

# MICRONEEDLE TECHNOLOGY IN TRANSDERMAL DRUG DELIVERY: INNOVATIONS AND CLINICAL POTENTIAL

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**ABSTRACT:**

Microneedle technology has emerged as an innovative solution in transdermal drug delivery, offering a minimally invasive, patient-friendly alternative to traditional methods like injections and transdermal patches. This review explores the principles, advancements, and clinical potential of microneedles, highlighting their ability to deliver a wide range of therapeutic agents effectively, from small molecules to large biologics. We examine the various microneedle types including solid, coated, dissolvable, and hydrogel-forming microneedles and discuss recent innovations in fabrication, materials, and design aimed at enhancing drug delivery efficiency, safety, and patient comfort. Notable clinical applications, such as vaccine delivery, pain management, and cosmetic treatments, underscore the versatility of microneedles in addressing diverse therapeutic needs. Clinical studies demonstrate promising efficacy and safety profiles, with high patient compliance. However, challenges in large-scale production, regulatory approvals, and cost remain barriers to broader implementation. Future directions include the development of "smart" microneedles, integration with wearable technologies, and applications in personalized medicine. This review emphasizes the transformative potential of microneedle technology in healthcare and calls for further research to realize its full clinical impact.

**KEYWORDS:** Microneedles, Transdermal Drug Delivery, Clinical Applications, Fabrication Innovations, Patient Compliance

## INTRODUCTION

Transdermal drug delivery systems have gained significant attention due to their ability to provide a non-invasive route for administering medications. Traditional methods, such as patches and gels, have been widely used for delivering drugs through the skin. However, these methods exhibit limitations, including poor skin permeability, low bioavailability, and the potential for irritation or allergic reactions at the application site. Patches often require prolonged application times and may not deliver sufficient drug quantities for effective treatment, while gels can be messy and may not adhere well to the skin<sup>146</sup>.

Microneedle technology has emerged as a promising solution to overcome these limitations associated with conventional transdermal delivery systems.

Microneedles are tiny needles, typically ranging from 25 to 2000 micrometers in height, designed to penetrate the outermost layer of the skin (stratum corneum) without reaching nerve endings, thus minimizing pain and discomfort during application. This technology allows for the creation of micro-sized pathways in the skin

that facilitate enhanced drug delivery and absorption. Various types of microneedles have been developed, including solid, coated, dissolving, and hollow microneedles, each offering unique advantages for specific applications.

The purpose of this review article is to explore the advancements in microneedle technology and its applications in transdermal drug delivery. Key areas of discussion will include the different types of microneedles, their fabrication methods, material selection, and the potential benefits they offer over traditional delivery systems. Additionally, the review will address ongoing challenges and future directions in microneedle research and development, emphasizing their role in improving patient compliance and therapeutic outcomes.<sup>1</sup>

## Principles of Microneedle Technology

Microneedle technology operates through a mechanism that allows for the efficient delivery of drugs by creating micro-sized channels in the skin. When microneedles are applied, they penetrate the stratum corneum, the outermost layer of the skin, without reaching the deeper nerve endings, thus minimizing pain and

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discomfort. This penetration facilitates drug delivery by allowing therapeutic agents to bypass the skin's barrier properties, enabling them to reach the more permeable layers of the epidermis and dermis. The use of microneedles enhances drug absorption and bioavailability compared to traditional transdermal methods, which often struggle with limited permeability due to the stratum corneum's structure.

There are several types of microneedles, each designed for specific applications:

**Solid Microneedles:** These are primarily used for creating microchannels in the skin. After application, a drug patch is placed over the microneedles, allowing drugs to diffuse through the created pores into the skin. Solid microneedles are commonly utilized in procedures like collagen induction therapy.

**Coated Microneedles:** These consist of solid microneedles that have a drug coating on their surface. Upon insertion into the skin, the drug is released from the coating into the surrounding tissue, facilitating transdermal delivery without overcoming the stratum corneum barrier directly.

**Dissolvable Microneedles:** Made from biodegradable polymers, these microneedles encapsulate drugs within their structure. Once inserted into the skin, they dissolve and release the drug over time, providing a sustained release profile and improving patient compliance.

**Hydrogel-Forming Microneedles:** These utilize hydrophilic polymers that swell upon contact with interstitial fluid in the skin. They create channels that allow drug passage while also functioning as a reservoir for sustained drug release.

Materials used in microneedle fabrication include metals, polymers, and silicon. Each

### **Material Offers Distinct Benefits and Limitations:**

**Metals (e.g., stainless steel):** Known for their strength and durability, metal microneedles can provide precise penetration but may be more costly to produce. They are often used in applications requiring high mechanical integrity.

**Polymers:** These materials are versatile and can be engineered for specific properties such as biodegradability and flexibility. While polymer microneedles can be produced at lower

costs, they may have limitations in mechanical strength compared to metals.

**Silicon:** Silicon microneedles are favored for their ease of fabrication and ability to form sharp tips. However, they can be brittle and may break during use, posing risks if fragments remain in the skin.<sup>2</sup>

### **Fabrication and Design Innovations**

Microneedle technology has advanced significantly through various fabrication and design innovations that enhance drug delivery efficiency and patient comfort. Key manufacturing techniques include laser cutting, micromolding, and 3D printing, each offering unique advantages.

Laser cutting is a prominent method used to create microneedles from materials such as polymethylmethacrylate (PMMA). This technique allows for rapid and precise production of microneedle structures, facilitating modifications in geometry with ease. The use of CO<sub>2</sub> lasers enables the creation of master molds, which can then be utilized to fabricate microneedles with high mechanical strength suitable for skin penetration. Micromolding, particularly soft lithography, involves creating a mold from a master template, often made from silicone or other polymers. This method is advantageous for producing arrays of microneedles with consistent shapes and sizes. Meanwhile, 3D printing has emerged as a revolutionary technique that allows for the customization of microneedle designs, enabling the production of complex geometries and tailored drug delivery systems at lower costs.

Design advancements in microneedles focus on optimizing their shapes, sizes, and materials to enhance performance. Innovations include varying the height and width of microneedles to improve penetration depth and drug delivery efficiency. For example, designs such as rocket-shaped or mosquito-fascicle-shaped microneedles have been explored to maximize surface area while minimizing pain during insertion. Additionally, the incorporation of hydrogel-forming materials allows for sustained drug release by swelling upon contact with interstitial fluid, further enhancing therapeutic efficacy and patient comfort.<sup>3</sup>

Safety and biocompatibility are critical considerations in microneedle design to minimize adverse reactions. Materials used for microneedles must be biocompatible to prevent irritation or inflammation at the application site.

Common materials include silicon, metals like aluminum, and biodegradable polymers. Each material's properties such as mechanical strength, degradation rate, and potential toxicity are carefully evaluated to ensure patient safety. Furthermore, rigorous testing is conducted to assess the mechanical integrity of microneedles during insertion and their ability to deliver drugs effectively without breaking or causing harm. Overall, these innovations in fabrication techniques and design considerations are pivotal in advancing microneedle technology for safe and effective transdermal drug delivery.<sup>4</sup>

### **Advantages of Microneedle-Assisted Drug Delivery**

Microneedle-assisted drug delivery offers several advantages that enhance therapeutic outcomes and patient experiences.

**Improved Patient Compliance:** One of the most significant benefits of microneedles is their ability to reduce pain and ease the application process. Unlike traditional hypodermic needles, which can cause anxiety and discomfort, microneedles are designed to penetrate only the outermost layer of the skin, the stratum corneum, without reaching deeper nerve endings. This minimizes pain during administration, making the process more tolerable for patients. Furthermore, microneedles can be self-administered, allowing patients to take control of their treatment without needing professional assistance, which can further improve adherence to medication regimens.<sup>5</sup>

### **Enhanced Drug Bioavailability:**

Microneedles significantly enhance drug absorption and bioavailability compared to oral or traditional transdermal routes. By creating microchannels in the skin, microneedles facilitate the direct delivery of drugs into the dermal and epidermal layers, bypassing the stratum corneum's barrier properties. This method allows for a higher concentration of drugs to be delivered more efficiently than oral administration, where drugs often undergo first-pass metabolism in the liver, reducing their effectiveness. Studies have shown that microneedles can improve the bioavailability of various compounds, including large molecules like insulin and vaccines, which are typically challenging to deliver through conventional methods.

**Potential for Self-Administration:** The design and functionality of microneedles enable patients to administer them themselves, particularly beneficial for those with chronic conditions requiring regular medication. This self-administration capability not only increases convenience but also empowers patients by reducing reliance on healthcare providers for routine treatments. For instance, individuals managing diabetes can use microneedle devices for insulin delivery without needing frequent visits to a clinic or hospital. This aspect is particularly advantageous for improving overall treatment adherence and quality of life for patients with long-term medical needs.

In summary, microneedle-assisted drug delivery systems provide a painless, efficient, and user-friendly alternative to traditional methods, enhancing patient compliance and therapeutic efficacy while enabling self-administration for chronic conditions.<sup>6</sup>

### **Applications in Transdermal Drug Delivery**

Microneedle technology has found diverse applications in transdermal drug delivery, significantly enhancing the efficacy and convenience of various therapeutic interventions.

**Vaccine Delivery:** Recent advancements in microneedle technology for vaccine delivery have shown great promise, particularly in the context of COVID-19 and influenza. Microneedles can facilitate painless and efficient administration of vaccines, which is crucial for increasing vaccination rates. For instance, studies have demonstrated that microneedle patches can deliver COVID-19 vaccines effectively while minimizing discomfort associated with traditional injections. Research indicates that microneedles can enhance immune responses by targeting the skin's abundant immune cells, potentially leading to improved vaccine efficacy. Additionally, microneedles can simplify the vaccination process by allowing for self-administration, which could be particularly beneficial in pandemic scenarios where rapid mass vaccination is required.

**Delivery of Biologics:** Microneedles are also being explored for delivering larger molecules such as peptides, insulin, and monoclonal antibodies. These biologics typically face challenges with traditional delivery methods

due to their size and stability. Microneedles enable the direct delivery of these molecules into the dermal layer, bypassing the gastrointestinal tract and first-pass metabolism that often diminish their effectiveness when taken orally. For example, studies have shown that insulin delivered via microneedles achieves higher bioavailability compared to subcutaneous injections or oral formulations. This method not only enhances absorption but also provides a more controlled release profile, making it suitable for chronic conditions like diabetes.<sup>7</sup>

**Pain Management and Anesthesia:** In the realm of pain management, microneedles have been utilized for local anesthesia applications. They can deliver anesthetics like lidocaine directly into the skin with minimal discomfort. Research has demonstrated that drug-coated microneedle arrays can induce rapid and painless local anesthesia by releasing anesthetic agents quickly upon insertion. This approach not only reduces the pain associated with traditional injections but also accelerates the onset of analgesia, making it an attractive option for procedures requiring immediate pain relief. For instance, a bubble microneedle patch has been developed that allows for efficient delivery of lidocaine and hyaluronic acid, providing effective analgesia within seconds.

**Cosmetic and Dermatological Applications:** Microneedles are increasingly being used in cosmetic and dermatological treatments, such as anti-aging therapies and scar treatments. The technique known as microneedling involves creating micro-injuries in the skin to stimulate collagen production and enhance the absorption of topical agents. This method has been shown to improve skin texture, reduce fine lines, and treat scars effectively. Additionally, microneedle patches can be used to deliver vitamins and other active ingredients directly into the skin, enhancing their efficacy compared to conventional topical applications. The ability to combine drug delivery with cosmetic procedures positions

microneedles as a versatile tool in both medical and aesthetic fields.<sup>8</sup>

## Conclusion

Microneedle technology offers a groundbreaking approach to transdermal drug delivery, overcoming many limitations of traditional methods by enhancing drug absorption, safety, and patient compliance. Its versatile applications ranging from vaccine administration to cosmetic treatments demonstrate significant clinical promise. Despite challenges in manufacturing and regulatory hurdles, ongoing research and innovation are likely to drive further advancements. Microneedles have the potential to transform healthcare, warranting continued exploration to unlock their full therapeutic impact.

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