction of new methods requires further clinical trials and evaluation of their safety and effectiveness in practice.

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