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Electrical impedance performance of metal dry bioelectrode with different surface coatings

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ABSTRACT

To improve the electrical impedance performance of bioelectrodes, a novel metal dry bioelectrodes with different coating layers are developed with laser micromilling and electroplating technology. Based on the analysis of the coating layer on the bioelectrode surface, the effect of different coating layers on the electrical impedance performance of bioelectrodes is investigated. The results show that the silver content increases with electroplating time when the silver layer is coated on the bioelectrode surface. However, the decrease of silver layer weight is observed with much longer electroplating time, and the optimal electroplating time is 20 min. Compared with the uncoated bioelectrode, the bioelectrode coated with silver layer exhibits much lower impedance value and better impedance stability. Especially, when the silver-coated bioelectrode is subsequently coated with silver-silver chloride layer, the lowest impedance value and best impedance stability are obtained.

1. Introduction

Biomedical electrodes are extensively used in clinic diagnostics and therapeutic stimulation, including electrocardiographs (ECG), electroencephalograms (EEG), electromyography (EMG) and electrical impedance tomography (EIT) [1–4]. Since the bioelectrical signal belong to a kind of weak electrical signal, the design and fabrication of the bioelectrodes are a critical role for the measurement process of bioelectrical signal. Meanwhile, the interface properties between the bioelectrode and the skin also have drawn the attention of researchers from around the world. Generally, the lower contact impedance between bioelectrode and skin is desirable for measurement system. The higher contact impedance causes the larger attenuation of signal amplitude. Fortunately, the attenuation of signal amplitude could be compensated with modern high input-impedance amplifiers. However, the signal distortion and interference phenomenon is easy to produce in the process [5,6]. To avoid these problems, many new types of bioelectrodes have been developed using different design and fabrication methods.

Wet electrodes, such as Ag/AgCl electrode, are widely applied to record the bioelectrical signal. The outer layer of human skin is composed several layers of dead cells, called the stratum corneum. The stratum corneum is electrically insulated and leads to produce the high contact impedance. In order to reduce the influence of stratum corneum, the wet electrodes need the processes of skin abrasion and a conductive gel. However, the skin abrasion is time-consuming and uncomfortable for the patients. Meanwhile, the conductive gel will dry up gradually and even cause swelling and allergy in some cases [7–9]. These disadvantages make the wet electrodes difficult to accurately measure the bioelectrical signal in a long time. To solve these problems, some kinds of dry bioelectrodes are developed because the skin preparation and gel usage are not necessary. As in the earlier study, the metal plate dry electrode had a large noise and poor signal quality. These bioelectrodes could not conform to the irregular surface of skin during movement and the additional noise gets [10]. In recent years, there is a growing interest in the development of novel dry bioelectrodes, including foam backing dry bioelectrodes [11–13], fabric dry bioelectrodes [14] and microstructure dry bioelectrodes [15]. Among these bioelectrodes, the dry bioelectrodes with microstructure array show outstanding advantages of collect biosignal with less noise. The surface microstructure array of bioelectrodes can increase the actual contact area between electrode and skin with the same geometrical dimension, resulting in the decrease of the contact impedance. In addition, the bioelectrodes with surface microstructure array can maintain good contact status with skin when a relative sliding

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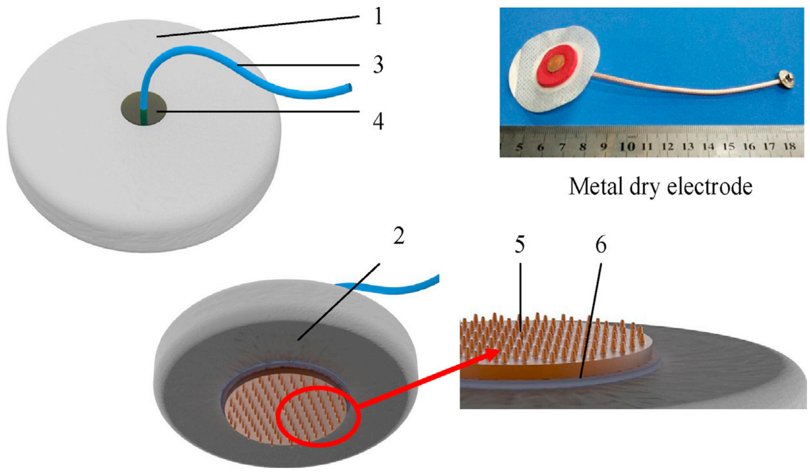

Fig. 1. Structural design of metal dry bioelectrode: 1-Back side of bioelectrode; 2-Front side of bioelectrode; 3-Shielding wire; 4-Conductive silver glue; 5-Metal electrode core with surface microstructures arrays; 6-Foam backing material.

occurs at the interface between electrode and skin, which contribute to a small motion artifact and a higher signal-to-noise ratio (SNR).

Up to now, many micro/nano fabrication technologies have been used to develop the dry bioelectrodes with surface microstructure array, including MEMS technology [16–18], vacuum casting technology [19], 3D printing technology [20], thermal drawing [21], micromolding [22] and magnetization-induced self-assembly [23]. The MEMS technology has been widely used to fabricate the spiked electrodes. Two different technologies such as deep dry etching combined with isotropic wet etching as well as mechanical dicing combined with chemical wet etching were selected to fabricate the microneedle arrays of dry electrode. And the 50/300 nm Ti/Au was sputtered on the microneedles and the backside of the wafers to measure the EEG signal [16]. Griss et al. [17,18] fabricated silicon-based micromachined spiked electrodes by deep reactive ion etching method and were subsequently covered with a silver-silver chloride (Ag–AgCl) double layer. Ng et al. [19] developed the micro-spike dry EEG electrodes by a vacuum casting method using a master pattern piece made by CNC micro-machining. A layer of conductive Ag coating was then deposited onto the surface of the dry micro-spike electrode by means of electroless plating. Salvo et al. [20] proposed 3D printing method to fabricate the dry bioelectrodes using the insulating acrylic photopolymer. The adhesion promotion layer of titanium (150 nm) and a gold layer (250 nm) was coated to reduce the impedance and prevent both corrosion and oxidation. Moreover, the thermal drawing method [21] and micromolding method [22] were also used to fabricate the polymer bioelectrodes with surface microstructured arrays. Recently, Jang et al. [23] employed magnetization-induced self-assembly method to fabricate a microneedle array bioelectrode coated with Ti/Au film. Thus, the surface coatings is an important factor to improve the testing effectiveness when the bioelectrodes with microstructure array are used to measure the biopotential signal [24,25].

In this study, the laser micromilling technology was utilized to fabricate the dry bioelectrode with surface microstructure array. In order to reduce the contact impedance, the Ag layer and Ag–AgCl double layer were coated on the surface of bioelectrode by electroplating technology. The equivalent circuit model of electrode-skin interface was established to analyze the measured impedance of bioelectrode. Finally, the measured impedance of bioelectrodes with different surface coatings was compared to evaluate the electrical impedance performances.

2. Material and methods

2.1. Structural design of metal dry bioelectrode

The design of metal dry bioelectrode with surface microstructure array is shown in Fig. 1. The metal dry bioelectrode consisted of a metal electrode core, a foam substrate, shielding wires, and conductive silver glue. The metal electrode core (Diameter = 10 mm, Thickness = 0.5 mm) was made of copper material (purity > 99.9%). In order to improve the contact status between bioelectrode and skin, the microstructure array was fabricated on the surface of bioelectrode core by laser micromilling. Both Ag layer and Ag–AgCl double layer were deposited on the surface of bioelectrode core to enhance the biological compatibility and protect the substrate material from oxidation. A foam substrate was attached to the smooth surface of bioelectrode core. The shape and the diameter of the foam backing were round and 15 mm, respectively. The design of the foam backing could reduce the signal interference caused by the movement. The shielding wire penetrated into the foam backing and was connected to the smooth surface of bioelectrode core through conductive silver paste. Compared to other welding methods, the use of conductive silver glue could avoid the high impedance nodes.

2.2. Laser micromilling process of bioelectrode core

The surface microstructure array of bioelectrode core was fabricated by laser micromilling technology [26–28]. In the laser micromilling process, the heated metal liquid or gas is condensed and generate the metal recasting layer in the adjacent area. The metal recasting layer is usually undesirable which affects the flatness of the workpiece surface. Interestingly, by adjusting the laser processing parameters, the recasting layer was successfully utilized to produce the regular microstructural array on the surface of the bioelectrode core. In this study, a prototype pulsed fiber laser (IPG, No:YLP-1-100-20-20-CN, Germany) was used as the fabrication laser, as shown in Fig. 2. The used laser was adjusted to produce 100ns pulse with central emission wavelength of 1064 nm at the repetition rate of 20 kHz. Laser output power was set as 20 W while the number of scans was 20 times and the scanning speed was 500 mm/s. The specifications of characteristic parameters of the fiber laser system are given in Table 1. Following the laser micromilling process, the bioelectrode core was dipped in 1 mol/L hydrochloric acid (HCl) solution for 20 s and was quickly dried up by air pump gun under high pressure. The surface mor-