Numerical Simulation of Pulsed Electromagnetic Field (PEMF) Tissue Therapy

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ABSTRACT

Pulsed Electromagnetic Field (PEMF) therapy involves the use of pulsed radiofrequency (rf) electromagnetic waves to treat a range of maladies from chronic wounds to fractured bones. This non-invasive therapy is applied using an external coil that is pulsed and generates a time-varying magnetic field within the treated tissue. This in turn induces a time-varying electric field and associated current flow in the tissue that stimulates a variety of biological processes from increased blood flow to an enhanced cellular function that collectively promotes healing of bones and tissue. In this paper, we demonstrate a 2D-axisymmetric computational model for predicting electromagnetic aspects of PEMF therapy. Specifically, the model predicts the generation and penetration of a coil-generated rf magnetic field, the induced electric field and current by taking into account the different tissue layers and their individual frequency-dependent electrical properties. In addition, we use the Pennes' bioheat equation to predict the temperature rise due to the current induced Joule heating throughout the treated tissue. The computational model provides a fundamental understanding of PEMF-tissue coupling and enables the rational design of novel PEMF medical devices.

Keywords: pulsed electromagnetic field, PEMF, pulsed rf electromagnetic therapy, wound healing, field-tissue interaction, bio-electromagnetics, bioheat transfer

1 INTRODUCTION

Applications of PEMF therapy [2] have grown steadily over the last 40 years as clinical evidence of the effectiveness for various treatments, e.g. pain relief, bone and wound healing etc., has emerged [1]-[4]. An example of a commercial PEMF wound healing therapy is shown in **Fig. 1**. Here, a PEMF coil surrounds the perimeter of a chronic wound and delivers a 27.12 MHz rf signal to the affected tissue that is amplitude modulated with a low-frequency square pulse (≤ 1 kHz). The coil produces a time-varying magnetic field burst that inductively couples to the conductive tissue (Faraday's Law) and induces an electric field and associated current density distribution within it. The induced field and current stimulates a variety of biological processes that range. from increased blood flow to enhanced cellular function, which have been shown to reduce edema and pain and promote healing of bones and tissue.

Figure 1: PEMF therapy: PEMF coil surrounding a chronic wound [1]

While the use of PEMF therapy is widespread and growing, relatively few theoretical studies have been reported that elucidate fundamentals of PEMF-tissue coupling. In this paper, we introduce a 2D-axisymmetric computational model for predicting the electromagnetic aspects of PEMF therapy in an inhomogeneous tissue. This model predicts the generation and penetration of a coil-driven rf magnetic field and the induced electric field and current density in human tissue taking into account the different tissue layers and their individual frequency-dependent electrical properties. The induced current gives rise to Joule heating and we use this electromagnetically calculated power density as a heat source in the Pennes' bioheat equation to predict the temperature rise throughout the treated tissue, which we limit to avoid tissue damage. The computational model demonstrated herein provides a fundamental understanding of PEMF-tissue coupling and

Coil Configuration	**Multi-turn Coil**
Number of turns	1500 [4]
Coil diameter	5 mm
Coil radius (r)	4 cm
Height of coil above tissue (h)	0.5 mm
Carrier excitation frequency	6.2 MHz, 27.12 MHz, 62 MHz, 250 MHz
Coil excitation current	1 A

Table 1: Parameters for 2D-axisymmetric PEMF model.

enables the rational design of novel medical devices for PEMF treatment.

2 PEMF SIMULATION

In this paper, we implement a 2D-axisymmetric PEMF model using the COMSOL Multiphysics program (Version 5.3a, www.comsol.com). We use the COMSOL finite-element based AC/DC and Heat Transfer modules for the analysis. We use a multi-turn coil in our analysis with parameters described in Table 1.

The PEMF model is shown in **Fig. 2a**. Here, a copper rf coil of radius *r* is positioned a height *h* above a cylindrical tissue sample. The tissue layers taken into account are shown in **Fig. 2b**. The model includes the frequency-dependent electrical and thermal properties of these layers as reported in the literature [5]. **Fig. 2c,d** show the current density

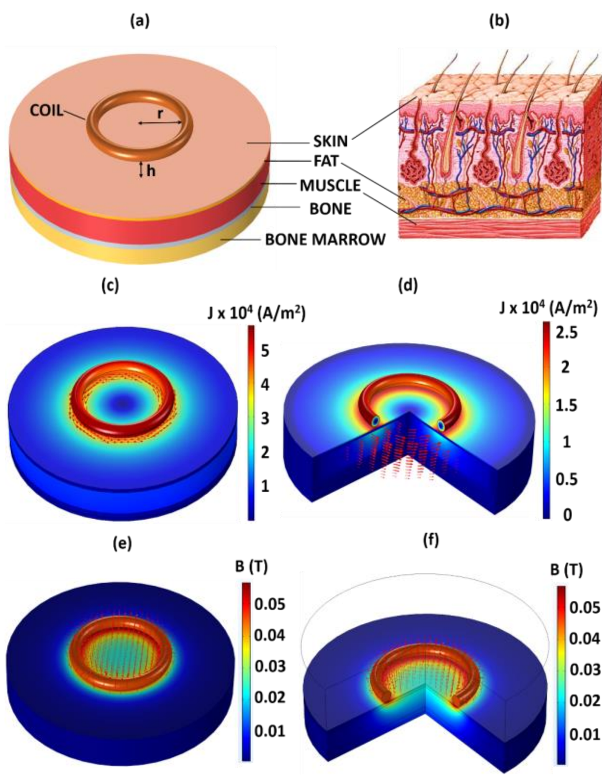

Figure 2: 2D-axisymmetric PEMF model for tissue therapy: (a) computational model; (b) layers of human skin tissue; (c), (d) PEMF-induced current in perspective and cut-away views; and (e), (f) Magnetic field in perspective and cut-away views.

induced in the tissue with a 27.12 MHz carrier frequency. **Fig. 2e,f** show the magnet flux density due to the coil at the same frequency.

2.1 Current Density

We used the model to investigate PEMF-tissue coupling for four distinct rf frequencies used by known medical devices i.e., 6.2 MHz, 27.12 MHz, 62 MHz and 250 MHz.

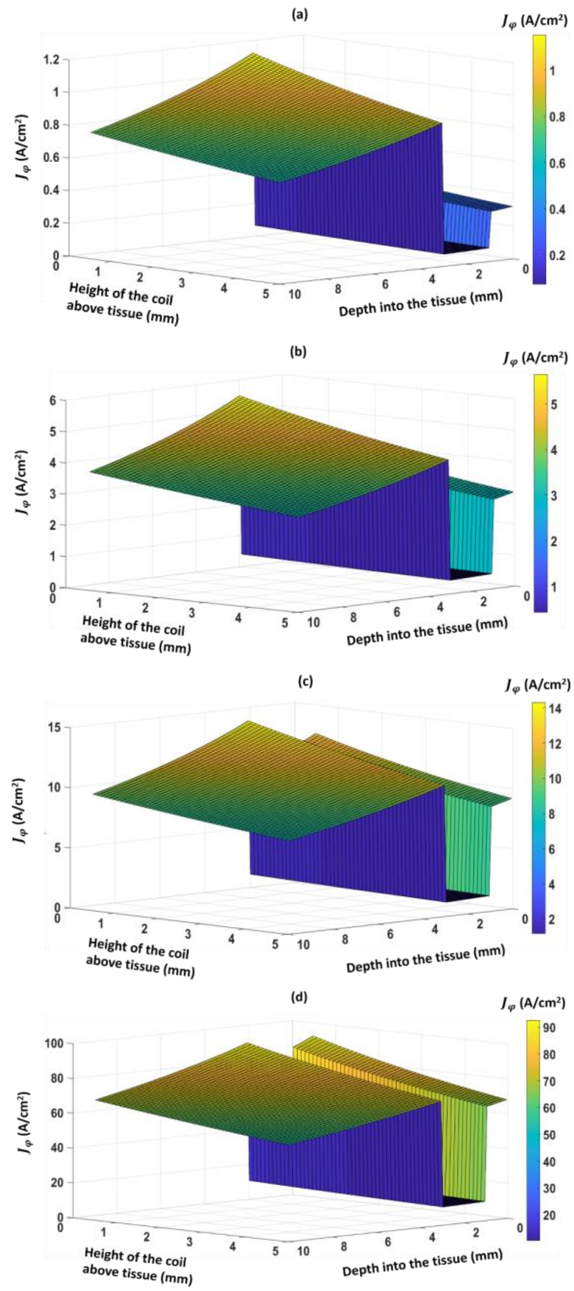

Figure 3: Surface plots showing penetration of current density for varying heights of the coil above tissue at (a) 6.2 MHz (b) 27.12 MHz (c) 62 MHz and (d) 250 MHz

We first compare the penetration of the induced current density into the tissue at these frequencies as shown in **Fig. 3**. Only the azimuthal component of the current density (J_ϕ) is relevant due to axisymmetric nature of the model.

Our analysis shows that as the height *h* of the coil increases above the tissue from 0.5 to 5 mm, the penetration of current density into the tissue decreases substantially. Also, the induced current density is different in each tissue layer due to the difference in their electrical conductivities [6]. For example, at 27.12 MHz, the electrical conductivity is 0.328 S/m for skin, 0.061 S/m for fat and 0.654 S/m for muscle. Since the conductivity of fat tissue is 5-10 times lower than the surrounding layers, the current density in the fat layer is reduced, relative to the skin and muscle layers. It

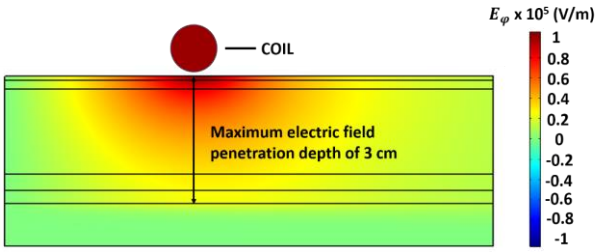

Figure 4: Cross-sectional plot showing the electric field penetration at a carrier frequency of 27.12 MHz.

is important to note that the induced current density in the layers increases with frequency.

2.2 Electric Field

In this section, we evaluate the behavior of the electric field in the tissue layers. As shown in **Fig. 4**, the field is maximum on the surface of the skin directly beneath the coil and decays in a continuous fashion into the tissue layers.

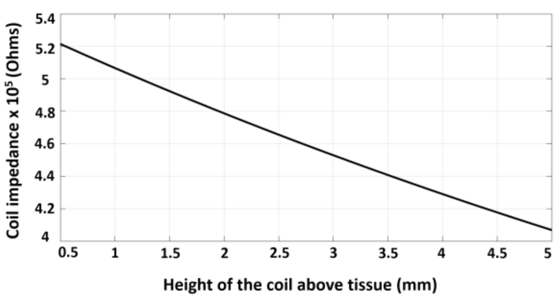

Figure 5: Variation of coil impedance at 27.12 MHz as a funtion of height (h) above the tissue.

2.3 Coil Impedance

In **Fig. 5**, we examine the coil impedance. Our analysis demonstrates that the impedance increases as the coil approaches the tissue. This is because the inductive coupling between the coil and tissue increases as the separation between the two is reduced. Since the tissue is a lossy medium, it loads the coil, which manifests as an increasing load impedance.

2.4 PEMF Modulation

The magnetic coil is driven by a periodic, amplitude modulated excitation waveform. The waveform is periodic but non-sinusoidal. The amplitude modulated excitation waveform used to excite the coil is shown in **Fig. 6**.

In our work, we use an inverse Nonuniform Fourier Transform (NFT) [7] to transform the frequency dependent solution, consisting of 50 weighted harmonic frequencies to 751 time samples in time domain, necessary for acceptable

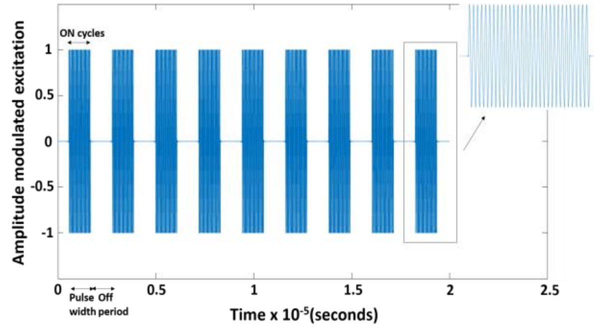

Figure 6: Amplitude modulated excitation waveform used to excite the coil.

time resolution. It is important to note, that this approach is necessary because the electrical properties of the tissue layers are dependent on individual harmonic frequencies. We adopt this Fourier analysis approach because performing a time domain simulation directly will provide inaccurate results due to the non-harmonic nature of the amplitude-modulated waveform. The general expression for the inverse NFT is as follows:

$$u(t_k) = \sum_{j=0}^{N-1} \omega(f_j) e^{i2\pi f_j (t_k - t_0)} \quad for\ k = 0, \ldots\ldots, K-1 \qquad (1)$$

Here, $u(t_k)$ is an arbitrary field variable in the time domain, $\omega(f_j)$ is an arbitrary field variable in frequency domain, K is the number of output time samples and N is the number of harmonic frequency terms (N $\neq$ K).

As an example, let us pick the electric field as the field variable of interest. To transform the sum of 50 weighted frequency harmonic electric field solutions to 751 time sampled solutions the inverse NFT sum is:

$$E(t_k) = \sum_{j=0}^{49} E(f_j) e^{i2\pi f_j (t_k - t_0)} \quad for\ k = 0, 1, \ldots., 750 \qquad (2)$$

If we desire to find the electric field at a particular time instant , for example the last time sample t_{750}, the summation needs to be expanded as follows:

$$E(t_{750}) = E(f_0) e^{i2\pi f_0 (t_{750} - t_0)} + \ldots. + E(f_{49}) e^{i2\pi f_{49} (t_{750} - t_0)} \qquad (3)$$

It is important to note that each field term $E(f_j)$ needs to be properly weighted with coefficients dicated by a Fourier series expansion of the modulated rf waveform.

3 THERMAL ANALYSIS

As noted above, the PEMF induced current gives rise to Joule heating throughout the treated tissue. We use Pennes' bioheat equation to predict the temperature rise due to this dissipated energy. We set the total coil current to 1 A and use the dissipated power density distribution as a heat source for the thermal analysis. The power is applied in accordance

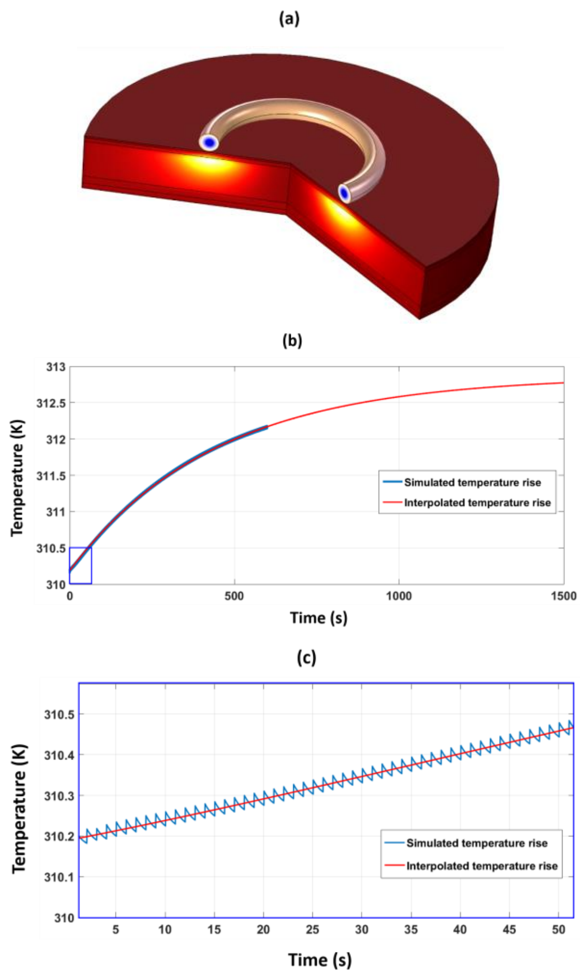

Figure 7: (a) Tempertaure distribution in the tissue at 40 seconds (b) Temperature rise pattern in the tissue for 1500 seconds and (c) 50 seconds showing pulsing,

with a 1 kHz PEMF modulation frequency, with an on pulse duration of 1 millisecond, off pulse duration of 50 milliseconds and a period of 1 second. The temperature is observed at a specific point of interest, 0.5 mm below the skin layer and directly beneath the coil conductor.

The tissue is assumed to be at an initial temperature of 98.6 °F (310.15° K). Due to the periodic heating produced in the tissue, a temperature rise of 2 Kelvin is observed at the point of observation after a period of 600 seconds. A maximum temperature of 312.15° K is observed after the temperature rise saturates. The temperature distribution in the tissue after 40 s of excitation is shown in **Fig. 7a** and the temperature rise plot in **Fig. 7b,c**.

4 CONCLUSION

PEMF therapy has been demonstrated to reduce edema and pain and accelerate tissue and bone healing. However, models that predict PEMF-tissue coupling within a layered human tissue are lacking. Such models are needed for the rational design of PEMF devices. Key challenges of this modeling are accounting for the frequency dependent electrical properties and thermal properties of the various human tissue layers. In this paper, we have accounted for these challenges by developing a computational COMSOL model using rigorous calculations based on a synthesis of the modulated waveform using Fourier analysis, which should be of use in the design and optimization of new technology for PEMF therapy.

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