1. INTRODUCTION

1.1. Electromyograms

Modern humans are immersed in an environment filled with a background of electromagnetic radiation. Some of the sources are very low in public exposure intensity (TV, radio and other communication stations; 60-Hz power lines), some are of moderate 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, many research teams are studying how exposure to this electromagnetic radiation affects the body, and therefore are interested in modeling the electrical properties of tissue.

Cells are the building blocks of the tissues of the body, and various types and sizes of cells make up a large proportion of the body's volume. A single cell (Fig. 1A) can 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.

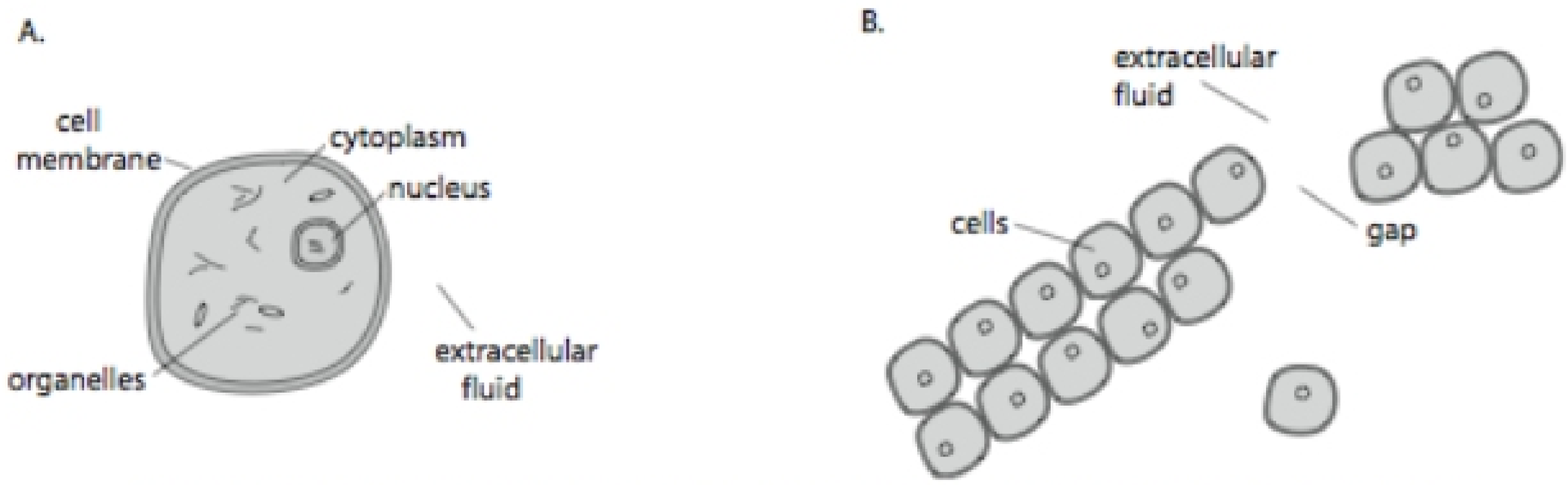

Fig. 1 A) Simplified diagram of a single cell, whose size can vary between 10 μm to nearly 1 mm; B) Tissue is composed of collections of cells. Gaps between the cells allow current to flow through shunt paths.

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.

With cells in mind, 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 (e.g., 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.

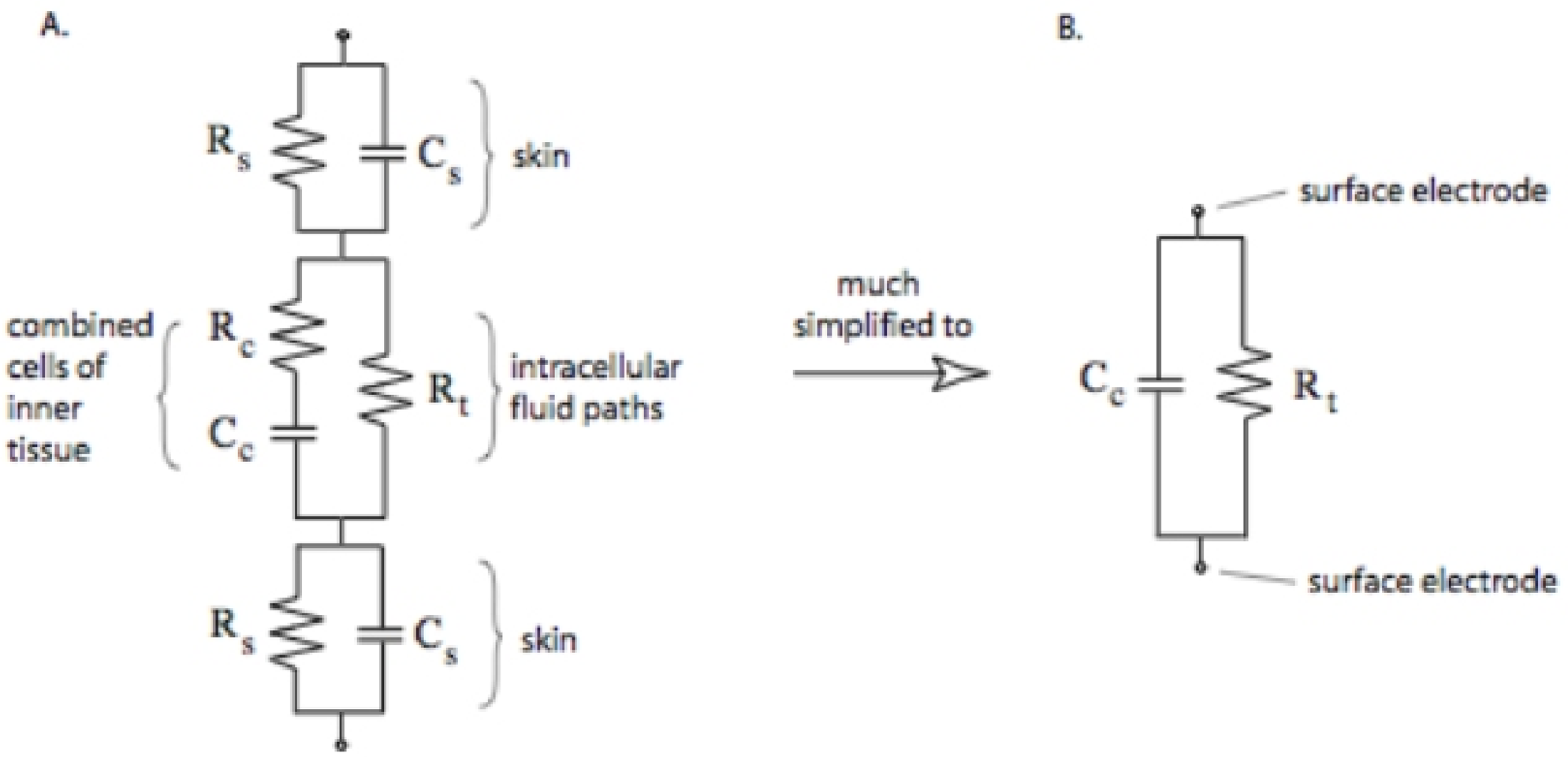

Fig. 2 – A) Lumped-element model of the electrical behavior of tissue bordered by skin; B) After several simplifications, the model reduces to its essence, a parallel RC circuit.

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.

1.2. The Design Project

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 and C for a parallel RC model of the tissue. You will use an oscilloscope to make the necessary magnitude and phase-shift measurements.

2. DESIGN OSCILLATOR

2.1. Frequency-Domain Circuit

The Wien-bridge oscillator in Fig. 3 consists of an op-amp and two voltage dividers. One voltage divider consists of components on the left side: R_1, C_1, R_2, and C_2. The other voltage divider consists of components on the right side: R_3 and R_4. These two voltage dividers deliver a fraction of the op-amp output voltage, v_0, to the + and – inputs of the op-amp. Because the circuit has negative feedback, changes in v_0 act to make the voltages at the op-amp inputs equal. Because the circuit also has positive feedback, changes in v_0 also act to make the voltages at both op-amp inputs change in tandem, however. At first glance, the equilibrium value for v_0 would seem to be 0 V. This is true in all cases except the special case when the two voltage dividers output exactly the same voltage. In this case, the bridge is said to be balanced. Though it may be counterintuitive, a balanced bridge leads to oscillation, as we discuss next.

When the bridge is balanced, *any* value of v_0 causes the + and – input voltages of the op-amp to be equal. Because we are dealing with reactive components, the bridge is balanced for one particular frequency of sinusoid. If the bridge is balanced, this sinusoid may have any amplitude. This is equivalent to saying the circuit is an oscillator.