



Microneedle Technology in Drug and Vaccine Delivery: A Comprehensive Review

Mr.Rushikesh Vitthal Khetmalis

Miss.Vaishnavi Ganpat Kasurde

Mr.Ainkya Balaso Devkar

Miss.Aarati Avinash Bodake

Mr.Ajay Balaso Kale

Guide Name: Prof Rushikesh Lohar

Organization:Sarsam College Of Pharmacy,Palshiwadi,Morgaon,Tal-Baramati 413102

Abstract

Microneedle technology has emerged as a groundbreaking advancement in transdermal drug and vaccine delivery. Unlike conventional hypodermic needles, microneedles are minimally invasive, painless, and capable of delivering therapeutic agents across the skin barrier with high efficiency. This review explores the types of microneedles, fabrication techniques, mechanisms of action, applications in drug and vaccine delivery, advantages, limitations, and future prospects. The integration of microneedle systems with nanotechnology, smart polymers, and digital health platforms highlights their potential to transform global healthcare.

Keywords: Microneedles, Transdermal delivery, Vaccines, Drug delivery, Biomedical technology

1. Introduction

Drug and vaccine delivery methods have traditionally relied on oral administration and hypodermic injections. However, these approaches face challenges such as poor bioavailability, patient non-compliance, and needle-associated pain or phobia. Microneedle technology offers a novel solution by enabling painless, self-administrable, and efficient transdermal delivery. Since the skin is a natural barrier, microneedles create microchannels that allow drugs and vaccines to bypass the stratum corneum without reaching pain receptors, ensuring patient comfort and compliance.

2. Types of Microneedles

Microneedles are generally classified into following :

- Solid Microneedles
- Coated Microneedles
- Dissolving Microneedles
- Hollow Microneedles
- Hydrogel-forming Microneedles

1. Solid Microneedles:

Solid microneedles are micron-scale needle structures, usually 50-900 µm long, designed to penetrate the outermost skin layer (stratum corneum) without reaching deeper nerves and blood vessels.

They are one of the first generations of microneedle technologies and are primarily used for skin pre-treatment to enhance drug or vaccine delivery.

Mechanism of Action:

Solid microneedles work mainly by a "poke and patch" or "poke and diffuse" mechanism:

1. Poke: Microneedles puncture the stratum corneum ← create micropores (microchannels).
2. Patch/Diffuse: Drug (cream, gel, patch, nanoparticle, or liquid) is applied over the treated skin → drug diffuses through micropores into epidermis/dermis.

2. Coated Microneedles:

Coated microneedles are solid microneedles with a drug or vaccine coated on their surface. Unlike plain solid microneedles (which just make microchannels), coated microneedles deliver the drug directly into the skin upon insertion.

They belong to the second generation of microneedle systems and provide a one-step, rapid delivery method.

Mechanism of Action:

1. Coating - The microneedle surface is coated with drug formulation.
2. Insertion – MN patch is pressed into the skin.
3. Dissolution - Upon contact with interstitial fluid, the coating dissolves rapidly (within minutes).
4. Drug release – The active agent diffuses into epidermis/dermis → absorbed systemically or acts locally.

3. Dissolving Microneedles:

Dissolving microneedles are drug-loaded, biodegradable microneedles made from water-soluble polymers or sugars.

Unlike solid or coated MNs, dissolving MNs do not leave behind sharp waste - the entire needle dissolves inside the skin after insertion, releasing the drug.

They are considered the third-generation microneedle system, designed for one-step, safe, and patient-friendly drug/vaccine delivery.

Mechanism of Action:

The "poke and release" principle:

1. Insertion – Microneedle patch is pressed into the skin.
2. Dissolution - MNs absorb interstitial fluid dissolve/disintegrate within minutes to hours.
3. Drug Release – The incorporated drug is released into epidermis/dermis ← systemic circulation or acts locally. enters
4. Biodegradation - No needle remains in the skin, eliminating sharps waste.

4. Hollow Microneedles:

Hollow microneedles are microscale needles with a hollow bore (lumen) through which liquid drug formulations can be actively delivered into the skin. They work just like miniature versions of hypodermic needles, but they only penetrate the upper skin layers (epidermis/dermis), avoiding pain and deep tissue damage.

They belong to the fourth generation of microneedles, enabling controlled, precise, and continuous infusion of drugs.

Mechanism of Action:

The "poke and flow" principle:

1. Insertion → Hollow microneedles pierce the stratum corneum and reach epidermis/upper dermis.
2. Injection/Infusion → Liquid drug flows through the hollow lumen, driven by pressure, gravity, or micro-pumps.
3. Distribution → Drug spreads in interstitial fluid and diffuses systemically or acts locally.

Unlike dissolving or coated MNs, drug delivery can be continuous or on-demand.

5. Hydrogel-forming Microneedles:

Hydrogel-forming microneedles are solid microneedle arrays made from crosslinked hydrophilic polymers that swell upon contact with interstitial fluid (ISF) in the skin.

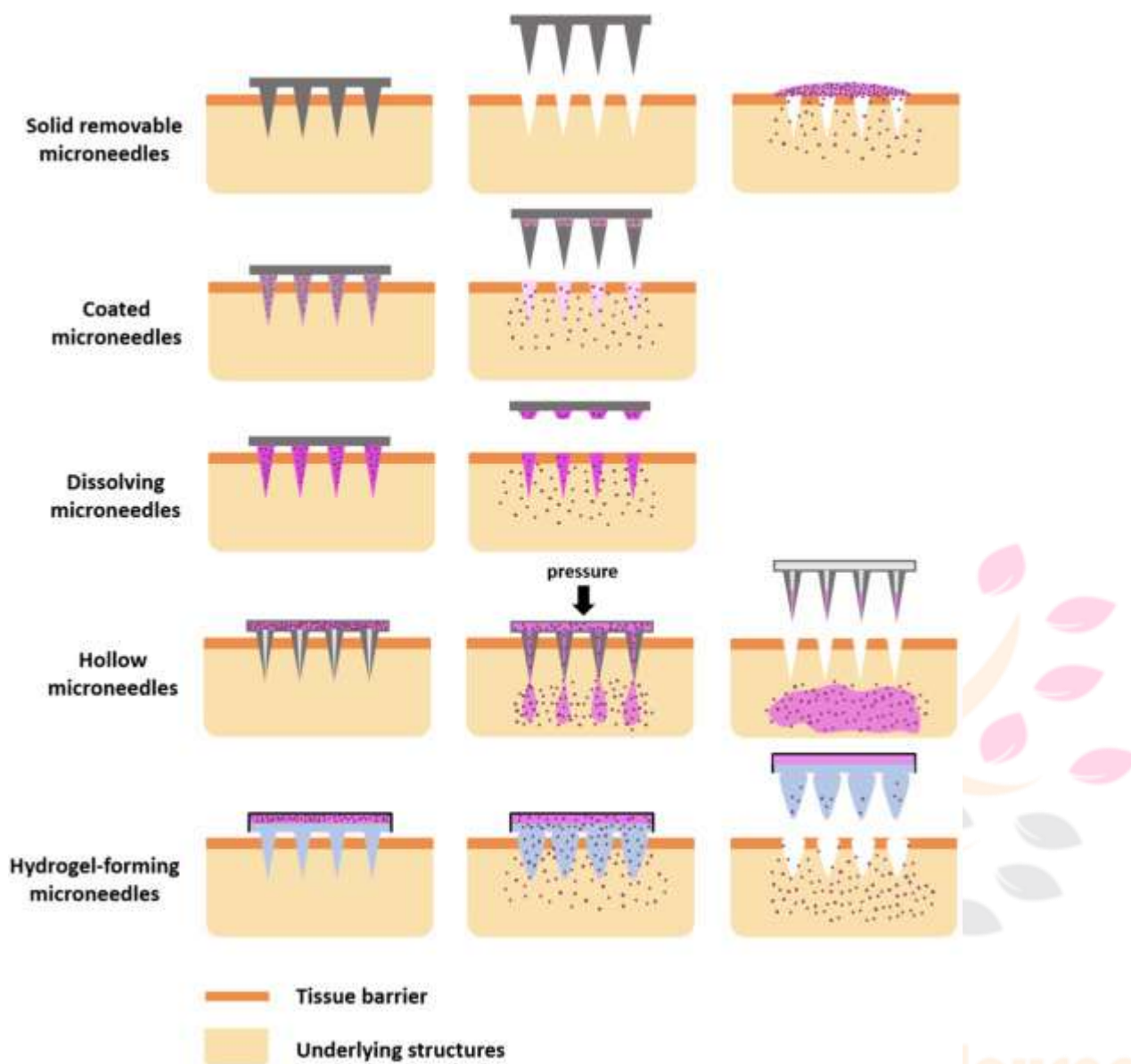
Unlike dissolving microneedles, these do not release their own material into the skin. Instead, they act as conduits that allow drugs from an attached drug reservoir/patch to diffuse into the body.

They are considered a fifth-generation microneedle system, combining mechanical strength (for insertion) and hydrogel properties (for drug transport).

Mechanism of Action:

The "poke, swell, and diffuse" principle:

1. Insertion – Hydrogel MNs penetrate stratum corneum into viable epidermis/upper dermis.
2. Swelling - Contact with ISF ← needles absorb water and swell, creating aqueous channels.
3. Drug diffusion - Drug molecules from the attached reservoir diffuse through swollen hydrogel into the skin.
4. Removal - After delivery, MN patch is removed; swollen hydrogel microneedles remain intact (no sharps waste).



Type	Description	Application
Solid microneedles:	Used to create microchannels in the skin before applying drug Patches	Pre-treatment for Transdermal patches
Coated Microneedles:	Drug coated on the surface dissolves upon insertion	Vaccine delivery, rapid drug release
Dissolving Microneedles:	Made of biodegradable polymers that dissolve after insertion	Insulin, vaccines, peptides

Hollow Microneedles: Allow liquid drug injection through hollow channels Large molecule delivery, biologics

Hydrogel-forming
Microneedles : Swelling polymers absorb interstitial fluid and release drugs Sustained release formulations

3. Fabrication Techniques

Microneedles are fabricated using advanced microengineering and nanotechnology methods.

Lithography – Photolithographic techniques for precise microneedle arrays.

Molding – Polymer-based microneedles using silicon or metal molds.

Laser cutting and etching – For metallic microneedles.

3D Printing – Emerging method for customizable microneedle designs.

4. Diagrammatic Representation:

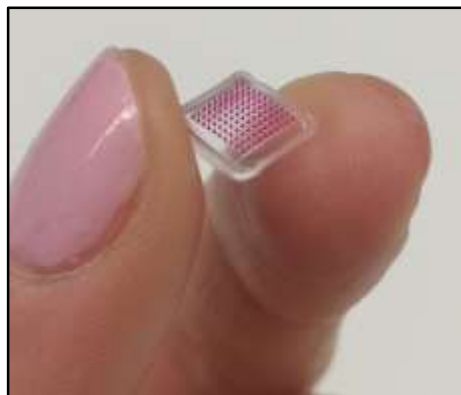


Fig 1 : Microneedles

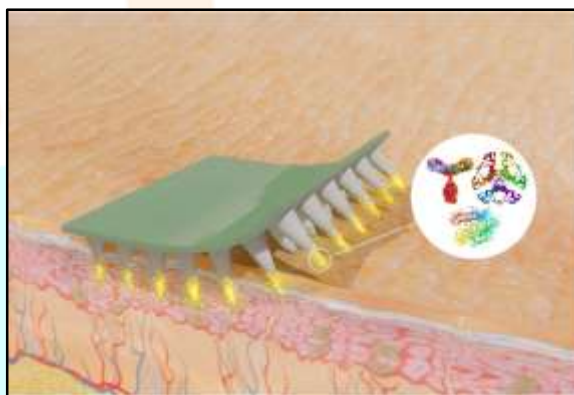


Fig 2 : Application on Skin

Transdermal Microneedle Structure

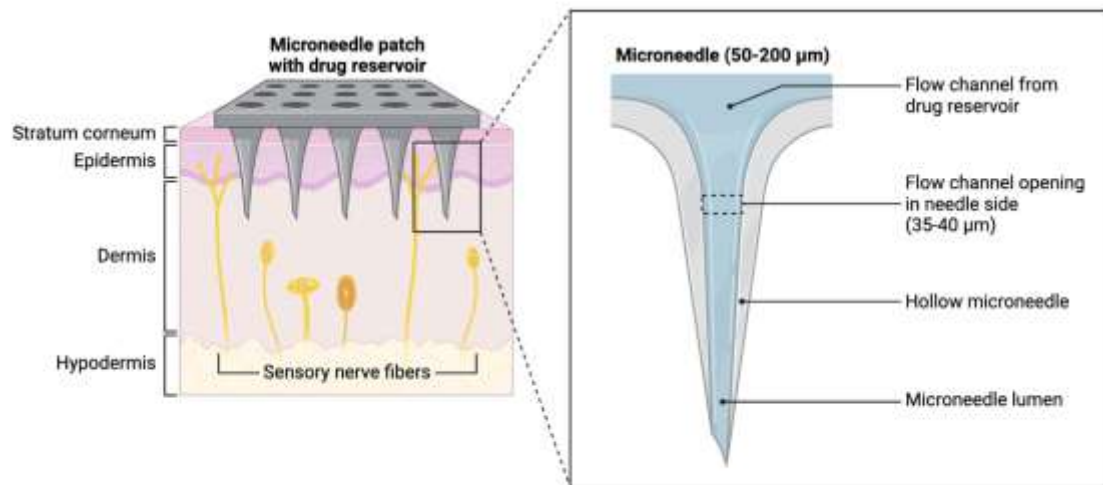


Fig 3 : Transdermal Microneedle structure

5. Applications in Drug Delivery

Insulin Delivery: Dissolving microneedles provide painless administration for diabetic patients.

Cancer Therapy: Targeted delivery of chemotherapeutics with reduced systemic toxicity.

Pain Management: Transdermal delivery of analgesics.

Hormone Therapy: Microneedle patches for contraceptives and hormone replacement.

6. Applications in Vaccine Delivery

Microneedles have shown remarkable potential in immunization programs.

Influenza Vaccine: Clinical trials demonstrate equivalent or superior immune response compared to intramuscular injection.

COVID-19 Vaccine: Research on microneedle patches for mRNA and protein-based vaccines.

Polio and Measles Vaccines: Potential for mass immunization in low-resource settings.

Advantages in Vaccination:

Painless and needle-free administration.

Reduced need for cold chain storage (especially with dry-coated vaccines).

Self-administration possible, reducing healthcare burden.

7. Advantages And Limitations

Microneedle Type	Advantages	Limitations
Solid	Simple design; reusable	Requires pretreatment
Coated	Rapid drug release; precise dosing	Limited drug load; coating uniformity issues.
Dissolving	No sharps waste; biocompatible	Mechanical strength; manufacturing complexity
Hollow	Liquid delivery; continuous infusion	Needle clogging; expensive fabrication
Hydrogel	Hydrogels are generally biocompatible and non-toxic	potentially leading to breakage or deformation during insertion

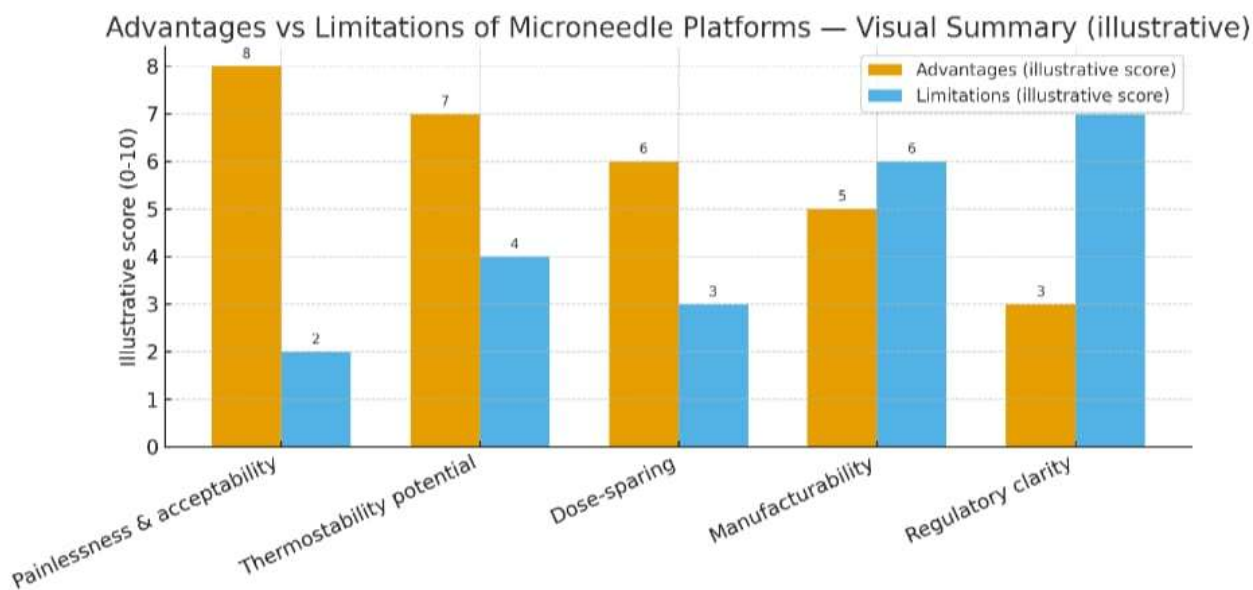


Fig: Visual summary of advantages and limitations of microneedle approaches.

8. Advantages

Microneedle technology offers several advantages, including:

Painless Delivery: Microneedles minimize pain and discomfort, making them an attractive option for patients.

Targeted Delivery: Microneedles allow for targeted delivery of therapeutic agents, reducing side effects and improving efficacy.

Improved Patient Compliance: Microneedles can increase patient compliance due to ease of use.

Enhanced Drug Delivery: Microneedles can enhance the delivery of drugs through the skin, making it an attractive option for treating various diseases.

Versatility: Microneedles can be used for delivering various therapeutic agents, including vaccines, drugs, and genes.

Minimally Invasive: Microneedles are minimally invasive, reducing tissue damage and promoting faster healing.

Potential for Self-Administration: Microneedle patches can be designed for self-administration, making them a convenient option for patients.

9. Future Prospects

Smart Microneedles: Integration with biosensors for real-time monitoring and controlled release.

Combination with Nanotechnology: Nanoparticle-loaded microneedles for targeted therapy.

Global Vaccination Programs: Potential to revolutionize immunization in developing countries.

3D Printed Microneedles: Personalized medicine applications.

10. Conclusion

Microneedle technology represents a paradigm shift in drug and vaccine delivery. By combining patient comfort, efficiency, and versatility, microneedles address the limitations of conventional delivery systems. With ongoing advancements in materials science, nanotechnology, and biomedical engineering, microneedles are poised to become a mainstream platform for global healthcare delivery.

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