REVIEW ARTICLE

Microneedle Patches: Present State, Challenges, and the Way Forward

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Abstract

Transdermal drug delivery has gained significant attention as an alternative to conventional methods due to its non-invasive approach and potential to enhance patient compliance. Among the various techniques, microneedle (MN) patches have emerged as a revolutionary tool for effective drug delivery through the skin. These patches work by creating micro-scale channels in the skin, enabling the transport of therapeutic agents while minimizing pain, discomfort, and the risk of infection commonly associated with traditional injections. Recent developments in MN technology have focused on optimizing their design, fabrication, and material selection to improve efficiency, biocompatibility, and safety. Various types of MNs, such as solid, dissolvable, and hollow structures, have been developed to suit specific drug delivery applications. The use of biodegradable and bio-responsive materials has further expanded the scope of MN patches, enabling controlled and sustained release of drugs. This review explores the recent advancements in MN patch technology, highlighting innovative approaches that have been employed to enhance their clinical efficacy and scalability. Applications of MN patches span a wide range of therapeutic areas, including vaccine delivery, hormone therapy, and pain management, offering promising solutions to challenges in modern healthcare. However, despite these advantages, challenges, such as large-scale manufacturing, cost-effectiveness, and regulatory standardization continue to limit widespread clinical adoption. By bridging the gap between non-invasive techniques and efficient drug delivery, MN patches have the potential to transform transdermal therapy. This article aims to provide a comprehensive overview of present trends, challenges, and future perspectives in MN patch development, emphasizing their role as a key innovation in skin-based drug administration.

Key words: Biodegradable materials, biomedical technology, drug delivery systems, needles, three-dimensional, transdermal drug delivery systems, vaccination, printing

INTRODUCTION

Transdermal drug delivery systems (TDDS) are a way to deliver medicine through the skin without needing to take pills or get injections. These systems allow drugs to enter the body slowly and steadily, avoiding problems, such as stomach acids breaking down the medicine or it having to go through the liver first.[1] Traditional TDDS, such as patches used for nicotine or hormone therapy, are only suitable for small, fat-friendly molecules because they need to pass through a tough outer skin layer called the stratum corneum. As a result, bigger molecules, such as those in vaccines or insulin, and drugs that mix well with water, cannot use these systems effectively. For these types of medicines, injections are often necessary, but injections can be uncomfortable for many people, can cause fear of needles, and result in a lot of medical waste.[2] Studies show that trypanophobia, or fear of needles, affects up to 25% of adults and can lead to avoidance of necessary

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medical care, including vaccinations and chronic disease treatments.

Microneedle (MN) technology is a promising new method for delivering medicine. MN technology effectively combines traditional injections with the simplicity of patches. These tiny needles, ranging from 25 to 2000 µm, make small pores in the outer skin.[3]

This method allows the medicine to enter the body without causing pain or affecting blood vessels or nerves. MN patches provide important benefits in contrast to traditional drug delivery methods through the skin:

- They can deliver large molecules, such as proteins, DNA, and vaccines
- They improve drug availability by avoiding breakdown from enzymes
- They allow for lower drug doses by targeting areas of the skin with many immune cells. For instance, MN -based vaccine delivery has demonstrated up to a 50% higher immunoglobulin G (IgG) antibody response compared to traditional intramuscular injections in pre-clinical studies
- They enable easy, painless use at home, improving how well patients follow treatment plans.

The text discusses important progress in MN patch design and highlights new materials, such as biodegradable plastics and new manufacturing methods, such as 3D printing.[4,5] It also covers new applications, including messenger RNA (mRNA) vaccines and diabetes treatment. Challenges remain, such as producing patches in large quantities and meeting safety standards. Future possibilities include systems that automatically adjust doses and designs enhanced by artificial intelligence (AI). By combining knowledge from various fields, the goal is to speed up the use of MN technology in healthcare.

FUNDAMENTALS OF MN TECHNOLOGY

MNs are a cutting-edge method to deliver medicine through the skin, as shown in Figure 1. They are a hybrid between needle injections and skin-on-skin patches. These tiny needles range from 25 to 2000 µm in height, and they penetrate the skin's outer layer where blood vessels are located, known as the stratum corneum. Importantly, MNs do not penetrate deeper areas where pain receptors are located, hence giving a painless experience while administering drugs.[6] MNs create small pores through the skin where medicine can enter effectively. This approach allows for a painless experience, and it is also less invasive than needles. The process of drug administration starts with MNs piercing the skin gently. Second, they facilitate the movement of drugs into the skin through small pores and then the skin heals quickly, closing the channels after a few hours. This technology is particularly useful in applications where medicines typically do not go through the skin easily, that is, large molecules, proteins, or water-loving (hydrophilic) substances.[7]

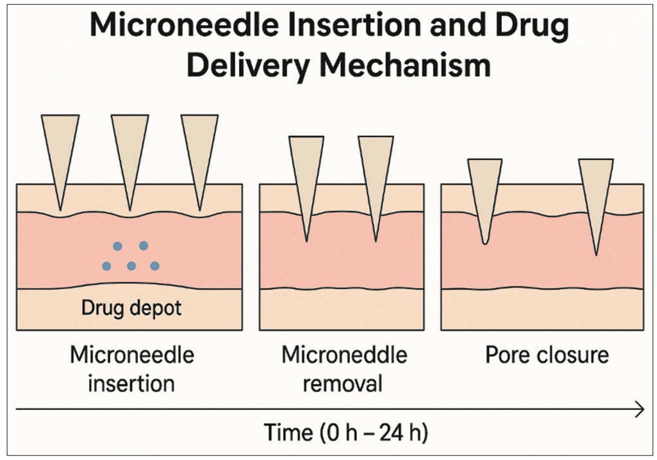

Figure 1: Mechanism of drug delivery through microneedle penetration and subsequent skin healing

MNs come in a few different types and materials. Figure 2 illustrates these five types of MNs along with their delivery mechanisms.

Solid MNs are made from metals, such as stainless steel or titanium. They are used to create small holes in the skin, which are then used to apply medication in a two-step process.[8] This is an effective and painless drug delivery method, but it is not as convenient as other options. Coated MNs are also a different type of MNs that dissolve quickly when inserted into the skin upon application, as mentioned in Table 1.[9] Dissolving MNs are made from biodegradable materials, such as polyvinyl alcohol (PVA) or sugars. These materials dissolve in skin fluids and release the medicine with a time gradient.[10] Hydrogel-forming MNs are made from materials that swell upon contact with water. They release medicine slowly over time, ideal for conditions that need continuous treatment, such as chronic illnesses.[11] Finally, hollow MNs consist of micro-channels that allow the medicine to pass through. The design mimics the traditional injection method but with less pain and less skin damage.[12]

Different MN patches have their own advantages and disadvantages. Solid MNs are strong, but they need the additional step of drug application, hence they are less convenient for everyday use for patients.[13] Coated MNs are designed to deliver the medicine quickly, but they cannot hold larger amounts of drugs than injections, and may not be good for sensitive drugs. Dissolving MN patches are easy to use, but they are soft and cannot be used on thick skin types. Hydrogel-based MN patches release drugs slowly over time, but they are harder to manufacture; hence, hindering the ability for mass manufacturing. Hollow MN patches can carry more drug quantities, but they tend to clog and need careful handling to prevent leaks. Despite these challenges, MN drug patches technology is advancing, and

Table 1: Comparison of microneedle types

Type	Materials	Release mechanism	Advantages	Limitations	Applications	References
Solid	Stainless steel, titanium	Skin pre-treatment	Reusable, strong	Two-step process	Permeation enhancement	[8]
Coated	PVP, sugars	Coating dissolution	Rapid delivery	Limited drug stability	Vaccines (e.g., flu)	[18]
Dissolving	PVA, hyaluronic acid	Matrix dissolution	No sharps waste	Low mechanical strength	Insulin, biologics	[19]
Hydrogel	PMVE/MA, polymers	Swelling-controlled release	Sustained release (days)	Complex fabrication	Chronic diseases	[20]
Hollow	Silicon, metals	Liquid infusion	High-volume delivery	Clogging risks	Monoclonal antibodies	[12]

PVP: Polyvinylpyrrolidone, PVA: Polyvinyl alcohol

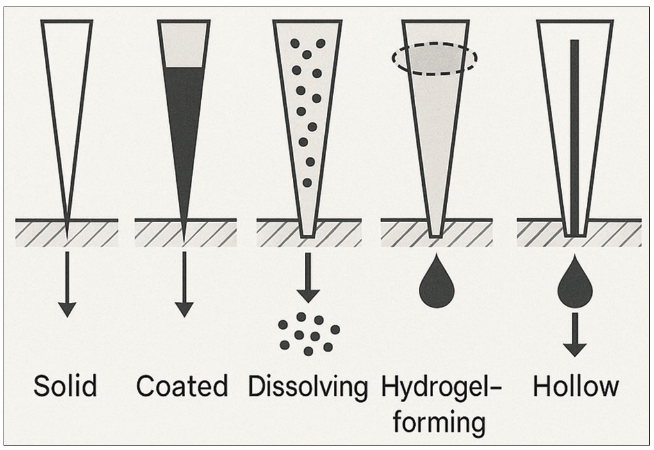

Figure 2: Mechanism of drug delivery through microneedle penetration and subsequent skin healing

researchers are improving the effectiveness of this drug delivery method.

MN technology is adaptable to the required needs and can be used in a variety of treatments. In vaccines, MNs, whether coated or dissolvable, can create strong immune responses. They can also pave the way for self-applicable vaccine patches, as demonstrated in a study where MN -induced vaccine gained a potent humoral response with higher total IgG response.[14] They also maintain stability under different temperatures better than traditional needles and syringes. This makes them particularly useful, especially with recent studies involving MNs for COVID-19 and flu vaccines.[15] For managing chronic illnesses, such as diabetes, new MNs made from hydrogels or dissolving materials have been designed to release insulin in a carefully controlled manner, reducing the frequency of injections needed. In dermatology, MNs carrying growth factors or siRNA show promising results for treating various skin conditions, such as acne and skin cancer.[16] Beyond medicines, MNs are being paired with biosensors for real-time health marker tracking, which opens up possibilities for advanced drug delivery systems.

Keeping the drugs in MNs, especially biological ones, stable over time needs more work. Health agencies are developing ways to test MN safety and effectiveness, and there is progress. For instance, in 2023, a flu vaccine with MNs started clinical trials. Patients tend to like MNs because they are painless, but informing people will be crucial to overcoming any initial doubts they might have.[17]

In the future, MN technology is set to change how we deliver medicines. This will happen through new developments in personalized medicine, smart materials, and connecting with digital health tools. Scientists are working on using 3D printing to make MN patches that match each person's specific needs. Some systems are designed to respond to different conditions, such as glucose-sensitive MNs for diabetes, which can adjust medicine release automatically. When MNs are combined with wearable devices and AI, it may allow real-time dosage changes based on sensor feedback. As these technologies advance, MNs could become very common and might replace traditional injections for many treatments.

RECENT ADVANCES IN MN PATCH DEVELOPMENT

MN patches rely on their materials and manufacturing precision for their effectiveness in a specified situation. Researchers are currently working on improving the safety of these materials for the human body, and how strong these materials need to be for different drugs and application conditions. They are also focusing on which manufacturing processes are suitable for mass production and keeping the cost low. Polymers have become the most popular materials for MNs that dissolve or create hydrogels because they can be easily adjusted and break down naturally over time. Popular choices include PVA and polyvinylpyrrolidone because they dissolve quickly and are compatible with many drugs.[21] Chitosan, another popular material, is a natural biopolymer known for killing bacteria and sticking well to body tissues, which makes it great for delivering vaccines.[22] Recent studies in 2024 have explored novel polymer blends such as PVA-hyaluronic acid (HA) composites, which combine the mechanical strength of PVA with the skin-repairing and biocompatible properties of HA, resulting in improved structural integrity and enhanced drug permeation across the stratum corneum.

New polymer mixes, like those with HA, are also promising for skin care and beauty because they help repair the skin, as shown in Figure 3. Metals, such as stainless steel and titanium, are still used in making solid and hollow MNs because they are very strong and can be reused. Recent advancements have led to the development of ultra-thin and flexible metal designs that make insertion less painful yet still strong. However, concerns exist regarding the risk of breaking and the creation of hazardous waste, making biodegradable alternatives more attractive and widely used.[23]

Silicon and ceramic MNs have some special advantages due to their precision and compatibility with the human body. Silicon MNs are made using special processes, such as photolithography and etching. These MN methods are particularly helpful in marinating the sharpness of the MN patches, which are good for effective drug delivery, and sensing ionic transport within the body. However, silicone MN patches are very expensive to make. To mitigate these problems, ceramic alumina or zirconia MNs are being explored. These materials can resist heat and chemicals well, making them suitable for delivering drugs that might be administered in acidic or high-temperature environments.[24]

MNs production has been transformed through the advent of 3D printing technology. 3D printing technology uses stereolithography and fused deposition modeling to create complex MN shapes. This is particularly useful when personalized medicine is needed to cater to patient-specific needs. While personalized MN patches created using 3D printing are a promising concept, most applications are currently limited to pre-clinical studies or early-stage trials. Clinical testing remains limited, with further validation required before widespread clinical adoption. Meanwhile, the laser micromachining method helps create very sharp and hard MN patches with minimal material wastage. These manufacturing techniques can reduce the cost of production for personalized MN patches and make it easier to produce MNs on a large scale.[25]

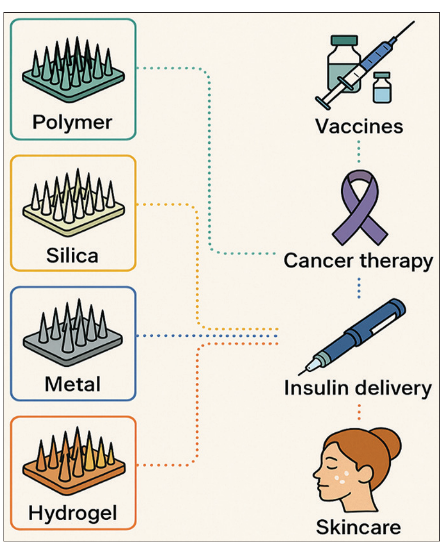

Figure 3: A mapping of microneedle materials to their respective applications across healthcare and cosmetics

Researchers are making progress in improving MN patches to enhance drug loading methods and drug release profiles to better suit the needs of the patient. This research will help in the wider compatibility of MN patches with available drugs, including vaccines, proteins, genetic materials, and drugs that do not dissolve easily.[26] By the use of nanoparticles and liposomes, scientists are now able to develop new methods to deliver drugs that can struggle to mix with water, as well as large molecules that are difficult to enter through the skin route. If drugs are placed inside liposomes or polymer nanoparticles, they become more stable and release at a controlled rate, making it easier for drugs to penetrate the skin. For example, using lipid nanoparticles in dissolving MNs for mRNA vaccines provides better stability than regular liquid forms. In addition, when polymeric nanoparticles are embedded within hydrogel MNs, they can release drugs steadily over days or even weeks. This slow release is especially useful for treatments that need to last a long time, such as hormone therapy or managing chronic pain.[27,28]

Smart and responsive MNs are an advanced way to deliver drugs right when the body needs them. Some of these MNs are designed to release drugs when they detect an acidic environment, such as in inflamed or infected tissues. This targeted approach is helpful for administering antibiotics or anti-inflammatory medications precisely where they are needed. Other MNs respond to changes in temperature. They use special materials that release drugs when they come into contact with the skin or are heated.[29] This process makes sure that the medication is administered only when required. Another innovative solution is to use light, particularly near-infrared light, to trigger drug release. These methods help locate and time the drug release, reducing unwanted side effects and enhancing the effectiveness of the administered drug, as shown in Figure 4.[30]

There has also been significant progress in the realm of advanced MN patch production with biodegradable polymers for controlled drug release. These materials can break down in the body and can be scheduled to break down within specified time intervals for controlled drug administration. For example, MNs made from poly (lactic-co-glycolic acid) degrade slowly over several weeks. They are effective in long-term use cases, such as birth control or managing chronic illnesses.[31] On the other end of the spectrum, MN polymers, such as carboxymethyl cellulose degrade faster upon application, making them ideal for quick-release

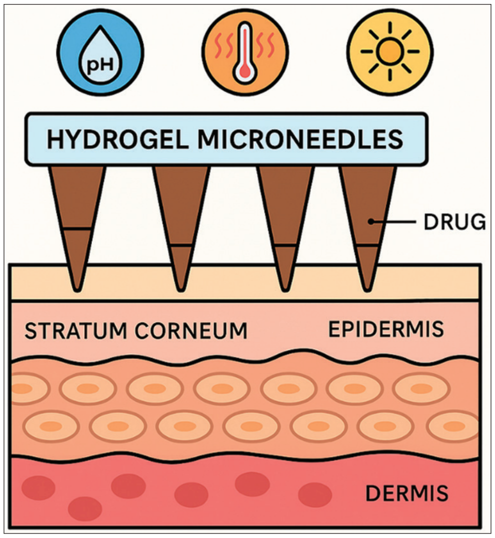

Figure 4: Stimuli-responsive microneedles triggered by pH, temperature, or light to release drugs selectively

applications, such as emergency vaccines.[32] These two types of profiles can be combined for co-administrating several drugs, specified for the patient's needs.

APPLICATIONS OF MN PATCHES IN DRUG DELIVERY

MN patches technology is a promising modern drug delivery technology, which reduces pain and is easy to use. However, real-world use of MN is hindered due to doubts about its performance concerning traditional drug delivery methods, such as injections. Practical issues are also important to address. Older adults or those with limited hand movement might struggle to use MNs on their own.[33] This situation might require designing special patches or tools to help them apply MNs correctly at home. To fully realize the benefits of MN drug delivery systems, ongoing research, and innovative solutions to these challenges are essential.

MN patches are becoming very important, especially for delivering vaccines. They help with big issues, such as people fearing regular needles, the need to keep vaccines refrigerated, and making it easier to get vaccines to people all around the world. During the COVID-19 pandemic, scientists researched more into vaccines using MN patches. These patches can keep mRNA and viral vector vaccines safe at room temperature. For example, a Phase I clinical trial tested a MN patch delivering a COVID-19 vaccine called HexaPro subunit antigen in a cohort of 40 healthy adults. The results showed that the MN patch could produce the same level of antibodies as traditional injections, but with an added advantage. The patch can remain stable for up to 4 weeks at 25°C, or room temperature, which makes storing and distributing the vaccine much easier.[34]

Influenza vaccines have improved with the help of MN technology. In 2023, a significant study in The Lancet showed that a special MN flu vaccine helped make stronger mucosal immunity. This means it produced more immunoglobulin A antibodies compared to regular flu shots. This might lead to better protection against respiratory infections, which affect the breathing system.[35,36] In cancer treatment, MN patches are being used for immunotherapy. These patches deliver medications, such as checkpoint inhibitors, such as anti-PD-1 antibodies, or tumor antigens directly to specific skin cells called dendritic cells. This method helps activate the immune system more effectively while causing fewer side effects throughout the rest of the body. For example, researchers tested a dissolving MN patch loaded with melanoma antigens and substances called TLR agonists.[37] This approach led to complete tumor removal in 60% of mice because it triggered a strong immune response right where the tumor was located.[38]

MNs are more commonly used for pain relief, providing fast and needle-free options for both short-term and long-term pain management. Lidocaine in MN patches is used for things, such as blood tests or skin treatments, numbing the skin in just 10–15 min, which is much quicker than using creams.[39] A study in 2023 found that a MN patch with both lidocaine and prilocaine cut down pain by 80% during laser skin treatments, and patients preferred it over anesthetic injections.[40] This study included adults aged 18–60 with Fitzpatrick skin types I-IV, indicating applicability across a range of common skin tones. For long-lasting pain, MN patches with drugs, such as diclofenac, a type of non-steroidal anti-inflammatory drug (NSAID), release medicine slowly over a day or 2. There's also a new kind of "smart" MN patch. These patches have special gels that react to the heat of inflammation, releasing medicine only when needed. This is especially helpful for those with arthritis, as it reduces the stomach issues often associated with taking NSAID pills.[41]

MN patches are changing how we manage chronic health issues, such as diabetes, osteoporosis, and hormonal disorders. These patches allow for pain-free and long-lasting medication delivery. In diabetes, MN patches for insulin are showing major progress. A 2022 study highlighted a unique MN patch with insulin and special enzymes. This patch can release insulin when blood sugar is too high, much like the pancreas does. Tests in diabetic pigs showed it kept blood sugar normal for over 20 h, outperforming regular insulin shots.[42] Hormonal birth control is also advancing. A new biodegradable MN patch for levonorgestrel, a hormone, such as progesterone, is in development. This patch can replace monthly injections. It dissolves in the skin and releases the hormone over 1–3 months.[43] Early tests showed that all patients preferred it because it was painless and did not require clinical visits. Similarly, MN patches for osteoporosis, such as teriparatide, and hormone replacement therapy with estradiol are being tested.[44] These patches may improve how well people stick with their treatments compared to daily injections or pills.

MN patches are getting more popular for skin care and beauty, beyond just medicine. These small patches have special ingredients, such as HA, peptides, or exosomes.[45] They help the skin make more collagen and become more elastic. A study showed that these patches with retinol helped reduce wrinkles by 40% in just 12 weeks.[46] This reduction was quantified using high-resolution skin imaging and profilometry, providing objective evidence of efficacy. Plus, they caused fewer side effects than retinol creams. For treating acne, MN patches use things, such as antimicrobial peptides or salicylic acid. These special constituents, normally incorporated in dermal creams, can work on destroying acne bacteria, and practically work better than creams. In applications, such as wound healing MN patches use vascular endothelial growth factor (VEGF) or platelet-derived growth factor (PDGF) to help enhance the growth of new blood vessels, speeding up the healing process.[47]

MN patches are getting special consideration in use cases related to skin care and cosmetic treatments, in addition to their uses in traditional medicine. In anti-aging treatments, these patches incorporate skin-beneficial ingredients, such as HA, peptides, or exosomes. These components help improve the elasticity of skin and boost collagen production. To treat acne, MN patches are coated with antimicrobial peptides, such as LL-37 or salicylic acid, which target the bacteria responsible for acne formation in the hair follicles.[48] These patches allow better penetration of the medication than creams. In the area of wound healing, MN patches that deliver VEGF or PDGF promote the regeneration of new tissue by fostering the formation of new blood vessels. An interesting example is a trial where patches loaded with fibroblast growth factor resulted in diabetic foot ulcers shrinking by 50%.[49,50]

CHALLENGES AND LIMITATIONS

MN technology shows a lot of promise, but some key challenges need solutions before it can be used widely in healthcare. A big challenge is producing MNs on a large scale while keeping each batch consistent. Present production methods work well in small labs but face difficulties with larger batches, ensuring the needles maintain their shape and have the right amount of medicine. Switching from precise methods, such as photolithography to larger-scale methods, such as roll-to-roll manufacturing, remains a difficult task, especially for making complex designs, such as hollow or dissolving MNs.[51]

Differences in people's skin can be a big challenge, especially for things, such as MNs. As people age, their skin gets thinner, and ethnic backgrounds can mean different thicknesses in the outer skin layer. Plus, skin tightness can vary in different parts of the body. All these differences affect how well MNs can penetrate the skin and deliver medicine reliably. Because of these variations, it's tough to create a single MN design that suits everyone. We might need to develop solutions that cater to each person's unique skin traits. Right now, researchers are exploring ideas, such as adjustable-length MNs and special creams or treatments that prepare the skin to be more uniform before applying the patch.[52]

The stability of drugs in MN patches is a big issue, especially for sensitive biologic drugs. Vaccines with MNs handle temperature changes better than liquid vaccines, but protein-based medicines and nucleic acid treatments still need work to last longer on the shelf. How the drug is packed in the patch, along with factors, such as humidity and the drug's own stability, cause complex problems. Solving these is crucial to make sure the medications can be stored for a long time without losing effectiveness. Maximizing the shelf life of these formulations remains an area needing significant improvement to ensure that they remain effective for as long as possible.[53]

The rules for MN products are still changing, which makes it challenging for the people who make them to know what to do. In different places, MN patches might be classified as medical devices, drug products, or sometimes a combination of both. This means that developers have to carefully understand and follow the various rules depending on where they are. There are also safety issues that need attention, such as the risk that the MNs might irritate the skin, not dissolve completely, or not stay sterile while stored or used. To solve these problems, developers need to conduct thorough testing to make sure these products are safe and work well.

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Over the next 10 years, MN technology will shift from being just experimental to becoming common in the medical world. This change is driven by four major trends. First, we are looking at personalized MN patches. These patches will be customized for everyone, thanks to progress in 3D printing and new materials. Soon, clinics may be able to produce patches that perfectly fit a person's skin thickness or their body's specific needs.[54] For example, there might be cancer treatment patches carrying specific medicines targeted at particular tumors, or versions for children that are soft and gentle on their sensitive skin.[55] This development is part of a larger move toward precision medicine, where treatments are tailored to meet the exact needs of the patient. At the same time, improvements in point-of-care manufacturing are making headway. This means that small, portable 3D printers might be used to create patches right when and where they are needed, whether for unusual medical conditions or in urgent situations.[56]

Over the next 10 years, MN technology will change from being a test idea to a common part of medical care because of four major changes. First, we can now make personalized

MN patches that meet each patient's needs. This is possible because 3D printing and new materials have improved a lot. In the future, clinics might be able to create special patches that perfectly fit how thick a patient's skin is or their body's unique needs. Imagine patches for cancer treatment with ingredients that target a patient's specific tumor or patches made for children's soft skin. This shift toward personalized treatment fits with new ways to make these patches right at the clinic. With portable 3D printers, it might soon be possible to quickly produce these patches for rare diseases or in urgent situations.[57]

The market for MN technology is growing fast. It's expected to increase from USD1 billion (2022) to over USD 9 billion (2027).[58] Vaccine delivery drives this growth. Companies, such as Vaxxas are working on MN patches for vaccines, such as the flu and measles. These patches do not need cold storage and have shown better results than regular injections in early tests. The beauty industry is already using MN technology, with brands selling anti-aging patches that include peptides and growth factors.[59] Big pharmaceutical companies are investing a lot in MN platforms for biologic drugs. They see the potential to reach more people since these do not require refrigeration. However, for MN products to really succeed, companies must find ways to handle payment issues. They need to prove that these products can reduce hospital visits and help patients follow treatments better than traditional methods.

As technology advances, it's important to think about fairness and ethics in its use. Ensuring that people in low-resource areas have access to these technologies is crucial, especially for MN vaccines, which can significantly improve immunization programs in developing countries. Protecting privacy will also be very important as wearable MN biosensors gather sensitive health information.[60] This means we need strong laws and rules to safeguard medical data. In addition, we must focus on the environment. Scientists are creating biodegradable MN materials to replace present plastics, which will help cut down on medical waste.

In response to this ambiguity, regulatory agencies, such as the U.S. Food and Drug Administration have begun issuing draft guidance – most recently in 2023 – clarifying the classification, safety, and quality standards required for MN -based combination products. We could also start finding AI-designed personalized patches in pharmacies. Using MN technology in worldwide vaccination efforts could finally help end needle fear in children, and this technology might even replace injectable cosmetics in skincare. Achieving this vision needs teamwork among engineers, doctors, regulators, and patients. The benefits could go beyond just better treatments; it could change the way we go through healthcare. MN technology could lead to pain-free vaccinations and automatic management of chronic diseases, possibly making syringes a thing of the past.

CONCLUSION

MN patch technology is an exciting new way to deliver medicine. It blends how well injections work with how easy skin patches are to use. In the past 10 years, improvements in materials and manufacturing have turned MN patches from simple ideas into real medical tools. Some key advancement include as follows Biodegradable polymer MNs – These offer a slow and steady release of medicine; Hollow MNs – These are used for delivering liquid medications; and Smart systems – These adjust the amount of medicine they release based on what's happening in the body. Nanotechnology has made MN patches even better. Now, they can deliver complex treatments through the skin, such as mRNA vaccines, special antibodies, and gene-editing tools. These innovations help overcome many challenges that older skin patch methods face, especially for large medicines that used to need injections.

MN technology is making a big impact in various medical fields, such as vaccines and managing chronic diseases. In global health, MN-based vaccines could help solve the problem of keeping vaccines cold, as they can remain stable at room temperature for weeks. This is crucial for pandemic preparedness and areas with fewer resources. For conditions, such as diabetes, MN patches allow for insulin delivery without any pain, representing a significant improvement. In skincare, MN technology is utilized for acne treatment and reducing signs of aging, outperforming regular creams. A particularly useful aspect of using MN patches is the ability of patients to use them themselves; this could lead to fewer hospital visits and improved treatment conditions across healthcare conditions. However, there are several challenges with the widespread use of MN patches. One main challenge that is faced is the manufacturing of such large quantities of MN, especially with the manufacturing of custom 3D prints. Regulatory bodies also need to cover such products that combine drugs with physical devices. Although many people are adopting the pain-free experience of MN patches, education is needed to increase trust in MN patches compared to traditional injections.

Despite these rising challenges, MN patches have a bright future ahead. New developments, such as wearable smart patches and AI-enhanced designs, can derive new methods of drug delivery within the realm of MN patches. Researchers are working to overcome hurdles by manufacturing these patches with reduced costs and making these patches widely available. MN patches could change healthcare, making treatments without the need for painful needles, and added features that is, control the release of drugs. It is also a way forward to enhance patient comfort through combining scientific advancements with practicality. MN patches might replace syringes for most treatments at primary healthcare facilities, ushering in a future where drugs are painless, fair, and effective for everyone.

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