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Impedance Spectroscopy Paragraphs

Main Idea

Impedance is the total response of a system to an alternating current. It is made up of the various resistances and reactances of the system's constituent parts, added either in series or in parallel depending how they are situated relative to each other. An important aspect of impedance is that it is a complex quantity due to the contribution of reactance. Since the reactance of non-resistive components, such as capacitors and inductors, is dependent on the frequency of the alternating current, they can be described as imaginary quantities. This introduction of complex algebra into our electrical system allows us to "salvage" Ohm's law, through the use of complex voltage and current "phasors", with which we can derive the total impedance of a system. This makes impedance measurements very useful, since we are able to find the total response without necessarily knowing the makeup of the system. By running some current or voltage signal through a system and measuring the output, we are able to "work backwards" and determine many qualities of how a given system or material responds to electrical signals. One useful way to go about this is by selecting a band of frequencies and testing the system's response at each step. This is ultimately the idea behind impedance spectroscopy.

Instrumentation Focus: Lock-In Amplifier

The lock-in amplifier is an amazing piece of equipment that is used to extract signal information out of potential very noisy input signals. This is done by taking a sinusoidal reference signal at the same time as an input signal and multiplying them together in two frequency mixers, also known as "phase-sensitive detectors" (PSDs). The output of each PSD results in two new orthogonal sinusoidal functions (called the "in-phase" and "quadrature" components respectively) and spread of frequencies in the frequency domain. The two most dominant frequencies will be centered around the difference and the sum of the input and reference signal frequencies. A low-pass filter is then applied to the mixed signal to attenuate all frequencies higher than the difference frequency. If all goes write and the reference frequency has been correctly set, the difference frequency should go to zero, leaving us only with the "in-phase" component, or two orthogonal components at the phase angle between them. In the latter case, the orthogonality of the two outputs can be exploited to find the input signal amplitude by adding them together in quadrature, along with the phase angle by dividing them and taking the inverse tangent.

Data Analysis

The data were collected in two stages with two different systems under test (SUTs). For each SUT, a different "dominant" resistor (10 kOhm, 100 kOhms, and 1 MOhm) was placed before, and in series with the SUT. In the first stage, a circuit, designed to approximate a biological cell (figure 4) was tested over a range of frequencies from 100 Hz to 100 kHz, with steps of 5 per decade, totaling 16 test frequencies. On the schematic, we can understand R1 to model the medium between each cell, C2 to model the capacitance of each cell membrane, and R2 to model the conductive medium inside of all the cells. The magnitude of the impedance for the circuit was derived by adding the constituent parts together and normalized in order to simplify our calculations by working in natural units. In the second, our SUT was a russet potato. This was tested in an attempt to compare the model from the first SUT to that of a real biological cell. Each “sweep” was performed three times per dominant resistor and averaged in order to reduce our overall error. The magnitude of the impedance and the phase angle were then plotted as functions of the frequency and fit using a non-linear least squares function.

(second paragraph for slides with data)

The data collected from the circuit SUT gives us the plots you can see here (one slide 6). We can see at low frequencies that the impedance is dominated by R1. This is something that we can predict using our equation for the total impedance on slide 5. From there we can see that in series addition of C2 and R2 results in a reactance that is proportional to the frequency, meaning that its contribution is small at low frequencies. There is then a drop, followed by a leveling of at the magnitude of R2. This is similarly predictable given our equation on slide 5 if we take the limit of the impedance magnitude as omega goes to infinity. Applying l’Hopital’s rule shows us that every term except for R2 goes away, making it the dominant term at very high frequencies. Interestingly, we would expect the phase angle to drop as the frequency increases. This does in fact happen at first, but it then bounces back up. It was Dr. Tagg’s suggestion that this may have something to do with inductance behavior developing at higher frequencies. On a final point, our error for both the impedance and phase is much lower than expected and had to be scaled in order to even be visible. This suggests some error in our error propagation. Additionally,the data gathered for russet potato SUT had massively overblown error, to the point where any relationship between the frequency and impedance or phase angle was hidden. Due to this, it was not included. This may also be due to our own error propagation, but may also possibly be due to our positioning of the electrodes in the potato. As Dr. Tagg pointed out, our placement was quite far.

Special Topic

Generally, bioimpedance analysis is a noninvasive approach used in body composition measurements and healthcare assessment systems. Like the impedance in our experiment, the bioimpedance is a complex quantity composed of resistance, caused by the total body water, and reactance, caused by the capacitance of cell membranes. These two quantities are put together in a complex expression, which can be used to determine phase angle and impedance magnitude. Bioimpedance measurements can be used to estimate body composition by determining body volume through basic resistance measurements. The volume of a human body is generally composed of fat mass, which is a non-conductor of electric charge and is equal to the difference between body weight and fat free mass. Fat free mass acts as the conducting volume through which electric current passes due to conductivity of electrolytes dissolved in body water. The measurements themselves are taken by running a weak current through the body and then measuring the voltage. From here, the impedance is calculated. Since fat free mass acts as a conducting volume, a greater presence of it will correlate to lower impedance. Therefore, these measurements can be useful for estimating body fat composition and helping to determine body fat percentage and body mass index. While these measurements can be used to make estimates, they are generally not extremely accurate. However, these measurements are easy to make and can be useful for tracking changes to body composition over time.