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Interference of Skin Hierarchical Structure on the Signals of Bioelectronics Patches and Optimization Strategies

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Abstract:
Skin-integrated bioelectronics patches have been widely used in continuous physiological monitoring, but their signals are often affected by the skin's hierarchical structure and dynamic interference. This paper focuses on the interference mechanism of skin impedance characteristics on signal quality. A multilayer equivalent circuit model based on RC-CPE is proposed to describe the electrical response characteristics of the stratum corneum, epidermis, and dermis at different frequencies. The simulation results show that the model has better fitting accuracy than the traditional single-layer model in the low-frequency region, and can more accurately reflect the polarization and impedance fluctuation of the interface. The introduction of constant phase elements (CPE) effectively improves the modeling ability of non-ideal capacitor behavior. It enhances the adaptability to disturbances such as motion artifacts, hydration changes, and contact instability. In addition, the model is capable of capturing the impedance evolution process under motion through a multi-layer structure and variable parameter design, thereby demonstrating good physiological relevance and engineering scalability. The overall modeling framework has a solid physical foundation and can fill the research gap in dynamic modeling and multi-source interference response. The results provide theoretical support for the personalized signal acquisition and anti-interference optimization of wearable devices in complex scenarios. They are expected to promote the development of intelligent closed-loop systems towards adaptive and multimodal directions.

Keywords: Bioelectronics patch; Impedance model; Constant phase element; Multilayer equivalent circuit model.

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1. Introduction

Bioelectronics patches, as a new generation of wearable medical devices, are widely used in health monitoring, sports rehabilitation, and individualized medical care. The patch is typically made from flexible materials and integrates multiple physiological sensors, enabling the continuous and non-invasive acquisition of physiological signals. It can continuously and non-invasively obtain physiological signals, including indicators such as electrocardiogram (ECG), electromyography (EMG), sweat components, and skin impedance. Its “skin-level” compliance not only significantly enhances the comfort of use but also makes the device more suitable for continuous collection in long-term dynamic environments [1]. In recent years, with the advancement of flexible electronics, microsystem manufacturing, and low-power circuits, patches have been optimized in terms of sensitivity, integration, and signal fidelity, and are gradually evolving into real-time closed-loop feedback systems [2]. In practical applications, signal quality is often interfered with by the structural characteristics of the skin. There are differences in thickness, hydration status, and conductivity among various layers of the skin. These factors can easily cause impedance mismatch, capacitance drift, and polarization effects at the patch interface. Exercise, sweating, or prolonged wear will further intensify these interferences, manifested as distortion of low-frequency signals, fluctuations in contact voltage, and the mixing of multi-source noise, which can seriously affect the stability and measurement accuracy of the patch system. Therefore, to thoroughly understand the interference mechanism of the skin’s hierarchical structure, construct a modeling method with strong physiological relevance, and propose stable and reliable optimization strategies, is key to improving the performance of patch systems.

The electrical response of the skin exhibits non-uniform characteristics at different frequencies and is closely related to the hierarchical structure, hydration state, and dielectric parameters. The stratum corneum of the skin will produce a significant shielding effect in the low-frequency band, leading to an increase in interface impedance. The ultra-flexible tattoo electrode can mitigate this effect due to its high adhesion performance, thereby improving the stability of signal transmission [3]. After circuit fitting in combination with CPEs, the model can maintain high accuracy in fitting the impedance amplitude and phase; thus, the polarization characteristics and non-ideal capacitance behavior of the interface can be effectively reflected [4]. To further enhance the modeling adaptability to non-ideal structures, the hybrid fractional-order modeling strategy combines CPE with distributed circuit elements, enabling the model to express the dispersion and hierarchical structure differences of skin tissue in the frequency domain, which is suitable for skin areas with uneven barrier function or high variability [5]. In terms of material design, hydrogels are considered ideal materials for the next generation of neural interfaces due to their softness, adjustable conductivity, and ion conduction properties, which provide a stable, low-impedance interface while maintaining tissue mechanical matching [6]. In addition, a multi-layer perception model combining LSTM and a one-dimensional convolutional neural network has been used for motion artifact recognition of sweat conductance signals, which achieves high detection accuracy in the raw data and shows better performance than traditional algorithms in the dynamic monitoring environments [7]. Overall, modeling methods, material selection, and signal processing strategies provide complementary paths for understanding skin-level interference; however, there remains a lack of systematic solutions for dynamic integrated modeling under multi-source interference.

Although existing methods have made some progress in skin structure modeling and interference inhibition, they are still insufficient in addressing physiological differences and dynamic environmental changes. First, most modeling strategies are based on static assumptions, which make it challenging to characterize the unstable evolution of skin impedance in the frequency and time dimensions. Secondly, the significant differences in skin thickness and hydration status between individuals weakened the adaptability and generalization ability of the model. In addition, motion artifacts and multi-source interference still lack efficient and real-time compensation mechanisms in practical applications. This study aims to systematically reveal the interference mechanism of skin layers and structures on bioelectronics patch signals, and explore multi-dimensional optimization paths to improve stability and accuracy. Therefore, a set of multi-layer equivalent circuit models based on RC-CPE is proposed. Combined with simulation analysis, the formation mechanisms of signal attenuation, noise disturbance, and dynamic artifacts are thoroughly discussed. On this basis, the synergistic effect of material selection, signal processing, and structural design in interference suppression is further evaluated. Finally, an integrated framework encompassing interference source analysis and multi-strategy response is constructed, providing theoretical support and practical guidance for the design of intelligent and personalized next-generation bioelectronics patches.

2. Method and Model Development

2.1 Model Selection and Principal Analysis

The skin is a multi-layered, heterogeneous structure with significant differences in thickness, conductivity, charge distribution, and hydration state among its various layers. These factors will directly influence the stability and efficacy of signal transmission at the interface between the patch and the skin. The characteristics of the hierarchical structures cause the electrical impedance to fluctuate with frequency, which is the core cause of signal attenuation, error, and motion artifacts. The establishment of electrical impedance models that can reflect different layers of skin is the basis for improving the stability and adaptability of the patch.

2.2 Constant Phase Element (CPE)

In this study, to simulate the electrical behavior of the skin-patch interface, CPE was used to construct a non-ideal capacitance model. The dielectric response of skin tissue is dispersive. Due to its uneven structure distribution, the traditional capacitor model cannot accurately reflect the characteristics of each level. The CPE model can better fit this non-ideal dielectric behavior.

In a study of incomplete cuticle development and barrier function defects in a psoriasis model, CPE elements were used to mimic the capacitive response behavior of the stratum corneum (SC) and the keratinocyte layer (KL) with better structural discrimination [8]. The formula is expressed as:

$$Z_{CPE} = \frac{1}{Q(j\omega)^{\alpha}} \tag{1}$$

Q is the fitted constant, ω is the angular frequency, j is the imaginary unit, and $\alpha \in (0,1)$ represents the fractional-order. This formula describes the continuous behavior between the pure resistance ($\alpha = 0$) and the ideal capacitance ($\alpha = 1$). By changing the Q and α, CPE can flexibly fit the skin's non-ideal dielectric response curve between resistance and capacitance. Values of α between 0.7 and 0.9 perform best, and can better match the non-ideal behavior of actual skin structure [9].

2.3 Resistor-capacitor (RC) Equivalent Circuit Modeling

To simulate the multi-layer impedance of the skin, a multi-layer RC equivalent circuit model was constructed to describe the different effects of stratum corneum, epidermis, and dermis in electrical signal transmission. This model treats each layer of the skin as an independent RC unit, connected in series to construct the overall impedance response. Figure 1 illustrates the model's structure. The CPE is introduced to replace the ideal capacitor, more accurately representing the electrical behavior under non-ideal interface conditions and improving the model's ability to fit the real skin impedance characteristics.

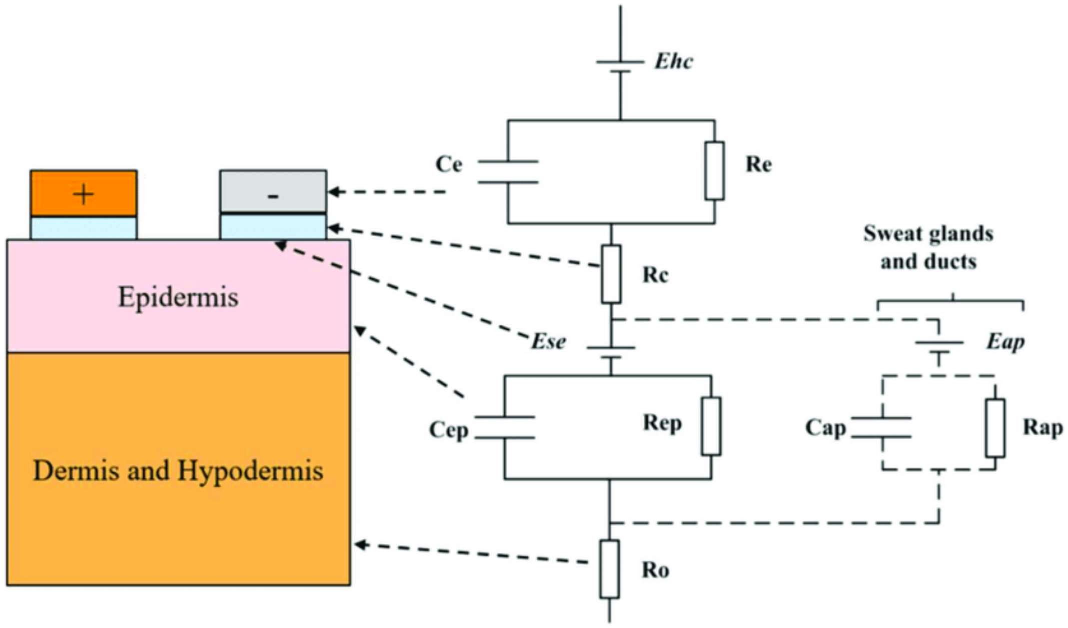

Fig. 1 Schematic diagram of a multilayer equivalent circuit model of the skin-electrode interface and sweat gland duct region

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The mathematical expression is:

$$Z_{total} = \sum_{i=1}^{N} (R_i + \frac{1}{j\omega C_i})(2) \quad (2)$$

R_i and C_i represent the resistance and capacitance of the i-th skin layer, respectively, and i is the total number of skin layers. This model enables the analysis of the local impedance characteristics of various skin layers. By parameterizing the electrical characteristics of each layer, the model tracks the attenuation and phase changes of signals as they penetrate the skin. The parameterized equivalent circuit model (TPB-ECM) has stronger physiological interpretability and can be flexibly adjusted according to changes in individual tissue parameters, thereby supporting personalized electrical stimulation parameter design [10]. By comparing the measured impedance of the phantom system with the human forearm, it was found that TPB-ECM exhibited good fitting accuracy across different frequency ranges and could realistically reproduce the impedance evolution between tissue layers [10]. The stability of the model can be determined by observing the effect of parameter changes on the impedance curve through sensitivity analysis and frequency domain distance comparison [9].

2.4 Parameter Estimation and Data Sources

In this study, the stratum corneum capacitance value typically ranges from 0.5 to 1.5 nF, and the corresponding parallel resistance can be as high as tens of kilo ohms (kΩ), reflecting its barrier to current and its extremely weak polarization ability in a low-hydrated state [11]. In the dermis region, due to the high concentration of water and electrolytes, the impedance value is low, usually fluctuating in the range of 1-10 kΩ, mainly reflecting the conductive properties of tissue fluid [11]. To improve modeling accuracy, the study introduces CPE to replace the ideal capacitor and simulate the non-ideal polarization behavior of the cuticle and electrode contact interface. The CPE's fractional order exponent, n, was set between 0.6 and 0.9, which more realistically reflects the impedance frequency response characteristics of the skin in dry and wet conditions. The impedance measurement utilizes a dual-frequency AC signal, comprising 500 Hz (low frequency) and 100 kHz (high frequency), to collect resistance and capacitance information, respectively. The entire test is completed within 5 seconds, which can effectively reduce the interference caused by sweating or changes in contact pressure [11]. The estimated prediction error of the surface water content of the stratum corneum is 5.4 mass-%, and the root mean square error (RMSE) of the thickness is 2.3 μm, which is consistent with the confocal measurement results, verifying the stability and accuracy of the model [11].

3. Result - Simulation Analysis

3.1 Impedance Frequency Response Characteristics of Skin Structure

CPE models and multilayer RC equivalent circuit models are widely used in research when performing structured analysis of the electrical properties of the skin. Figures 2(a) and 2(b) show the frequency changes in impedance amplitude and phase angle of 10 body parts in the frequency band from 2×103 to 2×105 Hz, respectively, overall presenting the electrical layered structure and frequency-dependent characteristics of skin tissue [9]. Figure 2(a) shows that in the low-frequency band (< 10^4 Hz), the impedance values of various parts are high and vary significantly, indicating that the outer layer structures, such as the stratum corneum, have a significant inhibitory effect on signal transmission. In the high-frequency band (>104 Hz), the impedance tends to be consistent, indicating that the signal has penetrated deeper into the tissue structure of the skin. This finding is consistent with the impedance modeling theory of the multi-layer structure of the skin, in which the stratum corneum dominates the low-frequency response. At the same time, the deeper tissue has a greater impact on the high-frequency response [12]. The phase angle response shown in Figure 2(b) verifies the fractional order characteristics of dielectric behavior. That is, in the low-frequency band, the phase angle is maintained at approximately -70° to -60°, reflecting typical non-ideal capacitive behavior. As the frequency increases, the phase angle gradually approaches zero, which is consistent with the CPE model, where the non-ideal capacitance behavior is reflected in n and phase changes [12]. The emergence of such frequency responses is reproducible in multiple skin impedance modeling studies, further supporting the complementarity and rationality of the CPE model and the RC equivalent circuit across different frequency bands.

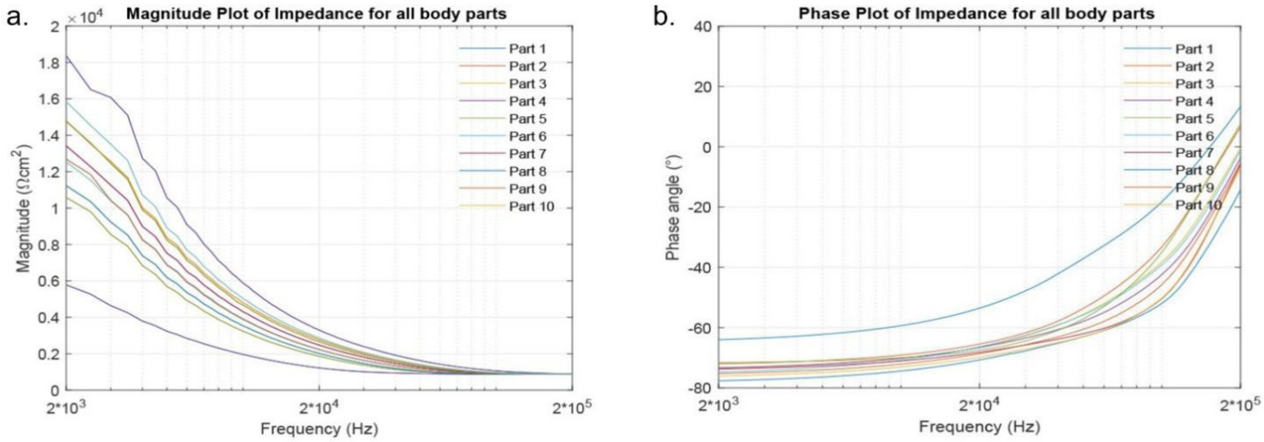

Fig. 2 Frequency-dependent impedance characteristics of skin at different body sites: (a) magnitude; (b) phase angle

3.2 Simulation and Fitting of Multi-layer RC Model

This paper uses a three-layer parallel RC equivalent circuit model, corresponding to the stratum corneum, epidermis, and dermis, to simulate their independent roles in frequency response. The stratum corneum dominates the low-frequency response, the epidermis plays a transitional role in the mid-frequency range, and the dermis determines the high-frequency behavior. This structure exhibits good fitting capabilities across the frequency range of 10 Hz to 1 MHz, enabling it to stably capture the electrical changes in each skin layer at various frequencies, thereby improving the model's adaptability and effectiveness in practical applications.

Figure 3 illustrates the expanded structure of this model: each layer consists of multiple R || C units, with resistance decaying exponentially with depth. This design more accurately reproduces the electrical response characteristics under varying physiological conditions, demonstrating strong stability in complex situations such as sweat penetration and unstable electrode contact.

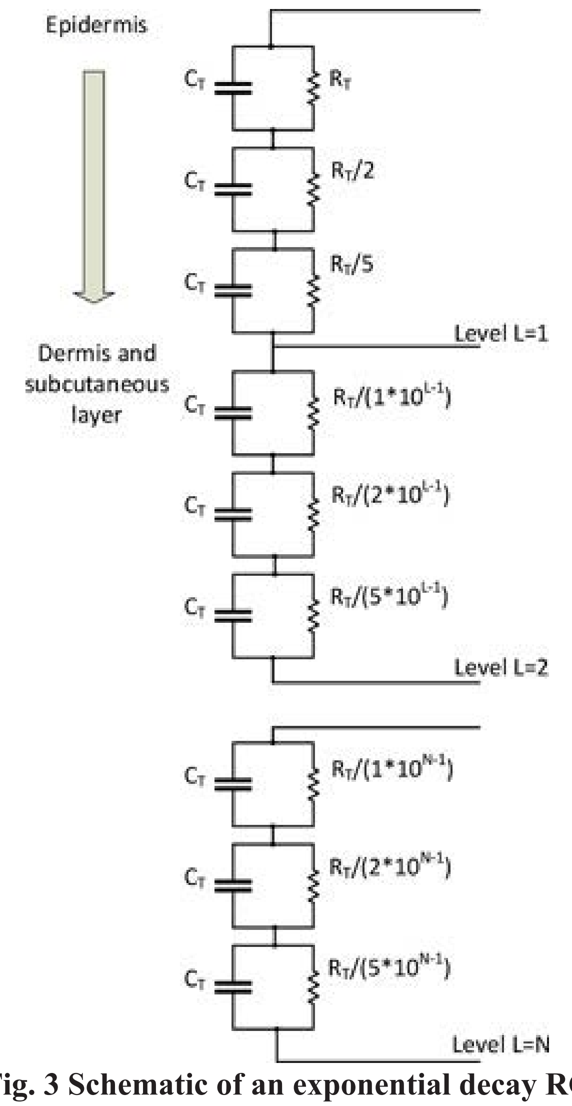

Fig. 3 Schematic of an exponential decay RC network model for a multilayer skin structure

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The reconstructed skin tissue was measured using the electrochemical impedance spectroscopy (EIS) method, which verified that the use of a two-layer or above structure can effectively separate the frequency domain responses of capacitance and resistance parameters, and can more accurately evaluate the skin barrier function. In particular, when simulating abnormal keratinization or barrier-damaged skin, the model fitting is more sensitive [13].

3.3 Model Adaptability Evaluation under Motion Artifacts and Mechanical Perturbations

During the actual wearing process, bioelectronics patches are affected by mechanical motion, including muscle contraction, joint flexion and extension, and skin traction, which occur during daily activities. These factors often cause slippage and changes in contact area between the electrodes and the skin, leading to signal distortion and noise. Motion artifacts constitute a significant interference factor in wearable physiological signal acquisition, especially at low frequencies, where they can mask key physiological signatures. This model simulates the effects of sweat, electrode pressure changes, and other factors on the interface impedance by setting variable capacitance units, which confirmed that the skin impedance changes significantly in frequency response and phase angle during exercise. By introducing a CPE to enhance the description of non-ideal interface behavior, the model demonstrated good motion artifact suppression capabilities in multiple simulations and surface ECG signal acquisition [14]. Additionally, the RC-CPE model, constructed with a multilayer parallel structure, performed well in describing changes in skin electrical properties in response to mechanical perturbations. This model treats the stratum corneum, epidermis, and dermis as independent units with distinct impedance characteristics, and constructs an overall interface through parallel connections. Simulation analysis revealed that the overall impedance of the model increases during motion, while signal stability decreases. However, compared to traditional models, the RC-CPE model more accurately captures changes in electrical parameters and exhibits superior adaptability and interpretation of patch signal variations. This helps improve the signal stability and modeling accuracy of bioelectronics patch systems under real-world motion scenarios.

4. Discussion

Although the multilayer RC-CPE equivalent circuit model proposed in this study showed good accuracy and stability in fitting skin impedance, frequency response, and motion artifact processing, it still has several limitations. First, the model structure is still based on simplifying assumptions, and the parameters of each skin layer are considered to be uniform and stable. In contrast, actual skin tissue has significant differences in hydration status, temperature, and sweat distribution. Meanwhile, different skin pre-treatment methods (e.g., alcohol wiping, water cleansing) will cause discrepancies in impedance levels in the early stages. Still, over time, these differences tend to be balanced by natural sweating [15]. This phenomenon shows that the equivalent circuit model based on fixed parameters is complex to accurately describe the time evolution behavior of impedance, and a dynamic adjustment mechanism needs to be introduced into the model [15]. Secondly, although motion artifacts are partially suppressed in simulation, in real applications, factors such as lateral skin traction, muscle contraction, and electrode micro displacement can lead to more complex nonlinear interference. This type of dynamic mechanical disturbance is the main challenge of current impedance modeling. This study mainly evaluates the equivalent circuit model based on its degree of fit with experimental measurement results under different frequency conditions. Although this spectrum-based method can reflect the accuracy of the model under static conditions, its stability and accuracy are still difficult to fully reflect in actual use, especially in the face of long-term wear or frequent exercise, and there is a lack of system verification based on actual timing signals (such as ECG and EMG). Since bioelectronics patches are inevitably affected by changes in skin hydration status, electrode micro-displacement, and local pressure fluctuations in practical applications, their interfacial impedance often evolves continuously over time. Such dynamic changes are difficult to capture using traditional fitting methods entirely. Furthermore, there are significant differences in skin structure between individuals, including stratum corneum thickness, electrolyte concentration, and water content, which limit the transferability of model parameters between different users or body parts, further restricting its generalization performance.

Future research should focus on the model's dynamic responsiveness and individualized adaptability. One feasible approach is to incorporate real-time sensory feedback, such as sweat hydration, contact pressure, and skin temperature, to construct an equivalent circuit model that can automatically adjust to changes in the environment and physiological state. In recent years, the application of artificial intelligence technology in multimodal electronic skin systems has been continuously expanded. Deep learning has been proven to extract stable features, reduce artifact interference, and improve recognition accuracy in complex environments, thereby providing stronger generalization capabilities for modeling [16]. Deep learning models such as a convolutional neural network (CNN), a recurrent neural network (RNN), and a transformer architecture can automatically extract data features and identify potential patterns. It shows significant advantages in processing e-skin data containing time series, multi-dimensional, and multi-modal signals. It is more suitable for unstructured and real-time changing input data streams [16]. At the same time, by integrating multi-source sensing input and a neural network, state classification and response recognition in complex tasks can be achieved, and the recognition efficiency is significantly improved over that of traditional algorithms [17]. These results provide a practical foundation for the future application of AI in modeling the non-ideal behavior of skin-electrode systems. Moreover, the model should be gradually extended to model impedance in deeper tissues, such as subcutaneous structures, vascular coupling, and neural responses, to support advanced applications such as neural stimulation or implantable electrophysiological monitoring devices. The validation method should also be expanded from the laboratory to more complex real-world scenarios, covering a wide range of populations and dynamic activity states, with a focus on evaluating their performance in timing signal acquisition, such as ECG, EMG, and sweat sensing. In addition, the establishment of an open skin impedance database and standardized measurement modes will help the implementation of clinical applications. As bioelectronics patches gradually develop into closed-loop systems that integrate monitoring and stimulation, future modeling should further consider electrochemical bidirectional action mechanisms (such as interfacial polarization and Faradaic reactions) to meet the needs of the next generation of smart wearable devices.

5. Conclusion

This study systematically analyzed the mechanism by which the skin's hierarchical structure affects the bioelectronics patch signal by constructing a multi-layer RC-CPE equivalent circuit model, revealing the key role of the stratum corneum, electrode interface, and deep tissue in frequency response, impedance attenuation, and motion artifact generation. The results demonstrate that, compared to traditional single-layer models, the multilayer structure offers greater physical interpretability and physiological relevance, effectively fitting the impedance behavior of different skin layers under low- to high-frequency signals and improving the patch's stability under dynamic conditions. The model's responsiveness to motion disturbances has been validated, particularly with the introduction of constant-phase elements, which more accurately capture non-ideal capacitance characteristics and demonstrate good consistency and adaptability between simulation and measured data. Therefore, this study provides a more physiologically accurate modeling method for the skin-electrode interface and lays a theoretical foundation for designing wearable devices with enhanced immunity to signal interference. The results will help improve the accuracy and adaptability of models in personalized physiological signal acquisition systems. In particular, the results address existing challenges in modeling skin structure related to dynamic changes and response to mechanical disturbances. The proposed model also exhibits strong scalability, enabling its extension to modeling deeper layers of biological tissue, such as vascular structures or neural interfaces. Furthermore, it provides a theoretical framework for developing interface-level impedance models in intelligent closed-loop systems. Looking ahead, future research may further integrate real-time sensing from multiple sources with artificial intelligence algorithms to enhance the capabilities of these systems. This combination could enable dynamic adjustment of model parameters related to hydration, pressure, temperature, and other physiological factors. These advances are expected to support the evolution from static equivalent circuit modeling to adaptive, multimodal, and personalized impedance modeling, better adapting to complex and realistic application environments.

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