Resistivities of the live monkey skulls

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Abstract— **In the present study, the resistivities of the live monkey skulls were measured in the frequency range of 1Hz–3 MHz and in a carefully controlled experimental situation. The measurement results showed that the resistivities of monkey skulls were inhomogeneous and ranged from 6630 to 11243 Ω.cm (*f*=1 kHz). Due to the absence of the suture and pure compact skull, the resistivity variation of monkey skull is not remarkable compared to that of human skull. The resistivity spectroscopy of monkey skull showed that there was an inverse relationship between skull resistivity and frequency in a wide frequency range, especially when the frequency was higher than 10 kHz. In order to parameterize the resistivity spectroscopy properties of monkey skull, four characteristic parameters (ρ_0、ρ_∞、α and f_c) of resistivity spectroscopy were extracted and calculated respectively, and the characteristic frequency of monkey skull was around 750 kHz.**

Keywords— **skull, resistivity, frequency, characteristic parameter**

I. INTRODUCTION

EEG or MEG source localization and cranial Electrical Impedance Tomography (EIT) depend essentially on accurate volume conductor model of head to model head shape and resistivity. Because the skull resistivity is evidently high compared to that of other tissues of head (white and grey matter of brain, cerebrospinal fluid and scalp), only a very small fraction of the current can penetrate through the skull eventually. Thus, the skull plays a most important role in the model, and the misspecification of skull resistivity can strongly affect the magnitude and distribution of electromagnetic fields, and lead to a significant error in electromagnetic calculations and source localizations [1]-[3].

Experimental animal model is the essential foundation for medical research. In our research group's studies on EIT of head, a monkey, most similar to human being, was used to establish the animal model. In order to establish the accurate volume conductor model of monkey head, the resistivity of monkey skull should be accurately measured. Up to now, the study on the resistivity of monkey skull is not found. In the present study, we performed the measurement on the resistivity of monkey skull over the upper surface, and obtained the resistivity spectroscopy in a wide frequency range. Furthermore, four characteristic parameters (ρ_0、ρ_∞、α and f_c) of resistivity spectroscopy of monkey skull samples were extracted and calculated to parameterize the resistivity spectroscopy properties.

This report is intended to elucidate the resistivity variations and spectroscopy properties of the live monkey skulls in a wide frequency range, and provide the theoretical basis and essential parameters for the related analysis in the future. In that only one monkey calvaria was studied, the intent of this paper was more instructive in nature rather than in defining "standard".

II. MATERIALS AND METHODS

A. Materials

A monkey (Macaque, female, 3 years old, 5kg), supplied by the Experimental Animal Center of the Fourth Military Medical University, was studied. Immediately after sacrifice, the calvaria was removed and kept in gauze soaked with physiological saline to prevent from air drying.

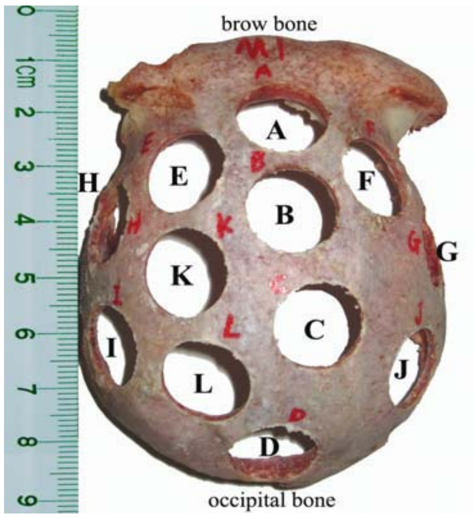

Fig.1. The top view photograph of monkey calvaria and locations of skull samples

A total of 12 three-layer skull samples were drilled perpendicular to the outer and inner surfaces of the calvaria using a trephine with a 14mm inner-diameter. During the waiting

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periods for measurements, the skull samples were conserved in saline-soaked gauze. The top view of monkey calvaria and the locations of skull samples were showed in Fig 1. This study was approved by the Medical Ethics Committee of the Fourth Military Medical University.

B. Measurement system and methods

The measurement system of skull resistivity was established based on an Impedance Analyzer (Schlumberger, Solartron SI1260), and an infant incubator was used to control the experimental conditions. Measurements were performed using four-electrode method which was widely used to measure impedance of biological tissue [4]-[6]. We measured the complex impedance spectrum (include real part and imaginary part) of each skull sample, with 0.5mA drive current in the frequency range of 1Hz–3MHz. Each sample was measured three times continuously and the average was calculated to decrease measurement error. The skull samples wrapped with saline-soaked gauze were placed in the infant incubator, set at 36.5℃ (body temperature), at least half an hour to warm up before measurements. More details on the measurement system and assembly can be found in reference [7].

C. Data Processing

In 1941, Cole KS and Cole RH proposed the “Cole-Cole” equation (1) to describe the impedance loci of biological tissues [8].

$$Z_{Cole} = Z' + jZ'' = R_\infty + \frac{R_0 - R_\infty}{1+(j\omega\tau)^\alpha} \tag{1}$$

where R_0 is the resistance at zero frequency, R_∞ is the resistance at infinite frequency, α represents the dispersion coefficient, and τ is the time constant. Characteristic frequency (f_c) can be calculated by (2).

$$f_c = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\tau} \tag{2}$$

$$\rho = \frac{RS}{L} = \frac{\pi D^2 R}{4L} \tag{3}$$

Normally, R_0, R_∞, α and f_c are called the characteristic parameters of impedance spectroscopy, which are often applied to represent the impedance spectroscopy properties of different biological tissues. The values of R_0 and R_∞ are related to the sizes of measured samples, and α and f_c only depend on the intrinsic property of different biological tissue. In this study, the four characteristic parameters (R_0, R_∞, α, f_c) were extracted respectively from the impedance spectroscopy data of all the skull samples. In consideration of the different thicknesses of skull samples, R_0 and R_∞ were converted to ρ_0 and ρ_∞ according to equation (3) and the size of each skull sample to facilitate the comparison. Therefore, ρ_0, ρ_∞, α and f_c can be called the four characteristic parameters of resistivity spectroscopy of the live human skull. The calculating method of skull resistivity was detailed presented in reference [7].

III. Results and Discussions

In this experimental study, we intended to obtain accurate resistivity of monkey skull by applying the classical measurement method on the samples of live monkey skull in the frequency range of 1Hz–3 MHz and in a carefully controlled situation with a stable temperature (36.5 ℃). Measurements on freshly excised skull can determine more realistic resistivities due to the presence of vascular tissue and fluids that fill the bone pores. By controlling the measurement temperature at body temperature, we can further approach the condition of *in vivo*.

Table 1. The results of resistivity of the monkey skull samples. (f=1kHz)

Skull samples	R(Ω)	ρ (Ω.cm)
MS-A	2682	10280
MS-B	2140	9410
MS-C	2557	11243
MS-D	2040	6630
MS-E	2537	11848
MS-F	2102	10136
MS-G	1630	7167
MS-H	2238	9558
MS-I	2426	10667
MS-J	2088	9459
MS-K	2376	10763
MS-L	2458	10808
Mean	2273	9831
S.D.	292	1555

A total of 12 samples of monkey skull were measured and the results were showed in Table 1. The measurements of resistivity for these samples ranged from 6630 to 11243 Ω.cm (f=1 kHz), which indicated that the resistivities of monkey skulls were inhomogeneous. Except for the influence of the measurement system and external conditions (temperature, humidity etc.), the key reason for the inhomogeneity should be the structural variations of monkey skull. Similar to the structure of human skull [7], the monkey skull is mainly composed by three-layer skull, and at different positions of monkey calvaria, the structure and thickness of the three-layer skull are not homogenous mainly because of the variation of diploe, which leads to the inhomogeneity of skull resistivity. However, the suture structure and pure compact skull are not clearly visible on the monkey calvaria, which gives the reason why the resistivity variation of monkey skull (6630 - 11243 Ω.cm) is not remarkable compared to that of human skull

(5782 - 26546 Ω.cm) [7]. Furthermore, we also found that the resistivity of monkey calvaria was not bilateral symmetry by comparing the resistivities of skull samples at symmetrical positions (e.g. MS-E & MS-F and MS-I & MS-J). The asymmetry of skull resistivity suggests that we cannot infer the skull resistivity of a certain position according to the value of contralateral position.

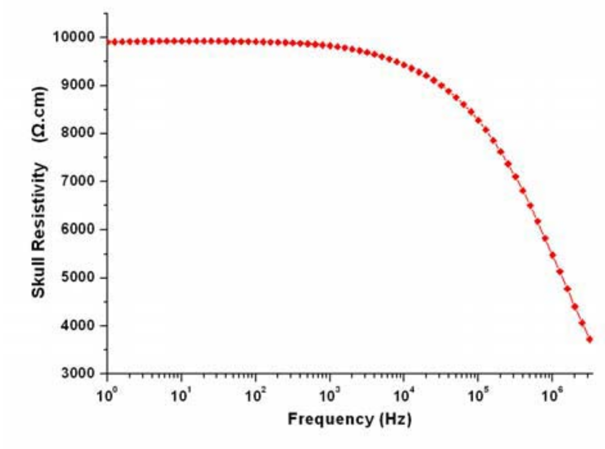

Fig.2. The resistivity spectroscopy of the live monkey skull.

Table 2. The results of resistivity spectroscopy characteristic parameters of the monkey skulls.

Characteristic Parameters	Mean	S.D.
ρ_0 (Ω.cm)	9916	1590
ρ_∞ (Ω.cm)	1351	270
α	0.5775	0.0169
f_c (Hz)	747950	41607

It should be noted that the skull resistivity is not constant in a wide frequency range. The resistivity spectroscopy of monkey skull (Fig. 2) have shown that there is an inverse relationship between skull resistivity and frequency in the frequency range of 1 Hz-3 MHz, especially when the frequency is higher than 10 kHz. The resistivity locus (Fig. 2) was calculated from the mean value of data measured on all the samples. In order to parameterize the resistivity spectroscopy properties of monkey skull, four characteristic parameters (ρ_0、ρ_∞、α and f_c) of resistivity spectroscopy of the skull samples were extracted and calculated respectively from the impedance spectroscopy data. The statistical results were showed in Table 2, and the characteristic frequency of monkey skull was around 750 kHz. These parameters can provide the basic data for the theoretical analysis and the establishment of equivalent circuit model in the future.

In summary, the resistivities of live monkey skulls are not homogenous and appear to be influenced by the variation of local structures. However, the resistivity variation of monkey skull is not remarkable compared to that of human skull because of the absence of the suture and compact skull. In a wide frequency range, the resistivity of monkey skull decreases as the frequency increases, especially when the frequency is higher than 10 kHz.

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