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Microneedles for advanced drug delivery: a short review

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ABSTRACT

Microneedles represent an innovative and minimally invasive modality for drug administration, effectively addressing the limitations of conventional techniques such as hypodermic injections and topical applications. These instruments penetrate the stratum corneum without activating nociceptive nerve endings, thereby enabling painless delivery of both low- and high-molecular-weight pharmacological agents. Fabricated from diverse materials (including polymers, metals, and ceramics), microneedles can be engineered in various forms: solid, hollow, coated, and dissolvable. Each type offers distinct advantages for systemic drug delivery and targeted localized treatments. The clinical applications of microneedles span multiple disciplines, including dermatology, vaccination, wound healing, ocular therapy, oncology, and cosmetic procedures. Despite their promise, challenges remain in material selection, drug encapsulation, and manufacturing scalability. Continued advancements in microneedle technology signal substantial potential for enhancing patient adherence, improving therapeutic precision, and reducing adverse effects. This review outlines recent developments in microneedle systems, highlighting design classifications, fabrication methods, constituent materials, and pharmaceutical applications.

1. Introduction

The oral route remains the oldest and most convenient method of drug administration, offering acceptable ease for patients. However, its long-term use is associated with systemic side effects, particularly impacting vital organs such as the liver and the kidneys[1]. Microneedles significantly enhance formulation permeability – includ-

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ing ointments, creams, lotions, gels, liniments, matrix systems, reservoir systems, and foams – thus improving transdermal drug delivery[2]. Conventional skin-based delivery methods, such as hypodermic needles and topical creams, present limitations: needles often cause patient discomfort, while topical formulations suffer from low bioavailability. The skin's structure acts as a robust barrier, permitting only lipophilic and low-molecular-weight drugs to penetrate it. This restricts formulation efficacy and presents considerable challenges in topical drug design. Among emerging solutions, microneedles stand out by overcoming these intrinsic barriers and formulation challenges[3]. Transdermal delivery offers additional advantages, such as reducing systemic organ involvement and enabling sustained drug release[1]. This review examines the rising interest in microneedles as novel transdermal delivery systems, with particular attention to their potential in vaccine administration.

2. Characteristics of microneedles

Microneedles are designed to penetrate the epidermis at depths ranging from 70 to 200 μm. Their short, slender geometry prevents contact with dermal nerves, thereby enabling painless administration of pharmaceutical agents[2]. These devices are fabricated from various materials, including silicon, titanium, stainless steel, and biocompatible polymers. Microneedle systems support the delivery of both small and large therapeutic agents, ranging from conventional drugs and proteins to genetic materials and nanomedicines. Owing to their structural adaptability and minimal invasiveness, microneedles are regarded as highly versatile tools that are less painful, safer, and less damaging than traditional needle-based technologies[3].

3. Categorization of microneedles

3.1. Solid microneedles

Solid microneedles facilitate skin pre-treatment by forming micron-sized pores. Their pointed tips penetrate the epidermis in order to create microchannels, thereby enabling subsequent drug delivery *via* patches and improving drug permeation. Once absorbed into capillaries, the drug may exert systemic or localized effects. Solid microneedles, commonly used in dermatology for collagen induction therapy, enhance bioavailability and mechanical strength through passive diffusion. Stainless steel variants have demonstrated improved efficacy in delivering drugs such as captopril and metoprolol tartrate[3].

3.2. Hollow microneedles

Hollow microneedles deliver liquid formulations through a central bore and are typically fabricated from stainless steel, silicon, or glass. With dimensions ranging from 27 to 35 gauge and lengths starting at 150 μm, they are significantly smaller than conventional hypodermic needles (2 mm or longer; 26–30 gauge)[4]. These microneedles are primarily used in order to administer high-molecular-weight substances, including proteins, vaccines, and oligonucleotides[3].

3.3. Coated or layered microneedles

Coated microneedles use the "coat and poke" technique, in which a drug formulation is applied to the surface of solid microneedles. Upon insertion into the skin, the coating dissolves, rapidly releasing the therapeutic agent. This method is suitable for the delivery of macromolecules such as vaccines, proteins, peptides, and DNA. Despite its simplicity and efficiency, the approach is limited by the small quantity of drug that can be coated, thereby restricting its use to potent molecules[5].

3.4. Dissolving microneedles

Dissolving microneedles are fabricated from biodegradable polymers that encapsulate the drug within the microneedle structure. Upon skin insertion, the microneedles dissolve, releasing the drug without the need for removal. Controlled degradation of the polymer matrix enables sustained drug delivery, making this design particularly advantageous for long-term

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therapies. The use of non-toxic, biocompatible polymers also supports improved patient adherence[3].

4. Materials for microneedles

4.1. Metal materials

Metals are extensively used in the production of solid, coated, and hollow microneedles. Commonly employed metals include stainless steel, gold, platinum, titanium, nickel, and iron[2]. Stainless steel and titanium are especially prevalent due to their favourable mechanical properties. However, one major concern is the potential for microneedle fracture within the dermis, which poses safety risks and necessitates the exploration of alternative materials. Additionally, metal microneedles may trigger allergic responses in susceptible individuals[1].

4.2. Inorganic materials

Inorganic substances such as silicon, glass, and ceramics are often used in order to manufacture solid, coated, and hollow microneedles. While these materials offer precision in fabrication, limitations exist (including incompatibility with biological membranes and the potential for fragment breakage, particularly with silicon), thus narrowing their practical applicability[2].

4.3. Polymeric materials

Polymers present highly attractive alternatives for microneedle fabrication due to their excellent biocompatibility, biodegradability, and minimal toxicity[6]. Biodegradable polymers such as polylactic acid and polyglycolic acid enable safe drug release and environmental breakdown, while non-degradable polymers like photolithographic epoxy offer structural rigidity for specific applications[7].

5. Applications of microneedles

5.1. Disease diagnosis

Microneedles enhance diagnostic capabilities by accessing serum inhibitory factors through epidermal penetration. Metabolites derived from the serum interstitial fluid serve as potential biomarkers for the detection of health conditions, including cancer and cardiovascular diseases[3].

5.2. Drug and vaccine delivery

Microneedles enable direct drug administration into the bloodstream, thereby supporting controlled release and improved therapeutic efficacy[8]. Extensive research has explored microneedle-based techniques for combating pathogens such as influenza, measles, poliovirus, rotavirus, adenovirus, the Calmette-Guérin bacillus, botulinum toxin, as well as hepatitis B and C[9].

5.3. Ocular therapy

In retinal disease treatment, microneedles allow precise drug delivery to the sclera or suprachoroidal space, thereby minimizing systemic exposure. They are employed in order to administer anti-inflammatory and anti-glaucoma agents for the management of ocular inflammation and intraocular pressure[4].

5.4. Cancer therapy

Microneedles facilitate the administration of chemotherapeutic agents such as paclitaxel and gemcitabine in breast cancer therapy. Various microneedle systems have been employed in treating superficial malignancies[8].

5.5. Cosmetic applications

Widely used in dermatological and cosmetic procedures, microneedles promote skin rejuvenation and hair growth. Notable examples include dissolvable patches delivering ascorbic acid and retinyl retinoate[1]. Their growing significance in dermatology addresses conditions ranging from skin blemishes to aesthetic enhancement[9].

6. Advantages of microneedles

Microneedle arrays enable targeted skin delivery by penetrating the stratum corneum and accessing the dermis[6]. Their ease of use permits self-administration with minimal training, while minimizing pain and enhancing patient compliance. The reduced invasiveness supports faster recovery, mitigates infection risk, and facilitates efficient wound healing. Microneedles inflict minimal skin damage, thereby lowering the chance of bacterial entry and adverse cutaneous responses[3].

7. Challenges of microneedle fabrication

Although polymeric microneedles are increasingly favoured, they present fabrication challenges such as mechanical instability under stress and difficulties in achieving precise geometries[1]. Silicon microneedles exhibit brittleness, which may cause fractures during skin insertion and provoke foreign body reactions like abscesses or granuloma formation. Conventional manufacturing techniques (including molding and etching) are often labour-intensive, costly, and offer limited scalability[7].

Drug delivery *via* microneedles primarily relies on passive diffusion into the dermis. Administering large drug volumes remains problematic, as considerable loss may occur at the epidermal surface. In vaccine delivery, dosage inconsistencies can reduce bioavailability and impair immune response[10]. Moreover, safety evaluation is essential in clinical trials, focusing on variables such as skin irritation, sensitization, and immune response. Erythema is a noted adverse effect. Improper microneedle application may result in the retention of foreign materials, thereby increasing the risk of infection. Additional concerns include allergic reactions, cutaneous irritation, and restricted drug-loading capacities[3].

8. Conclusion

Microneedles represent a pivotal innovation in drug delivery, offering numerous advantages including pain-free administration, improved patient adherence, and enhanced therapeutic precision. Their versatility in material composition and manufacturing techniques enables customizable designs tailored to diverse clinical needs. Nonetheless, critical challenges (such as material refinement, safety assessment, and drug loading efficacy) must be addressed in order for them to realize their full potential.

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Conflicts of interest

None exist.

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