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Microneedle technology: a gateway to transformative healthcare solutions

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Evidence in Context

• Microneedle technology offers minimally invasive healthcare solutions, enhancing access and compliance. • It improves vaccine delivery and chronic disease management with pain-free administration. • Innovations include dissolvable microneedles and non-invasive monitoring patches. • Challenges include social stigma, regulatory hurdles, and manufacturing complexities. • Promises to simplify medical procedures and reduce global healthcare barriers.

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Abstract

Microneedle technology has emerged as a significant advancement in medical science, revolutionizing approaches to vaccine delivery, chronic disease management, and dermatological treatments. Its minimal invasiveness, ease of use, and potential to enhance healthcare access are particularly beneficial in resource-limited settings. The application of this technology spans various domains such as simplifying vaccination processes, facilitating non-invasive chronic disease monitoring, and improving the delivery of dermatological treatments. Recent studies have demonstrated the potential to increase vaccination rates, provide pain-free chronic disease management, and offer efficient drug delivery systems in dermatology and cancer treatments. However, certain challenges remain, including overcoming social stigma, regulatory hurdles, and manufacturing issues. Continued research and collaboration are essential to overcome these barriers and realizing the full potential of microneedle technology in transforming healthcare.

Keywords: *Microneedle technology, vaccine delivery, chronic disease management, non-invasive monitoring, drug delivery systems*

Introduction

In recent years, microneedle technology has emerged as a pivotal innovation in medical science, offering revolutionary approaches to vaccine delivery, chronic disease management, and dermatological treatments [1,2]. This technology is particularly noteworthy for its ability to enhance patient compliance, minimize invasiveness, and expand healthcare access, especially in resource-limited settings. This article delves into the various applications of microneedle patches and discusses their potential impacts on global health systems.

Table 1 provides a comprehensive overview of key studies on microneedle technology, highlighting recent advancements and diverse applications. The studies cover various aspects of microneedles, including wound management [3], vaccine delivery [4], transdermal drug delivery [5,6] and cancer treatment [7]. Additional research examines the potential of dissolving microneedles for dermatological conditions [8], the role of microneedles in biosensing and health monitoring [1,9], And the challenges associated with their fabrication, materials, and regulatory approval [2,10]. Overall, these studies underscore the transformative potential of microneedle patches in enhancing drug delivery efficiency, improving patient comfort, and expanding healthcare accessibility.

Figure 1 highlights the potential applications of microneedle technology in healthcare, with a focus on targeted drug delivery systems, depicted through detailed anatomical and physiological illustrations including the skin's response to microneedle penetration and the related biological processes.

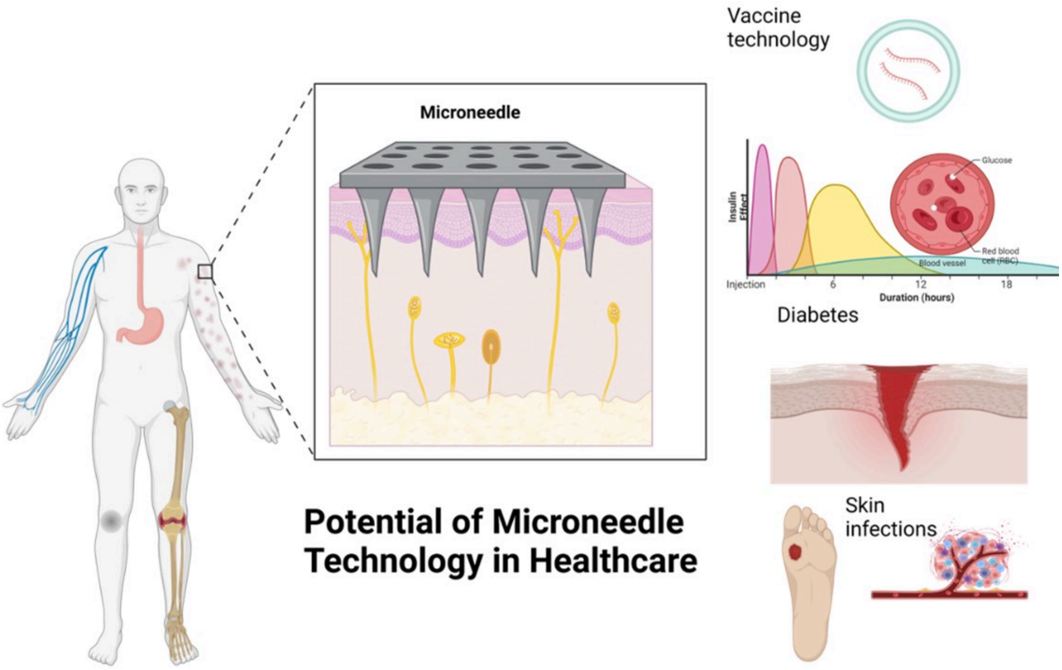

Figure 1: Potential applications of microneedle technology in healthcare

Revolutionizing Vaccine Delivery

The concept of microneedles was proposed in the 1970s, but it wasn't until the 1990s that it was experimentally demonstrated. This was made possible by the microfabrication tools provided by the microelectronics industry, which allowed for the creation of such small structures. Since the first studies on transdermal drug delivery in 1998 there has been a growing interest in the field [11]. Most of the activity has been focused on the development of novel needle fabrication technologies within the microfabrication community and the creation of microneedles for pharmaceutical applications within the drug delivery industry [12].

Transdermal drug delivery is a noninvasive method of administering biologically active agents through the skin for local or systemic effects. It can be self-administered and offers several advantages. However, there are certain requirements for drugs that are suitable for transdermal administration. For example, the maximum molecular weight should not exceed 1000 Da, and there should be a balance between hydrophobicity and polarity to overcome the barrier posed by the stratum corneum [13].

Most protein and peptide drugs, due to their hydrophilic and macromolecular nature, face difficulties in penetrating the skin. In recent decades, various chemical and physical methods have been developed to enhance transdermal drug permeation. These methods include the use of penetration enhancers [14], microjet technology [15], laser [13], electroporation [16], sonophoresis [17], and iontophoresis [18]. However, these techniques are often expensive and cumbersome to use, and their efficiency in facilitating the successful transdermal delivery of macromolecular drugs remains limited [19].

One of the most promising applications of microneedle technology is in vaccine administration. Traditional vaccination methods often face challenges such as the need for skilled healthcare workers, the risk of needle-stick injuries, and the complexities of biomedical waste management. Microneedle patches offer a compelling solution by simplifying the vaccination process and eliminating the need for hypodermic needles [20].

A notable advancement in this field is the development of microneedle patch tested in the Gambia [21]. This patch represents a significant stride toward improving vaccine accessibility and efficacy in regions plagued by healthcare delivery challenges. The patch's ease of use and storage, coupled with its ability to administer vaccines without traditional syringes, promises to increase vaccination rates in hard-to-reach populations, thereby enhancing community health resilience.

Enhancing Chronic Disease Management

Microneedle technology also plays a critical role in the management of chronic diseases, such as diabetes [22]. Traditional management techniques, which often require frequent blood sampling, can be cumbersome and painful for patients. Microneedle patches, however, facilitate non-invasive monitoring of physiological markers. For example, a microneedle patch developed for diabetic diagnosis can monitor multiple biomarkers simultaneously, offering a more comprehensive and less invasive alternative to conventional glucose testing methods.

This technological innovation not only improves patient comfort but also provides real-time data that can lead to more precise and timely adjustments in therapy. Such advancements have the potential to transform chronic disease management by enhancing the accuracy of diagnoses and the efficacy of treatments. This can improve accessibility and reduce healthcare costs.

Advancing Dermatological Treatments

In the field of dermatology, microneedle patches enhance the delivery of cosmetic and therapeutic agents directly into the skin [23]. These patches are used for a variety of purposes, including skin regeneration, anti-aging treatments, and the reduction of scar formation. For instance, a novel core-shell microneedle patch has been developed for scarless skin repair, delivering bioactive compounds that promote tissue regeneration and reduce inflammation.

These dermatological applications highlight the dual benefits of microneedle patches: targeted therapy with minimal systemic exposure and enhanced patient acceptance due to reduced pain and discomfort. By providing a controlled release of therapeutic agents, these patches ensure effective treatment while minimizing side effects, thereby offering a superior alternative to traditional topical applications and injections.

Addressing Social Stigma and Healthcare Challenges

While microneedle technology offers numerous benefits, it also faces unique challenges, particularly in addressing the social stigma associated with certain treatments [14]. For example, the management of leprosy using clofazimine has resulted in skin hyperpigmentation, which can lead to social stigma and isolation. Microneedle patches could potentially deliver similar therapeutic effects with reduced cosmetic side effects, thereby mitigating these social challenges.

Furthermore, the development and implementation of microneedle technology must navigate issues related to patient education, regulatory approval, and manufacturing challenges. Ensuring the quality and safety of these patches is paramount to their success and acceptance in global health markets.

Strengths and limitations of microneedle technology

Microneedles have the potential to enhance patient compliance and overcome the skin barrier for the delivery of protein and peptide drugs. Microneedles have been developed in various designs and

With different delivery strategies. These designs can be broadly categorized as solid microneedle, coated microneedles, hollow microneedles, dissolving microneedles, and hydrogel-forming microneedles. The skin plays a unique role in biology and immunomodulation. Its active immune environment can work in synergy with microneedles-mediated vaccine delivery to combat infectious diseases and treat cancers. Microneedles also have important applications in diabetes treatment, enabling safer closed-loop glucose-responsive therapies. Furthermore, microneedle mediated transdermal delivery of checkpoint inhibitors has demonstrated reduced off-target effects and achieved localized targeted delivery for the treatment of superficial cancers [24]. In summary, microneedle hold great promise as a strategy for the delivery of protein and peptide drugs to treat a wide range of diseases. However, there are some limitations to microneedle technology. Microneedles have a limited ability to penetrate the skin deeply, which may restrict their use for medications that require deeper delivery. Additionally, the fabrication of microneedle arrays (MNA) with precise dimensions and structures can be complex and expensive, which limits their widespread adoption. The effectiveness of microneedle delivery may also vary depending on factors such as skin thickness, hydration level, and individual anatomical differences among patients. While microneedles are minimally invasive, there is still a risk of infection if proper sanitation procedures are not followed during application. Moreover, microneedles have a limited capacity to deliver large volumes of drugs or vaccines.

Conclusion

Microneedle technology represents a significant leap forward in the field of medicine, offering less invasive, more accessible, and potentially more effective treatments across various domains of healthcare. From revolutionizing vaccine delivery in resource-limited settings to enhancing chronic disease management and advancing dermatological treatments, microneedle patches have the potential to reshape standard medical practices and improve global health outcomes.

As we continue to witness the evolution of this technology, ongoing research and development will be crucial in overcoming existing challenges and maximizing the therapeutic potential of microneedle patches. The continued collaboration between researchers, healthcare providers, and regulatory bodies will be essential to ensure that this innovative technology reaches its full potential in improving patient care worldwide.

Table 1: Overview of key studies of microneedle technology

Study	Characteristics	Key findings
Zhao et al., (2023) [3]	In this article, author provided the current status and constraints of microneedle patches, alongside a prospective analysis of the forthcoming trajectory of microneedles in wound care, to foster enhanced and more intelligent wound management approaches.	▪ Microneedles enhance the efficacy of wound healing through the improvement of drug delivery efficiency. ▪ Various research endeavors focusing on microneedles in wound management explore aspects such as hemostasis, antibacterial properties, cell proliferation, scar reduction, and wound surveillance.
Dugad et al., (2023) [5]	This study examines the process of transdermal drug delivery (TDD) across intact skin, taking into account constraints related to the characteristics of the drug such as its molecular weight and hydrophilicity. The investigation explores into the utilization of dissolving microneedles for vaccine delivery and coated microneedles for effective drug delivery.	▪ The article offers an extensive overview of the present status of MNA research. ▪ It examines approaches, challenges, applications, and categories of materials employed.

Feng et al., (2023) [4]	This article provides an overview of the present advancements in microneedles as a method for delivering vaccines, highlighting its potential for enabling widespread immunization against SARS-CoV-2.	▪ Microneedles address the issues of discomfort and anxiety associated with conventional injection-based vaccinations. ▪ Microneedles enhance the reach of vaccination, particularly among specific demographic groups.
Laskar et at., (2023) [6]	The concept of microneedles has garnered interest from researchers due to its extensive applications and distinctive advantageous characteristics of pain-free medication administration by traversing the impermeable stratum corneum barrier of the skin effectively in a minimally invasive approach as delineated in this study.	▪ The study offers a perspective on the latest developments in microneedles technology. ▪ It examines different categories, methods of production, and uses of microneedles.
Ganeson et al., (2023) [7]	In this manuscript, the authors underscore the various categories of microneedles, techniques for fabrication, and selection of materials, in addition to recent progress and potential prospects. Furthermore, they examine the obstacles and constraints associated with microneedles in the realm of cancer treatment, offering resolutions based on ongoing research.	▪ Microneedles provide effective drug administration in the treatment of cancer. ▪ Microneedles enhance patient survival outcomes with minimal discomfort.
Nguyen et al., (2023) [9]	This paper provides an overview of the latest research findings to offer a thorough analysis of the microneedle-facilitated administration of large molecules.	▪ Microneedles improve the transdermal administration of a variety of large molecules. ▪ 3M's Hollow Microstructured Transdermal System (hMTS) apparatus successfully transports equine tetanus antitoxin and human growth hormone.
Luo et al., [10](2023)	The authors reviewed various types of materials utilized in the construction of microneedles, alongside an in-depth analysis and comparison of the fabrication techniques employed for both solid and hollow microneedles. The merits and demerits of each respective process are thoroughly scrutinized.	▪ The discussion pertains to the materials, manufacturing techniques, and medical uses of microneedles. ▪ The advantages, obstacles, and practical uses of microneedles in the healthcare sector are emphasized.
Azizi et al., (2023)[25]	In this article, the utilization of polymers, bioceramics, and natural substances in the manufacturing of microneedles is elucidated, along with the technical obstacles linked to miniature needle-like instruments for transdermal administration of drugs, detection, and immunization distribution.	▪ Microneedles are employed in drug delivery, biosensing, and the administration of vaccines. ▪ Microneedles are capable of identifying molecules within the interstitial fluid for health monitoring.

Umesh et al., (2023) [2]	The progression of microneedle technology faces numerous obstacles, including concerns related to stability, dosage accuracy, skin irritation costs, and other factors as discussed by scholars. This article analyses the classifications, materials, and methodologies of construction, along with the applications of the miniature drone-based drug delivery system.	▪ The manuscript examines the varieties, composition materials, and utilization of microneedle drug administration mechanisms. ▪ The manuscript underscores the obstacles encountered during the advancement of microneedles.
Malek-Khatabi et al., (2023) [26]	The authors discussed the latest developments in microneedles (MNs) based on polylactic glycolic acid (PLGA) and comprehensively reviewed the potential applications of microneedles.	▪ PLGA-based microneedles showed promises in the realm of drug and vaccine administration. ▪ The article deliberates on the latest progressions about PLGA-based microneedles.
De Decker et al., (2023) [8]	In this article, the authors present a thorough examination of the existing clinical data regarding the application of dissolving microneedles (DMN) in the management of different skin ailments.	▪ DMN is efficient and painless in delivering drugs for a variety of skin conditions. ▪ The utilization of microneedle technology presents a non-invasive option for drug administration.

Supporting information

None

Ethical Considerations

None

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Additional information

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Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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