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Comparative Characteristics of Electrolyte Solutions Using Electrical Impedance Spectroscopy Method

Adinda Fajar Mila*, Wahyu Sugianto, Mira Setiana

Biomedical Engineering, PGRI Yogyakarta University, Bantul, Special Region of Yogyakarta, Indonesia
*E-mail: Adindamila000@gmail.com

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Abstract: Electrolyte solutions can conduct electric current and help maintain balance in the human body. This study compares the electrical impedance characteristics of various electrolyte solutions using the Electrical Impedance Spectroscopy (EIS) method. Three types of electrolyte solutions were tested: NaCl solution, Ringer's Lactate (RL) solution, and Simulated Body Fluid (SBF) solution with concentration variations of 20%, 40%, 60%, 80%, and 100%. Measurements were conducted over a frequency range from 1 Hz to 1 MHz to compare electrolyte solutions using a frequency of 10 kHz with an electric current of 50 µA. At a frequency of 10 kHz, a comparison of the three types of electrolyte solutions with concentration variations from 20% to 100% was made. The measurement result showed that the NaCl solution had an impedance value of 200Ω to 900Ω at high frequencies. The Ringer's Lactate (RL) solution exhibited impedance variations with impedance values ranging from 800Ω to 300Ω, which is more complex due to the other hand, the Simulated Body Fluid (SBF) solution demonstrated impedance stability at high frequencies with impedance values ranging from 400Ω to 200Ω, indicating its electrical properties suitability with human body conditions. Each electrolyte solution has its characteristics in impedance values at a frequency of 10 kHz, which allows for comparing the three types of electrolyte solutions. For further research, additional studies could include impedance characteristics of electrolyte solutions to broaden understanding of their electrical properties, considering variations in frequency and current conditions to optimise impedance characteristic measurements for various electrolyte solutions.

Keywords: Electrolyte solution; Frequency; Impedance.

Introduction

The body has electrolytes and fluids, which are inseparable units [1]. In general, electrolytes can be acids, bases, or salts. Certain gases can also act as electrolytes under specific conditions, such as at high or low pressures [2]. Electrolytes are necessary and influenced by most metabolic processes [3]. Maintaining electrolyte balance is crucial for bodily functions [4].

In some cases, electrolytes are present in acid, base, or salt solutions [5]. Electrolyte solutions can conduct electric current [6]. Based on their electrical conductivity, electrolyte solutions can be classified into two categories: a) Strong electrolyte solutions with high electrical conductivity cause light bulbs to light up and gas bubbles to form around the electrodes. Examples include HCl solution and NaOH solution. b) Weak electrolyte solutions have low electrical conductivity. Examples include CH3COOH (acetic acid) and NH3 (ammonia) solutions.

In 1884, Stevane Arrhenius proposed that electrolyte solutions contain freely moving ions, and these solutions can dissociate into electrically charged atomic or molecular groups called ions. Therefore, if a substance dissociates into ions in its solution, it can be considered an electrolyte. Negatively charged ions are called anions, and positively charged ions are called cations [7]. Many issues can arise due to abnormal electrolyte levels. An electrolyte balance is necessary because electrolytes are essential and can affect cell and fluid function. The human body has two types of electrolytes: cations and anions. Anions and ions influence the osmotic pressure of intracellular and extracellular fluids. Magnesium (Mg), potassium (K^+), sodium (Na^+), and calcium ($Ca2^+$) are human body ions, and chloride (Cl^-), bicarbonate (HCO3), and phosphate (PO3) are anions [3].

Several types of electrolyte solutions are used in the research: NaCl, Ringer's Lactate, and Simulated Body Fluid. One of the main electrolytes in the human body is the NaCl solution [8]. NaCl is a physiological solution present throughout the body [9]. NaCl solution is the best way to remember the salt content in body fluids, as it is an adequate physiological fluid for body fluids [10]. Meanwhile, as an electrolyte and water, Ringer's Lactate (RL) solution is a body fluid balancing solution that contains sodium chloride, potassium chloride, calcium chloride, and sodium lactate. Electrolytes and fluids are essential for maintaining body health [11]. Ringer's Lactate (RL) solution is an isotonic fluid replacement comparable to plasma [12]. Simulated Body Fluid (SBF) is a solution that contains ions with a composition similar to human body fluids or blood plasma [13]. pH 7,4 is almost the same as the body's acidity [14].

In this study, measurements of electrolyte solution were conducted. One method used for measurement is electrical impedance spectroscopy. This method produces the material's voltage response output, which is then processed to improve the sample's impedance. Some advantages of spectroscopy are its affordability and ease of use, and the sample extraction process can be done with distilled water (without chemicals) [16-18].

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In previous research by Sugianto and Wismaya, "Electrical Impedance Characteristics of NaCl Solution at Various Concentrations Using Electrical Impedance Spectroscopy Method," it was revealed that the optimal measurement of NaCl solution impedance is in the frequency range of 10 kHz—100 kHz. However, this study is different, as it uses three types of electrolyte solutions and compares their characteristics [8].

This study aims to compare three solutions (samples) using the electrical impedance spectroscopy (EIS) method to determine the characteristics of electrolyte solutions. Within the frequency range of 1 Hz – 1 MHz and a current of 50 µA, the impedance results are used to measure the electrical properties of NaCl, RL, and SBF solutions at various concentrations. The measurement results determine each solution's electrical properties and compare the electrolyte solutions' impedance characteristics.

Research Methods

This study used the electrical impedance spectroscopy method with a bioimpedance spectroscopy device for impedance measurements and electrolyte solutions as samples. The electrolyte solutions used in the study are NaCl, RL, and SBF solutions. Each sample solution underwent data collection with three repetitions to obtain electrical impedance measurement results. The preparation of electrolyte solution test samples involved determining the concentrations and sample preparation stages. The solution samples were prepared before data collection to minimise oxidation due to exposure to outside air when the samples were open for too long, as shown in Figure 1.

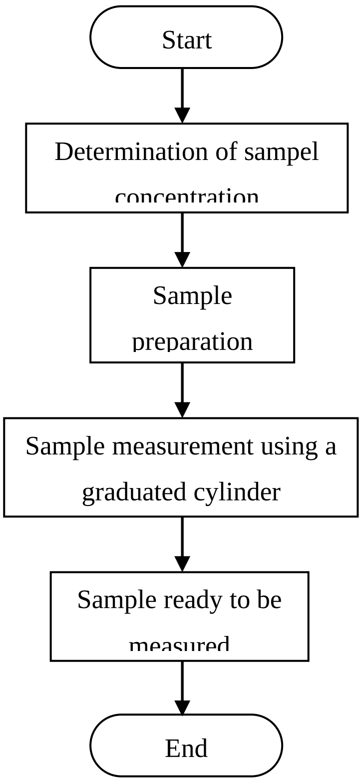

Figure 1. Diagram of Electrolyte Solution Sample Stage

Measurements were conducted within a frequency range of 1 Hz to 1 MHz. The current used for the electrolyte solution samples in this study was 50 µA.

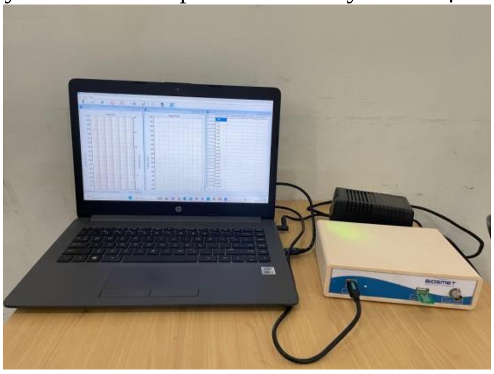

Figure 2. Data Collection of Electrolyte Solutions

In Figure 2. Electrical impedance spectroscopy (EIS) data collection for electrolyte solution measurements, using the EIS method, is used to analyse the electrical properties of electrolyte solutions. Measurements were conducted using a *Bioimpedance Spectroscopy* device with a frequency range of 1 Hz to 1 MHz and a current of 50 µA. With varying concentrations, as shown in Table 1 below:

Table 1. Variation of Solution Concentration

Sample	Volume of Solution	Volume of Distilled Water	Concentration
1	10 mL	50 mL	20 %
2	10 mL	25 mL	40 %
3	10 mL	16.6 mL	60 %
4	10 mL	12.5 mL	80 %
5	10 mL	-	100 %

Measurements were conducted three times to obtain accurate results. The data obtained from these measurements will be used to compare the impedance characteristics of electrolyte solutions.

Results and Discussion

The relationship between the frequency of 10 kHz and the impedance value of an electrolyte solution with a 100% concentration is shown in Figure 3.

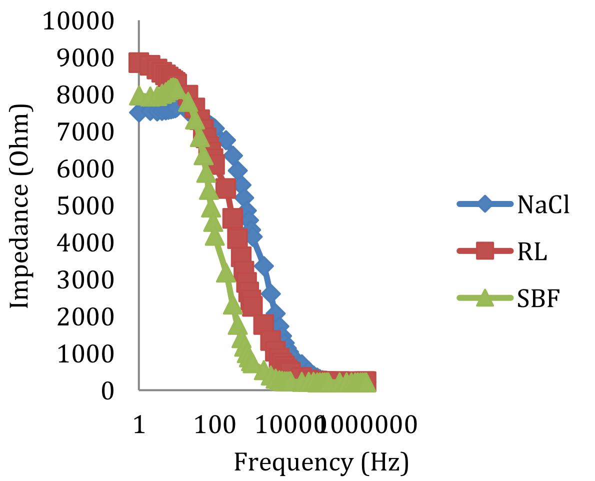

Figure 3. Graph Electrolyte Solutions

The relationship between frequency and impedance value for various electrolyte solutions (NaCl, Ringer's Lactate, and Simulated Body Fluid) at 100% concentration. Figure 2 shows how the impedance value of the electrolyte solution decreases with increasing frequency, covering a frequency range from 1 Hz to 1 MHz. The impedance value of the electrolyte solution decreases with increasing frequency. In the 1 Hz to 100 Hz frequency range, the impedance value is still relatively high, ranging from 9.000Ω to 7.000Ω. Meanwhile, in the frequency range of 1000 Hz to 10000 Hz, the impedance value is moderate, ranging from 5.000Ω to 1.000Ω. In the frequency range of 100000 Hz to 1MHz, the impedance value is low, ranging from 200Ω to 100Ω. The frequency used to measure the electrical impedance of these three types of electrolyte solutions is 10 kHz.

At low frequencies, alternating current (AC) causes charge accumulation in the double layer, increasing due to the slower movement of ions through the diffusion layer. Conversely, at high frequencies, capacitance allows charge to flow more quickly through the capacitive layer, resulting in lower impedance values. At higher solution concentrations, more ions are available from a thicker and denser double layer, changing impedance characteristics, especially at low frequencies where the resistance effect is more pronounced.

It can be seen in the graph that the formation of the double layer at high frequencies (10 kHz – 1 MHz) causes the total impedance value to become low, which appears in the graph as impedance values approaching zero at high frequencies. Conversely, the double layer causes the total impedance value to be high at low frequencies, as shown in the graph with high impedance values at low frequencies.

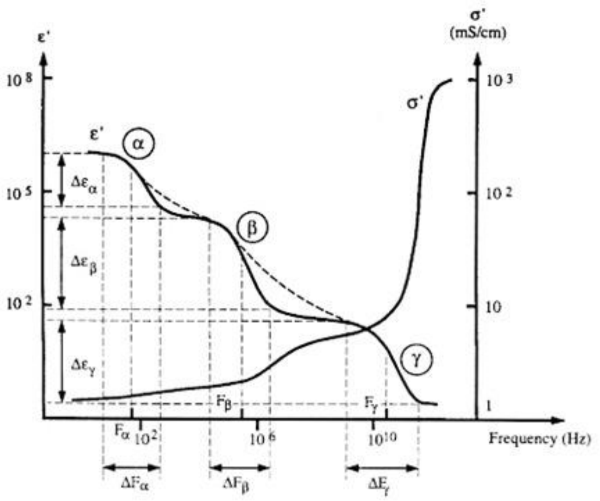

Figure 4. Types of Dispersion in Electrical Impedance [19].

There are three types of dispersion: α dispersion, β dispersion, and γ dispersion. These three types of dispersion depend on the frequency value. In α dispersion, impedance value decreases at low frequencies (mHz - Hz) due to the counter-ion effect near the membrane surface, extracellular structures, and ionic diffusion. β dispersion occurs at 1 kHz – 100 MHz frequencies, caused by the cell membrane's capacitance. γ dispersion occurs in the frequency range between 100 MHz – 100 GHz, caused by the dipolar mechanism in polar materials such as salts, water, and proteins [20]. Alpha dispersion is one of several types of dispersion that occur at a low frequency range of 1 Hz to 100 Hz, as shown in Figure 3. and is usually associated with the formation of a double layer and slow ion exchange processes. This double layer affects electrical impedance, especially at low frequencies. The double layer influences the impedance values in the decreasing graph, and at frequencies approaching 1 MHz, the impedance value is very small.

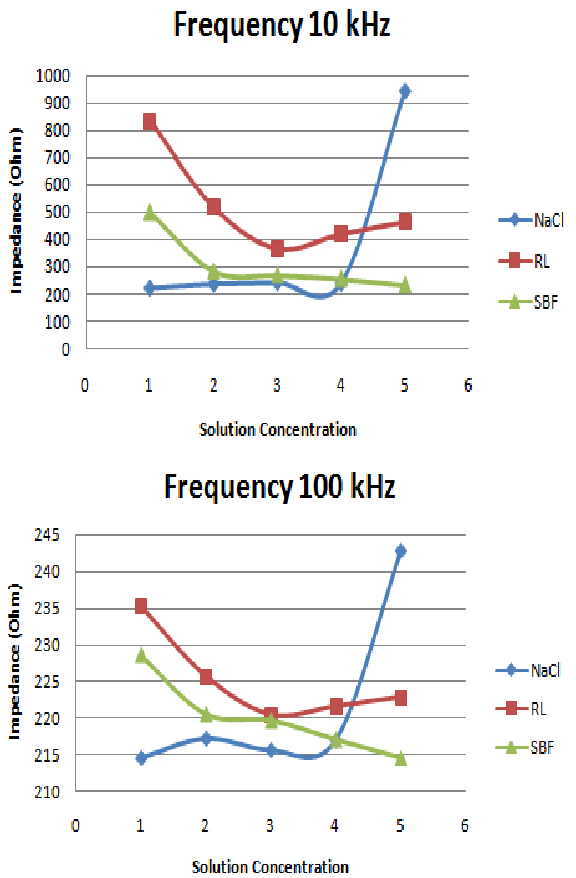

Figure 5. Differences in the Frequency 10 kHz – 100 kHz

In Figure 5, the selected frequency range for the study is determined, specifically the 10 kHz frequency range. This is because it shows the impedance measurement results for electrolyte solutions at various concentrations, ranging from 20% to 100%, illustrating how electrolyte solutions react to a frequency of 10 kHz. This graph shows that NaCl's impedance value tends to decrease with increasing frequency, with impedance values ranging from 200Ω to 900Ω. The Ringer's Lactate solution graph shows more dynamic variations than NaCl. At low frequencies, the impedance tends to be high, but as the frequency increases, there is a significant drop in impedance, ranging from 800Ω to 400Ω. The SBF solution graph shows a different pattern compared to NaCl and RL. At low frequencies, the impedance is relatively high, but as the frequency increases, there is a decrease in impedance, ranging from 500Ω to 200Ω. SBF shows stable impedance characteristics at high frequencies.

The impedance versus frequency graph is obtained in the impedance measurements with varying concentrations of electrolyte solutions, as shown in Figure 3. This figure compares electrical impedance at different concentrations of electrolyte solutions. At a frequency of 10 kHz, the impedance values of the electrolyte solutions at various concentrations can be distinguished, with higher concentrations having lower impedance values.

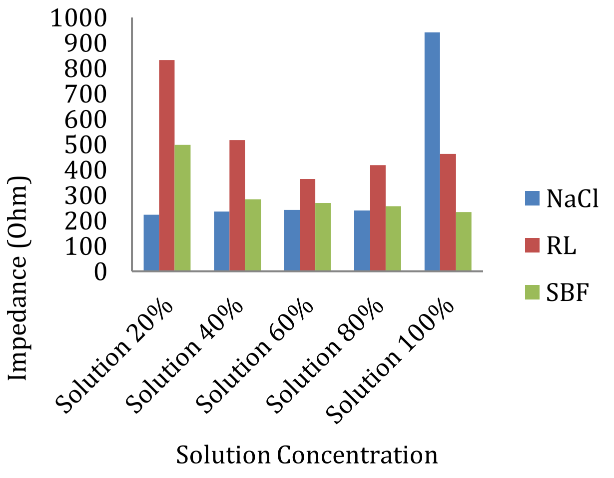

Figure 6. Comparison of Electrolyte Solutions

Based on the comparison of impedance values in Figure 6. the three types of electrolytes show differences. The frequency showing these differences is taken from the frequency range with stable impedance. The impedance value of NaCl is low at high concentrations, whereas RL and SBF show high impedance at the same concentrations, but this difference decreases at higher frequencies. At a frequency of 10 kHz, the NaCl solution has an impedance value ranging from 200Ω to 900Ω, whereas RL and SBF have impedance values ranging from 800Ω to 200Ω, indicating different impedance characteristics.

Conclusion

The impedance characteristics of the measured electrolyte solutions show that the impedance values of NaCl, RL, and SBF solutions decrease with increasing frequency. At a frequency of 10 kHz, NaCl solution has a high impedance value of around 900Ω at a concentration of 100% and the lowest impedance value of around 200Ω at a concentration of 20%. RL solution shows a high impedance value of around 800Ω at a concentration of 20% and the lowest impedance value of around 300Ω at a concentration of 100%. SBF solution has a high impedance value of around 400Ω at a concentration of 20% and a low impedance value of around 200Ω at a concentration of 100%

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