A Non-contact Wearable Device for Monitoring Epidermal Molecular Flux: Design, Application, and Interdisciplinary Innovation

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Abstract

This study introduces a novel non-contact wearable device platform designed for continuous monitoring of epidermal molecular flux. Unlike existing wearable technologies that rely on physical coupling, this device forms a sealed chamber on the skin surface through physical decoupling and utilizes integrated wireless sensors to precisely quantify changes in the chamber's microenvironment caused by vaporized molecular substances (such as water vapor, volatile organic compounds, and carbon dioxide) passing through the skin. A programmable bistable valve dynamically controls the connection between the chamber and the surrounding environment. By analyzing the time-dependent readings of the sensors, the transient response is quantitatively correlated with the inward and outward flux of target substances. This system demonstrates a unique ability to measure water vapor, volatile organic compounds, and carbon dioxide flux at different body sites, which are closely related to clinical care and/or exposure to harmful vapors. Studies on skin wound healing processes in healthy and diabetic mouse models, as well as the response in infected wound models, reveal characteristic flux changes, providing important insights, especially in scenarios where the device's non-contact operation avoids potential damage to fragile tissues. From the perspective of design-driven interdisciplinary innovation, this study delves into the system design, experimental methods, and application potential of this device in health monitoring and disease diagnosis, emphasizing its innovative value in promoting personalized medicine and intelligent health management.

Keywords: Non-contact wearable device; Epidermal molecular flux; Design innovation; Health monitoring; Biosensor

1 Introduction

1.1 Background and Challenges

The skin, as the primary interface between the human body and the external environment, plays a profound role in human health through the flux of chemical substances both inward and outward. These fluxes include medically significant compounds such as water, volatile organic compounds (VOCs), and carbon dioxide (CO2). Imbalances in transepidermal water loss often indicate dysfunctions in skin homeostasis [13], while certain pathologies and infections at wound sites are associated with the emission of vaporized chemical substances [5, 41]. Simultaneously, the influx of external substances provides valuable insights into the health impacts of atmospheric chemicals [2]. Existing wearable devices primarily monitor the dynamic flow of liquids like sweat through microfluidic networks [23, 32], but these methods are not suitable for gas monitoring. Furthermore, traditional wearable technologies typically rely on physical coupling with the body to establish optical, fluidic, thermal, and/or mechanical measurement interfaces [40, 25, 51, 20]. In some cases, this can cause potential damage to fragile tissues or limit long-term wearing comfort and accuracy. Therefore, developing a non-invasive, high-precision wearable device capable of continuously monitoring epidermal gas flux is of great significance for personalized health management, early disease diagnosis, and environmental exposure assessment.

1.2 Design-Driven Interdisciplinary Innovation Perspective and Opportunities

In the rapidly evolving technological landscape, design is no longer confined to traditional product forms or visual presentations. Instead, it is increasingly integrating with various disciplines such as engineering, biomedicine, and materials science, forming a new paradigm of 'design-driven interdisciplinary innovation.' This paradigm emphasizes solving complex real-world problems and creating forward-looking, socially valuable innovative solutions through interdisciplinary thinking and methods. Addressing the challenges of epidermal molecular flux monitoring, a design-driven interdisciplinary innovation perspective offers unique opportunities:

1. **User Experience and Wearing Comfort Design:** Traditional medical monitoring devices are often bulky and invasive, affecting user compliance. Design innovation can focus on lightweight, flexible, and ergonomic designs, ensuring high-performance monitoring while maximizing wearing comfort and discretion to meet long-term wearing needs. 2. **Intelligent Sensing and Data Visualization Design:** By combining advanced sensor technology with data processing algorithms, intelligent systems can be designed to capture multi-dimensional molecular flux data in real-time and with high precision. Simultaneously, intuitive and easy-to-understand data visualization interfaces can transform complex physiological parameters into actionable health insights for users, empowering them in self-health management. 3. **System Integration and Miniaturization Design:** Highly integrating multiple functional units such as sensors, valves, wireless communication modules, and power sources into a miniaturized platform achieves device compactness and portability. This is not only

an engineering challenge but also a comprehensive consideration of design elements such as spatial layout, material selection, and energy management. 4. **Application Scenario Expansion and Service System Design:** Breaking through the limitations of traditional medical scenarios, the device's application can be extended to diverse settings such as daily health monitoring, athletic performance optimization, and environmental exposure warnings. This requires designing a complete service system, including data transmission, cloud-based analysis, personalized feedback, and remote medical support, to build a full-chain health solution.

This study is based on the aforementioned design-driven interdisciplinary innovation concept, proposing and implementing a non-contact wearable device (Epidermal Flux Sensor, EFS). It aims to overcome the limitations of existing technologies and provide a novel and efficient solution for epidermal molecular flux monitoring. The core innovation of this device lies in its unique physical decoupling design and programmable valve control mechanism, enabling precise quantification of gas flux inside and outside the skin, and offering unique insights for clinical decision-making and basic research.

1.3 Core Innovations and Advantages of This Study

The non-contact wearable epidermal molecular flux monitoring device (EFS) proposed in this study has achieved significant breakthroughs in both design concept and technical implementation, mainly reflected in the following aspects:

1. **Non-contact Measurement Principle:** Unlike traditional contact-based measurement methods, EFS achieves physical decoupling from the skin by constructing a sealed micro-environmental chamber on the skin surface. This design avoids direct pressure or irritation to the skin, making it particularly suitable for monitoring fragile or damaged skin (e.g., burns, trauma, or infant skin), significantly reducing the risk of infection and discomfort. This non-contact feature also allows the device to be worn for longer periods, enabling continuous monitoring. 2. **Programmable Bistable Valve Control:** EFS integrates an innovative programmable bistable valve that dynamically controls the connectivity between the chamber and the external environment. By precisely controlling the opening and closing of the valve, the device can capture the transient response of molecular flux inside and outside the skin. This dynamic measurement mechanism allows EFS to differentiate molecular flux changes caused by the skin's own physiological activities (e.g., transpiration, metabolic product release) from those caused by external environmental factors (e.g., harmful gas adsorption), thereby providing more refined and insightful data. 3. **Multi-modal Sensor Integration:** The device integrates various wireless sensors, including water vapor sensors, volatile organic compound (VOCs) sensors, and carbon dioxide (CO2) sensors. These sensors can quantify real-time and precise changes in molecular concentrations within the chamber's microenvironment. Additionally, temperature, electrical impedance, and thermal conductivity sensors are integrated at the bottom of the device to obtain contextual information about the skin, such as skin temperature, sweat secretion status, and skin barrier function, providing multi-dimensional support for the interpretation of molecular flux data. 4. **Data-Driven Quantitative Analysis:** By analyzing the time-dependent readings of the sensors and combining

advanced computational models and compensation schemes, EFS can accurately calculate the molecular flux density of the skin. Particularly for water vapor flux, the device can differentiate between transepidermal water loss (TEWL) and sweat evaporation, and evaluate skin barrier function (Rsw). This quantitative analysis capability provides reliable quantitative indicators for clinical diagnosis, treatment efficacy evaluation, and basic physiological research. 5. **Broad Application Potential:** EFS can not only monitor key biomarkers such as water vapor, VOCs, and CO2 but also be extended to monitor other molecules with clinical significance or environmental safety relevance. It shows immense application prospects in wound healing monitoring, skin barrier function assessment, environmental harmful substance exposure warning, and personalized health management. For example, by monitoring VOCs changes at wound sites, infections can be detected early; by assessing skin barrier function, the selection and use of skin care products can be guided.

In summary, this study aims to elaborate on the design principles, system composition, experimental validation, and multi-scenario applications of EFS. We will highlight its innovativeness in research methods, system design, and experimental processes, hoping to provide new ideas and practical examples for the development of non-contact wearable biosensing technology and promote the deep integration and development of design-driven interdisciplinary innovation in health technology.

2 Methodology

The core of this study lies in the designed non-contact wearable epidermal molecular flux monitoring device (EFS), whose sophisticated system design and unique operating principles are key to achieving high-precision, non-invasive monitoring. This section will detail the overall architecture of EFS, key component design, working mechanisms, and data acquisition and analysis methods.

2.1 Device Design and System Architecture

The EFS (Figure 1a) is designed to achieve continuous quantitative analysis of key epidermal fluxes such as water vapor, volatile organic compounds (VOCs), and carbon dioxide (CO2), which are important indicators for assessing skin barrier function, body homeostasis, environmental safety, and wound healing [1, 45, 22]. The device has a compact overall architecture and can be flexibly worn on different parts of the body (Figure **??**b), mainly consisting of the following three subsystems:

1. **Chamber and Sensor Unit:** This unit contains a sealed chamber closely adjacent to the skin surface, with multiple sensors suspended inside to measure target molecular concentrations (c_c) and skin characteristics in real-time. Specifically includes: * **Gas/Temperature Sensors:** Used to monitor water vapor (BME280, Bosch), VOCs (BME680, Bosch), and CO2 (STC31-R3, Sensirion) concentrations in the chamber, as well as chamber temperature. * **Skin Interface Sensors:** Located at the bottom of the chamber, used to measure skin temperature, electrical impedance, and thermal conductivity, providing contextual information for molecular flux measurements. These sensors help assess the physiological state of the skin, such as sweat

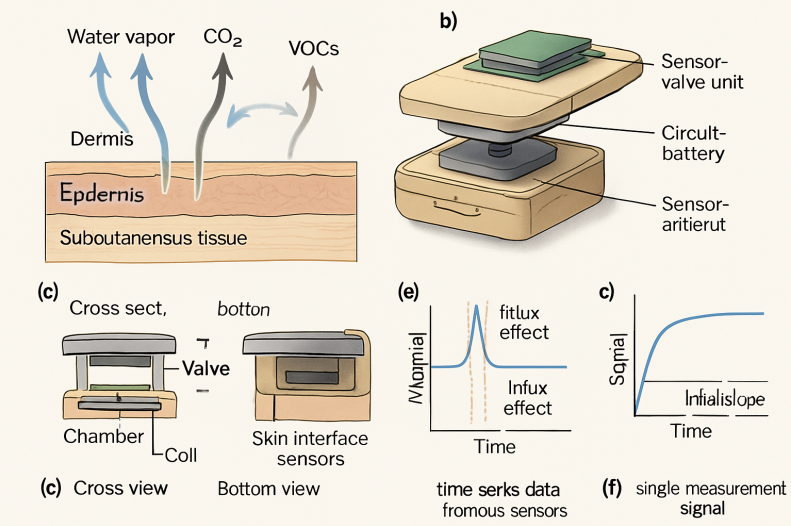

Fig. 1 EFS device design and system architecture. (a) Overall device structure showing the compact design. (b) Flexible wearing on different body parts. (c) Cross-sectional view of the sensor-valve unit. (d) Bistable valve mechanism. (e) Dynamic concentration changes in the chamber. (f) Flux calculation principle.

secretion and skin barrier integrity. 2. **Programmable Valve Unit:** This is an innovative electromagnetic valve used to dynamically regulate chamber ventilation, thereby affecting molecular concentrations within the chamber. The valve uses a thin electromagnetic coil to drive a permanent magnet disk, achieving rapid switching between open and closed states of the chamber through bistable magnetic potential generated by soft magnetic materials (¡10 ms) (Figure 1d). The rapid opening and closing of the valve is fundamental to achieving transient response measurements and precise flux calculations. 3. **Electronic Circuit and Wireless Communication Unit:** A flexible printed circuit board (FPCB) serves as the platform, integrating a 130 mAh lithium polymer battery and all the aforementioned commercial electronic components. This circuit is responsible for device power supply, sensor data acquisition, signal processing, and wireless communication with user interfaces through a custom smartphone application. This allows users to conveniently view real-time data and control the device. The entire EFS device weighs only 11 grams and can operate continuously for at least one day on a single charge.

Figure 1c shows the overall structural cross-section and bottom view of the sensor-valve unit, detailing the layout of the chamber, valve, coil, and skin interface sensors. The device's mechanical locking mechanism ensures tight coupling between the top cover and base, forming a complete sealed system. These design details collectively ensure the stability and reliability of EFS in practical applications.

2.2 Operating Principle and Flux Calculation

The core operating principle of EFS lies in controlling the ventilation state of the chamber to induce dynamic changes in molecular concentrations within the chamber

and extract skin molecular flux information from these changes [31, 18]. When the valve is in the open state, baseline flux enters and exits the chamber based on concentration gradients between the skin and ambient air. After the valve rapidly closes, the molecular concentration (c_c) in the chamber undergoes dynamic changes determined by skin inward and outward flux (Figure 1e).

To accurately calculate flux density (f), this study proposes a compensation scheme and quantitative analysis method. The initial rate of change in chamber concentration (c_c) after valve closure ($\partial c_c/\partial t|_{t=0}$) reflects the natural flux density ($\tilde{f}$) (Figure **??**f). Through computational models, we established an empirical relationship between flux density and chamber concentration change rate (Equation 1):

$$\tilde{f} = k(V/S \times \partial c_c/\partial t|_{t=0}) \tag{1}$$

where $\tilde{f}$ is the flux density before valve closure, k is the correction coefficient, V is the chamber volume, and S is the skin area. For water vapor, simulation results show k = 0.92. This correction coefficient compensates for spatiotemporal non-uniformity in concentration distribution within the microenvironment and the occlusion effect of EFS.

Water Vapor Flux Measurement: Epidermal water vapor flux (f_w) is a key indicator of overall homeostasis, including both transepidermal water loss (TEWL,f_TEWL) and sweat evaporation (f_se) components (Figure 2a). f_w is proportional to the water concentration difference between the skin surface and a reference point (such as the Nilsson zone) [31]. This study sets the reference point 6 mm above the skin surface, within the typical Nilsson zone thickness range. Under quasi-steady-state conditions, Fickś first law applies to f_w (Equation 2) [30, 42, 29].

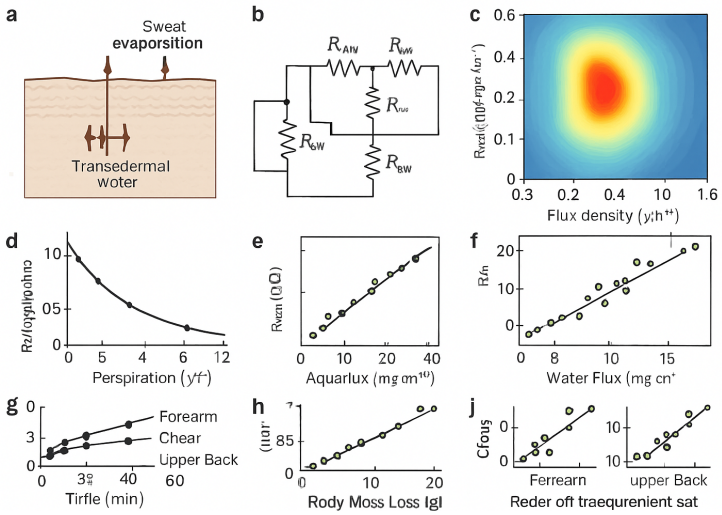

Fig. 2 Water vapor flux measurement and validation. (a) Schematic of water vapor flux components. (b) Equivalent electrical circuit model. (c) Skin barrier function assessment. (d) Sweat secretion detection. (e) Barrier function recovery monitoring. (f) Device comparison with Aquaflux. (g-j) Body fluid balance monitoring across multiple body sites.

$$f_w = \Delta c/R = (c_{sw} - c_{aw})/(R_{sw} + R_{aw}) \quad (2)$$

where R is the effective diffusion resistance, composed of epidermal resistance (R_sw) and resistance from air above the skin to the reference level (R_aw). Δc represents the water vapor concentration difference between the dermis (c_sw) and reference level (c_aw). The value of c_sw equals the saturation value at skin temperature (T_s). Figure 2b shows the equivalent electrical circuit model, where R_sw and R_aw are in series. The contributions of TEWL (R_TEWL) and sweat evaporation (R_se) form R_sw in parallel.

VOCs, CO2, and Exogenous Substance Flux Measurement:

EFS can also monitor VOCs and CO2 flux, which are produced through skin microbiome and skin respiration [48, 28, 26, 4, 12]. Environmental VOCs can also flow into the skin. Simultaneous measurement of inward and outward flux provides unique and complementary insights (Figure 3a,b). For example, monitoring underarm VOCs flux can assess skin hygiene status (Figure 3c,d). The integrated CO2 sensor enables precise measurement of transcutaneous CO2 flux (f_tco2) (Figure 3e), which can even be used for non-invasive estimation of arterial CO2 levels [10, 33]. For inward flow of exogenous substances, such as concentrated ethanol vapor, EFS evaluates skin barrier function by measuring chamber concentration changes (Figure 3g) and calculating transcutaneous chemical diffusion resistance (R_sx) (Figure 3f,h) [49, 6, 24, 17]. These measurement methods are all based on similar dynamic responses and computational models but are adjusted according to the diffusion characteristics and concentration gradients of different substances.

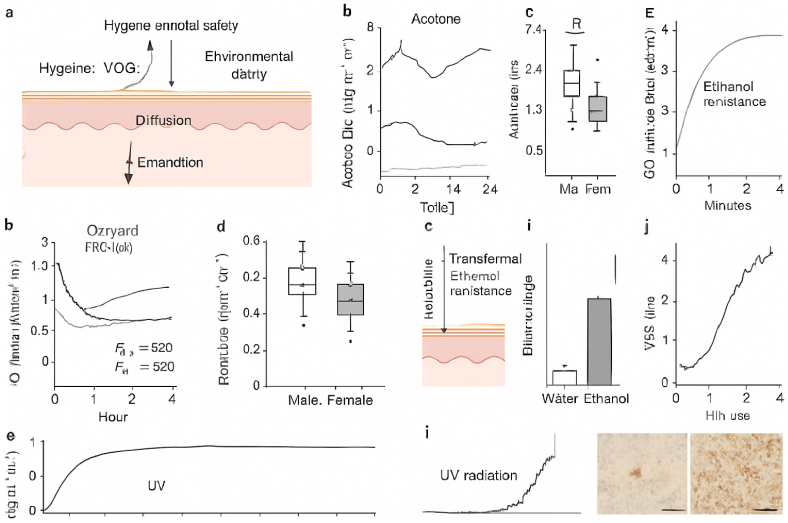

Fig. 3 VOCs and CO2 flux monitoring applications. (a,b) Bidirectional flux measurement principles. (c,d) Skin hygiene assessment through underarm VOCs monitoring. (e) Transcutaneous CO2 flux measurement. (f,h) Ethanol permeation testing for barrier function assessment. (g) Chamber concentration changes during ethanol exposure. (i,j) UV radiation-induced VOCs flux and oxidative stress markers.

3 Experiments and Results

To comprehensively validate the performance of EFS and its effectiveness in different application scenarios, this study conducted a series of rigorous experiments, including device bench testing, human participant studies, and animal model research. The experimental design aims to highlight EFS's unique capabilities in monitoring skin barrier function, fluid balance, skin hygiene, environmental exposure, and wound healing.

3.1 Device Performance Validation and Bench Studies

Before applying EFS to biological measurements, we first conducted detailed device performance validation and bench studies to ensure measurement accuracy and stability. These studies mainly included:

1. **Soft Magnetic Material and Circuit Preparation:** Soft magnetic components were prepared by mixing magnetite nanoparticles (50-100 nm) with polydimethylsiloxane (PDMS) prepolymer, degassing, spin-coating, and thermal curing. Laser cutting processes defined the required annular shapes for integration into the valve. Flexible printed circuit boards (FPCB) were used to mount lithium polymer batteries (130 mAh) and various commercial electronic components, including water vapor sensors (BME280, Bosch), VOCs sensors (BME680, Bosch), and CO2 sensors (STC31-R3, Sensirion). 2. **Device Assembly:** 3D printing processes (Form 3+, Formlabs) were used to define the system framework to accommodate circuit-battery assemblies, soft magnetic structures, and magnetic plungers. Mechanical locking mechanisms connected the top and bottom frameworks, completing the enclosure packaging. 3. **Data Acquisition and Analysis Protocols:** Through secure database management servers, custom smartphone applications were used to upload, archive, and download raw measurement data from EFS devices. Subsequently, custom Python (v.3.11.0) and Microsoft Visual Basic for Application (v.7.1) codes were used to process downloaded JSON format raw data to derive measurement results. 4. **Bench Testing:** Uncured PDMS resin was used to bond PDMS membranes of different thicknesses to small container lids with circular openings. Containers were filled with liquid water or gaseous substances for different experimental setups. We measured temperature and gas flux in the form of transmembrane permeation at the center of PDMS membranes. To measure influx, we used a device connected to the side of the membrane facing the container interior. These tests validated EFS's basic measurement capabilities and response characteristics under controlled environments.

3.2 Human Participant Studies

Human studies aimed to evaluate EFS performance under real physiological conditions and explore its applications in skin barrier function assessment and fluid balance monitoring [44, 7]. All participants voluntarily participated and signed informed consent forms, and the research protocol was approved by the Northwestern University Institutional Review Board.

1. **Adaptation Protocol:** Before device wearing, each participant rested for 15 minutes in the environmental laboratory atmosphere. After device wearing, they rested

for another 15 minutes before data collection began. 2. **Device Comparison:** To validate the accuracy of EFS measurements, we compared it with traditional clinical devices (such as Aquaflux). In experiments, EFS and Aquaflux performed three measurements in the same skin area, with 5-minute intervals between measurements. Results showed that water vapor flux (f_w) measured by EFS had high correlation with Aquaflux results ($r = 0.98$), indicating that EFS has measurement accuracy comparable to existing gold standard devices (Figure 2f). 3. **Skin Barrier Function Monitoring:** Through partial removal of the stratum corneum on healthy adult forearms (tape stripping), EFS monitored the recovery process of skin barrier function (R_sw) [19, 11]. Results showed that R_sw significantly decreased after stripping and recovered with a characteristic time of 15.2 days, consistent with the stratum corneum renewal cycle (14 days) (Figure 2e). Additionally, skin impedance (r_s) measurements could identify different stages of sweat secretion (no sweat, insensible sweating, and sensible sweating), enabling reliable skin barrier assessment in the no-sweat state (Figure 2d). 4. **Fluid Balance Monitoring:** EFS simultaneously recorded water vapor flux at six different body regions every 3 minutes for 3 hours [38, 35, 46, 50]. Body mass loss (BML) was measured every 15 minutes. Without drinking or excretion, BML represents insensible water loss. Estimated epidermal water loss (E_j) was calculated by multiplying cumulative flux (f_i) by regional skin area (A_j). Results showed strong correlation between E_sum and BML ($r = 0.99$), and similar results were obtained even with fewer measurement points (such as anterior thigh and posterior calf) (Figure 2g-j), proving that EFS can simply and accurately assess total body insensible water loss.

3.3 Animal Model Studies

Animal model studies mainly focused on evaluating EFS applications in wound healing monitoring and environmental exposure effect assessment, particularly for UV radiation-induced skin damage and wound infection [39, 47, 21, 27]. 2. **Mouse Wound Model:** In healthy and type 2 diabetic mouse models, EFS monitored water vapor and VOCs flux during excisional dermal wound healing [15, 16]. The wound creation process included hair removal, 6 mm diameter punch biopsy excision of dermis, and fixation of acrylic splints with nylon sutures to prevent skin contraction. Laser-cut occlusive dressings were used to protect splints and external skin. Results showed that f_w in healthy mice gradually decreased to baseline levels of healthy skin, while f_VOC temporarily increased in early recovery and then gradually returned to baseline (Figure 4b). 3. **Wound Healing Monitoring:** Wound closure time in diabetic mice (27 days) was longer than in healthy mice (13 days) (Figure 4d). Skin barrier function recovery in healthy mice was consistent with the wound closure process, while the diabetic group failed to recover barrier function at the wound closure point (t_wc) and only achieved post-closure barrier recovery in the subsequent 3 weeks (Figure 4e). Immunofluorescence analysis showed that the diabetic group lacked filaggrin (FLG) activity after t_wc, indicating impaired keratinocyte differentiation leading to delayed skin barrier function recovery (Figure 4f) [37, 14]. 4. **Wound Infection Monitoring:** In infected wound mouse models, EFS monitored VOCs release [9, 36, 3]. Results showed that control group f_VOC values remained low, while the

infected group increased approximately 100-fold within 2 days after bacterial introduction (Figure 4h). Antimicrobial treatment reduced f_VOC to near control levels and significantly reduced bacterial load. These results indicate that EFS can assess wound healing status by tracking changes in f_w and f_VOC and identifying sudden exponential increases in f_VOC, such as tissue integrity, wound closure, and bacterial infection.

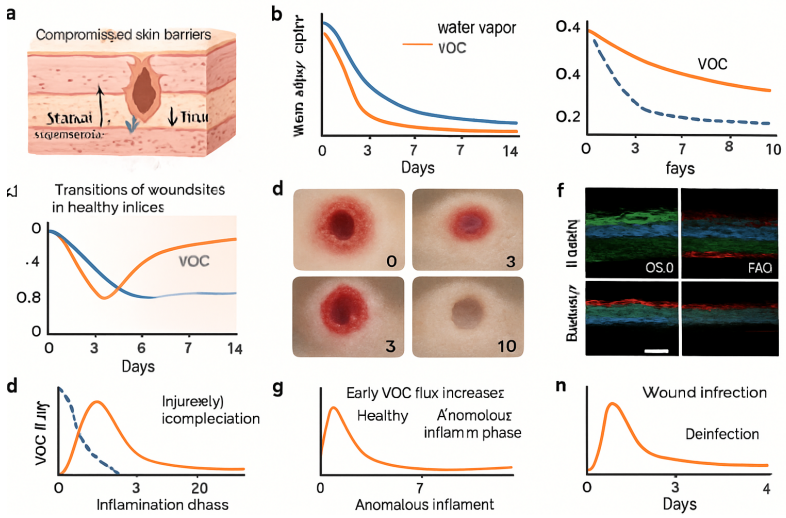

Fig. 4 Wound healing monitoring in animal models. (a) Experimental setup for wound healing studies. (b) Flux changes during normal wound healing. (c) Wound closure progression. (d) Comparison of healing times between healthy and diabetic mice. (e) Barrier function recovery patterns. (f) Immunofluorescence analysis of filaggrin expression. (g) Infection model setup. (h) VOCs flux changes during wound infection and treatment.

3.4 Statistical Analysis

All statistical analyses in this study strictly followed academic standards [34, 43, 8]. Regression fitting used generalized reduced gradient nonlinear optimization algorithms, with inverse exponential, linear, and negative exponential models for data fitting. All regression fitting results are expressed as R^2 values, while matrix comparisons use Pearson's r values. For data involving 5 or more participants, Student's t-distribution methods were used to calculate 95% confidence intervals. Analysis of variance (ANOVA) was used for data analysis, followed by post-hoc pairwise comparisons using the least significant difference method, and effect sizes (Cohen's d) were calculated. Data analysis primarily used SPSS (v.24) and Microsoft Excel (v.16.94) software.

4 Conclusion and Outlook

This study successfully developed and validated a novel non-contact wearable device for continuous monitoring of epidermal molecular flux (EFS). Through its unique physical decoupling design and programmable bistable valve control mechanism, EFS achieves high-precision, non-invasive, and continuous monitoring of skin water vapor, volatile organic compounds (VOCs), and carbon dioxide (CO2) fluxes. Experimental results fully demonstrate EFS's powerful capabilities and broad application prospects in assessing skin barrier function, monitoring fluid balance, evaluating skin hygiene, detecting environmental exposure effects, and real-time monitoring of wound healing processes.

4.1 Theoretical Value

The theoretical value of this study is mainly reflected in the following aspects:

1. **Deepening the Understanding of Skin Physiological Mechanisms:** The non-contact, continuous molecular flux data provided by EFS offers an unprecedented tool for in-depth understanding of the complex physiological mechanisms of the skin as the largest organ of the human body. In particular, the precise differentiation between transepidermal water loss (TEWL) and sweat evaporation, as well as the monitoring of metabolic product fluxes such as VOCs and CO2, helps to reveal the dynamic responses of the skin in maintaining homeostasis, disease development, and interaction with the environment. 2. **Innovative Biosensing Paradigm:** The physical decoupling and dynamic valve control strategies proposed in this study open up a new research paradigm for wearable biosensing. It breaks through the limitations of traditional contact sensors, providing a theoretical basis and technical reference for developing applications suitable for fragile tissues, long-term monitoring, and scenarios requiring minimal interference. 3. **Promoting Multidisciplinary Integration:** The successful development of EFS is a paradigm of deep interdisciplinary integration of design, engineering, materials science, biomedicine, and data science. It not only demonstrates the key role of design innovation in solving complex scientific problems but also provides new ideas and methodologies for future interdisciplinary research, especially on how to organically combine user experience, aesthetic design, and high-tech functions. 4. **Improving Quantitative Models of Physiological Parameters:** By combining advanced computational models and compensation schemes, this study achieved precise quantification of skin molecular flux. This not only improved the reliability of measurement data but also laid the foundation for building more comprehensive and accurate human physiological parameter models, which will contribute to personalized health management and precision medicine in the future.

4.2 Application Prospects

EFS has broad practical application prospects and is expected to have a profound impact in multiple fields:

1. **Clinical Medicine and Disease Diagnosis:** * **Wound Healing Monitoring:** EFS can real-time monitor water vapor and VOCs flux at the wound site, detect

early signs of infection, assess healing progress, and guide clinical interventions, especially for long-term management of chronic wounds, burns, and diabetic foot ulcers. * **Dermatological Diagnosis and Treatment:** Precise assessment of skin barrier function (e.g., TEWL and R_sw) helps diagnose skin diseases such as atopic dermatitis and psoriasis, and evaluate the effectiveness of treatment plans. Its non-contact nature makes it an ideal choice for patients with sensitive skin. * **Neonatal and Elderly Care:** For newborns and the elderly with fragile skin, EFS provides a safe and comfortable physiological monitoring method, helping to prevent and manage skin damage and monitor fluid balance. 2. **Personalized Health Management and Sports Science:** * **Fluid Balance and Dehydration Warning:** Athletes and outdoor workers can use EFS to real-time monitor insensible water loss, timely replenish water, and prevent dehydration and heat stress. * **Skin Health and Cosmetics:** Consumers can use EFS to understand their skin condition, choose more suitable skin care products, and evaluate their effects. * **Environmental Exposure Monitoring:** EFS can be used to monitor exposure to harmful gases (e.g., VOCs) in polluted environments for specific occupational groups (e.g., chemical plant workers) or the general public, providing early warning. 3. **Basic Research and Drug Development:** * **Skin Physiology Research:** Provides new experimental tools for studying the mechanisms of molecular exchange in the skin under different physiological and pathological conditions. * **Transdermal Drug Delivery Research:** Evaluates the efficiency of transdermal drug absorption and optimizes drug formulations and delivery routes. * **Environmental Toxicology:** Studies the impact of environmental pollutants on skin barrier function and their potential health risks.

4.3 Challenges and Future Work

Despite the great potential shown by EFS, there are still some challenges and future research directions:

1. **Multi-target Molecular Detection:** Current EFS mainly focuses on water vapor, VOCs, and CO2. In the future, more types of gas sensors can be integrated to achieve synchronous monitoring of a wider range of biomarkers (e.g., ammonia, hydrogen sulfide) to meet more complex clinical needs. 2. **Miniaturization and Integration Improvement:** Further optimize device size and weight, and improve integration to make it more discreet and comfortable, adapting to a wider range of daily wear scenarios. 3. **Artificial Intelligence and Big Data Analysis:** Combine machine learning and artificial intelligence technologies to develop more intelligent data analysis algorithms to achieve pattern recognition, anomaly detection, and personalized health prediction for complex physiological signals. At the same time, establish large-scale databases to provide stronger data support for disease diagnosis and treatment. 4. **Energy Efficiency and Battery Life:** Optimize the power management system to extend battery life to support longer continuous monitoring and reduce user charging frequency. 5. **Commercialization and Clinical Translation:** Transforming laboratory prototypes into mass-producible commercial products and promoting their widespread application in clinical practice requires overcoming challenges such as regulatory approval, cost control, and market promotion.

In summary, this study lays a solid foundation for non-contact wearable epidermal molecular flux monitoring technology. Its breakthroughs in design innovation, system integration, and application expansion foreshadow a bright future in personalized medicine and smart health management. Through continuous interdisciplinary cooperation and technological innovation, EFS is expected to become a key bridge connecting the human body's internal physiological state with the external environment, contributing significantly to human health and well-being.

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