WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
Coden USA: WJPRAP Impact Factor 8.63
Volume 15, Issue 22, 1003-1023. Review Article ISSN 2277–7105

REVIEW ON: 3DPRINTED MICRONEEDLES FOR TRANSDERMAL DRUG DELIVERY FORMULATION STRATEGIES, RECENT ADVANCES, APPLICATIONS AND FUTURE PERSPECTIVES

M. Pavitra[1], P. Amulya[1], Syed. Arshiya[1], Prasanna Kumar Desu[1], B. Srinidhi[1], K. Abhinaya[*1]

[*1]Department of pharmaceutics, Dr. Samuel George Institute of Pharmaceutical Sciences, Markapur, Andhra Pradesh.

Article Received on 15 Oct. 2026,
Article Revised on 05 Nov. 2026,
Article Published on 16 Nov. 2026,

https://doi.org/10.5281/zenodo.24300366

***Corresponding Author**

K. Abhinaya

Department of pharmaceutics, Dr. Samuel George Institute of Pharmaceutical Sciences, Markapur, Andhra Pradesh.

How to cite this Article: M. Pavitra[1], P. Amulya[1], Syed. Arshiya[1], Prasanna Kumar Desu[1], B. Srinidhi[1], K. Abhinaya[*1] (2026). Review On: 3dprinted Microneedles For Transdermal Drug Delivery Formulation Strategies, Recent Advances, Applications And Future Perspectives. World Journal of Pharmaceutical Research, 15(22), 1003–1023.
This work is licensed under Creative Commons Attribution 4.0 International license.

ABSTRACT

3D printed microneedles or innovate technique used for transdermal drug delivery this techniques health to overcome limitations for improving drug penetration through the skin with tissue damage. Microneedles contain very small structure that can delivery medicine into the skin. The microneedles has several types including solid, coated, hollow, dissolving, hydrogel forming microneedles along with 3D printing technologies to improve bioavailabity. It also contain several materials such as hydrophilic polymers, biodegradable polymers and other materials. 3D printed microneedles have various applications including vaccination, wound healing. Cosmetic and bioseng, cancer therapy, skin disease treatment, insulin delivery. For this techniques material selection is an important factor to perform quality printed microneedles. The integration of digital modeling, artificial integellence and sensor based technologies help to improve formulation development. So the 3D printed microneedles are innovative techniques for next generation transdermal drug delivery and their improve controlled drug relief so it is safe for patients.

KEYWORDS: 3D printing; Transdermal drug delivery; Artifical Intelligence, additive manufacturing, skin Permeation.

INTRODUCTION

The drug is delivered directly into the skin which is called as transdermal drug delivery which provides a noninvasive systemic route without any pain sensation. Many of the scientists developed the transdermal drug delivery dosage forms. In the transdermal drug delivery we can understand how the drug penetrates into the skin. It helps to understand the layers of the skin. In transdermal drug delivery our skin contains many types of layers like epidermis, dermis, hypodermis etc.[1]

In our day to day lives the additive manufacturing is developing very rapidly in the advanced manufacturing. It is also termed as layered manufacturing, rapid prototyping, In the year 1980s, the additive manufacturing was firstly developed and the 3D Printer technology was originated by chuck hull. The micro sized structures help to penetrate into the skin through the stratum corneum which is called as microneedles (MNs). Microneedles consist of various types of components like metals and polymers which is intended for intradermal delivery of bioactive molecules. It consists of different types of microneedles like hydrogel-basedmicroneedle, coated microneedles. The microneedle consists of different types of advantages in the tissue regeneration. The microneedle helps to improve patient compliance. It has been used at the delivery site which increases the concentration of the drug. In the transdermal drug delivery different studies are conducted in the transdermal patches which are used to solve the barrier problem stratum corneum.[2]

In the transdermal drug delivery, it has been used as a lipid rich outer layer which is called as a stratum corneum(SC). The skins outer layer is used in the preparation of the percutaneous drug delivery like ointments, gels etc. In the stratum corneum the transdermal absorption consists of different models in the transdermal delivery of xenobiotics. It consists of mainly 3 different pathways which is intracellular pathway, trans follicular pathway, intercellular pathwaywhich reaches to the passive diffusion and the transdermal drug delivery is not necessary to be administered by the skilled persons. It mainly passes through the first pass metabolism[3] in which their translocation is developed and also improve the efficacy. It mainly eliminates the pain caused due to the injection, and also the changes in the blood level and it consists of various types of disadvantages like irritation of the skin, redness, and rashes on the skin. In the transdermal drug delivery the patch surface area should be covered where the surface of the patch comes in contact with the skin due to this reason the drug should be controlled like the size of the dosage is determined by the skilled medical professional. The

manufacturing of the 3D objects which is based on the digital design is developed more than30years ago.[4] In our human body the skin is the largest organ and also it is defense against xenobiotic entrance which covers the overall body. In the world population the skin diseases become a major problem which is mainly affected by the skin disorder like ringworms, rashes, acne etc. It mainly referred as a crucial problem as a one third of population.

Now a days the skincare products is becoming an important role which includes face creams, facewashes, etc. Which is prepared and manufactured by using modern nanotechnologies. In pharmaceutical products they focuses on the skin diseases (or) disorders and consists of specific properties like shape, redness, swelling and drug release. For the development of the recent healthcare products the 3D Printing become innovative in previous years. In 3D printing they consists of various pharmaceutical dosage forms which consists of implants, chewable tablets and also contains different release products consists of the sustained release products etc.

Overview of Microneedles

The skin outermost barrier which is stratum corneum which transports the therapeutics without stimulating the receptors of pain which is mainly intended by the Microneedles which is micro scaled minimal devices. The microneedle which is micro sized structures consists of a function of micro array ranges from 50 to 1500 length in micrometers[5] in between transdermal spot and hypodermic needle. For the drug administration it provides a bloodless and pain free which completely by pass the blood vessels which consists of the only penetrating superficial layers of the skin. The Microneedles are mainly divided into different types[6] which are dissolving Microneedles, Coated Microneedles, Solid Microneedles and hydrogel forming microneedles like composed polymer degeneration, quick surface dissolution, and direct fluid infusion toconvey active type of compounds. For assisting the continuous diagnostic observing it enhance the specific transporting of the macro molecules which is modernized by the multiple platforms in the microneedles.

Types of Microneedles

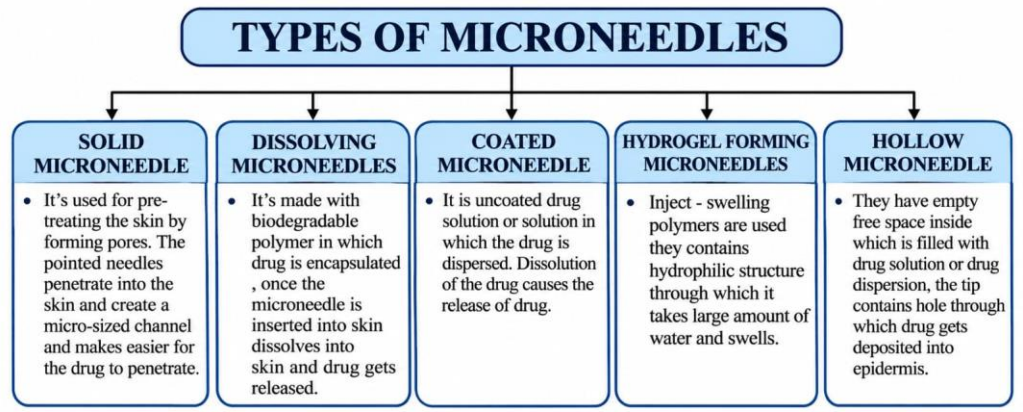


Figure 1: Different types of microneedles solid microneedles, dissolving microneedles, coated microneedles, hydrogel forming microneedles, hollow microneedles.

1. Solid Microneedles

The easiest forms of structure and design which is solid microneedles and it doesn't contain any excipients or drug. The skin creates a small sized pore through the epidermis. for a shorter time it is the basic function of the solid microneedles it doesn't reaches to the deep which causes the blood loss. The solid microneedle consists of the certain formulations like creams, gels which is applied on the skin surface. It mainly enhances the systemic absorption of the drug permeability which smoothly diffuses into the micro channels. The solid microneedle is made up of polymers, stainless steel.[7] In solid microneedles it has less skin penetration specifically for the molecules which increases the bioavailability by moving the protective stratum corneum. It prevents the contamination and also used for both commercial and therapeutic uses.

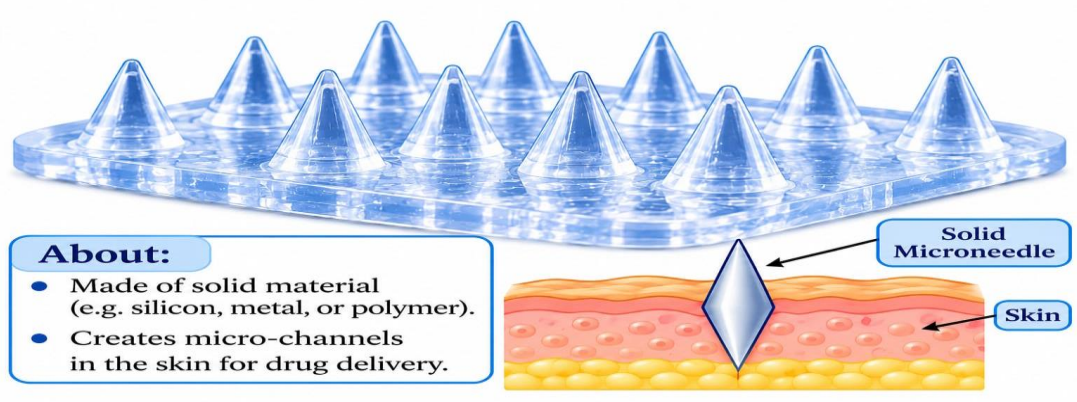


Figure 2: Solid microneedles create tiny channels in the skin to facilitate effective drug delivery.

2. Coated Microneedles

Coated microneedles use a different method of delivering drugs through microneedles by coating the exterior surface of the solid microneedles with pharmaceuticals. Once inserted into the skin the drug will slowly dissolve from the surface and enter the tissue layers. This provides a fast release of the drug and can allow for a relatively quick pharmacological effect.[8]

Dip coating is a common method used to create coated microneedles. The devices are dipped into a solution containing the desired pharmaceutical.[9] The amount of drug applied can be controlled by adjusting the depth of the dip and the length of time it is inserted for. A consistent coating is required to ensure accurate dosing. The formulation must have the correct viscosity to ensure that the coating forms a stable layer and sticks to the surface of the device. This will help increase transfer efficiency if the drug is concentrated at the tip of the microneedles as this is where they will firstly enter the skin. However, the drug loading capacity is limited. For higher dosage pharmaceuticals this may be an issue. Multiple coats beapplied but this can become complicated and require extra steps when manufacturing.

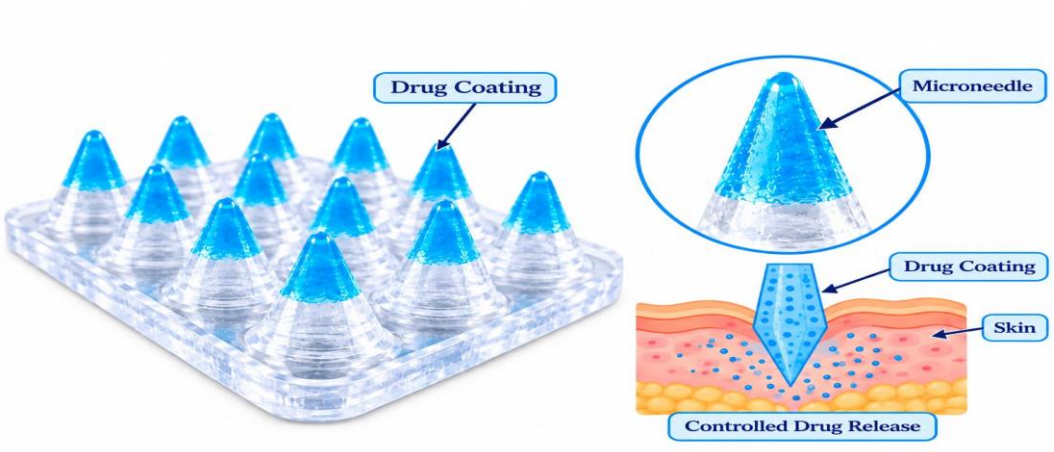


Figure 3: Coated microneedles have a drug-coated surface that releases the drug into the skin for rapid and controlled delivery.

3. Hollow Microneedles

The hollow microneedles comprises of a structure with a cavitated compartment in which the drug is administered.[10] In higher dosage the hollow microneedles when it is an contrast with the solid microneedles. A hollow microneedle have capability to the transport of drug into the living dermis in which it is appropriate for the molecular weight compounds which is higher.

In the liquid vaccine formulations which is appropriate and it also regulates the release of the drug.

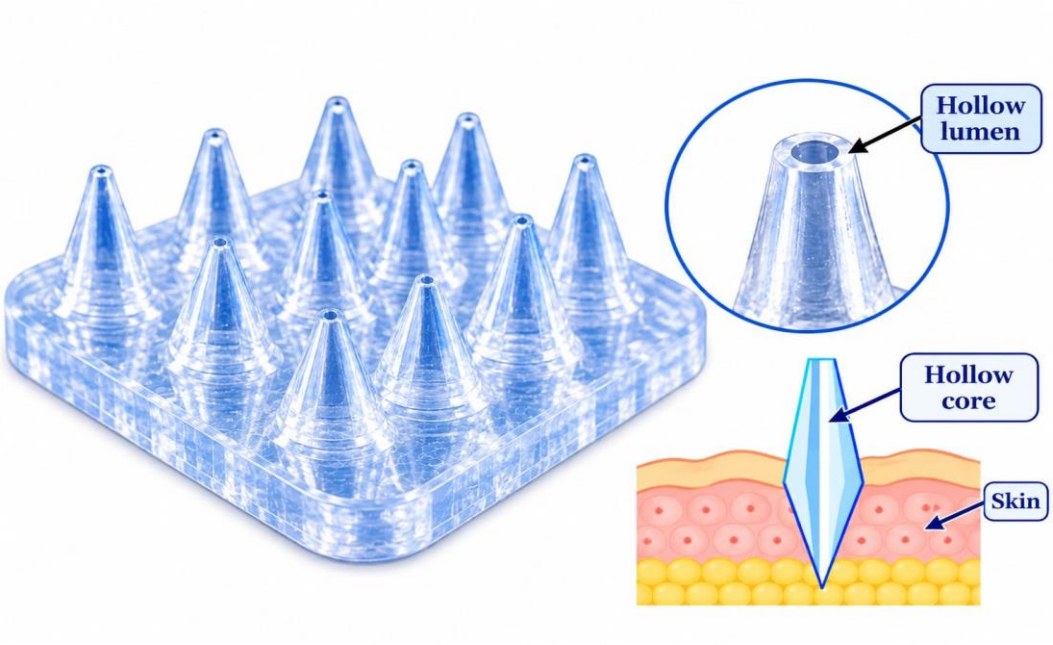


Figure 4: Hollow microneedles have a hollow core that delivers drugs directly into the skin for effective drug administration.

In solid microneedles which are mainly release the drug which is depend on the osmotic pressure and the hollow microneedles is an active drug which creates for diffusion of the drug depended on pressurized drug reservoir. Both of the material composition and manufacturing the factors for the hollow microneedles can be utilized to the adjustable drug release rate. Similar to the hypodermic needles, the hollow microneedles can be designed to allow the regulation of the flow rate and the pressure.[11] The hollow microneedles it has been successfully useful in the various types of vaccines. During the injection process it causes some of the problems like blocking.

4. Dissolving Microneedles

Dissolving microneedles are an advanced drug delivery system made from biodegradable or water soluble materials containing the drug substance. These microneedles are developed to completely dissolve inside the skin, leaving no needle waste and preventing the risk of needle waste and preventing the risk of needle reuse or injury. Usually, they are prepared by the solvent casting method, in which drug and polymer mixtures are poured into molds and allowed to become solid.

Commonly used polymers include carboxymethyl cellulose (CMC) methyl cellulose, and sugars such as trehalose and sucrose.[12] These materials are safe, body friendly, and able to form strong structures containing the drug. In these microneedles, the tip part enters the skin first. It must have enough physical strength to enter the skin without breaking. It should also have low thickness to fill the mold properly without forming air bubbles.

The base part of the microneedles may not contain any drug. It can be made from a weaker or water insoluble material, which helps hold the needle in place during application. However, these designs have some limitations when large amount of drugs are required. Therefore, further research is being carried out to increase the drug loading capacity of dissolving microneedles[13] without reducing their strength and stability.

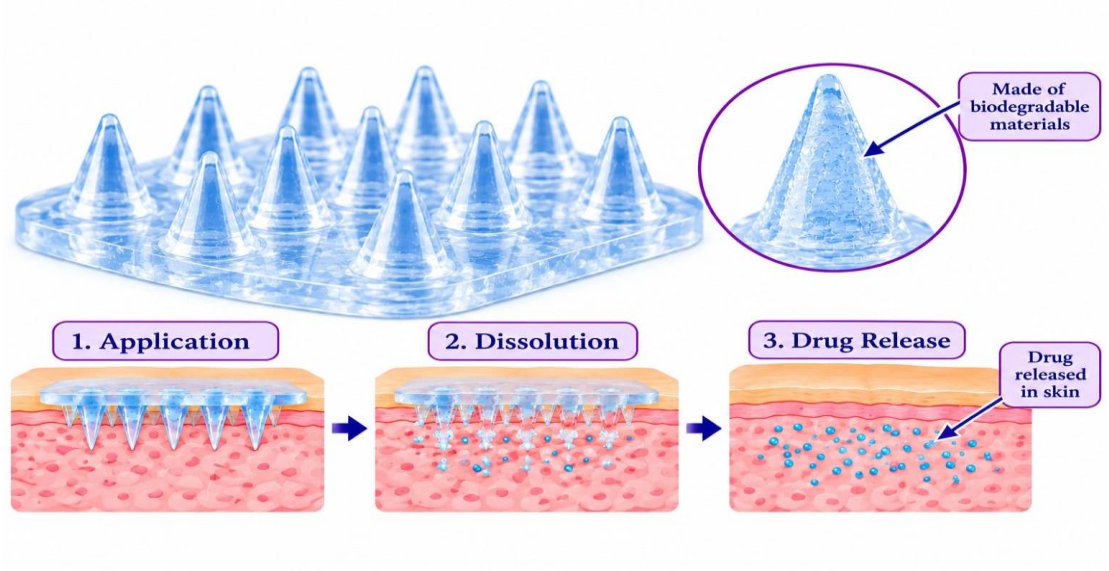


Figure 5: Dissolving microneedles are made of biodegradable materials that dissolve in the skin and release the drug for effective delivery.

5. Hydrogen Forming Microneedles

The hydrogen forming microneedles doesn't dissolve and swell when it is exposed to the fluids in the skin which contains of a crosslinking hydrophilic polymers. It diffuses slowly into the skin which absorbs into the skin, and gets swelled when the microneedle is inserted at once. There are manyadvantages in the hydrogel forming microneedles like sustained release of the drug.[14] It consists of some of the major factors foreffective performance and the drug diffusion is slower in the long patches.

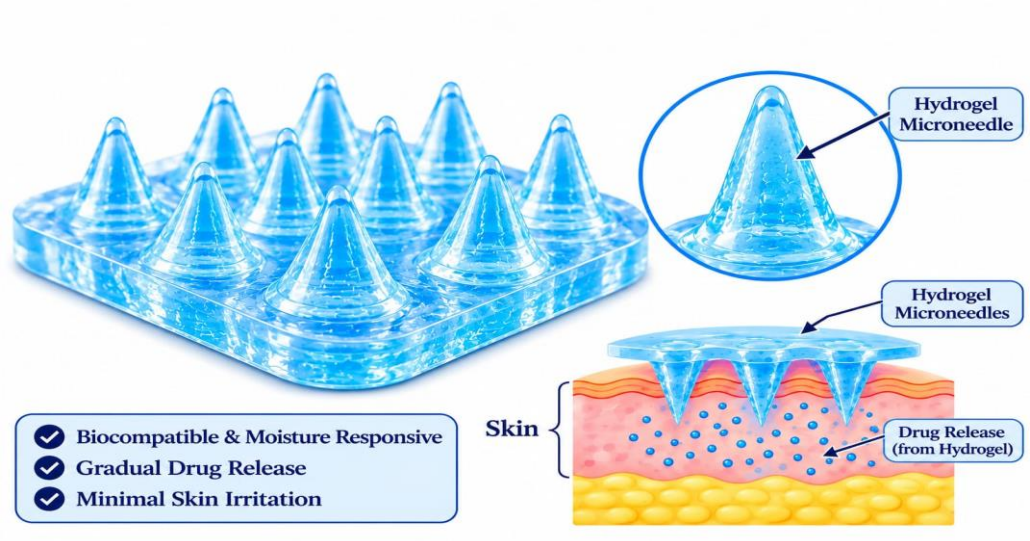


Figure 6: Hydrogel forming microneedles absorb moisture and provide gradual drug release with minimal skin irritation.

3D Printing Technologies

The 3D printing technologies is developed due to its different functions and it includes mainly 7 varieties[15] like material extrusion, power bed fusion, material jetting, sheet lamination, power bed fusion, directed energy deposition etc.

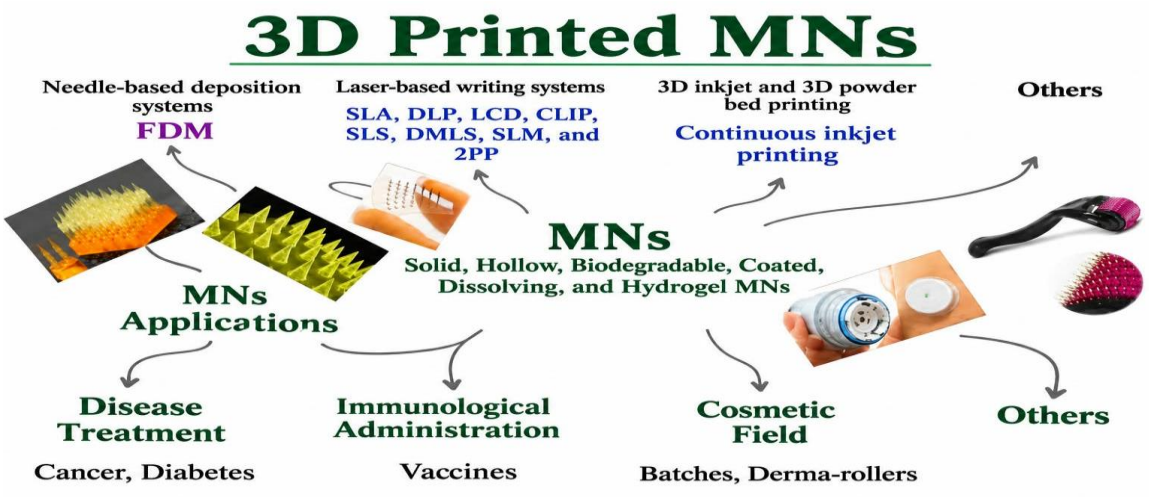


Figure 7: 3D-printed microneedles(MNs)are classified into different printing methods, types and applications such as disease treatment, vaccine delivery and cosmetic treatments.

1. Directed Energy Deposition

The directed energy deposition is a more complicated printing process which is frequently used to repair additional materials to prepare existing components. The procedure of the

directed energy deposition is same as the principle to the material extrusion, but the deposition head is not attached to the particular position. Moreover the procedure can be utilized in the polymers, but generally it is utilized in the metal based hybrids in the form of powders.[16]

2. Binder Jetting

The binder jetting is a fast prototyping and a 3D printing procedure in which a liquid binding agent is specifically deposited to join into the powders and technology used in the jet chemical binders to form a layer by spreading the powder. There are many applications for the binder jetting which consists of the raw products of larger volume products from sand. It consists of a various types of materials which includes ceramics, polymers, sands, etc.[17] Finally the procedure of the binder jetting is very quick, low cost etc.

3. Material Extrusion

In 3D Printing technology it is mainly utilized to print different materials and in multiple colors of the living cells which is referred as material extrusion. This procedure is frequently utilized due to its lower cost.[18]

4. Material Jetting

The material jetting contains a print head dispenses droplets of a photosensitive material under the UV light. It consists of a finishing of a soft surface with higher dimensional accuracy Different material printing is utilizes different types of materials such as composite, ceramics, hybrids which is available.

5. Powder Bed Fusion

It consists of the electron beam melting, selective heat sintering[19] which is referred as powder bed fusion. There are some of the examples of the materials which is utilized in the metals, polymers, ceramics. In the year 1987 the SLS technology is developed by the scientist Carl Deckard.[20]

6. Sheet Lamination

The sheet lamination process consists of the 3D printing technologies which utilizes that the procedure is laminated. There are some of the benefits of the sheet lamination like it can do full color printing, low expensive etc. It has the capability of producing for manufacturing of the complicated geometrical parts.

Material used in 3D printed Microneedles

Material choice is an important part of the formulation.[21] It should be printable, have sufficient structural integrity to penetrate the skin, be compatible with the drug being encapsulated, remain stable during storage and be safe to have contact with the skin. Depending on the type of microneedle being produced will affect the material requirements. For dissolving microneedles the material needs to be strong enough prior to insertion but dissolve well once inserted. For hollow microneedles a strong material is required which has a channel. Hydrogel forming microneedles need to be hydrophilic and swell whilst having good structural integrity.[22]

Polyvinyl alcohol (PVA), polyvinylpyrrolidone (PVP), hyaluronic acid, gelatin, pullulan, carboxymethyl cellulose and various cellulose based polymers are commonly used within dissolving and swelling microneedles. This helps increase hydrophilicity and increase drug release. However, they are often hydrophilic and therefore can cause issues with mechanical strength and variations in viscosity. Structural and sustained release parts can be made using synthetic polymers. Polylactic-co-glycolicacid (PLGA), polylacticacid (PLA), polycaprolactone (PCL) and specific medical grade plastics can be used.[23] The degradation characteristics and processing will depend on material chosen. A material which could be used for a structural, rigid part may not be suitable for a drug loaded dissolving needle. Photocurable resins can be useful to produce high accuracy, detailed microneedles. However care needs to be taken when considering safety in medical applications. Monomers, photoinitiators, degradation products and extractables should be considered. A material may be deemed biocompatible for one application but not be suitable for long term skin contact, deeper skin penetration or different sterilization techniques.

Formulations Strageries for 3D- Printed Microneedles

Formulation Strageries I: Incorporating the Drug

The method of including the drug in the microneedles needs to be determined early on as will influence the printing and drug delivery.

1. Bulk Incorporation

The drug is included into the polymer solution, melted material or resin during printing.[24] This means the drug will be included throughout the microneedle or targeted areas. Can be used for drugs that are stable in solvents, heat, light and processing conditions. The drug needs to be well mixed.

2. Tip Loading

The drug is focused towards the tip of the microneedle[25] which will penetrate into the skin. The tip can be manufactured using a material containing the drug and the base using a stronger material without any drug. This means there will be less waste of the drug and more efficient drug delivery. However the bond between the two materials should be strong.

3. Surface Coating

A thin film of drug is coated onto the surface of pre-manufactured microneedles. The film thickness, flowability, drying conditions and good spreading properties will effect how much drug there is. If there is too much drug it may cause damage to the tip of the needle or cause the film to come away. If there is too little there may not be enough drug.

4. Post Printing

The drug is included after the microneedles have been printed. The microneedles are dipped into a drug solution or exposed to the drug.[26] However it may not spread evenly and may go into areas where you don't want it to. The final microneedle product should be tested to ensure the right amount of drug has been included; it has been spread evenly and delivered in the correct way.

Formulation Strategies II: Controlling Drug Release

Drug delivery from dissolvable microneedles occurs via hydration and subsequent polymer dissolution/degradation.[27]

Apart from theslowly dissolvable polymers wherethe drug is gradually released over a period of time, there are some formulation where by the drug is delivered in extended periods of time; however it is important that the materialused has good biocompatibility and stability in the skin.

Hydrogel microneedles work by absorbing interstitial fluid which causes the polymer to swellOnce hydrated the drug can pass through the microneedle from the drug reservoir attached to the tip into the skin. Depending on the design of the microneedle the structure can remain largely intact upon removal meaning there is a reduced chance of any polymer left in the tissue. Efficiency of drug delivery will depend on the degree of swelling, polymer structure, and degree of crosslinking and diffusion of the drug.

The drug formulation is generally stored in an external reservoir or contained within a syringe like system. The rate of drug delivery will depend on the size of the channels, viscosity of the formulation, the pressure applied and resistance from the tissue. If too much pressure is applied to deliver the drug this may cause leaking of the formulation or damage to the tissue. It is therefore important to consider the flow of the drug within the skin under physiological conditions.

Depending on the design of the microneedle the structure can remain largely intact upon removal meaning there is a reduced chance of any polymer left in the tissue.

Multilayer/multiphasic microneedles allow greater flexibility[28] as they can be used to keep incompatible components separate and deliver the drug in a controlled manner. One layer of the polymer can be designed to deliver an immediate dose of drug whilst the second layer can control the release of drug over a longer period of time. These more complex systems need to be investigated to ensure good adhesion between the layers, diffusion of the drug between the layers, consistency of dosing and incomplete drug release. The drug release profile should match the required therapeutic application and can be investigated using in vitro and ex vivo methods.

Formulation Strategies III: Biologics and Stability

Biologic therapeutics (Proteins, Peptides, vaccines and nucleic acid formulations) are very susceptible to high temperatures, organic solvents, light, mechanical stress, changes in PH and interfaces. Therefore incorporation into a thermally or chemically reactive Photo Polymer may have a negative impact. An effective approach to formulations of these sensitive drugs is to manufacture the microneedle matrix first and then incorporate the biologic using gentle conditions.[29] Using aqueous Polymer systems with additives such as carbohydrates, amino acids and buffers will help to protect the molecules. The type of additive should be considered in relation to the Properties of the drug itself. Controlling water content is also important in Polymer microneedles due to the effect it can have on their mechanical Properties and degradation.

Nucleic acid may also need Protection from enzymes. Therefore, analysis should look at the concentration of the drug and activity of the drug. The stability of the final formulation should be assessed. This should include looking at the appearance, mechanical Properties, drug content, degradation Products, water content, dissolution, drug release and biological

activity. Accelerated stability testing will give useful data on Potential degradation Pathways. Long term stability testing is required to determine the appropriate shelf life. To improve the stability of the Product, water Proof Packaging and desiccants may be included depending on the formulation requirements.

Recent Advances in 3D- Printed Microneedles

Recent research has shown an increase in the use of stereolithography (SLA) and digital light processing (DLP) There has been a great deal of interest in designing hollow microneedles with microchannels for transporting drugs. Many recent publications have looked to design microneedle systems with microchannels, fabrication methods, testing approaches and integration with microfluidics and electronics.

Another key research area is biodegradable and water soluble polymers. This has looked to improve bio-compatibility, mechanical robustness and dissolution properties. By combining polymers it may improve the mechanical properties. Other research areas include multi material printing, selective drug loading, bespoke design, responsive polymers, non-invasive sampling and integration of sensors. However many of these new systems are still being investigated for proof of concept.

A key aspect of recent research is moving from design and fabrication of microneedle prototypes to reproducible systems that can be taken forward. This has moved from being able to produce microneedles to ensuring that they can be manufactured consistently to produce microneedle patches. Recent reviews have been published in 2024 and 2025[30] providing an insight into these advances.

Pharmaceutical Applications

1. Vaccination

Microneedle patches have become a promising method for administrating vaccines due to their ability to deliver antigens to the layers of skin containing antigen presenting cells. Microneedle formulations which dissolve in the skin have been a popular area of research. The stability of antigens, correct dosage and storage temperatures should however be considered for each type of vaccine.

2. Diabetes and peptide pharmaceuticals

Insulin is an important peptide drug which cannot be administered orally due to it degrading in the gastrointestinal tract. Microneedles are therefore being researched as a method of delivering insulin and other peptide drug. There are also glucose responsive and externally controlled microneedles. being researched to provide a responsive drug delivery method. These are still in development however should be noted to be different to standard approved methods.

3. Other pharmaceutical applications

Microneedles may also be useful for delivering certain hormone drugs, analgesics and other pharmaceutical drugs via the transdermal route.[31] The amount of drug that can be loaded onto a microneedle patch will depend on multiple factors such as patch size, needle shape, drug solubility and loading method. This will not be useful for all drugs and so will not be a universal solution. Drugs that require high dosages or large volumes of liquid to be delivered quickly would not be suitable for this method.

Skin, Cancer and Cosmetic Application

Microneedle based drug delivery systems can be applied to skin to allow the delivery of drugs to specific regions of the skin. A range of skin related diseases are currently under investigation for treatment using microneedle platforms. These include acne vulgaris, scarring, hyperpigmentation, inflammatory skin disease, alopecia and wound healing.[32] Localised drug delivery could help to increase the concentration of drug at the site of action. This would reduce the amount of drug entering the systemic circulation. However, this will depend on the properties of the drug and the skin.

In cancer, studies are looking into delivering anti-cancer drugs, immunomodulatory drugs and nanoformulations locally to treat skin cancers and superficial cancerous lesions. However, this is still a novel field of researching. Tumours have complex biological propertiesmeaning that just getting the needle through and releasing the drug will not guarantee therapeutic effects. Extensive pre-clinical and clinical research would be required.

Microneedle platforms are being looked into within cosmetics and cosmeceuticals[33] to increase the penetration of specific the active ingredients, polymers and breakdown products needs to be considered.

Microneedle formulations can be developed to deliver antimicrobial, anti-inflammatory and regenerative drugs locally. This can aid in delivering drugs to the skin. significantly. This could result in a higher risk of microorganisms entering the site, irritation and unpredictable penetration of drug. The formulation would need to be designed, using suitable materials and assessed accordingly depending on the type of wound.

Diagnostic, Biosensing and Applications

Interstitial fluid is an important biological sample[34]which contains different chemicals that can be quantified; for example glucose, electrolytes and disease related biomarkers. Hollow and porous microneedles can allow small volumes of fluid to be obtained. whilst modification of the microneedle surface allows selective recognition of target chemicals.

By designing smart microneedle platforms by incorporating electrodes, optical sensors, microfluidics and wireless technology into microneedle arrays continuous monitoring of physiological factors can be achieved.3D printed microneedles give great design flexibility allowing bespoke devices to be manufactured with channels, reservoirs and sensor integrated. Research has shown that there is increasing integration of microneedle technology with diagnostic and biosensing capabilities.[35]

Biosensor performance should be assessed to ensure accurate, repeatable, selective and fast results are obtained. Therefore it is important that correct calibration, interpretation, compatibility and patient safety is taken into consideration when developing the device. When designing devices for both diagnostics and drug delivery there are further concerns. If the sensor fails the wrong dose of drug will be delivered. Therefore microneedle systems with integrated sensors need to have fail-safe mechanisms. Software should be reliable and any connected systems should have sufficient security. The whole platform needs to be thoroughly tested on patients.

Advantages of 3D printed Microneedles

This method has many benefits as the CAD software can be used to manipulate all the microneedle parameters.[36] These include changing the length, shape, spacing, channel design and patch designs. This can allow different models to be made and compared. Microneedle patches can be designed depending on the needs of the drug. Complex microneedle designs can be made that would not normally be feasible. Any design changes can be easily changed into a prototype without having to make a new mould. This can speed

up the early development of the formulations. This leads to less expenditure as many different designs won't need to be made. More efficient material usage can be achieved by additive manufacturing as only areas where polymers are needed can be printed. However, more material will beused due to the need for support structures, failed prints and reprocessing.

If the compound is suitable it can be administered trans dermally meaning it will not degrade in the gastrointestinal system and first pass metabolism in the liver.[37] Certain macromolecule therapeutics could also be administered using microneedles as they can penetrate through the skin barrier.

However, the overall performance of the 3D printed microneedles should still be considered. Additive manufacturing may not be a cheaper or quicker method for making products than traditional moulding methods especially for larger quantities. Having a highly accurate prototype may not mean that production will be accurate when scaled up. All formulations will need to be thoroughly tested to ensure they are patient friendly, accurately dosed and stable and effective.

Challenges and Limitations

The choice of materials can be an issue with 3D printed microneedles. Some printable polymers do not have enough mechanical strength, can be hygroscopic or may be incompatible with biological tissues. If the photo polymerization technique is used then any incomplete washing and curing may leave any residual reactive species[38] meaning they may not be as safe with biological systems. The use of a thermoplastic technique can cause any therapeuticagents to be exposed to high temperatures so may lose stability.

The accuracy and reproducibility can also be an issue. Small differences in the geometry could impact the penetration force of the microneedle, amount of drug delivered and drug release. High accuracy printing techniques require high investment and may not be as efficient as standard moulding techniques.

The drug loading can be an issue due to the small size of microneedles. They would be best suited to highly potent therapeutics. where only a small amount is needed to create a pharmacological effect. If a higher amount of drug is required then extra reservoirs may be required. Uneven drug distribution and drug migration during drying can impact the

consistent dosing of the drug. Protein and other sensitive therapeutics can be an issue as they need to remain bioactive throughout.[39]

Depending on the type of product, application and regulations microneedles can be seen as either a pharmaceutical product, medical device or combination product. Education of users, preventing accidental re-use, safe disposal of waste, good packaging and having safety monitoring after marketing will need to be considered.

Future Perspectives

The future development of 3D-printed microneedle devices requires collaboration between multiple disciplines, such as pharmaceutical technology, materials science, microtechnology, clinical science and regulatory science. Printers can be developed to provide increased precision and thus produce improved needle designs, accurate dimensions and improved internal channels. Using multi-material printing techniques, more rigid polymers can be combined with drug compatible polymers in specific areas of the microneedle design. Improved low temperature printing techniquescan also be used to increase print quality, and the incorporation of drugs after printing can help preserve the stability of therapeutics that are sensitive to heat/light.

Personalised microneedles are an exciting area of research. Using digital modeling techniques the size of the patch, number of microneedles and amount of drug loaded could be adjusted to meet individual requirements. Using artificial intelligence techniques, microneedle formulations can be optimized.

Microneedle designs can be modelled and monitoring of the printing process can be performed. Intelligent microneedles incorporating drugdelivery, sampling and sensing can be developed. Feedback drug delivery systems can be used to control the delivery depending on detected biomarkers.[40]

CONCLUSION

3D printed microneedles have become an exciting new method of delivering drugs through the skin in a minimally invasive manner .They offer many benefits including customisable designs, quick prototyping, internal channels and sensors can be inserted, and different drug loading and release methods can be studied. Some potential uses include vaccines, peptide delivery, skin treatments, cancer treatment, wound care, cosmetics and biosensors.

The development of microneedles requires accurate material choice, drug stability, accurate reproducible printing, strong mechanical properties, controlled release of drug, safe to biological systems and convincing clinical evidence. Future research should focus on using quality by design techniques during manufacture, standard testing and manufacturing at scale up.

REFERENCES

1. Hao Y, Li W, Zhou XL et al (2017) Microneedles-based transdermal drug delivery systems: a review. J Biomed Nanotechnol, 13(12): 1581–1597. https://doi.org/10.1166/jbn.2017.2474.
2. Yadav PR, Dobson LJ, Pattanayek SK et al (2022) Swellable microneedles based transdermal drug delivery: mathematical model development and numerical experiments. Chem Eng Sci 247: 117005. https://doi.org/10.1016/j.ces.2021.117005.
3. Boehm RD, Miller PR, Schell WA et al (2013) Inkjet printing of amphotericin b onto biodegradable microneedles using piezoelectric inkjet printing. JOM, 65(4): 525–533. https://doi.org/10.1007/s11837-013-0574-7.
4. Cahill EM, Keaveney S, Stuettgen V et al (2019) Metallic microneedles with interconnected porosity: a scalable platform for biosensing and drug delivery. Acta Biomater 86: 493–495. https://doi.org/10.1016/j.actbio.2018.09.007.
5. Cai B, Xia W, Bredenberg S et al (2015) Bioceramic microneedles with flexible and self-swelling substrate. Eur J Pharm Biopharm, 94: 404–410. https://doi.org/10.1016/j.ejpb.2015.06.016.
6. Caudill CL, Perry JL, Tian S et al (2018) Spatially controlled coating of continuous liquid interface production microneedles for transdermal protein delivery. J Control Release 284: 122–132. https://doi.org/10.1016/j.jconrel.2018.05.042.
7. Chen DS, Mellman I (2013) Oncology meets immunology: the cancer-immunity cycle. Immunity, 39(1): 1–10. https://doi.org/10.1016/j.immuni.2013.07.012.
8. Chen X, Prow TW, Crichton ML et al (2009) Dry-coated microprojection array patches for targeted delivery of immunotherapeutics to the skin. J Control Release, 139: 212–220. https://doi.org/10.1016/j.jconrel.2009.06.029.
9. Chen J, Qiu Y, Zhang S et al (2016a) Dissolving microneedle-based intradermal delivery of interferon-α-2b. Drug Dev Ind Pharm, 42(6): 890–896. https://doi.org/10.3109/03639045.2015.1096282.

10. Chen MC, Lin ZW, Ling MH (2016b) Near-infrared light-activatable microneedle system for treating superficial tumors by combination of chemotherapy and photothermal therapy. ACS Nano, 10(1): 93–101. https://doi.org/10.1021/acsnano.5b05043.
11. Geethu Madhusoodanan, Amrita Arup Roy, Tejaswini Kalkundri, Namitha K. Preman, Komal Rana, Deepanjan Datta, Namdev Dhas, Srinivas Mutalik; Evolving transdermal therapeutics: a review on self-dissolving polymeric microneedles via 3D printing. RSC Adv, 2025; 15(40): 33312–33335. https://doi.org/10.1039/d5ra05275k.
12. Prausnitz MR, Langer R (2008) Transdermal drug delivery. Nat Biotechnol, 26(11): 1261–1268. https://doi.org/10.1038/nbt.1504.
13. Kovacik A, Kopecna M, Vavrova K (2020) Permeation enhancers in transdermal drug delivery: benefits and limitations. Expert Opin DrugDeliv, 17(2): 145–155. https://doi.org/10.1080/17425247.2020.1713087.
14. Al Hanbali OA, Khan HMS, Sarfraz M et al (2019) Transdermal patches: design and current approaches to painless drug delivery. Acta Pharm, 69(2): 197–215. https://doi.org/10.2478/acph-2019-0016.
15. Bhatnagar S, Gadeela PR, Thathireddy P et al (2019) Microneedle-based drug delivery: materials of construction. J Chem Sci., 131: 90. https://doi.org/10.1007/s12039-019-1666-x.
16. Aldawood FK, Andar A, Desai S (2021) A comprehensive review of microneedles: types, materials, processes, characterizations and applications. Polymers, 13(16): 2815. https://doi.org/10.3390/polym13162815.
17. Li WZ, Huo MR, Zhou JP et al (2010) Super-short solid silicon microneedles for transdermal drug delivery applications. Int J Pharm, 389(1): 122–129. https://doi.org/10.1016/j.ijpharm.2010.01.024.
18. Kim S, Shetty S, Price D et al (2006) Skin penetration of silicon dioxide microneedle arrays. In: International Conference of the IEEE Engineering in Medicine and Biology Society, p.4088–4091. https://doi.org/10.1109/IEMBS.2006.260142.
19. Liu H, Nail A, Meng D, Zhu L, Guo X, Li C, Li HJ. Recent progress in the 3D printing of microneedle patches for biomedical applications. Int J Pharm, 2025; 668: 124995. https://doi.org/10.1016/j.ijpharm.2024.124995.
20. Aldawood FK, Parupelli SK, Andar A, Desai S. 3D printing of biodegradable polymeric microneedles for transdermal drug delivery applications. Pharmaceutics, 2024; 16(2): 237. https://doi.org/10.3390/pharmaceutics16020237.

21. Ghaznavi A, Xu J, Lee CU, Hara SA. 3D-printed hollow microneedles array with Luer lock connection for facile and painless intradermal injection: a proof of concept. Adv Mater Technol, 2024; 9(18): 2400286. https://doi.org/10.1002/admt.202400286.
22. Lijnse T, Mendes M, Shu W, O'Cearbhaill ED. Low-cost fabrication of digital light processing 3D printed conical microneedles for biomedical applications. Appl Mater Today, 2024; 41: 102482. https://doi.org/10.1016/j.apmt.2024.102482.
23. Ghaznavi A, Alavi S, Lin Y, Hara SA, Gemeinhart RA, Xu J. 3D printed hollow microneedles for dermal and transdermal drug delivery: design, fabrication, application, and perspective. Mol Pharm, 2025; 22(6): 2747-2764. https://doi.org/10.1021/acs.molpharmaceut.4c01261.
24. Razzaghi M, Akbari M. 3D printed hollow microneedles: the latest innovation in drug delivery. Expert Opin Drug Deliv, 2025; 22(10): 1487-1507. https://doi.org/10.1080/17425247.2025.2531062.
25. Luo X, Yang L, Cui Y. Microneedles: materials, fabrication, and biomedical applications. Biomed Microdevices, 2023; 25: 20. https://doi.org/10.1007/s10544-023-00658-y.
26. Hong X, Wei L, Wu F, Wu Z, Chen L, Liu Z, Yuan W. Dissolving and biodegradable microneedle technologies for transdermal sustained delivery of drug and vaccine. Drug Des Devel Ther, 2013; 7: 945-952. https://doi.org/10.2147/DDDT.S44401.
27. Lee JW, Park JH, Prausnitz MR. Dissolving microneedles for transdermal drug delivery. Biomaterials, 2008; 29(13): 2113-2124. https://doi.org/10.1016/j.biomaterials.2007.12.048.
28. Kim YC, Park JH, Prausnitz MR. Microneedles for drug and vaccine delivery. Adv Drug Deliv Rev, 2012; 64(14): 1547-1568. https://doi.org/10.1016/j.addr.2012.04.005.
29. Prausnitz MR. Microneedles for transdermal drug delivery. Adv Drug Deliv Rev, 2004; 56(5): 581-587. https://doi.org/10.1016/j.addr.2003.10.023.
30. Prausnitz MR, Mitragotri S, Langer R. Current status and future potential of transdermal drug delivery. Nat Rev Drug Discov, 2004; 3(2): 115-124. https://doi.org/10.1038/nrd1304.
31. Cheung K, Das DB. Microneedles for drug delivery: trends and progress. Drug Deliv, 2016; 23(7): 2338-2354. https://doi.org/10.3109/10717544.2014.986309.
32. Indermun S, Luttge R, Choonara YE, Kumar P, du Toit LC, Modi G, Pillay V. Current advances in the fabrication of microneedles for transdermal delivery. J Control Release, 2014; 185: 130-138. https://doi.org/10.1016/j.jconrel.2014.04.052.

33. Sabri AH, Kim Y, Marlow M, Scurr DJ, Segal J, Banga AK, Kagan L, Lee JB. Intradermal and transdermal drug delivery using microneedles: fabrication, performance evaluation and application to lymphatic delivery. Adv Drug Deliv Rev, 2020; 153: 195-215. https://doi.org/10.1016/j.addr.2019.10.004.
34. Wang Y, Wu Y, Lei Y. Microneedle-based glucose monitoring: a review from sampling methods to wearable biosensors. Biomater Sci, 2023; 11(17): 5727-5757. https://doi.org/10.1039/D3BM00409K.
35. Kim G, Ahn H, Ulloa JC, et al. Microneedle sensors for dermal interstitial fluid analysis. Med-X, 2024; 2: 15. https://doi.org/10.1007/s44258-024-00028-0.
36. Mansoor I, Eassa HA, Mohammed KHA, et al. Microneedle-based vaccine delivery: review of an emerging technology. AAPS PharmSciTech, 2022; 23(4): 103. https://doi.org/10.1208/s12249-022-02250-8.
37. Shin CI, Jeong SD, Rejinold NS, Kim YC. Microneedles for vaccine delivery: challenges and future perspectives. Ther Deliv, 2017; 8(6): 447-460. https://doi.org/10.4155/tde-2017-0032.
38. van der Maaden K, Jiskoot W, Bouwstra J. Microneedle technologies for (trans)dermal drug and vaccine delivery. J Control Release, 2012; 161(2): 645-655. https://doi.org/10.1016/j.jconrel.2012.01.042.
39. Sanjanwal D, Shinde A, Patravale V. Formulation, sterilization, and clinical evaluation of microneedles for vaccine and biologic delivery: a review. Int J Pharm, 2025; 682: 125874. https://doi.org/10.1016/j.ijpharm.2025.125874.
40. Kim G, Ahn H, Ulloa JC, et al. Microneedle-based biosensing. Nat Rev Bioeng, 2024; 2: 64-81. https://doi.org/10.1038/s44222-023-00108-7.30. Prausnitz MR, Mitragotri S, Langer R. Current status and future potential of transdermal drug delivery. Nat Rev Drug Discov, 2004; 3(2): 115-124. https://doi.org/10.1038/nrd1304.