



Review Article

Emerging Advancements in Microneedle Technology in Health Care

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In this study, we comprehensively review the emerging advancements in microneedle (MN) technology as a novel and minimally invasive platform for transdermal drug delivery and cosmetic applications. Microneedles are micron-sized needle structures, typically ranging from 10 to 2000 μm in height, designed to transiently disrupt the stratum corneum without reaching dermal nerve endings, thereby enabling painless delivery of therapeutic and cosmetic agents. This article systematically discusses the various types of microneedles, including solid, dissolving, hollow, coated, hydrogel, and swellable microneedles, with emphasis on their mechanisms of action, material composition, and suitability for delivering hydrophilic drugs, macromolecules, vaccines, and biologics. Manufacturing technologies such as micro-molding, laser cutting, micro-electromechanical systems (MEMS), and stereolithographic 3D printing are reviewed, along with the physicochemical and mechanical evaluation parameters essential for ensuring device safety, efficacy, and stability. Key applications in cosmetic therapy, enhanced drug delivery, diagnostic sampling, biosensing, and collagen induction therapy are highlighted. Although microneedle-based systems offer significant advantages over conventional needle-based delivery—including improved patient compliance, reduced pain, and lower risk of infection—challenges related to regulatory standardization and potential skin damage persist. The study also outlines future prospects, emphasizing the potential role of artificial intelligence and machine learning in optimizing microneedle design and performance, thereby supporting their broader clinical and commercial translation.

Keywords: Microneedles; Transdermal drug delivery; Cosmetic applications; Dissolving microneedles; Hydrogel microneedles; Minimally invasive delivery; Biosensing; Artificial intelligence in drug delivery.

INTRODUCTION

Microneedle (MN) technology has emerged as a promising and minimally invasive approach for transdermal drug delivery and cosmetic applications. Microneedles are painless, micron-sized needle structures (typically 10–2000 μm in height and 10–50 μm in width) designed to create temporary and reversible micro-channels across the stratum corneum, the outermost barrier of the skin. These micro-conduits enable the efficient delivery of a wide range of therapeutic agents, including hydrophilic and lipophilic drugs, macromolecules, vaccines, and particulate drug carriers, without stimulating dermal pain receptors. As a result, microneedles offer a

patient-friendly alternative to conventional hypodermic injections and oral drug administration. The skin, being the largest and most accessible organ of the human body, serves as a protective barrier while maintaining physiological homeostasis. It consists of three principal layers: the epidermis, dermis, and hypodermis. The stratum corneum, with an average thickness of 20–30 μm , represents the primary obstacle to transdermal drug permeation. Microneedles overcome this limitation by mechanically disrupting the stratum corneum under mild application force, thereby creating microchannels that facilitate drug diffusion into deeper skin layers while minimizing tissue damage and infection risk. Microneedles can be fabricated

from a variety of materials, including metals, silicon, ceramics, and biodegradable polymers, and are classified into several types based on their structure and mechanism of drug delivery. These include solid microneedles for skin pretreatment, dissolving microneedles that release drugs upon degradation within the skin, hollow microneedles that enable fluid infusion, coated microneedles for rapid bolus delivery, hydrogel microneedles for controlled release, and swellable microneedles for responsive and sustained drug delivery. Each type offers distinct advantages depending on the intended therapeutic or diagnostic application. An ideal microneedle system should possess adequate mechanical strength to penetrate the skin without fracture, sharp tips to minimize insertion force and pain, biocompatibility and inertness to prevent adverse immune reactions, sterility to ensure patient safety, and flexibility to conform to skin contours. Additionally, ease of fabrication, controlled physical invasiveness, and, in the case of biodegradable systems, appropriate dissolvability are critical parameters influencing their clinical performance. Beyond pharmaceutical delivery, microneedles have gained significant attention in cosmetic dermatology for targeted treatments such as scar reduction, wrinkle therapy, hair growth stimulation, and collagen induction therapy. Their ability to enable self-administration, reduce pain, lower infection risk, and improve patient compliance makes them particularly attractive for both clinical and home-based applications. Furthermore, microneedle-based platforms are

increasingly explored for diagnostic sampling, biosensing, and point-of-care testing through minimally invasive access to interstitial fluid. Despite these advantages, microneedle technology faces several challenges, including regulatory uncertainty, potential skin irritation or infection, and variability in drug penetration efficiency. Nevertheless, ongoing advancements in materials science, microfabrication techniques, and the integration of artificial intelligence and machine learning are expected to optimize microneedle design, performance, and personalization. Collectively, these developments position microneedle technology as a transformative platform with substantial potential to advance transdermal drug delivery and cosmetic therapeutics.

Penetration mechanism

The penetration mechanism of microneedles through the skin is a complex process influenced by microneedle design, skin properties, and application conditions. When a microneedle patch is applied to the skin with gentle pressure, the microneedles initially deform the skin surface, creating localized mechanical stress. This stress enables the microneedles to pierce the stratum corneum and form transient microchannels. These microchannels, which can extend several hundred micrometers into the skin, facilitate the effective delivery of the active pharmaceutical ingredient into the underlying skin layers.

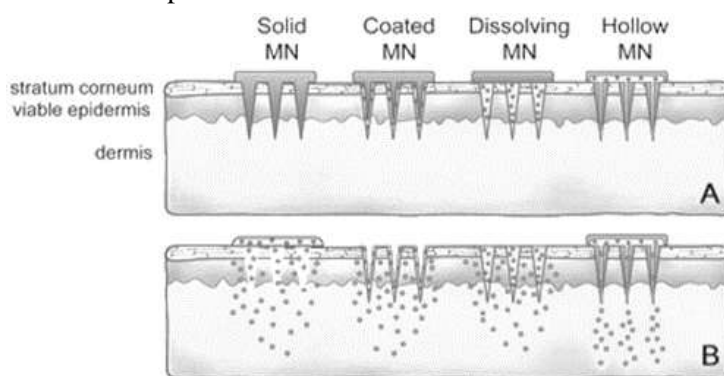


Fig No :1 Microneedle Insertion

Types of Microneedles and Their Composition

Microneedles are classified into solid, dissolving, hollow, coated, hydrogel, and swellable microneedles based on their structure, materials, and drug delivery

mechanisms. The selection of materials is critical to ensure adequate mechanical strength, biocompatibility, and efficient drug delivery. Solid microneedles are rigid structures primarily used for

skin pre-treatment to enhance transdermal drug delivery. They are commonly fabricated from metals such as stainless steel, titanium, nickel, or gold, as well as silicon and strong polymers. These materials provide high mechanical strength and sharp tip geometry, enabling penetration of the stratum corneum to form microchannels for subsequent drug diffusion or release from surface coatings. Dissolving microneedles are composed of biodegradable and water-soluble materials that encapsulate the drug within the needle matrix. Common materials include polymers such as polyvinylpyrrolidone (PVP), polyvinyl alcohol (PVA), polylactic-co-glycolic acid (PLGA), carboxymethylcellulose sodium, and natural polymers like hyaluronic acid, as well as sugars such as trehalose. Upon insertion, the microneedles dissolve in the skin, releasing the drug through a single-step “poke and release” mechanism. Hollow microneedles consist of needles with an internal lumen that allows direct delivery of liquid formulations into the skin. They are fabricated from materials such as metals, silicon, ceramics, polymers, or glass. While silicon offers precise microfabrication, it is more prone to breakage, whereas metals and polymers provide better mechanical stability for controlled infusion applications. Coated microneedles typically use solid microneedles made of metals or silicon as the base, with a thin drug layer coated on the surface. The

coating may contain vaccines, proteins, or other active agents, allowing rapid bolus delivery upon insertion. This approach enhances drug stability and is particularly effective for immunization by targeting skin immune cells. Hydrogel microneedles are prepared from crosslinked hydrophilic polymers such as chitosan, hyaluronic acid, and sodium alginate. These materials can absorb large amounts of water and respond to physiological stimuli, enabling controlled and sustained drug release. Hydrogel microneedles exhibit excellent biocompatibility and are used in both systemic and localized therapies, although their fabrication process is relatively complex. Swellable microneedles are made from hydrophilic polymeric materials such as polyvinyl alcohol (PVA) or chitosan. After insertion, they absorb interstitial fluid and swell, creating diffusion pathways for drug transport while leaving minimal polymer residue in the skin. Their biocompatibility, low infection risk, and responsiveness to environmental factors such as pH and temperature make them suitable for applications including insulin delivery, psoriasis, pain management, and diagnostics. Overall, materials such as silicon, metals, polymers, and hydrogels are carefully selected to balance mechanical integrity, safety, and effective drug delivery, ensuring optimal performance of microneedle-based systems.

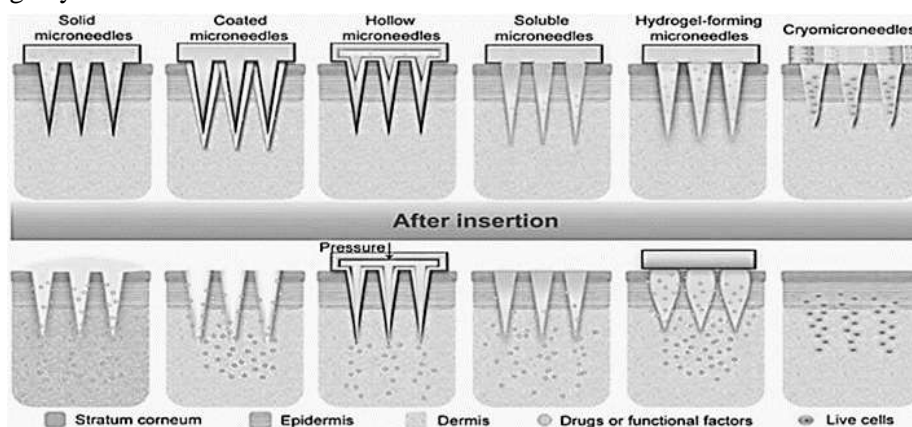


Fig No:2 Different types of Microneedles

Manufacturing technology of microneedles

The stratum corneum acts as a major barrier to transdermal drug delivery, necessitating precise design and fabrication of microneedles with appropriate geometry, material properties, and

mechanical strength. Various manufacturing technologies have been developed to produce microneedles with high accuracy and reproducibility, including micro-electromechanical systems (MEMS), micro-molding, laser cutting, atomized spraying, and stereolithography. MEMS techniques enable the

fabrication of solid and hollow microneedles through deposition, patterning, and etching processes, offering precise control over needle length and tip angle. Micro-molding is the most widely used method for polymeric, ceramic, and hydrogel microneedles due to its simplicity, low cost, and scalability, although it is less suitable for metals and silicon. Laser cutting is mainly employed for metal microneedles, producing sharp and mechanically robust structures through post-processing such as electropolishing. Atomized spraying allows the fabrication of drug-loaded

dissolving microneedles with uniform geometry and improved mass-production capability. Stereolithography, an advanced additive manufacturing technique, utilizes UV-induced photopolymerization to fabricate high-resolution microneedles with smooth surfaces and has been successfully applied to both solid and hollow designs. Collectively, these fabrication techniques play a crucial role in optimizing microneedle performance for effective and safe transdermal drug delivery.

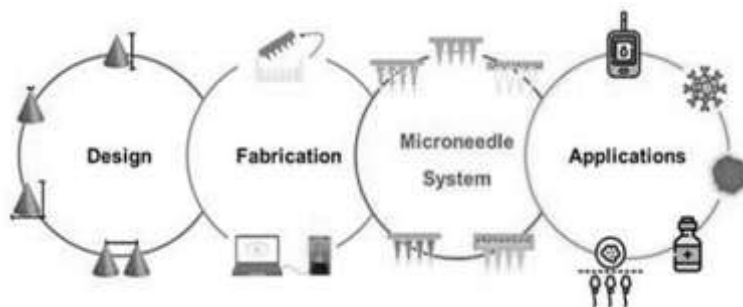


Fig No: 3 Manufacturing Technology of Microneedles

Evaluation

1. **Mechanical Properties:** Evaluation of the strength and flexibility of microneedles is carried out to ensure that they can pierce the skin without bending or breaking. This commonly involves measuring the force required for insertion as well as the fracture force of the needles.

2. **Insertion Efficiency:** Insertion efficiency is determined by assessing the percentage of microneedles that successfully penetrate the skin and the depth of penetration achieved. Techniques such as visual inspection, microscopy, and skin penetration studies are employed.

3. **Drug Delivery:** The rate and extent of drug release from microneedles are evaluated through both in vitro and in vivo studies. Franz diffusion cells are commonly used to monitor drug release profiles over time.

4. **Biocompatibility:** Biocompatibility studies assess the interaction of microneedles with the skin, including the potential for irritation, inflammation, or allergic reactions. These studies typically involve in vitro cell culture testing and in vivo animal models.

5. **Dissolution / Degradation:** For dissolving or biodegradable microneedles, the rate of dissolution or degradation in biological fluids is evaluated. This ensures appropriate drug release and prevents prolonged retention of microneedle material in the skin.

6. **Surface Characterization:** Surface morphology and composition of microneedles are analyzed using techniques such as scanning electron microscopy (SEM) and atomic force microscopy (AFM).

7. **Physicochemical Characterization:** Physicochemical parameters including moisture content, drug content uniformity, and tensile strength of microneedle patches are determined.

8. **Coating Uniformity:** Coating uniformity is visually analyzed under a microscope to assess consistent drug deposition and to ensure that coatings do not extend onto the base substrate of microneedle arrays. This is typically achieved by incorporating a colored compound or fluorescent dye into the coating solution, or by conjugating a fluorescent dye with the active molecule.

9. **Safety:** Safety evaluation investigates potential skin irritation, inflammation, or other adverse effects

caused by microneedles. In vivo studies, including histological examination and assessment of skin recovery, are essential for ensuring safety.

10. Failure Force: Microneedles are evaluated for failure force using mechanical testing and mathematical modeling. The force at which microneedles fracture, bend, or buckle under compression is measured using displacement press tests that simulate skin insertion. This ensures structural integrity during application.

11. Rigidity: Rigidity testing ensures that microneedles possess sufficient strength to withstand insertion forces without fracturing.

12. Penetration: Penetration studies confirm that microneedles are capable of delivering drugs to the required depth within the tissue.

13. In Vivo Evaluation: Preclinical in vivo studies are performed on animal models such as mice to evaluate delivery efficacy, penetration force, and bending resistance.

14. In Vitro Evaluation: In vitro evaluation focuses on laboratory-based assessment of mechanical strength, drug loading, drug release, and skin penetration prior to in vivo testing. These studies help determine the suitability of microneedle designs for transdermal drug delivery

Applications of Microneedles

Microneedles have emerged as a smart and effective approach for transdermal systems, overcoming the limitations of passive drug diffusion through the skin. By painlessly breaching the stratum corneum, microneedles enable enhanced drug delivery and support a wide range of therapeutic, cosmetic, and diagnostic applications. Cosmetic applications of microneedles focus on skin rejuvenation and scar management through controlled disruption of the stratum corneum, which stimulates collagen synthesis and deposition. Devices such as the derma roller, a handheld roller fitted with multiple solid steel microneedles, are used for treating large skin areas and stretch marks, while the derma pen, an electrically powered device delivering uniform, stamp-like micro needling, allows precise depth control and is

commonly used for acne scars and burn scars. Enhanced drug delivery is achieved by microneedles through the creation of microchannels in the stratum corneum, significantly increasing skin permeability and drug flux. Solid removable microneedles were the first platform developed for this purpose and later inspired the evolution of dissolving, hollow, coated, and hydrogel microneedles, enabling efficient delivery of vaccines, insulin, anticancer drugs, and other therapeutics. Diagnostic sampling using microneedles offers a minimally invasive, painless alternative for extracting interstitial fluid or small volumes of blood. These systems reduce bleeding and infection risks while improving patient compliance. Microneedle-based platforms are well suited for point-of-care testing, allowing rapid monitoring of biomarkers such as glucose and other physiological parameters directly at the site of care. Biosensing applications integrate microneedles with advanced sensing technologies for real-time biomarker detection. Examples include lab-on-microneedle devices combined with localized surface plasmon resonance for biomarker analysis and integrated microneedle–paper sensor systems for automated blood collection and diagnosis of glucose and cholesterol. Since interstitial fluid shares a high percentage of proteins with blood and also contains unique biomarkers, microneedle biosensors show strong potential for early disease detection and minimally invasive cancer diagnostics. Collagen induction therapy is a well-established dermatological application of microneedles, where repeated micro-perforations stimulate the skin's natural wound-healing response. This process enhances collagen and elastin production in the dermis and is effective in treating scars, wrinkles, pigmentation disorders, actinic keratosis, and promoting hair growth in conditions such as androgenetic alopecia.

CONCLUSION

In this study, microneedle (MN) technology has demonstrated a transformative potential in transdermal drug delivery and clinical dermatology by effectively bridging the gap between conventional topical formulations and invasive hypodermic injections. By engineering micron-scale structures that are small enough to avoid stimulating pain receptors yet robust enough to penetrate the stratum

corneum, MNs overcome the primary barrier imposed by the skin, enabling efficient and minimally invasive delivery of therapeutics. The versatility of this platform is reflected in its diverse classifications—solid, coated, dissolving, hollow, and hydrogel-forming microneedles—each tailored to specific clinical needs, ranging from rapid vaccine administration and sustained insulin release to the minimally invasive extraction of interstitial fluid for real-time biosensing and point-of-care diagnostics. In cosmetic applications, devices such as the Dermaroller and Dermapen have revolutionized collagen induction therapy, providing effective solutions for scar revision, anti-aging, and alopecia, while improving patient compliance and reducing infection risk compared to conventional surgical approaches. The integration of advanced manufacturing technologies, including stereolithographic 3D printing, and the potential for AI-guided personalization, promises to enhance dosage precision and therapeutic outcomes. Despite challenges related to regulatory frameworks and large-scale production, microneedle technology represents a cornerstone of future patient-centric healthcare, combining safety, efficiency, and virtually painless delivery with diagnostic and aesthetic capabilities. Its continued development in biodegradable and “smart” responsive systems is expected to drive widespread clinical adoption, ultimately transforming both disease management and cosmetic interventions.

Future aspects

Microneedles (MNs) hold great promise for delivering small and large molecules, including proteins and vaccines, but challenges such as limited drug loading, complex manufacturing, skin penetrability, and regulatory uncertainties remain. Solid MNs, while effective, often require a two-step application that may reduce compliance. With increasing regulatory guidance and industrial investment, MN-based patches are expected to expand rapidly. Long-acting MN and adhesive patches capable of sustained drug release—from

hours to months—have shown feasibility in preclinical and some clinical studies. Innovations like combinatorial patches with tunable release kinetics further highlight MNs’ potential for personalized and continuous drug delivery.

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