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Structural Study on Stretchable Interdigitated Electrodes for Transdermal Drug Delivery via Skin Electroporation

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Abstract

Aiming at the problems of traditional skin electroporation electrodes that the electric field easily diffuses to deep tissues and rigid electrodes have poor adaptability, this study introduced the interdigitated structure into electrode design. A short-range current path was constructed via the interlaced finger array to realize precise electric field regulation, which generates an effective electroporation electric field only in the stratum corneum and greatly reduces the risk of stimulation to deep tissues. To address the defect of a sharp rise in resistance of linear interdigitated electrodes under stretching, the electrode was optimized into a serpentine stretchable structure. The geometric redundancy of this structure was utilized to release stress, which significantly improved the electrical stability and mechanical reliability of the electrode under dynamic skin deformation. In addition, a wearable electroporation electrode adapted to facial skin was designed, which provides a safe and efficient flexible device solution for transdermal penetration enhancement in aesthetic medicine and clinical drug delivery.

Keywords: skin electroporation, interdigitated structure, structural optimization

1. Typical Application Scenarios of Interdigitated Structures

Interdigitated electrodes are planar structures composed of two sets of comb-shaped microelectrodes that are interlaced with each other, insulated from one another and arranged periodically. Owing to their advantages such as concentrated electric field, sensitive capacitive response, large interfacial contact area and easy flexibilization of the structure, they are widely applied in various fields including electrochemical detection, flexible sensing, wearable electronics, biomedical detection and transdermal electrical stimulation (Shayma Habboush et al., 2024; Elyana Kosri et al., 2022; Jianqun Cheng et al., 2025; S. Yao et al., 2017). With the rapid development of flexible electronics and wearable medical devices, interdigitated structures are no longer limited to traditional rigid substrates, but are gradually combined with flexible materials such as PDMS, Ecoflex, hydrogels and non-woven fabrics. They have become the core electrode configuration for achieving conformal skin contact and play a pivotal role in the integrated development of flexible electronic devices.

1.1 Electrochemical Sensing and Biological Detection

In the field of electrochemical sensing, interdigitated electrodes are important structural units for constructing high-sensitivity biochemical sensors. Due to the extremely small spacing between adjacent finger strips, the electrodes can generate a high-density local electric field in the gap area after voltage application, which significantly improves the efficiency of electrochemical reactions. Meanwhile, the interlaced structure greatly increases the effective contact area between the electrodes and the test solution, enabling the sensor to maintain a high response intensity even in the detection of low-concentration analytes.

Based on the above advantages, interdigitated electrodes are commonly applied in glucose sensors, lactate sensors, pH sensors, ion-selective sensors and immunosensors, which can realize the rapid, non-invasive and continuous monitoring of biomarkers in sweat, tear and interstitial fluid. In wearable health monitoring systems, flexible interdigitated electrodes can closely conform to the skin surface and provide stable and reliable detection signals for chronic disease management and daily health status assessment. Relevant research has achieved preliminary applications in scenarios such as blood glucose monitoring for diabetes.

1.2 Flexible Electronics and Wearable Strain Sensing

Interdigitated structures possess inherent geometric ductility, making them highly suitable for flexible and stretchable electronic devices. By combining interdigitated electrodes with elastic polymer substrates, high-sensitivity strain sensors, pressure sensors, temperature sensors and electronic skin devices can be fabricated. When an external stress is applied to the electrodes, the relative displacement in the interlaced regions of the fingers induces a change in the overall capacitance or resistance of the electrodes, thus enabling the accurate capture of micro-deformations.

In scenarios such as human motion monitoring, rehabilitation medicine and human-computer interaction, flexible interdigitated sensors can adapt to complex deformations including joint bending, muscle stretching and skin compression, while maintaining a stable signal output. In addition, interdigitated structures can be fabricated via micro-nano processing methods such as photolithography, printing and etching, and are easy to array and integrate. This provides a feasible implementation approach for high-density and multi-functional electronic skin systems, and drives the rapid development of flexible wearable electronic technology.

2. Innovative Design of Interdigitated Electrodes: Reducing Damage to Deep Skin Tissues

2.1 Introduction

Currently, there are three primary routes for drug administration, namely oral administration, injection, and transdermal delivery. Compared with traditional oral and injection therapies, transdermal delivery can bypass gastrointestinal absorption and the first-pass effect, while avoiding the discomfort caused by needle pricks. Traditional plasters represent a typical transdermal delivery approach, yet they face the challenge of the natural barrier formed by the skin stratum corneum and its hydrophobic properties. This barrier greatly limits the transdermal absorption of most drug molecules, especially macromolecular and water-soluble drugs, resulting in low transdermal delivery efficiency. To improve the efficacy of transdermal drug absorption, researchers have developed a series of advanced technologies, including iontophoresis, sonophoresis, microneedle technology, chemical enhancers, and electroporation. Among these methods, electroporation stands out due to its unique advantages. Electroporation technology can facilitate the smooth penetration of drug molecules with different molecular weights through the skin barrier, boasting a wider scope of application. The equipment for this technology features a simple structure, mainly consisting of a power supply capable of generating high-voltage pulses and appropriate electrodes, thus achieving low manufacturing costs. In addition, owing to its non-invasive nature, electroporation reduces the risk of infection and provides a safe mode of drug delivery.

In electroporation, the transdermal transport of drugs can be enhanced by applying high-voltage pulses exceeding the breakdown potential of the stratum corneum, which induces the formation of transient pores in the lipid bilayers of the stratum corneum. However, the application of such high-voltage pulses inevitably brings about certain problems. Primarily, the deep skin tissues are also affected by the high voltage, which may cause sensations ranging from mild stinging to severe pain, as well as obvious muscle contractions and transient erythema (A.-R. Denet, R. Vanbeverand & V. Préat, 2004; Y. Zhang, J. Yu, A.R. Kahkoska et al., 2019; Jos, eacute, J. Escobar-Ch et al., 2009; Kevin Ita, 2016; V. Preatand & R. Vanbever, 2003; R. Vanbeverand & V. Préat, 1999). These phenomena undoubtedly exert a negative impact on patients' treatment experience. Therefore, careful optimization of electrode structure is crucial for reducing adverse side effects. A skin electroporation device should only target the outermost layer of the skin and exert no effect on deep tissues.

2.2 Design of the Interdigitated Structure

The core innovation of this study is the innovative introduction of the interdigitated structure into the design of skin electroporation electrodes, which achieves precise spatial regulation of electric field distribution from the root of structural design. It successfully confines the electrical effects of electroporation strictly to the stratum corneum at the skin surface, fundamentally obviating issues such as neuromuscular stimulation and tissue damage caused by the electric field diffusing into deep tissues with traditional electroporation electrodes, and thus greatly improving the safety and comfort of transdermal drug delivery.

An interdigitated electrode consists of two arrays of finger-shaped electrodes with opposite polarities arranged in an interlaced pattern. When a pulsed electroporation voltage is applied, this unique structural layout enables the formation of an extremely short current transmission path between adjacent positive and negative finger strips. The current flows out from the positive electrode and quickly completes the circuit at the adjacent negative electrode, without irregular propagation into the deep layers of the skin. Based on this structural characteristic, the electric field intensity generated by the electrode shows a rapid attenuation trend with the increase in skin depth, forming a gradient electric field distribution feature of "strong at the surface, weak in the deep". The stratum corneum on the skin surface is exactly the core barrier for transdermal drug penetration, and this region requires a sufficiently strong electric field to realize the electroporation of lipid bilayers, thereby opening up channels for transdermal drug transport. For the dermis and subcutaneous tissues, benefiting from the electric field regulation of the interdigitated electrode, the electric field intensity there is precisely controlled below the threshold of nerve excitation and muscle contraction. This design not only meets the core requirement of electroporation-mediated penetration enhancement in the stratum corneum but also completely avoids excessive electrical stimulation to deep tissues, achieving dual optimization of electroporation penetration enhancement efficiency and tissue safety.

To intuitively verify the advantages of the interdigitated electrode in electric field regulation, this study designed two electrode structures—the traditional serpentine grid electrode and the interdigitated electrode—and conducted a comparative analysis via COMSOL finite element simulation. The structural designs of the two electrodes are shown in Figure 1.

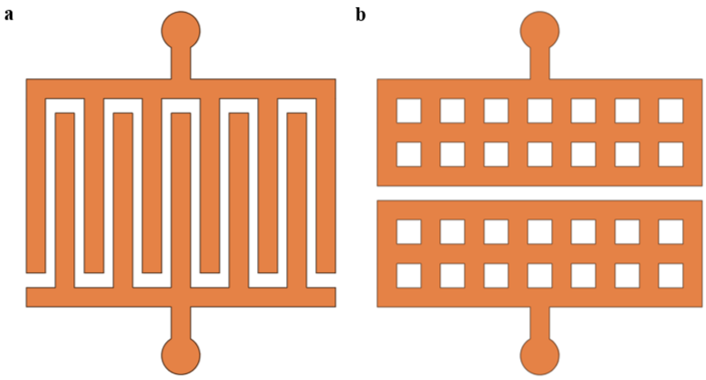

Figure 1. Two circuit models of conductive ink electrodes

(a) Traditional serpentine structure circuit. (b) Interdigital structure circuit.

During the simulation, the two electrode structures were attached to the surface of the skin model to simulate the electric field distribution. Referring to the physiological structure of human skin, the skin model was constructed as a four-layer structure consisting of the stratum corneum, epidermis, dermis and subcutaneous tissue, with the electrical parameters listed in Table 1.

Table 1. Skin parameters in the FEA

Components	Stratum corneum	Epidermis	Dermis	Hypodermis
Conductivity (S/m)	10^{-5}	2.0408×10^{-4}	2.0408×10^{-4}	0.02383
Relative dielectric constant	86	1130.6	1133.6	1085.3
Thickness (mm)	0.02	0.061	1.0	2.919

The simulation focused on observing and comparing the voltage distribution characteristics on the skin surface under the action of the two electrodes, as well as the attenuation law of voltage signals along the depth direction of the skin. The specific simulation method was as follows: the AC/DC module of COMSOL simulation software was adopted in this study, with the DC physical field selected for steady-state modeling; after the two electrode structures were precisely attached to the skin model, a DC voltage of ±100 V was applied to the two circular power supply terminals of the electrodes, respectively, and the domain point probe function of the software was used to accurately extract voltage data at different positions on the skin surface and at different skin depths. The simulation results are shown in Figure 2: the two electrodes exhibited similar voltage levels at the skin surface, which is exactly the core barrier impeding drug penetration; upon entering the dermis, the voltage of the interdigitated electrode was significantly lower than that of the traditional serpentine grid electrode; in the subcutaneous tissue layer, the voltage of the interdigitated electrode dropped to nearly 0 V, causing no electrical stimulation to the deep muscle tissue and thus greatly improving the safety. The above results indicate that the interdigitated electrode can effectively confine the electrical effect to the skin surface, avoiding damage to deep tissues while achieving efficient transdermal penetration enhancement.

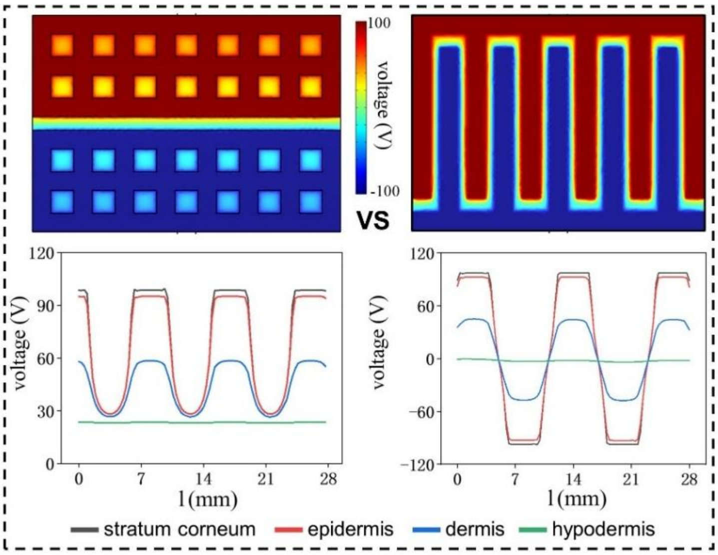

Figure 2. Simulated voltages generated by two models on the skin surface and at different skin depths (i.e., stratum corneum, epidermis, dermis, and hypodermis) via finite element analysis (FEA)

3. Material Selection and Structural Optimization of Interdigitated Electrodes

3.1 Key Limitations of Copper Foil as an Electrode Material

Copper foil was commonly used as the material for interdigitated electrodes in the fabrication of early prototypes due to its excellent electrical conductivity, easy availability and processability. However, in flexible wearable electroporation systems, the inherent material properties of copper foil result in multiple insurmountable limitations in practical applications.

First, copper foil features a high modulus, high rigidity and limited ductility, which makes it highly prone to plastic deformation and microcracks under repeated tensile and bending cycles, leading to electrode fracture and even complete failure during long-term use. Second, the interfacial adhesion between copper foil and polymer substrates is weak. Under the action of skin sweat, sebum and motion friction, the electrode edges are liable to warp, wrinkle and even delaminate, which causes poor skin-electrode contact and impairs the stability of electric field distribution. Third, copper is susceptible to oxidation and corrosion in humid environments, upon immersion in sweat or contact with skin secretions, forming products such as copper oxide and basic copper carbonate. This not only degrades the electrical conductivity of the electrodes but may also release copper ions, which irritate sensitive skin and trigger adverse reactions such as contact dermatitis, erythema and pruritus, meaning its biocompatibility fails to meet the requirements for long-term wearable use. In addition, it is difficult to fabricate high-precision serpentine microstructures on copper foil via low-cost printing methods; complex processes such as etching and lamination are usually required, which is not conducive to large-area, mass and low-cost production.

In summary, copper foil electrodes have obvious shortcomings in terms of flexibility, stretchability, biocompatibility and long-term stability, and thus cannot meet the practical application requirements of the new generation of wearable electroporation devices.

3.2 Feasibility of Adopting Conductive Inks in Subsequent Research

To address the inherent limitations of copper foil electrodes, flexible conductive inks can be adopted as alternative materials in subsequent research, such as graphene-based conductive inks, carbon nanotube-based conductive inks, and silver nanoparticle/nanowire conductive inks. Such materials exhibit excellent flexibility, stretchability, film-forming ability and printability, and enable the direct fabrication of high-precision serpentine interdigitated structures on flexible substrates via screen printing, inkjet printing, blade coating and other methods, with strong adhesion to substrates and resistance to delamination. Meanwhile, carbon-based conductive inks (e.g., graphene-based inks) possess good chemical stability and biocompatibility, with no risk of metal ion leaching and no irritation to the skin, making them suitable for prolonged skin attachment. Under tensile deformation, the conductive fillers inside the conductive inks can maintain a stable conductive path through slipping, contact and network reconstruction, with a much lower resistance variation than copper foil, which makes them more adaptable to the dynamic skin environment.

Referring to the existing study *Stretchable Electronic Facial Masks for Transdermal Drug Delivery via Electroporation* (X. Xu, L. Guo, H. Liu et al., 2023), the stretchable electronic facial mask proposed in this research can achieve efficient electroporation-mediated transdermal penetration enhancement while conforming to the facial skin, significantly improving the transdermal absorption efficiency of essence ingredients. Inspired by this, conductive inks can be used as the electrode material for transdermal penetration enhancement in the follow-up research of this paper.

3.3 Structural Optimization of Interdigitated Electrodes: From Linear to Serpentine Configuration

Although linear interdigitated electrodes exhibit distinct advantages in electric field distribution, they suffer from insufficient mechanical stability in the dynamic human body environment. The human skin undergoes complex deformations such as stretching during daily activities, with the tensile strain of the skin reaching 15%–25% especially in areas such as joints and the neck. The finger strips of linear interdigitated electrodes extend in a single direction, leading to significant stress concentration under stretching; this easily causes microcrack propagation, a sharp rise in resistance and even complete fracture, resulting in device failure.

To address this issue, the interdigitated electrode was structurally optimized in this study, with the linear interdigitated design modified into a serpentine stretchable configuration. The serpentine structure relieves external tensile stress through its continuously curved geometric configuration, which causes the electrode to undergo mainly unfolding deformation of the curved units under stretching rather than tensile deformation of the electrode material itself, thus greatly enhancing the overall ductility and fracture resistance of the electrode.

To verify the optimization effect, a finite element simulation software was used to conduct a coupled mechanical and electrical simulation of linear and serpentine interdigitated electrodes. In the simulation, conductive ink was set as the electrode material, uniaxial tensile strains of different levels were applied, and the resistance variation law of the electrodes was analyzed.

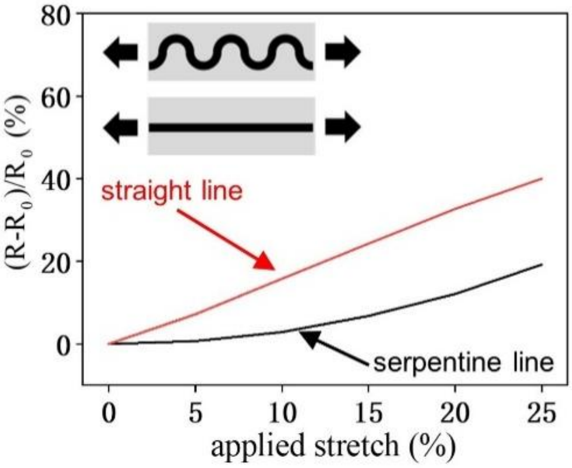

Figure 3. The relative resistance changes of the two patterns in the 0%-25% stretching range were obtained by FEA

The simulation results (Figure 3) indicated that with the increase in tensile strain, the serpentine configuration exhibited a smaller relative resistance change compared with the linear configuration. This phenomenon is attributed to the additional path length and curved structure of the serpentine configuration, which provide the electrode with greater geometric redundancy. When the material is subjected to stretching, these redundant parts can unfold to accommodate the deformation, thereby effectively mitigating the increase in resistance. In contrast, stretching directly elongates the conductive tracks of the linear configuration, leading to a substantial rise in resistance. Through structural optimization, the electrode can deform conformally with the skin, maintain good contact and stable electric field output, which provides a crucial guarantee for its application in high-movement areas such as joints and the face.

In this study, the optimized serpentine interdigitated electrode structure was integrally designed with a flexible mask substrate to fabricate a dedicated interdigitated electrode for wearable electroporation masks (Figure 4). This electrode device combines the dual advantages of the interdigitated structure and the serpentine configuration: it relies on the shallow electric field regulation characteristic of the interdigitated electrode to precisely confine the electrical effect of electroporation to the skin surface, fundamentally avoiding electrical stimulation and damage to deep skin tissues; meanwhile, by virtue of the high ductility and tensile resistance of the serpentine configuration, it well adapts to the dynamic skin deformation caused by facial expressive movements and maintains tight conformal contact between the electrode and the skin at all times. If flexible conductive inks such as graphene-based and carbon nanotube-based inks are adopted to replace traditional rigid electrode materials in the follow-up, the flexible fit and skin contact comfort of the electrode can be further improved, optimizing the wearable experience. The design of this serpentine interdigitated electrode can not only be directly applied to transdermal penetration enhancement scenarios in the aesthetic medicine field to achieve efficient transdermal delivery of essence ingredients and active factors, but also be extended to clinical treatment fields such as local anti-inflammation, analgesia, and targeted drug delivery for arthritis. It provides a novel structural solution for the research and industrial transformation of flexible wearable electroporation transdermal drug delivery devices, and has broad academic research value and practical application prospects.

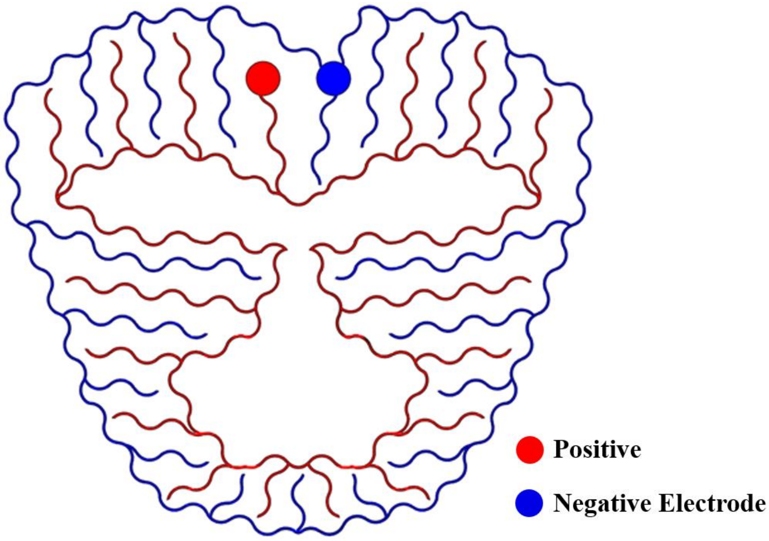

Figure 4. Interdigitated electrodes of the microcurrent enhanced permeation facial mask

4. Conclusion

Aiming at the pain points of traditional skin electroporation electrodes, such as easy diffusion of electric field to deep tissues and easy induction of muscle stimulation, this study innovatively introduced the interdigitated structure into the design of electroporation electrodes, proposed a novel interdigitated electrode scheme that can confine electrical effects to the skin surface, and completed the principle verification through COMSOL finite element simulation.

The simulation results show that the interdigitated electrode can achieve precise electric field regulation through a short-range current path. While forming an effective electroporation electric field in the stratum corneum, the electric field intensity attenuates rapidly with the increase of skin depth, and the voltage in the dermis and subcutaneous tissue is much lower than that of the traditional serpentine grid electrode, fundamentally avoiding the risk of electrical stimulation to deep tissues from the structural level and greatly improving the safety of transdermal drug delivery. Aiming at the problem of insufficient dynamic stability of linear interdigitated electrodes, this study further proposed a serpentine structure optimization scheme. Simulation verification shows that the serpentine structure releases tensile stress through geometric redundancy, and under 15%-25% skin tensile strain, the relative resistance change is much lower than that of the linear structure, which can adapt to dynamic skin environments such as the face. This study only completed the structural design and simulation verification, clarified the application potential of interdigitated electrodes in electroporation penetration enhancement, and provided a theoretical basis and structural reference for the subsequent physical development of wearable electroporation facial masks.

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