# Computational Modeling of a Wearable Device with Feedback to Advance the Healing of Chronic Skin Ulcers

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## 1. Abstract

This paper discusses how COMSOL Multiphysics modeling software allows for design ideas to be validated through computer simulation. The human forearm, thickness of approximately 1.3 mm, with an open skin ulcer and electrical pads on each side was modeled. This baseline simulation was performed with a parametric sweep of varying Voltage and Frequency applied to the electrical pads along with varying skin Impedance at the wound bed. The data generated a Voltage Density (V/m) plot showing minimal affect in the wound bed itself, but significant affect outside the bed and minimal penetration into the skin. Each layer of skin (Muscle, Fat, Dermis, Epidermis, and Stratum Corneum) was included with their respective properties; which were preloaded onto the COMSOL software. From the baseline data gathered, a second model was simulated with the same parametric sweep, but this time with a feedback device using an Organic Electrochemical Field Effect Transistor (OECT) placed in the center of the wound bed. The OECT used in the simulation incorporated a Polyimide (PI) Polymer microfluidic membrane, a Sodium Chloride electrolyte with pure gold for the Source, Drain, and Gate contacts; each needed to be added to the COMSOL software for accurate modeling. The data generated 2-dimensional Voltage Density (V/m) plots showing significant affects to the inside and the outside of the wound bed with little penetration into the skin, which validating the concept of an OECT as a sensor. The COMSOL simulation data would aid in the design of a common source FET configuration that would amplify the output signal to the needed range of the microcontroller. The simulations show the OECT with a Polyimide (PI) Polymer microfluidic membrane, a Sodium Chloride electrolyte with pure gold contacts would be able to monitor the hydration level at the wound bed, the rate of Cl- ionic movement, and voltage changes as an external electrical signal is applied. This concept would lead to an improved wound healing experience for patients with chronic skin ulcers. [1-4]

***Keywords:*** microfluidics, biofeedback, wound healing

## 2. Introduction

The physiology of human skin is in a state of flux throughout the day. There are five distinct layers of human skin with unique properties of their own, each can be represented as a parallel electrical circuit. The main focus of this work will deal with the upper three layers of skin, the Stratum Corneum, Epidermis and Dermis, where the skins ulcer will reside. Figure 1 presents the layers of human skin: Muscle, Fat, Dermis, Epidermis, Stratum Corneum and also includes the skin ulcer and electrodes. The thickness of the bottom two layers varies greatly from one part of the body to the next. For example, the human thigh can have a thickness of approximately 22.06 mm to the forearm which has an approximate thickness of 1.3 mm. These values can vary from individual to individual and from male to female, but for the purpose of this research, the forearm of a human male was chosen. [4, 5]

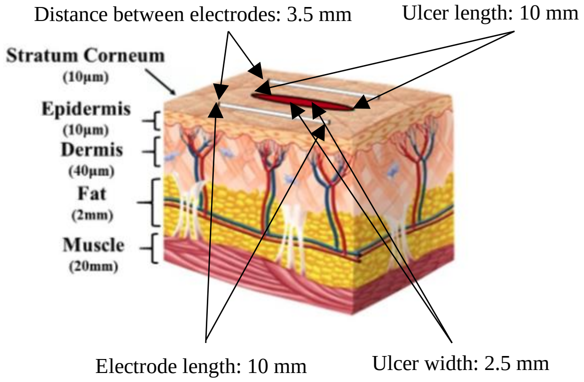
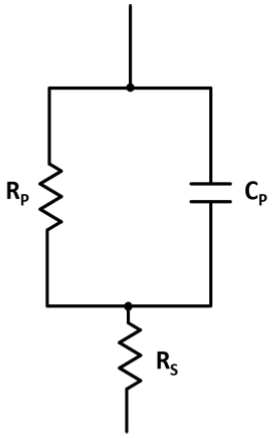


Figure 1: Human tissue layers with wound and electrodes [5]

## 3. Methods

The layers of human skin can be compared to a parallel electrical circuit, each layer consisting of its own unique resistance and capacitance properties, as shown in Figure 2. To calculate the equivalent impedance of the circuit, the general resistance-capacitance equations are used, reference Equation 1, Equation 2, and Equation 3 below. The resistance of the uppermost layer, the Stratum Corneum, is significantly higher than inner layers, so the parallel portion of the circuit is ignored. The Stratum Corneum is the protective layer with the highest impedance of approximately 10 kΩ.



Equation 1: $$\mathbf{Z_{eq}} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{R_P}} + \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{j\omega C_p}}}} + \mathbf{R_S}$$

Equation 2: $\mathbf{Z_{eq}} = \mathbf{Z_P} + \mathbf{Z_S}$

Equation 3: $\mathbf{Z_{eq}} \rightarrow \mathbf{R_S}$ **as** $\boldsymbol{\omega} \rightarrow \infty$

$Z_{eq} \approx 10$ kΩ, Stratum Corneum resistance

Note: Not used in the numerical model, but for a physical device not discussed in this paper.

Figure 2: Equivalent Circuit and Equations

## 4. COMSOL Simulation

### 4.1. Computational Model

For this study, the electric current physics was employed to perform numerical calculations. The model of human skin was generated with the parameters for each component loaded into the global definitions. The tissue layers were constructed with respective thicknesses, the muscle and fat layers was chosen to be that of a male forearm for easier calculations. Calculations in the parametric sweep started with an applied voltage of 0 V with a frequency sweep from 25 Hz to 10,000 Hz in 500 Hz increments. After the frequency reached 10,000 Hz, the applied voltage increased by 2 volts and this process continues until the applied voltage reached 36 volts. The parameters for the parametric sweep were chosen by the design requirements of the wound healing device, not discussed in this paper, and literature review. The numerical calculations generated 2 dimensional surface plots that provided the Voltage Density (V/m) across the entire surface. The basic skin properties were per-loaded onto the COMSOL Multiphysics software.

### 4.2. COMSOL Governing Equations

| COMSOL Governing Equations | |
|---|---|
| $\nabla^2 V = 0$ | $V_{Gnd} = 0$ |
| $E = -\nabla V$ | Electrical Potential: $V = V_0 = 36$ V |
| $J = (\sigma + j\omega\, \varepsilon_0\, \varepsilon_r)E$ | $D = (\varepsilon_0\, \varepsilon_r)E$ |
| Electric Insulation: $n \cdot J = 0$ | Insulation Boundary Condition |
| D is electric displacement | |
| V is electric potential | |
| E is electric field | |
| J is current density | |
| ω is angular frequency ($\omega = 2\pi f$ ) | |
| $\varepsilon_r$ is relative permittivity | |
| $\varepsilon_0$ is absolute permittivity | |
| σ is electrical conductivity | |
| ∇ is gradient vector | |
| n = is the normal vector to the surface pointing outward | |
| The electrical insulation boundary condition is imposed at all exterior boundaries, as it is assumed that negligible current flows through these. | |

## 5. Results

### 5.1. COMSOL Computational Model of Healthy Skin

The model shown in Figure 3(a) is that of a section of healthy human skin with two electrodes fixed on its surface; the dimensions shown in Figure 1 were used for the each model construction. The electrodes are made of copper with dimensions of the electrode are: length 10mm, width 0.05 mm, and height 0.05mm. Once the model was generated and all boundaries were established, the Physics was set with the electrical potential electrode and then the ground electrode identified. Figure 3(a) shows the healthy skin model before simulation and after the testing was completed. The parametric sweep was performed; 2D plots are shown in Figure 4(a)(b). Figure 4(b) shows the surface plot after the parametric sweep was completed. The bottom electrode is the 36 V electrical potential and the spots on the electrode are "hot" spots. The mesh analysis was chosen to be finer for more clarity of the simulation and also reduce the size of the "hot" spots. The continuous blue across the surface is an indicator of uniform Voltage Density (V/m), which is expected for healthy skin.

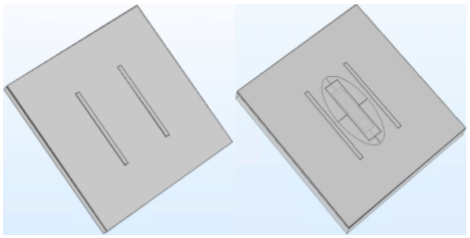
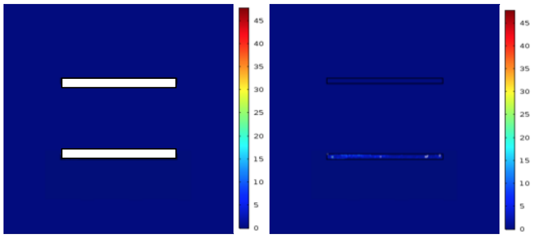

(a) (b)

Figure 3: (a) Orthographic view of healthy skin with electrodes. (b) Orthographic view of wound bed, electrodes and Organic Electrochemical Transistor.



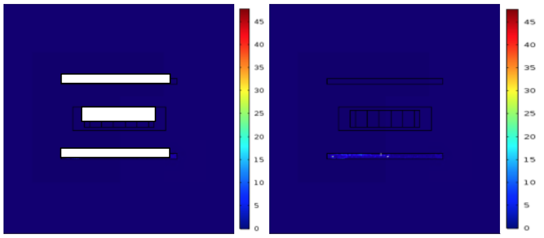
(a) (b)

Figure 4: (a) Healthy skin 2D top view of electrode, top ground, bottom 36 V. (b) Healthy skin 2D top view of showing "Hot" spots on the 36 V electrode. Voltage Density z component (V/m)

## 5.2. COMSOL Simulation of (OECT) in Wound Bed

The model shown in Figure 3(b) is the same as Figure 3(a), but the addition of the Organic Electrochemical Transistor placed in the wound bed. The Source, Gate and Drain dimensions of the sensor are: length 1.0 mm, width 1.5 mm and height 0.2 mm. The Polyimide (PI) Polymer dimensions are: length 1.5 mm, width 6.0 mm and height 0.04 mm. The Sodium Chloride dimensions are: length 2.0 mm, width 8.0 mm and height 0.08 mm.

The OECT with a Polyimide (PI) Polymer was the conductive polymer, Sodium Chloride (NaCl) was the electrolyte, and Gold for the contacts was chosen for this model. Sodium Chloride was chosen as the electrolyte because it is naturally secreted by the human body and would not have adverse reactions. Pure gold was chosen as the Source, Gate, and Drain contacts because it is inert for most humans, causing no adverse reactions from contact with open wounds. The modeling was the same as that as the healthy skin, but with a wound and an OECT inserted. Many of the skin properties were pre-loaded into the COMSOL software. Once the model was generated and all boundaries were established, the Physics was set with the electrical potential electrode and the ground electrode identified. Figure 5(a)(b) are 2D surface plots of the Voltage Density (V/m). The lower electrode in Figure 5(b) is the 36 V electrical potential electrode and the upper electrode is the ground electrode. The "hot" spots on the lower electrode are represented a light blue dots on the surface. A finer mesh analysis was chosen to get more accurate calculations and reduce the effect of seeing "hot" spots on the results. Figure 6 shows the 3D surface contour plot which shows an equally disperse Voltage Density (V/m) with the 36 V electrode showing "hot" spots in a green color. The OECT that in the wound bed is showing an intensity color that is higher than the surrounding skin. The more intense color is an indicator that the voltage density on the OECT is higher than the 1.2V the surrounding skin is showing. The cause for the greater voltage can be attributed the to the fact that the transistor is detecting ionic movement on the surface of the wound bed.



(a) (b)

Figure 5: (a) 3D side view contour plot. (b) 3D top view slice plot of wound bed results showing “Hot” spots on the 36 V electrode. Voltage Density (V/m).

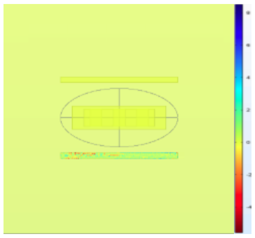


Figure 6: 3D top view slice plot of wound bed results showing “Hot” spots on the 36 V electrode. Voltage Density (V/m).

## 6. Conclusions

This paper discusses how the use of computational software like COMSOL can aid in the design of devices that can advance many fields of research. The COMSOL model employed in this work shows that, in theory, the concept discussed in this paper is feasible in the wound healing process. With the addition of the sensor that incorporates an Organic Electrochemical Transistor (OECT) and properly fixed onto the wound bed, the healing process would be significantly improved for the patient.

## 7. References

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