Research on Bioimpedance Technology Based on Real Axis Equidistant Method

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Abstract: Bioimpedance technology (BMI) is a non-invasive detection technology that widely applied in volume measurement, human tissue structure analysis and human body composition analysis. It uses the electrical characteristics, such as impedance, admittance and dielectric constant, and changes of biological tissues and organs to extract biomedical information about human physiological and pathological conditions. This paper analyzes the influence of the distribution of frequency points on the characteristic parameters in the measurement of bio-impedance spectrum. A new method of sampling frequency points, namely the real axis equidistant method, is proposed, and this algorithm is used in the actual test. Without changing the total number of measurement frequency points, this method can effectively improve the accuracy of feature parameter α and fc calculation by increasing the number of intermediate sampling frequency points, and improve the accuracy of human body composition estimation. At last, the impedance of human body section is measured, and the characteristic parameters of human body section bio-impedance spectrum are analyzed. The continuous bioelectrical impedance changes caused by water and sugar were observed. It was initially found that drinking water led to an increase in impedance and drinking sugar led to a decrease in impedance. It lays a theoretical foundation for further research on human body data.
***Keywords*:** real axis equidistant, bioimpedance, nondestructive testing, human body section, human body composition

1. Introduction

Diabetes is a common and frequently-occurring disease among middle-aged and elderly people. The treatment period of this disease is long, and blood glucose monitoring can help patients to know their blood glucose status in time, and provide support for treatment decisions and programs. For patients who need continuous monitoring of blood glucose, it is very inconvenient to monitor it several times a day. Therefore, in recent years, non-invasive blood glucose meters began to develop rapidly. At present, the non-invasive blood glucose meter commonly used in clinic is (1) infrared non-invasive blood glucose meter, which can be realized by irradiating the patient's fingers, palms, forehead and other parts. The disadvantage is that it is easy to be affected by the patient's body temperature, blood pressure and other factors [1]. (2) Compared with infrared spectrum, Raman spectrum has a higher wavelength and narrow spectral band, which makes it easier to separate signals and takes a long time to collect. At the same time, the intensity of laser will have a greater impact on the monitoring results [2]. The energy metabolism conservation blood glucose detection technology is mainly based on the biological theory. The near-infrared technology is used to dynamically detect the oxygen content of blood pressure, etc., and the energy conservation model is established to detect the glucose level in patients [3]. However, the non-invasive blood glucose meter needs to be calibrated before it is officially used, and the metabolic heat is greatly affected by the outside world, which increases the difficulty of use [4].

Biological impedance spectroscopy (BIS) is a detection technology that extracts the corresponding physiological and pathological information by using the electrical impedance characteristics of biological tissues [5]. Medical detection technology based on bioelectrical impedance is more and more applied in research and clinical, mainly due to the characteristics of human body and the principle of bioelectrical impedance method. When the human body passes through the AC current of different frequencies, the depth of human tissue penetration varies with the frequency. In recent years, many foreign research institutions have combined bio-impedance detection technology with non-invasive blood glucose testing, opening up a new direction of non-invasive blood glucose testing. The study found that human body impedance changes in the range of 1 to 200MHz, which proved that there was a relatively obvious relationship between blood glucose concentration and impedance value in the higher frequency range; The surface characteristic impedance monitor SCIM designed by Elden et al. uses 20KHz single frequency measurement to obtain blood glucose concentration=0.31 × Impedance modulus+0.24 × Phase angle relationship [6]. The research group conducted non-invasive blood glucose test by impedance spectroscopy and infrared spectroscopy, and the frequency range of the study was 10~76 kHz [7].

2. Bioelectrical Impedance and Body Composition Calculation

In living organisms, biological tissue is formed by a number of round cells in a certain proportion of volume. There are complex electrical interactions between these cells. Previous studies have found that low frequency alternating currents flow through tissues along the extracellular fluid. After the high-frequency alternating current flows through the tissue, the blocking ability of the cell membrane decreases continuously, and the current can pass through the cell membrane and enter the intracellular fluid [8]. See Figure 1.

Intracellular fluid resistance Ri and capacitance Ci are in parallel, cell membrane resistance Rm and capacitance Cm are in parallel, and cell membrane and intracellular fluid are in series. The extracellular fluid resistance Re and capacitance Ce are connected in parallel. The extracellular and intracellular are in parallel. Common Cole-Cole model is equivalent, and empirical formula (1) can be obtained:

$$Z = R_\infty + \frac{R_0 - R_\infty}{1 + j\omega\pi} \tag{1}$$

Formula (2) will be obtained by substituting $j^\alpha = e\left(j\alpha\pi/2\right) = cos\left(\alpha\pi/2\right) + jsin\left(\alpha\pi/2\right)$ into formula (1) using Euler formula.

$$Z = R_\infty + \frac{R_0 - R_\infty}{1 + j(\frac{f}{f_c})^{\alpha}\left[\cos\left(\frac{\alpha\pi}{2}\right) + jsin\left(\frac{\alpha\pi}{2}\right)\right]} \tag{2}$$

The resistance and reactance can be solved, and the bio-impedance spectrum can be fitted using the least square method using the real and imaginary values of bio-impedance. According to the bio-impedance characteristic equation, α, R0, R∞ and τ characteristic parameters are obtained to analyze the bio-impedance spectrum. Through these four parameters, the bio-impedance characteristic equation of the biological tissue can be obtained, and the impedance corresponding to different frequency values can be analyzed.

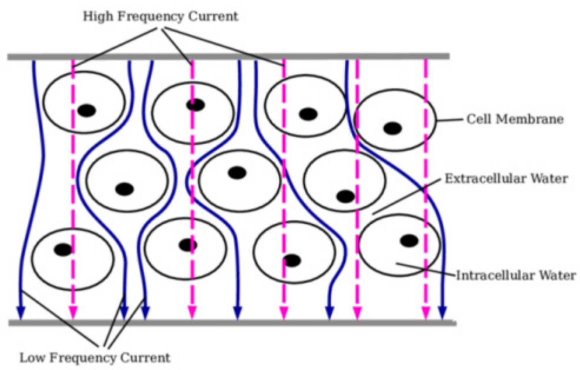

Figure 1. Schematic diagram of current passing through biological tissue.

3. Body Composition Analysis Method Based on Bioimpedance

The purpose of measuring bioimpedance is to estimate the composition of human body, mainly fat, non-fat tissue, total water weight, lean dry weight, intracellular fluid and extracellular fluid, etc. The relationship between human body composition is shown in Figure 2. The measurement method determines the method of analyzing human body composition. From single-frequency overall measurement to multi-frequency segmentation, the estimation method provided by the single-frequency measurement is more and more accurate.

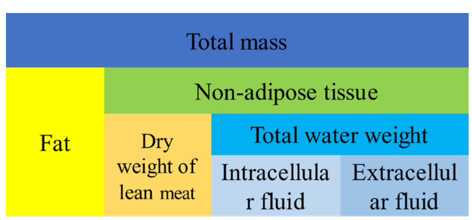

Figure 2. Relationship between body composition.

4. Bioimpedance Spectrum Trace Fitting

The least square method is used to measure the resistance (xi, real part) and reactance (yi, imaginary part) of the impedance of biological tissue. After fitting the measured data point as Zi (xi, yi), the center coordinates and radius can be calculated. The distance between the data point and the point fitting the semicircle in the same diameter direction can be set as the radial error of δ, and the optimal solution (x0, y0, r) can be obtained by calculating the minimum value of δ [9]. Using the measured bioelectrical impedance data, the complex impedance trajectories of biological tissues can be fitted. According to the geometric relationship, the arc radius and center coordinates of bioelectrical impedance spectrum fitting can be calculated, and the characteristic parameters α, R0, R∞ and τ can be extracted. The characteristic equation of bioelectrical impedance is obtained, as shown in Figure 3. Figure 4 is the fitted bio-impedance spectrum trajectory. The following section gives the method of calculating α, R0, R∞ and τ ($f_c = \dfrac{1}{2\pi\tau}$), and then the impedance characteristic equation of the biological tissue can be obtained. The flow chart of MATLAB bio-impedance spectrum fitting program based on the improved fitting arc least square method is shown in Figure 5.

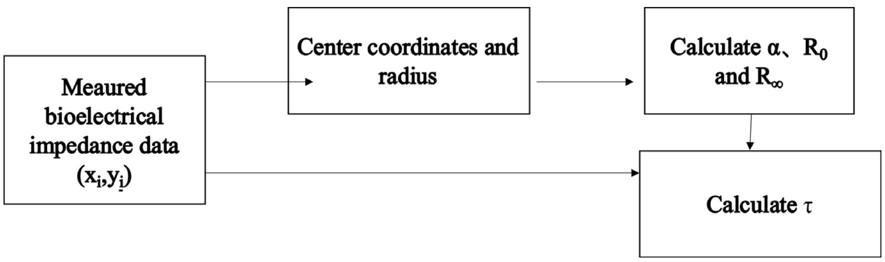

Figure 3. Steps of extracting feature parameters.

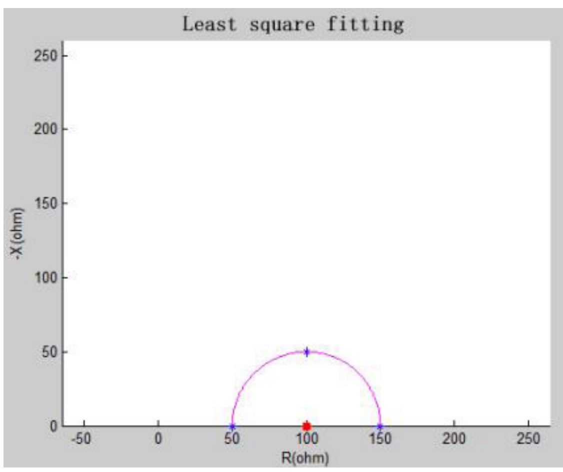

Figure 4. Bioimpedance spectrum trace.

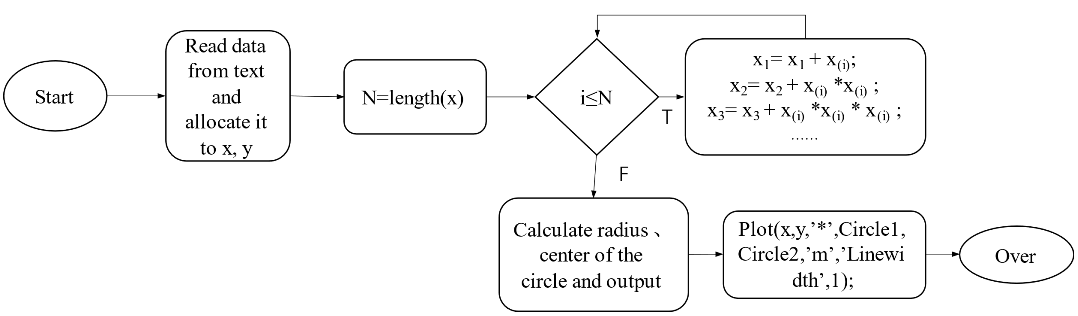

Figure 5. Flow chart of bio-impedance spectrum fitting.

5. Influence of Frequency Point Distribution on Characteristic Parameters of Impedance Spectrum

Bioimpedance spectroscopy usually uses a finite number of sampling frequency points, and many instruments take logarithmic equidistant or quasi-linear distribution of sampling frequency. And the more frequency points, the more expensive it is. Due to the complexity of the measured object, various interference factors need to be considered. These factors determine that bioelectrical impedance spectroscopy can only measure a limited number of frequency points, so how to reasonably select measurement points will become a breakthrough to improve the performance of the instrument [10]. In view of the difference of correlation between different characteristic parameters and human body composition, a new distribution method, impedance spectrum real axis equidistant distribution, is proposed, which makes the measuring points distributed in the bio-impedance track map in the way of real axis equidistant, and evenly distributed in the Nyquist map, and uses the bio-impedance spectrum characteristic parameters to compare the distribution of different frequencies.

5.1 Designing Frequency Distribution

According to logarithmic axis equidistant distribution, quasi-linear distribution and impedance spectrum real axis equidistant distribution, 33 measuring points are designed for each of the three frequency distributions in the range of 10Hz~10MHz. Log-axis equidistant distribution means that sampling frequency points are equidistant on the logarithmic axis, for example, 1.5, 2.25, 3.375, 5.062, 7.5937, 11.390, 17.085, 25.628, 38.443, 57.665. Quasilinear equidistant distribution is to set the sampling frequency points with the same geometric distance, for example, set the frequencies 17, 24, 31, 38, 45, 52, 59, 66, 73. Then multiply by the corresponding 10X (x=1~8). The real axis equidistant distribution of impedance spectrum is that the sampling frequency points are equidistant on the x-axis of the bio-impedance spectrum trace. The frequency corresponding to the x-axis equidistant is calculated according to the formula (2), avoiding the logarithmic equidistant distribution. The frequency points of quasi-linear distribution are distributed on both sides of the bio-impedance spectrum track map, so that the frequency points are relatively evenly distributed on the bio-impedance spectrum track map.

5.2 Establishing Simulation Data Model

In order to study the effect of different frequency point distribution on the characteristic parameters of bioelectrical impedance spectroscopy, the data for experiment is generated according to the characteristic equation of bioelectrical impedance, and the four characteristic parameters in the formula are α=0.8, R0=150 (ohm), R∞ =50 (ohm) and τ=3.0×10-7 (fc=53051.65(Hz)) [11]. According to the principle of logarithmic equidistant distribution, quasi-linear distribution and real axis equidistant distribution of impedance spectrum, 33 frequency points are selected for each group. Three frequency point distributions are obtained as shown in Figure 6, and each scatter chart contains 33 frequency points. It can be seen that the frequency points extracted from logarithmic equidistant distribution and quasi-linear distribution are mostly distributed on both sides of the bio-impedance spectrum track map, while the frequency points of the real axis equidistant distribution of the impedance spectrum map are relatively uniform. The characteristic parameters of bio-impedance spectrum were extracted and compared with the setting group.

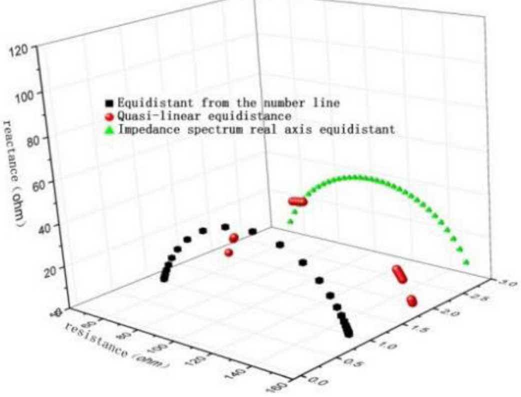

Figure 6. Distribution of different frequency points.

5.3 Results

According to the geometric relationship of the impedance trace of biological tissue, the center of the circle is (100,

-16.246) and the radius is 52.5731 for the three distributions. Ideally, the accurate value of characteristic parameter (α, R0, R∞ and fc) can be obtained from the data of three different frequency distributions. The availability of the program is proved. The simulation data of three different frequency distributions are added with different levels of noise. Figure 7 shows the influence of different frequency point distribution on the fitting accuracy of characteristic parameter α [12]. Figure 8 shows the effect of different frequency point distributions on the fitting accuracy of the characteristic parameter fc. Figure 9 shows the influence of different frequency point distribution on the fitting accuracy of characteristic parameter R∞. Figure 10 shows the influence of different frequency point distribution on the fitting accuracy of characteristic parameter R0 [13].

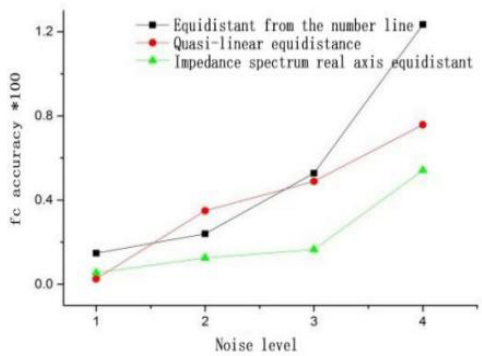

Figure 7. Distribution of different frequency points, α accuracy with different noise levels.

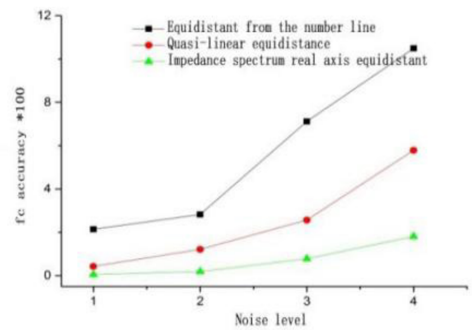

Figure 8. Distribution of different frequency points, f_c accuracy with different noise levels.

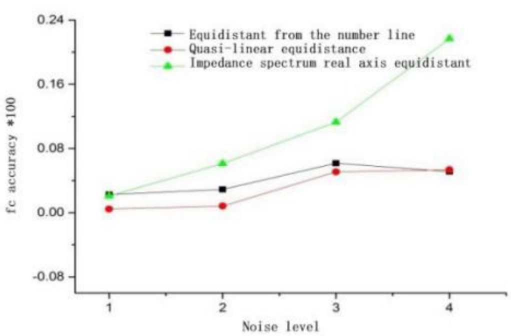

Figure 9. Distribution of different frequency points, R_0 accuracy with different noise levels.

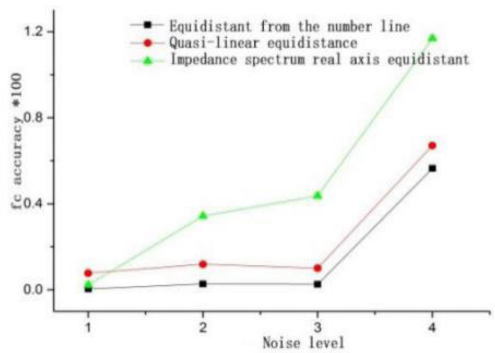

Figure 10. Distribution of different frequency points, R_∞ accuracy with different noise levels.

The frequency distribution will affect the characteristic parameters of bioimpedance spectrum. Because the measurement of bioimpedance spectrum is to select a limited number of frequency points for data fitting to obtain the bioimpedance spectrum, so as to calculate the characteristic parameter values. Most researchers generally adopt logarithmic equidistance and quasi-linear distribution [14]. However, with the improvement of frequency range and signal-to-noise ratio, the traditional equidistant distribution can no longer meet the requirements of practical applications, and the use of nonlinear exponential or power function for spectrum analysis has become a new trend. This distribution method makes the two ends of most bio-impedance spectrum tracks on the frequency points more and the middle is relatively small, so there are many measurement points near R0 and R∞ [15], while there are few measurement points near the characteristic frequency fc, resulting in a relatively high estimation accuracy of logarithmic equidistant distribution or quasilinear distribution for R0 and R∞. The number of frequency points in the middle section of the impedance spectrum is significantly increased while the number of total sampling frequency points remains unchanged. Compared with the isometric distribution, the real axis isometric distribution of impedance spectrum is simpler to calculate, and the measurement points are relatively uniform, so that there are more measurement points near the characteristic frequency fc, and the measurement points are not distributed on both sides of the track map. Therefore, the real axis equidistant distribution of impedance spectrum has relatively high estimation accuracy for α and fc [16]. The distribution of frequency points should be properly adjusted to improve the accuracy of target characteristic parameters when measuring biological impedance. Due to the complexity and non-repeatability of biomaterials, there are a large number of nonlinear effects, cross-terms and non-Gaussian factors in the bio-impedance spectrum, so it needs to be corrected. In the design of bio-impedance spectrometer, the frequency distribution should be considered [17].

6. Human Body Section Impedance Spectrum Analysis

The impedance spectrum experimental data were collected and the literature containing the corresponding impedance and reactance of three frequency points and the values of sampling frequency points was found. Using these results, an approximate formula is calculated and compared with the measured data, which proves that the approximate formula is reasonable and reliable. The approximate formula can be used as a new method for analysis in other fields. In the research paper that Bracco D is equal to estimating the composition of human body segments by dual-energy X-ray absorption measurement and biological impedance, the real and imaginary values of impedance measured at three frequencies and different impedance segments are proposed [18].

As shown in Figure 11 below, the bio-impedance trajectory is shown from left to right, followed by the trunk, legs and arms.

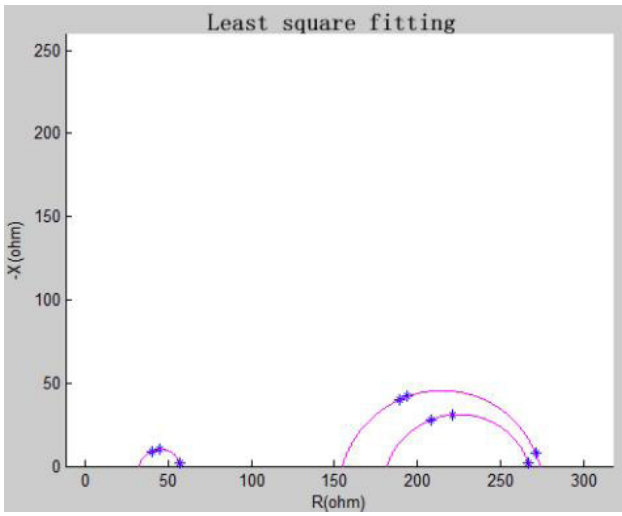

Figure 11. Impedance spectrum trace of human body section.

Table 1 below shows the characteristic parameters of impedance spectrum in different sections. It can be seen that the impedance value is relatively large at low frequency and relatively small at high frequency.

Table 1. Characteristic parameters of impedance spectrum in different sections.

NAME	R_0	R_∞	α	τ
Arm	267.7	181.4	0.79	3.28×10^{-6}
Leg	273.7	154.9	0.83	7.42×10^{-6}
Trunk	57.6	32.3	0.85	7.90×10^{-6}

It can be verified that when low-frequency current is conducted in extracellular fluid, high-frequency current is conducted in both intracellular and extracellular fluid. Organ L. W et al. found that the impedance contributed by the leg accounted for 50~53% of the total body impedance. It can be seen from Table 1 that the leg impedance is relatively large [19]. Bracco D. et al. showed that the contribution resistance is 43%. The analysis may be that the volume estimated by his BIA method is always smaller than the FFM measured by DXA, resulting in errors that make the leg contribution impedance smaller. The BMI index of the selected population is 23.9. It can be seen that when the current enters the human body, it will choose to flow along the tissues with good conductivity, resulting in the situation that the limb impedance is large and the trunk impedance is small, as shown in Table 1. The τ reaction is the capacitive component of impedance in the biological tissue equivalent circuit [20].

7. Summary and Outlook

In this study, the extraction method of characteristic parameters of bio-impedance spectrum is described, and the bio-impedance data is used, and MATLAB is compiled according to the least square method to fit the trajectory of bio-impedance spectrum, and its center and radius are calculated. At the same time, a new sampling frequency point distribution method, impedance spectrum real axis equidistant distribution method, is proposed to avoid quasi-linear equidistant distribution and logarithmic axis equidistant distribution. The uneven distribution of sampling frequency points significantly increases the number of intermediate sampling frequency points and effectively improves the calculation accuracy of α and fc under the condition that the total number of measurement frequency points remains unchanged. The distribution of sampling frequency points can be appropriately changed to obtain the desired more accurate characteristic parameters of bio-impedance spectrum.

The characteristic parameters of bio-impedance spectrum of human body section were analyzed by using Bracco D. research data. The results showed that the trunk τ value was larger than other sections. The formulas for estimating body composition based on impedance at home and abroad are reviewed. It provides a basis for human body segment analysis and the development of bio-impedance spectrometer. Through the statistics and analysis of the measurement results, it is concluded that there are certain differences in the test results obtained by different measurement methods; As the voltage signal amplitude or frequency increases, the measured impedance will also increase. Due to the limitations of the laboratory, we should improve the measurement method to make the experimental results more accurate and effectively analyze the changes of the characteristic parameters of the bioimpedance spectrum of human cross-section affected by physiological activities. The MATLAB program is improved so that it can process the characteristic parameters of bioimpedance spectrum independently. It is hoped that it can provide a reference basis for the follow-up study of blood glucose and other more abundant human data.

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