Transdermal Injection with Microneedle Devices in Healthcare Sector: Materials, Challenging Fabrication Methodologies, and its Limitations

A. Gowthami, B. S. Sreeja, and S. Radha

Abstract In recent years, the management of many health disorders takes place at home either by community nurses or by patients independently. However, the medication management inside domestic healthcare situations may be difficult, mainly while therapy is administered via injection. The large percentage of transcutaneous injuries during needle handling has become a hazard in healthcare settings. The proper incineration of needle waste disposal after treatment is a major concern in the medical field. The cost-effective, biocompatible, portable, microfluidic devices are a promising technology for monitoring and diagnosing health conditions. One of the microfluidic device systems is a Microneedle (MN), which is an alternative method of an oral and conventional hypodermic needle for biomedical applications. The development of microminiaturized needles with scale dimensions in the order of 1 mm or less with a biocompatible material is a challenging aspect of today's scenario. Microneedle-based devices are customized for a wide range of applications, including disease detection, drug delivery mechanisms, and metabolic pathway monitoring. The different types of microneedles are developed based on the applications and their fabrication methodologies are selected based on the material and geometrical structure. Numerous fabrication processes of these microneedle devices from small-scale to large-scale production, with regulatory approval for commercialization, is a challenging perspective. This chapter mainly focuses on the various types of microneedles and the selection of materials for the microneedle type, the benefits of microneedle technology in various health sectors, along with a critical assessment of its possible impact on healthcare being investigated and discussed. It also elaborates on the different challenging microfabrication technologies and their limitations for various types of microneedle devices.

Keywords Transdermal delivery · Microneedles · Fabrication · Applications · Types

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K. Guha et al. (eds.), *MEMS and Microfluidics in Healthcare*, Lecture Notes in Electrical Engineering 989, https://doi.org/10.1007/978-981-19-8714-4_9

1 Introduction

An effective pharmaceutical depends not only on its active component but also on the delivery mechanism to the body. Therefore, it is important to consider an appropriate delivery method based on the drug characteristics. In general, the most convenient and simple way of drug delivery is through oral administration, but it can be difficult to use it with a complex pharmaceutical drug. This challenge can be overcome by the use of injections and it is a rapid start of pharmaceutical action. However, the injection with a hypodermic needle requires specialization, and patient compliance is limited. The future best drug delivery strategy should therefore be as straightforward as oral administration and have a high solubility and great health benefits as a like injection.

The transdermal administration of a drug has the benefit of continuous pharmaceutical release to the exact site of action without any alteration in drug concentration. Yet, the skin outermost layer called stratum corneum acts as barrier and makes drug delivery challenging [1]. Microneedles (MNs) serve as a delivery system for transdermal medication; they are simple to use on oneself and have a high level of medication bioavailability. Additionally, it is a non-invasive and painless approach that aids in the quick passage of drug through the stratum corneum. This technology has unique features such as safety, patient compliance, self-administration, increased permeability, and better performance [2]. Although it has numerous benefits, it also has some drawbacks. The sensitive skin may subject to irritation or allergy. In some cases, the tips of microneedles may break and causes issues inside the skin. These limitations are solved by using excellent microneedle material selection. The microneedles are produced in such a way that it bypasses the stratum corneum and deliver the entire dose of loaded drug directly into the epidermis layer [3]. Moreover, the medication dosage, delivery rate, and effectiveness of drug passage can be controlled by geometry and drug composition. Studies have been done so far on microneedles designed to deliver drugs and cosmetics that were made with a variety of fabrication techniques [4].

2 Patient Monitoring: Limitations and Challenges of Therapeutic Monitoring in the Health Sector

In most countries, chronic diseases are associated with high healthcare costs and lower societal productivity. Modern technology tools should be exploited to their full potential in an effort to minimize healthcare costs, improve patient monitoring through continuous assessment of symptoms and indicators of disease, and ensure compliance with self-management initiatives and chronic disease prevention. Because of the inability to notice difficulties linked with the drug therapy, inadequate monitoring might result in the emergence of Adverse Drug Events [5].

In general, oral delivery is still the most preferred method for the administration of active pharmaceutical ingredients because of the advantages such as self, pain free administration, more safe, and better patient compliance. Even though oral administration has many benefits, it has some drawbacks, such as the possibility of first-pass effect, the drug concentration may be reduced [6]. In addition, drug absorption may be limited by intestinal permeability and solubility, which may naturally limit the bioavailability of medications. These problems repeatedly appear during the delivery of biopharmaceuticals. As a result, intravenous (IV) injection is one of the most promising drug delivery systems, as it can accomplish precise dosing with the balance of high bioavailability. This system can cause some discomfort, and sometimes skin-pricking leads to blood drawing. One of the major problems is the sharp biomedical waste generated after usage of injection. The transdermal route has been investigated as another potential route for improving peptide medication delivery in order to potentially overcome some of these drawbacks [7].

Transdermal drug administration has gained popularity during the past ten years as a result of its advantages over traditional oral dosing forms. By 2025, the market for transdermal medication delivery is anticipated to increase and reach around $95.57 billion [8]. The different approaches of drug administration are depicted in Fig. 1. Transdermal Drug Delivery (TDD) is a painless method of injecting the drug into the stratum corneum layer and the drug reaches into the dermis layer without any skin damage. TDD is superior to other traditional drug delivery methods in several ways. By offering a non-invasive alternative to parenteral routes, it can get around problems like needle fear. Numerous placement choices on the skin for transdermal absorption are possible due to the skin's enormous surface area and ease of access. It keeps medication concentrations consistent despite repeated dosage administration, and plasma level instability brought on by oral dosing and injections, and it makes it simple to administer drugs with short half-lives. TDD bypasses pre-systemic metabolism, resulting in increased bioavailability [9]. In general, transdermal systems are economical and affordable, and the market available patches are used for the medication for up to 7 days. These patches are cost-effective when compared to other therapies. With little risk of systemic toxicity, the transdermal route allows the use of powerful drugs [10].

Furthermore, the World Economic Forum has named this distribution platform as one of the "Top 10 Emerging Technologies of 2020." The World Economic Forum's support for the quick commercialization of MN products presently through regulatory evaluation and development strengthens that position. To guarantee that MN technology may have a favorable influence on patients and doctors across the whole medical profession, it is crucial that regulatory oversight for this growing technology is thorough and that all aspects of commercialization are thoroughly handled [11].

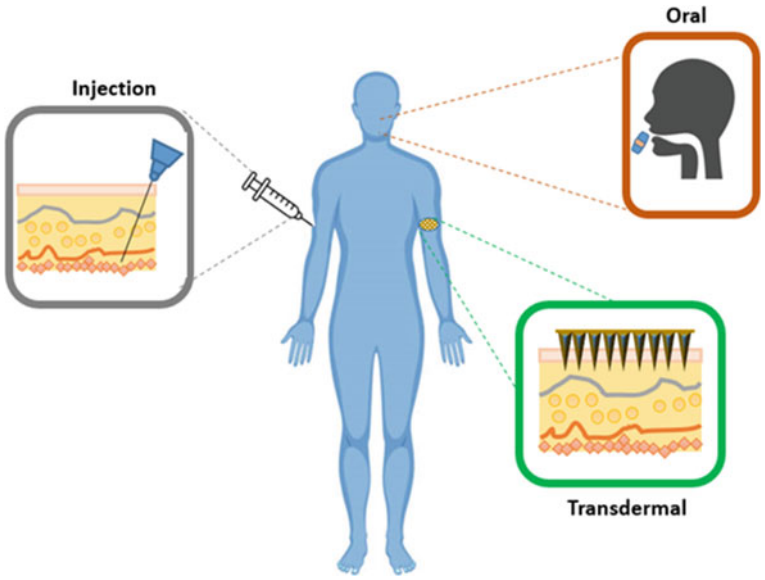

Fig. 1 Different approaches of drug administration

3 Evolution of Microneedle

Direct drug administration through the skin is referred to as transdermal delivery. The most popular method involves using hypodermic needles, which can cause pain to patients, needle aversion, and even the potential for infectious disease transmission [12]. These conventional injections can be substituted by microneedle technology, which is described as the non-invasive delivery of drugs through the skin surface. This technology has received interest from various research organizations and businesses. Microneedle delivery system is an appealing substitute for drug delivery technique to overcome the drawbacks of current traditional approaches [13]. The microneedle technology eliminates the needle phobia and more attracted the attention of the healthcare community. This technology also ensures the proper safe needle disposal is an added factor.

Microneedle patches are considered as minimally invasive devices that pierces the stratum corneum layer of the skin without pain and drawing blood. Microneedle devices are made to pierce the epidermis and deliver a medicine directly to the microcirculation beneath. These typically feature a variety of 50–900 μm long micron-sized projections. Needle length increment leads to more pain incredibly. Normally the needles have at least a certain length to overcome any deformation in the epidermis layer [14]. As compared to traditional needles, it attracts the industry with benefits such as non-hazardous, patient comforts, less painful, and cost-effective. Various designs of microneedles are progressed under research for efficient drug delivery

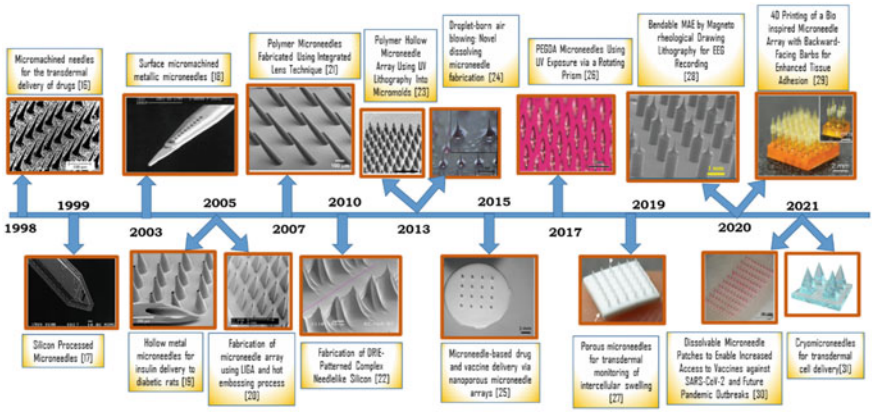

Fig. 2 Important developments in microneedle devices. Reproduced with permission from [16–31]

to avoid breakage of the needle. Many researchers reported that the sharpness and strength of the needle were decided by the proper material composition [15].

It is still challenging and difficult to exhibit the research idea at industry level. Some important problems and difficulties should be swiftly taken into account in order to move this novel technology from the lab level to practical products in the pertinent markets. Few of the innovative and significant advancements in MN research have been outlined in Fig. 2 [16–31].

4 Microneedle Classification

Based on fabrication, microneedles are generally divided into two categories, In-plane and Out-of-plane microneedles. In-plane MNs, needles are placed parallel to the substrate surface, and for out-of-plane MNs, needles are protruded out of the substrate surface. Out-of-plane MNs are ideal for two-dimensional geometry creation through wafer-level processing, but In-plane MNs are very difficult to produce with two-dimensional geometry [32].

Based on design, microneedles are classified as Solid, Hollow, Coated, Dissolving, and Hydrogel forming MN. The different types of microneedle representation are displayed in Fig. 3.

Solid Microneedles

Solid MNs are normally work in the principle of Poke with patch approach, it punctures a hole in the skin of the stratum corneum. They provide passage for the drugs to enter into the epidermis layer. The drug penetration or drug delivery rate depends on the depth of the opened pores. The micropores created on the skin that remain open for a week may cause infections. It is a major drawback for these types of microneedles

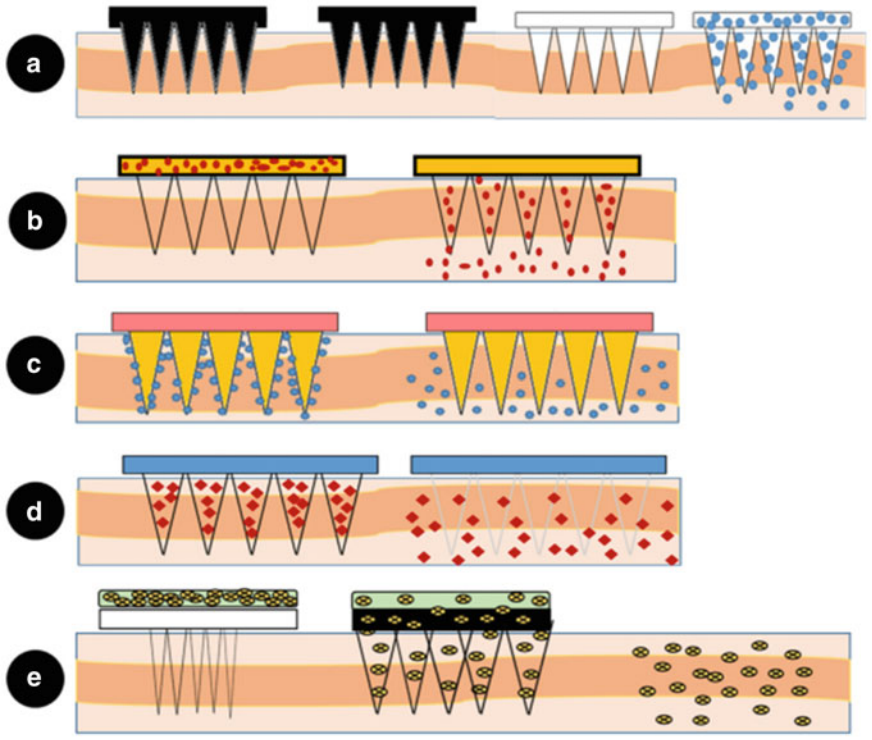

Fig. 3 Representation of Microneedle types **a**—Solid MNs; **b**—Hollow MNs; **c**—Coated MNs; **d**—Dissolving MNs; **e**—Hydrogel forming MNs [33]. Reproduced with permission from Sharma et al., Materials Science and Engineering C, (2019). Copyright © 2019 Elsevier

[34]. The materials used for developing solid MNs are typically silicon, metals, and polymers. Silicon is a fragile material and may break in the skin from an extended-release patch. The fabrication process for silicon-based solid MNs is very costly. The first silicon-based solid microneedles were manufactured using microfabrication technology. Some other fabrication methodologies are wet etching technology using mixtures of chemicals called HNA (Hydrofluoric acid, Nitric acid, Acetic acid) and reactive ion etching [36]. Some advantages of metal-based solid MNs are cost-effective and they have good mechanical strength. The frequently used materials for the fabrication of metal-based solid MNs such as stainless steel [35], titanium, and nickel. Polymer MNs are fabricated based on a mold-based method and usually made up of biocompatible polymers such as polyvinyl pyrrolidone, poly-lactic acid, poly-glycolic acid, and their copolymers. The fabrication method of polymer-based solid MNs is very inexpensive and easy for mass production.

Coated Microneedles

Based on the "coat and poke" strategy, these MNs are fabricated and the drug solution is applied to the microneedles before they are punctured into the skin. The coated drug will be dissolved and deposited into the skin surface by entering into the dermis layer. The amount of drug penetration into the skin mainly depends on the needle size and thickness of the drug-coated layer. But the important constraint is only a limited amount of drug can be coated on the body of the microneedle. Recent innovations in coating methods are developed for efficient Coated MNs in the field of drug delivery, biopharmaceuticals, and disease diagnosis [37]. It follows a single-step process of the fabrication either by dipping or micromolding techniques, with the use of materials such as stainless steel, titanium, and polymer.

Dissolving Microneedles

Dissolving microneedles are created using biocompatible (or) bio-degradable polymer (e.g., sugar, polyvinyl-pyrrolic (PVP), polyvinyl alcohol (PVA), poly-lactic acid (PLA), and poly-glycolic acid (PGA). They are fabricated based on the "poke and release" principle. The microneedle patch is loaded with the drug and it is inserted into the skin. The drug enters into the dermis layer and the dissolution of the drug takes place and it is released after a period of time. The dissolution of the drug depends on the polymer composition and the fabrication of the molding process. The preferred fabrication process for the dissolving microneedles such as micro-molding fabrication, which is a one-step process always convenient for patients [15]. It involves a polymer solution poured into mold structures and allowing the mold to dry under ambient conditions. A less expensive fabrication process with better patient compliance is the major benefit of dissolving MNs. The stability can be improved by processing the polymer under high temperature and extreme pH. The hazard of polymers deposition into the skin can be avoided by the proper selection of biocompatible polymers for drug delivery. Water-soluble polymers are preferably used for eliminating biohazardous sharp waste in the skin layers [38]. Some literature works with the solid microneedle developed as coated or dissolving patches are displayed in Fig. 4.

Hollow Microneedles

Hollow MNs are designed with hollow holes or lumens in the middle of the needles [39]. These empty spaces are filled with a drug solution. Some designs of hollow MNS have holes at the tip of the needles to deliver the drug into the inner layers of the skin using methods like diffusion, pressure, electrical assistance, or mechanical vibration. These hollow microneedles can bypass the stratum corneum and directly enters into the epidermis and deeper dermis layer. The principle called "Poke and flow" is suitable for the hollow microneedle to deliver the drug into the skin [3, 40].

Based on internal bores or lumens, the hollow microneedles can be classified as side opened single lumen, tip opened single lumen, side opened double lumen and tip opened double lumen. Preferably, side opened double-lumen-based hollow microneedles are more suitable for drug transport. Hollow MNs occupy larger doses

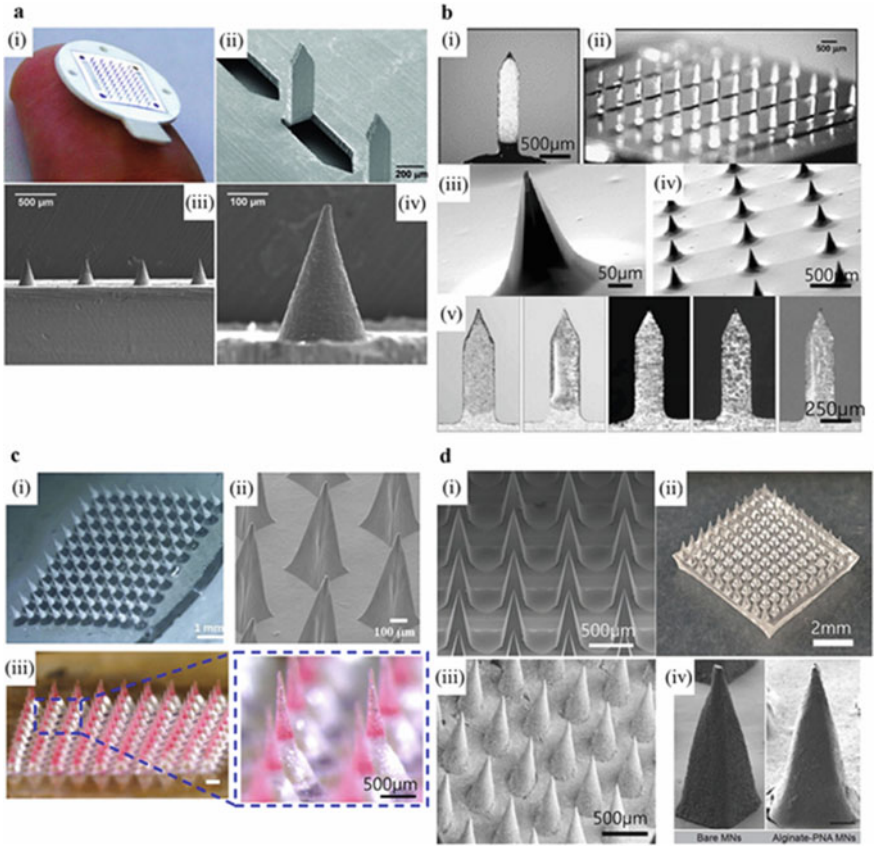

Fig. 4 Solid microneedles composed of stainless steel (i and ii) and titanium (iii and iv) b Coated microneedles composed of stainless steel (i and ii), silicon (iii and iv) and titanium (v) c Dissolving microneedles composed of CMC (i), HPMC (ii) and PLGA (iii) d Hydrogel microneedles composed of HA (i and ii), PVA (iii) and alginate (iv) [1]. Reproduced with permission from Jung, J.H., Jin, S.G. J. Pharm. Investig. 51, 503–517 (2021). Copyright © 2021 Springer

of the drug as compared to solid MNs, as it carries more amount of drug in the space inside the needle. The benefits of the hollow microneedle are that the diffusion of a drug is deeper into the skin, closer to blood vessels. Generally, it is preferred for high molecular weight substances like peptide or proteins, DNA or RNA molecules, and vaccines [41]. Continuous flow rate to be maintained with the adjustment of microneedle bore [42]. The major restrictions with the hollow type needles are flow resistance and clogging of the solution in the needle tip. Change in the hollow bore will increase the flow rate but it leads to a decrease in the strength and sharpness of the needle. To increase the needle strength, at times a metal coat is applied at the needle tip. The ongoing research studies with these limitations led to the innovative design of hollow microneedles. Side-opened sharp-tip hollow microneedles [43] are

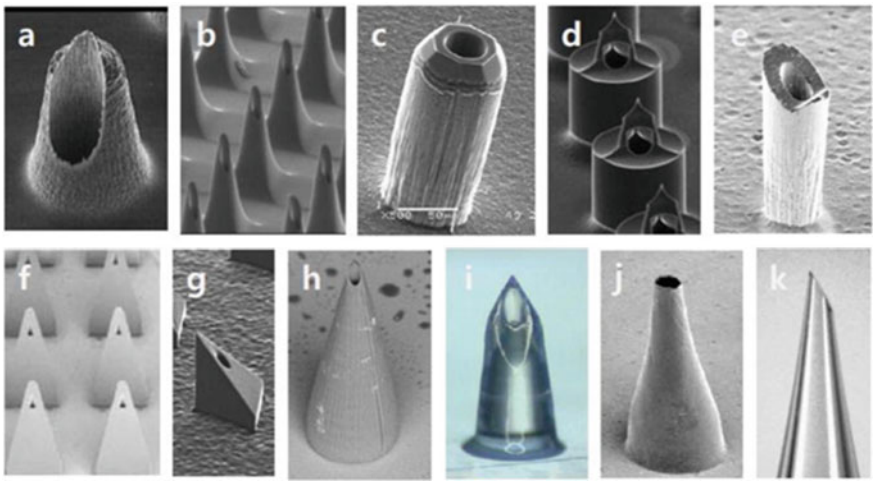

Fig. 5 Hollow microneedles made of silicon and polymers [44]. Reproduced with permission from Yeu-ChunKim et al., Advanced Drug Delivery Reviews, (2012). Copyright © 2012 Elsevier

repeatedly investigated as it leads to less prone of clogging and tranquil to insert. Predominantly used materials for the fabrication of hollow MNs are silicon, metals, polymers, glass, and ceramic. These microneedles are fabricated using processes like deep X-ray photolithography, laser micromachining, deep reactive ion etching, metal electroplating, two-photon polymerization, and a unified molding technique. The different types of the fabricated hollow microneedle are shown in Fig. 5.

Hydrogel forming Microneedles

This type of microneedle is made up of super-swelling polymers and these materials have a better capacity for water absorption. When the MN is injected into the skin, these polymers absorb the water and get swelled due to the presence of body fluid. This result in the development of conduits and these allow the discharge of drugs into the microcirculation from the reservoir. After injection, needles quickly absorb interstitial fluid from the tissue, causing the medication to diffuse from the patch through enlarged MNs. Specific polymeric components, such as poly methyl vinyl ether-co-maleic acid (PMVE/MA), carboxymethylcellulose (CMC), and amylopectin, are combined in aqueous solutions to create these types of microneedles [45].

5 Existing Methods: For Microneedle Fabrication

In the past few decades, the field of MN manufacturing technologies has experienced a steady flow of research and invention, with both conventional and cutting-edge methods being researched. The selection of an appropriate manufacturing method

for microneedles depends on drug type and dose, targets for use, optimized geometry and material. Most of the existing fabrication methodologies are very costly, comprise tedious procedures, and are challenging to implement for batch production. Most of the future research focuses on the cost-effective, repeatable fabrication process to enhance the usage of microneedle usage in the market. In the case of the financial side, micromolding or solvent casting methodology is more preferred [46]. However, MEMS-based metal or silicon microneedles are manufactured to obtain better precision and to ensure the repeatability of needle production. The various MN fabrication techniques are summarized in Table 1 [47–65].

Table. 1 Available microneedle manufacturing techniques

References	Fabrication method	Material used for fabrication	Type of MN	Geometry
[47]	3D microlens mask Lithography	Glass	Solid	Pyramidal
[48–50]	Deep Ion reactive etching, wet or dry etching	Silicon	Solid, Hollow	Conical, Bevel
[51, 52]	Laser ablation, etching, and micromolding	Polyhydroxyalkanoate, PMMA	Solid, Hollow	Conical
[53, 54]	Sacrificial Micromolding and Selective Electrodeposition	PLA mold, Metal	Hollow	Conical, Pyramidal
[55, 56]	Photolithography	PEGDA	Solid, Hollow, Dissolving	Cylindrical, conic, Pyramid
[57–59]	3D Printing (microstereolithography, Two-photon polymerization)	PEGDA, PVP, PEGDMA, PLA	Hollow, Solid, Coated	Square Pyramidal, Conical
[60, 61]	Soft Lithography	Polycarbonate MN master mold, thermoplastic polyurethane (TPU), PDMS	Solid, Hollow	Square Pyramid
[62, 63]	Atomized spraying process	Polyvinyl alcohol, polyvinylpyrrolidone, carboxymethylcellulose, hydroxypropylmethylcellulose, sodium alginate	Dissolvable, Hydrogel	Pyramidal
[64, 65]	Pulling pipette	Glass	Hollow, Solid	Conical

6 Benefits of Microneedle Technology in Various Health Sectors

In recent years, the use of needle-free transdermal administration methods moved closer to reality. Particularly, microneedle technologies came into reality and gained an attention of the healthcare community because it eliminates the issue of needle phobia. In addition, the usage of many biocompatible material made needles ensures the safety issues typically connected with needle disposal. Due to the small size of the needles, physical harm to the skin is low and the pores close within a few hours of the initial treatment. However, numerous studies have shown that as compared to conventional injection systems, the risk of infection from the use of microneedles is significantly lower. The introduction of needles made up of biocompatible polymer can further lessen the risk of infection from germs that may have unintentionally been pulled into the channel during patch administration [14]. Currently, the usage of microneedles is being expanded into new domains, such as disease diagnostics, immunobiological administration, and cosmetic applications as described in Fig. 6.

Immunobiological administration

Due to the COVID-19 pandemic, there has been a huge surge in research into microneedles and their wide benefits for the vaccine delivery and medications. Microneedles as a method of transdermal administration were created in 1976, but this idea was only recently applied to vaccination. Becton, Dickinson, and Company created Soluvia™ as the first intradermal vaccine. The vaccination antigen can be delivered into the dermis layer of the skin using the microneedle patch, which consists of a 30-gauge metallic microneedle implanted 1.5 mm into the skin. This

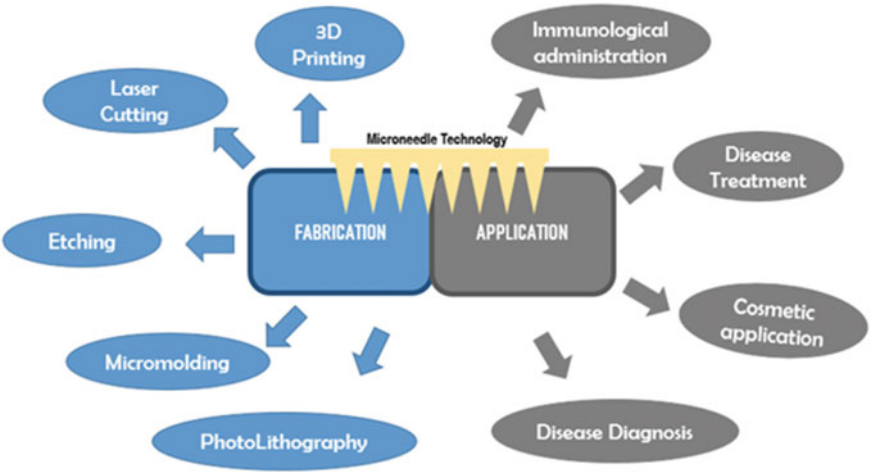

Fig. 6 Various microneedle fabrication methodologies and their applications

method was used to provide the influenza vaccine [66]. Cassie Caudill et al fabricated the microneedle patch using 3D printing and the transdermal vaccination provides many benefits over conventional vaccination such as less skin damage, self-implementation, minimally invasive, the potential to reduce cold chain dependency and there is no need of professional administration as like hypodermic needle [58].

Transdermal vaccination using biodegradable microneedles is a rapidly emerging area of research and application [67]. Dissolving microneedle patches made up of polymer material is very effective for vaccine delivery as they dissolve quickly in the skin and will not leave any biomedical waste [68].

Disease Treatment and Diagnosis

The most popular use for microneedles is still the transdermal drug delivery for disease therapy. In case of cancer disease, the effect of chemotherapy or surgery can cause serious side effects and in some anticancer therapy, only lesser amount of drug reaches the tumor site. The development of MNs offers a practical and minimally invasive method for administering drugs topically to treat surface malignancies. In general, MNs can lessen the effects of systemic toxicity as well as enhance drug distribution in the diseased position. Through MNs, the antigens enter the body and set off a generalized response that stimulates the immune cells, killing cancer cells [55]. Lan et al reported a method to cure cancer by developing a dissolving MN patch for the transdermal delivery of cisplatin to kill cancer cells. The cancer cells are killed by the dissolving patch loaded with pH responsive lipid nanoparticles by injecting directly into the tumor site. The author ensures the safety after administration and this method exhibits minimal side effects and less systemic toxicity [69]. In another study, researchers developed polymer-based dissolving microneedle patches for the treatment of breast cancer. The PVA and PVP microneedles are loaded with the combination of doxorubicin and docetaxel in aid for the photothermal and chemotherapy and increase the efficiency of cancer treatment [70].

For diabetes patient, the complex and multiple daily injections will reduce the patient compliance and increases the risk of hypo glycemia. The use of hypodermic needles in conventional ways has been discovered to cause tissue trauma and extremely discomfort. Nowadays, microneedle patches are used promisingly for diabetes management, which is an added benefit for patients with uncontrolled glucose levels or those at high risk of hypo glycemia. MN patches will release the medication when the blood glucose level raises and acts as an emerging drug delivery system that is being used to treat diabetic patients successfully [5]. Yu et al. developed insulin loaded biodegradable dissolving microneedle patch for the management of diabetes. The MN patch is made up of alginate and hyaluronate, these are noncytotoxic and also improve the mechanical functionality. The system exhibits a more sustained release of insulin and avoids steep fall in glucose levels [71]. Chang et al developed a swellable microneedle patch for the diabetes management and insulin delivery. Additionally, the technology is capable of extracting ISF instantly to detect both cholesterol and glucose levels and this value is observed to be the same as that measured using a traditional glucometer [72].

Microneedle patches were also applied in the treatment of other diseases. For illustration, Alzheimer disease is treated with tip-loaded dissolving microneedles encapsulated with a Donepezil hydrochloride (DPH) drug, resulting in efficient treatment when compared to oral administration. Problems such as neuropathic disorder are treated with analgesic microneedle patches as an alternative to clinical treatments. It was reported that the MN patches transdermally distribute anti-calcitonin gene-related peptide (A-CGRP) to reduce localized neuropathic pain by blocking CGRP receptors [73].

Cosmetic applications

Since 2005, when microneedles were first employed in the cosmetics business, a number of new products have been created, greatly increasing the usage of these tiny needles to treat skin disorders like wrinkles, scars, seborrheic keratosis, depigmentation, reducing fat, and other uses [74, 75].

The skin pigmentation is called seborrheic keratosis or lentigo and is usually observed in elder adults of age >50 and these can be cured by injection of retinoic acid into the skin. Hibrobe et al. created an all-Trans retinoic acid (ATRA) loaded microneedle patch (ATRA-MNs) and the patch was applied on the wound site for once in a week and continuously monitored for the next 4 weeks. This study has demonstrated that microneedles are used as a safe and effective treatment for senile lentigo and seborrheic keratosis [76].

A microneedle can deliver active cosmetic molecules straight into the skin by forming microchannels that do not enter the nerve with better effectiveness and safety. An innovative cosmetic patch loaded with retinyl retinoate and ascorbic acid is fabricated for anti-wrinkle purposes. The best example of a microneedle-based equipment is “Dermaroller,” and other approved microneedle devices for cosmetic procedures are “Derma Pen” [77]. These microneedles assisted equipments are utilized in home environments, and they are easily sterilizable for repeated usage. This area is still in a wide range of research with innovations for the delivery of cosmeceutical agents [78].

7 Microneedles: Challenges Involved in Their Development

Although various uses for microneedles have been proposed, only a small number of items have actually hit the market. When creating microneedles for the transport of both small and large molecules, safety and efficacy must be taken into account. Metallic microneedles may cause irritation, erythema, discoloration, or other negative side effects because metal traces are left behind beneath the skin. The above issues could arise if the microneedle is used repeatedly at the same location. The variation in skin thickness or use of microneedles at different sites may differ in bioavailability, which should be taken into consideration when developing the microneedles [4, 79, 80].

Currently, research is focused on developing new technologies for the safe administration of existing molecules, thereby reducing development time and increasing success rates. For this reason, many in the pharmaceutical industry strive for the successful development of microneedles as transdermal drug delivery systems [79].

The fabrication of various microneedle types encounters a variety of difficulties. The use of solid microneedles made up of metal may irritate the skin or cause metallic particles to remain in the skin. Additionally, after usage, they could leave behind biohazardous sharp waste, thus careful destruction is required. Dissolving microneedles dissolve completely into the skin and do not leave any waste. The major challenges in the development will be effective needle penetration, drug interaction into the skin, and loading the drug abundantly at the tip. Researchers are also becoming interested in the usage of hollow microneedles because they have the ability to administer a wider variety of molecules than other types of devices. However, this particular sort of microneedle lacks sufficient strength, so the researcher needs to emphasize overcoming this issue.

8 Conclusion and Future Perspectives

MNs provide numerous chances for the intradermal delivery of a variety of medications, including biopharmaceuticals. MN approach is a painless, efficient, secure form of drug delivery when compared to other intravenous methods. Moreover, this method can be useful for medications with low oral bioavailability. MNs come in a variety of types and can be created from a vast range of materials. They can be customized to treat particular diseases because of this feature. Since the academic and patent literature has accumulated mounting evidence showing that microneedles of many different designs can be successfully used to deliver drugs, vaccines, and active substances, the industrial effort to develop microneedle devices is likely to intensify. It is expected that newer applications of microneedle technology will become more popular. As the number of novel pharmaceuticals with biological origins keeps increasing, microneedles will significantly increase the transdermal delivery market value and become more significant during the succeeding years.

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