Laboratory Project 3: Model of Tissue Impedance

N. E. Cotter, D. Christensen
ECE Department, University of Utah
3280 MEB, 50 S. Central Campus Dr.
Salt Lake City, UT 84112

***Abstract*-You will build a oscillator circuit that generates a 25 kHz sinusoid. Using electrodes and a series resistor, you will pass the 25 kHz sinusoid through your arm and derive a numerical model of our arm's impedance. You will compare these numbers with published tables to estimate the makeup of tissue in your arm.**

I. Preparation

For Lab 3, which will last about three weeks, you will need the parts listed in Table I, (in addition to the breadboard and wire kit from Lab 1). You may purchase these parts from the stockroom next to the lab or purchase them elsewhere.

TABLE I
PARTS LIST

Item	Qnty	Description
1	1	LF353 Operational Amplifier
2	2	250 pF Capacitor
3	1	2 kΩ Resistor
4	4	Resistors (values determined during lab)
5	2	electrodes

II. Learning Objectives

1) Learn about impedance circuits.
2) Learn how to design a Wien-bridge oscillator circuit with an op-amp.
3) Learn how to interpret published data on impedance versus tissue type.

III. Introduction

A. Electromagnetic Fields and Tissues

Understanding the effects of electromagnetic radiation on tissues is valuable for determining safety parameters for wireless devices and for creating effective tools for modern medicine. Modern humans are immersed in an environment filled with a background of electromagnetic radiation. Some sources of this electromagnetic radiation are low in public exposure intensity (TV, radio and other communication stations; 60-Hz power lines), some are moderate in public exposure intensity (cell phones when placed against the head), and some are intentionally strong (MRI imagers; radio-frequency tissue ablation for cancer treatment). Around the world, research teams study how exposure to this electromagnetic radiation affects the body. Numerical modeling of the effects requires knowledge of tissue impedances at the frequencies of the electromagnetic radiation.

Because cells are the building blocks of tissues, insight into the impedance of cells aids in creating viable models. By investigating the structure of cells, modelers create simplified equivalent circuits suitable for numerical simulations. A single cell (Fig. 1A) may be viewed as a fluid-like substance with several species of mobile ions (the cytoplasm) contained within a semi-permeable cell wall (the cell membrane). Outside the cell is more fluid (the extracellular fluid), with again several species of mobile ions. Electrically, the cytoplasm can be modeled to first order as a conductive medium—due to the presence of the large concentrations of ions—characterized by a given value of conductivity, σ, (or its inverse, resistivity, ρ). The extracellular fluid can also be modeled as a conductive

medium. The cell wall, on the other hand, is relatively insulating and, since it is a thin layer, is modeled as a capacitive medium with a given relative permittivity, ε_r.

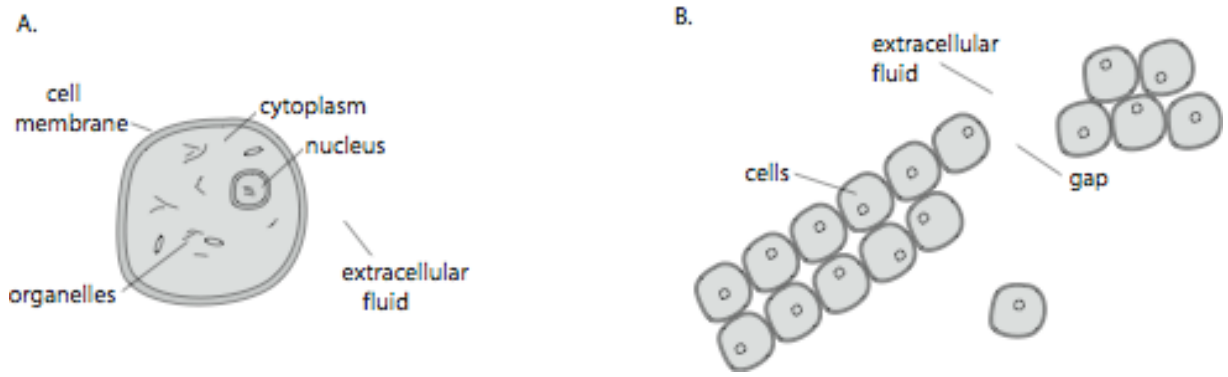

Fig. 1 – A) Simplified diagram of a single cell, whose size can vary between 10 μm to nearly 1 mm; B) Tissue is composed of collections of cells. Gaps between the cells allow current to flow through shunt paths.

Tissues are composed of arrangements of cells (Fig. 1B) surrounded by the conductive extracellular fluid. In some places, the cells are tightly bound together and any circulating current must pass through the cell membranes. In other places, there are gaps (shunt paths) through which current can flow. Modeling every detail of the cells and shunt paths would be impractical. We may, however, use simple circuits to obtain reasonable approximations to the aggregate behavior of cells in tissues.

We consider a region of the body where there is a volume of soft tissue (muscle and fat) covered by skin upon which two opposing electrodes can be attached, namely the biceps muscles of the upper arm. A simple equivalent electrical model of the tissue between the two electrodes is shown in Fig. 2A. This is a lumped-element model where all inner-tissue cells are combined together into a single series R_cC_c branch. This branch in turn is in parallel with a resistive branch, R_t, representing the shunt intracellular fluid paths. At both ends of this circuit are parallel R_sC_s segments representing the electrical properties of the thin skin directly underneath the electrodes.

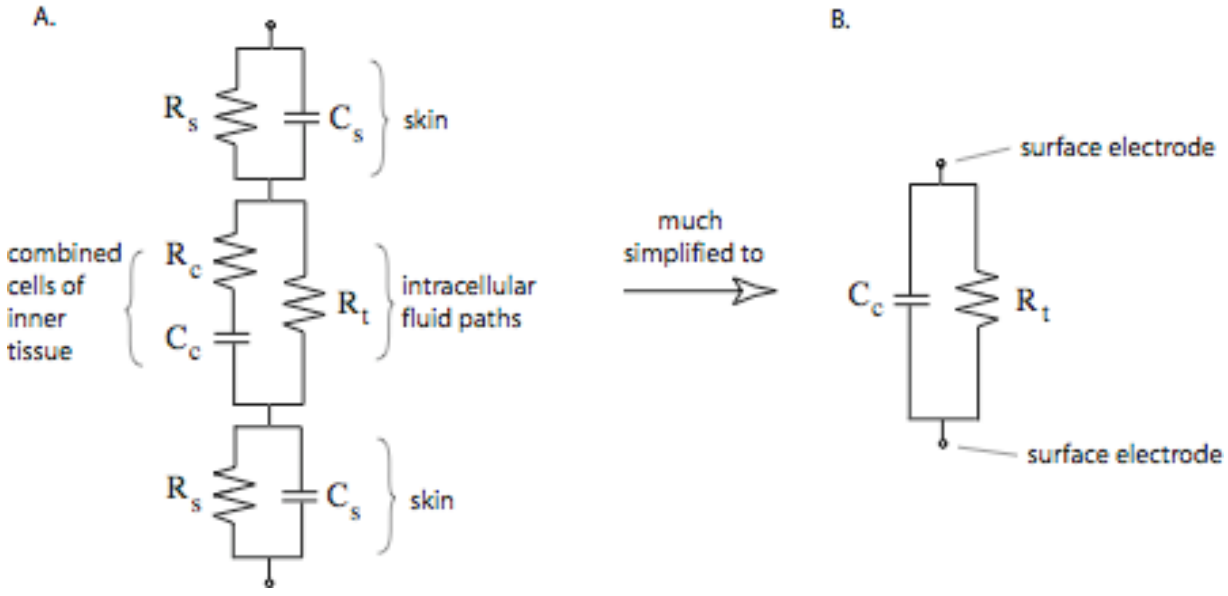

Fig. 2 – A) Lumped-element model of the electrical behavior of tissue bordered by skin, B) After several simplifications, the model reduces to its essence, a parallel *RC* circuit.

With some reasonable assumptions, this model can be greatly simplified. Assume that the combined resistance of the cell cytoplasm, R_c, is much lower than the reactance, $1/\omega C_c$, due to the cell membranes. Also, assume that the resistance of the thin skin, R_s, is much lower than both the skin reactance, $1/\omega C_s$, and the tissue resistance, R_t. (The validity of these assumptions depends very much upon the particular tissue region being modeled and the frequency of the electrical excitation, but for muscle and skin at a relatively low frequency of 25 kHz, these approximations are appropriate.) Then the model of Fig. 2A reduces to the simple R_tC_c parallel equivalent circuit shown in Fig. 2B. In the laboratory exercise detailed below, you will make measurements with the aim of finding typical values for the parameters of this simplified circuit.

B. Design Project Overview

Your project is to design an oscillator that will produce a sinusoidal waveform at a frequency of 25 kHz and use that signal to determine the value of resistance and capacitance for a model of tissue impedance based on measurements of your biceps. The oscillator is an op-amp Wein-bridge circuit that produces a sinusoid, as shown in Fig. 3. The sinusoidal output from the oscillator will drive a resistor in series with electrodes placed on both sides of your biceps. The resistor, whose value you will choose, and the tissue in your biceps will form a voltage divider. By measuring the magnitude and phase-shift of the voltage across the resistor relative to the 25 kHz sinusoid, you will be able to determine the value of R_t and C_c for a parallel RC model of the tissue. You will use an oscilloscope to make the necessary magnitude and phase-shift measurements.

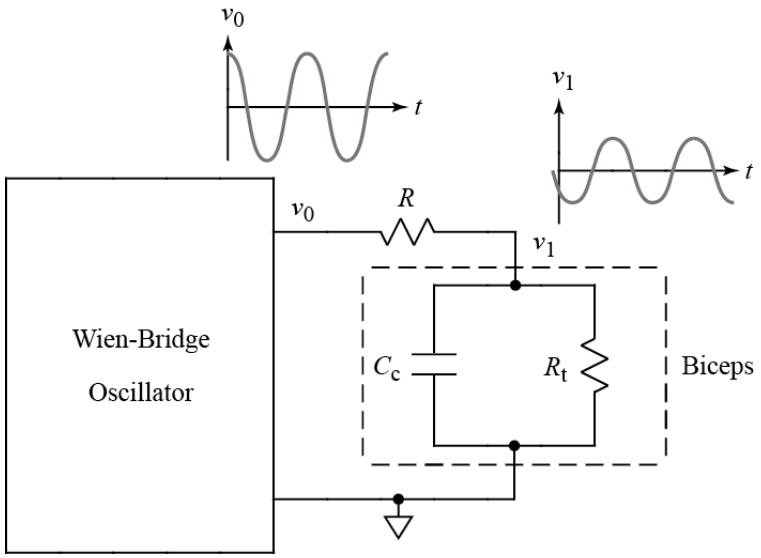

Figure 3. Block diagram of tissue measurement experiment.

IV. Wein-Bridge Oscillator

A. Wein-Bridge Oscillator Explanation

Fig. 4, below, shows the schematic diagram for the Wien-bridge oscillator (without the electrodes across the muscle and R) that you will build for Lab 3. The purpose of this oscillator is produce a sinusoidal signal at 25 kHz that can be used to measure tissue impedance. The oscillator has positive and negative feedback, and the op-amp may be thought of as trying to make the + and – input signals to the op-amp the same. If we think of the op-amp output, v_0, as a voltage source, then the Wien-bridge driven by the op-amp may be viewed as two voltage dividers producing v_- and v_+, as indicated by the shaded boxes. The bridge is said to be balanced when the two voltage dividers produce the same output voltages when driven by v_0. One's first impression upon viewing the circuit in Fig. 4 might be that the circuit should output $v_0 = 0$ V, whether the bridge is balanced or not, as this would result in $v_- = v_+ = 0$ V.

Note, however, that if the circuit is balanced, $v_0 \neq 0$ V would also be a solution. Since the left side of the Wien bridge is frequency dependent, this means there may be one frequency, ω_0, where the bridge is balanced and the

output phasor $\mathbf{V}_0 \neq 0$ V. In other words, the circuit may oscillate at frequency ω_0 that balances the bridge. Our design objective is to select component values that yield a value of $\omega_0 = 25$ kHz. Note that the preceding discussion establishes the circuit *may* oscillate. The presence of noise in the circuit starts the oscillation process but we will forego a detailed analysis of the circuit, as a complete analysis of the circuit involves many layers of increasing complexity.

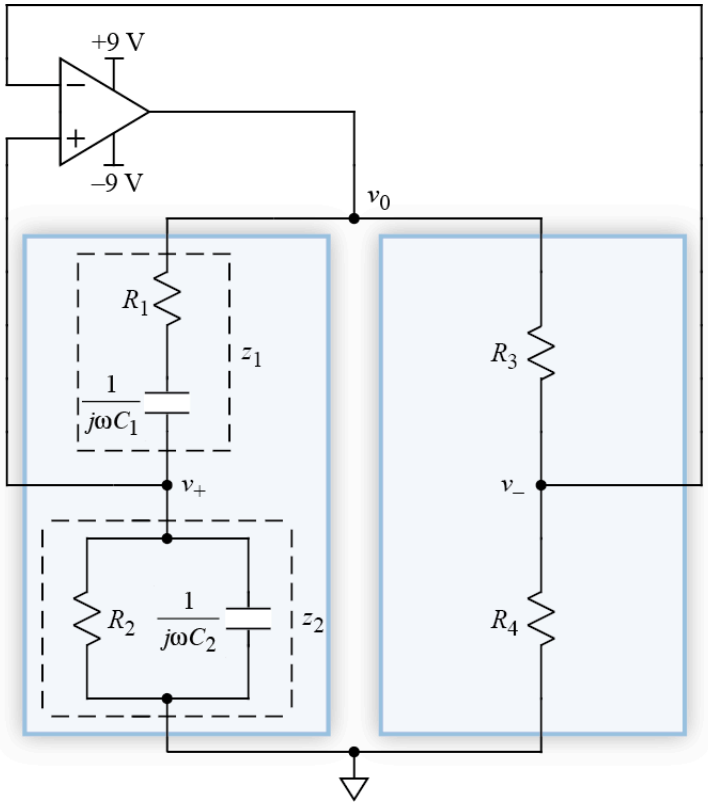

Figure 4. Wien-bridge oscillator schematic. Shaded boxes indicate voltage dividers.

B. Wein-Bridge Oscillator Analysis

Using the frequency-domain model, we can show that the bridge is balanced, i.e., $v_- = v_+$, when $Z_1/Z_2 = R_3/R_4$ where Z_1 is the combined impedance of R_1 in series with C_1 and Z_2 is the impedance of R_2 in parallel with C_2. We treat v_0 as a voltage source, and we treat the two voltage dividers in Fig. 4 as separate circuits, each with their own v_0 source.

C. Procedure

1) Show that the Wien bridge can be balanced only when (1) is satisfied: (transform the circuit to the frequency domain, set the voltage divider outputs equal to each other, and equate the real parts of the voltage divider formulas)

$$\frac{R_1}{R_2} + \frac{C_2}{C_1} = \frac{R_3}{R_4} \tag{1}$$

2) Find an expression for the frequency of oscillation, ω_0, at which the bridge is balanced: this expression will contain R_1, R_2, C_1, and C_2, and is found by equating the imaginary parts of voltage divider formulas in the frequency domain.

3) Compute the value for R_1: use $R_1 = R_2$, $\omega_0 = 2\pi(25$ kHz) (or as close as possible with a standard value for R_1), and the following values for the other components: $R_3 = 36$ kΩ $= 2R_4$ and $C_1 = C_2 = 250$ pF.

4) Build the Wien-bridge oscillator circuit: use the schematic in Fig. 4 and an LF353 op-amp. If your circuit fails to oscillate, make sure your components have closely matched values so they satisfy (1). Use extra capacitors in parallel and resistors in series or parallel if necessary to make values match.

5) Measure the Wien-bridge oscillator circuit output with no load: using an oscilloscope, record v_0, store the waveform in a file for later use, plot the waveform using Matlab®, and put the plot in your laboratory notebook. Fill out Table II with the following values:

i. Desired oscillator frequency, (25 kHz).
ii. Predicted oscillator frequency for standard component values chosen for the circuit. That is, assume the components have exactly the standard value shown on their label.
iii. Predicted oscillator frequency for measured component values.
iv. Oscillator frequency measured on the oscilloscope.

TABLE II
WEIN-BRIDGE OSCILLATOR DESIRED AND ACTUAL FREQUENCIES

ω_0 desired	ω_0 predicted (standard component values)	ω_0 predicted (meas. component values)	ω_0 actual

V. TISSUE IMPEDANCE MEASUREMENT

A. *Tissue Impedance Circuit Explanation*

As discussed earlier, a simplified model of tissue impedance consists of a parallel R_t and C_c. Nominal values for R_t and C_c are $R_t = 2\ \text{k}\Omega$ and $C_c = 2.5$ nF. To determine the precise values of R_t and C_c for your biceps, you will use a voltage divider consisting of a known resistance, R, in series with the biceps tissue that is between electrodes, as shown in Fig. 3.

B. *Tissue Impedance Analysis*

We measure the phasor voltage, $\mathbf{V}_0$, at the output of the Wien-bridge oscillator and across the total impedance consisting of R and the biceps, and we measure the phasor voltage, $\mathbf{V}_1$, across the biceps. Using these phasors, the voltage-divider formula, and algebra, we can determine the values of R_t and C_c.

C. *Procedure*

1) Derive formulas that give the values of R_t and C_c as a function of $\mathbf{V}_0$ and $\mathbf{V}_1$: (two ideas that will be helpful are to turn the voltage-divider equation upside-down and to equate the real parts and the imaginary parts of the two sides of the equations). Calculations are performed in the frequency domain, of course.

2) Measure the values of $\mathbf{V}_0$ and $\mathbf{V}_1$: use the circuit shown in Fig. 3, two electrodes placed on opposite sides of the biceps as shown in Fig. 5, and two oscilloscope probes to measure v_0 and v_1. Record v_0 and v_1, store the waveform in a file for later use, plot the waveform using Matlab®, and put the plot in your laboratory notebook.

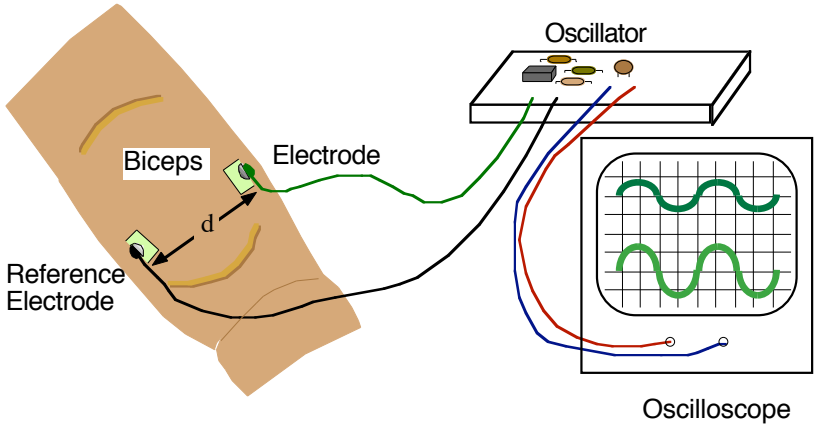

Figure 5. Tissue measurement configuration.

3) Measure the surface area, A*, of the electrodes and the approximate the distance,* d*, between the electrodes:* use a ruler to determine the conductive area of the electrode and the approximate value of *d*. The values of *A* and *d* will be used later.

4) Convert the measured sinusoids for v_0 and v_1 to phasors for $\mathbf{V}_0$ *and* $\mathbf{V}_1$: assume the phasor for $\mathbf{V}_0$ has a zero phase shift, and measure the phase shift of v_1 relative to v_0 to determine the phase shift for $\mathbf{V}_1$. Note that determining the phase shift of one sinusoid relative to another means determining what fraction of a cycle the second sinusoid lags the first sinusoid. The delay will be between 0° and 360°. A delay equal to one-half cycle corresponds to 180°, for example. List the values of $\mathbf{V}_0$ *and* $\mathbf{V}_1$.

5) Calculate the values of R_t *and* C_c *using the formulas you derived in item (1):* note that values for R_t *and* C_c may vary significantly from the nominal values listed in item (1).

VI. Tissue Parameters and Published Tissue Data

A. Procedure for Calculation of Conductivity, Relative Permeability, and Power Density

Use your calculated values of R_t and C_c along with *d* and *A* to find estimated values of the conductivity, σ, and relative permeability, ε_r, of your muscle for comparison with published values. Also, calculate the power density, *S*, used in the experiment. The equations you will need come from basic physics and involve *only products or quotients* of physical quantities. By ignoring fringing fields and modeling the tissue between the electrodes as a tube, as shown in Fig. 5, derive equations for the following terms:

1) R_t *as a function of* d*,* A*, and* σ *= tissue conductivity = 1/tissue resistivity in* Ωm.

2) C_t *as a function of* d*,* A*, and* $\varepsilon = \varepsilon_0\varepsilon_r$ *where* $\varepsilon_0 = 8.85$ *pF/m and* ε_r *= unitless const.*

3) Power density S *(= total power in tissue divided by electrode area) in W/m*^{2} *as a function of* I *= magnitude of electrode current,* R_t*, and* A.

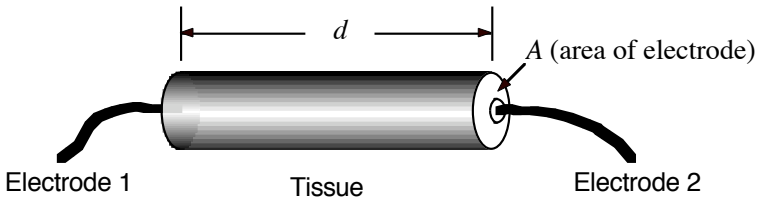

Figure 6. Tissue modeled as a tube.

To determine whether R_t or C_t are proportional or inversely proportional to *d* or *A*, think of the tube of tissue being subdivided into thinner or shorter tubes connected in parallel or in series. Increasing *A* corresponds to adding components in parallel, while increasing *d* corresponds to adding components in series. Rearrange your equations for R_t and C_t to solve for σ and ε_r. Use your measured value for $\mathbf{V}_1$, along with R_t and C_t, to calculate the magnitude of electrode current, *i*, and the value of *S*.

B. Procedure for Comparison of Measured with Published Values

1) Complete Table III: list your values of σ and ε_r along with values of these parameters for muscle and fat found in documents on dielectrics available via links on the course website. Explain the source you chose for the published values and why.

TABLE III
MEASURED TISSUE PARAMETERS AND PUBLISHED TISSUE PARAMETERS

σ measured	σ published	ε_r measured	ε_r published

2) Compare your value of power density, S*, with the FDA limit of 100 mW/cm*^{2} *(for higher frequency):* published on the web at:

http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet65/oet65.pdf

(see p. 67, Table I(B) value for 0.3 MHz). Comment on whether the power density is safe.