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Electromagnetic Simulation for the Diagnosis of Lipoprotein Density in Human Blood, a Non-Invasive Approach

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Abstract

With the rise in prevalence of Type II diabetes throughout the world, an increasing need for a portable monitoring system for both blood glucose and lipoprotein concentrations is in demand. Recent work has led to non-invasive wearable devices for monitoring changes in blood glucose concentrations using electromagnetic (EM) waves. However, this still fall short as a means of monitoring cholesterol levels in diabetic patients. The EM study on human tissues emphasized here may also relate to the safety guidelines applied to cellular communications, power lines, and other EM applications. The specific absorption rate (SAR) for the power of the non-ionizing frequency must not exceed a threshold as it impacts DNA and can lead to cancerous tissues. In this study, we used COMSOL software for the investigation of the viability of using EM within the frequency range of 64 MHz - 1 GHz as a means of monitoring the transmission properties of human blood and lipoprotein. In this approach, wave equations were solved within blood and lipoprotein boundaries. Research parameters, including frequency range, Power input (SAR), and lipoprotein densities, were investigated. The transmission properties, produced by the electrical and thermal characteristics of these physiological parameters, have led to proper diagnosis of lipoprotein density. Within the frequency range of 64 MHz to 1 GHz, and for a power range of 0.1 to 0.6 SAR, lipoprotein density from 1.00 g/mL to 1.20 g/mL was considered. A 2D model, with an antenna source that supplied the electromagnetic waves to human tissues, was created for the simulations. These were used for the study of the transmission properties of the EM energy into the blood and lipoprotein tissues. While the range of magnetic flux values between simulations varies only slightly or not at all, the distribution of these values is impacted by given parameters. As such, a device capable of comparing magnetic flux values and penetration depths could easily distinguish between samples of different lipoprotein densities. The results obtained in this study can be accommodated non-invasively by human tissues, and can be produced in a practical model using wearable devices. A practical model is proposed for future consideration.

Keywords

Non-Invasive Monitoring, Cholesterol, Electromagnetic, Biosensors, Wearable Devices

1. Introduction

Healthcare applications and wearable devices that allow for mobile monitoring and diagnosis of problematic health factors are a promising new avenue of treatment and diagnosis [1] [2]. Such new developments necessitate the need for devices capable of serving multiple diagnostic purposes. For more than a decade, attention has been given to the usage of electromagnetic waves as a means of non-invasively monitoring physiological characteristics of an individual [3]. Studies of electromagnetic (EM) radiation on human tissues are uniquely suited for medical diagnosis as they offer a wide range of frequencies and magnitudes for potential investigation. Previous studies have yielded promising results of electromagnetic based modalities for cancer research and treatment [4]. Furthermore, EM transmission properties within human tissues may be utilized in the diagnosis of various diseases [3] [4]. The efficacy of applying such forces to patients *in vivo* has also been evaluated with pleasing results [5].

The EM study for a given operating frequency range on human tissues may also be applied into high technology smart devices within cellular communication systems where the EM frequencies and power could be an issue of human safety [6] [7]. This may lead to proper safety guidelines for smart devices used in communication systems. Likewise, the EM power intensities generated from power lines may have an impact on human health subjects, and therefore, the study presented here may benefit such areas as public health and legal concerns as to the dangers posed by such forces [8] [9] [10]. Since the electromagnetic forces used by wearable devices are applied in a directed manner, there is limited exposure to individuals other than the user. As such, our study only concerns itself with SAR guidelines for the user.

In the Diabetic research area, type II patients, who compose an ever growing cohort, need to constantly monitor their blood glucose levels, often through the usage of "finger prick" glucometers, first invented in 1962 [11] [12]. Through extensive work, viable alternatives to traditional "finger prick" glucometer have been either completed or are nearing completion [11] [12]. In application, these systems use a wristband worn by the individual that provides a means of collecting impedance data via electromagnetic wave application [11] [12]. In addition to monitoring blood glucose levels, Type II diabetic patients must also be conscious of monitoring and managing their cholesterol levels [13]. Currently, this is done via a blood test, an invasive procedure often requiring the patient to fast prior to the test [14] [15]. The possibility of using the same newly developed non-invasive glucose monitoring devices to monitor separate health characteristics, specifically cholesterol levels, is the subject of this paper. Using the computer modeling software COMSOL, we undertook an investigation into the usage of electromagnetic waves as a means of monitoring cholesterol levels.

The frequency range used in the investigation was chosen so as not to interact with glucose concentration in the blood as a confining variable. Previous work indicated that impedance values for EM studies were noticeable in the range of 33 GHz to 90 GHz, far from the range used in this study [16] [17]. Our model is intended to serve as a proof of concept for the efficacy of using EM waves to properly diagnosis the density of lipoprotein tissue on the edge of a blood media. This model mimics the location of lipoprotein in the human body—found on the walls of veins, capillaries, and arties.

2. Methods

COMSOL Multiphysics was utilized in the investigation of electromagnetic application on human tissues. A model was created in order to simulate the effect of electromagnetic wave application onto a geometry containing blood and cholesterol of varying densities. **Figure 1** shows the 2D simulation model used in the study. The dimensions used here are in the cm range, making it appropriate for a practical model.

The dimensions of **Figure 1** are meant to mimic a human torso comprised solely of blood with a thin layer of lipoprotein lining its outer edge.

The wave equation and the parameters associated with the simulation model are given by:

$$\nabla \times \mu_r^{-1} \left(\nabla \times \mathbf{E} \right) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega \epsilon_0} \right) \mathbf{E} = 0$$

where σ is the conductivity of the material, ω is the radian frequency, ϵ_r is the relative permittivity of the blood. The boundary condition at the sample was obtained by matching the tangential components of the electric fields using $n \times \mathrm{E} = 0$.

The equations governing the magnetic field study are:

$$\begin{aligned} &\nabla \times \mathbf{H} = \mathbf{J} \\ &\mathbf{B} = \nabla \times \mathbf{A} \\ &\mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} + \sigma \mathbf{v} \times \mathbf{B} + \mathbf{J_e} \\ &\mathbf{E} = -j\omega \mathbf{A} \end{aligned}$$

The boundary conditions between the blood and lipoprotein materials are given by:

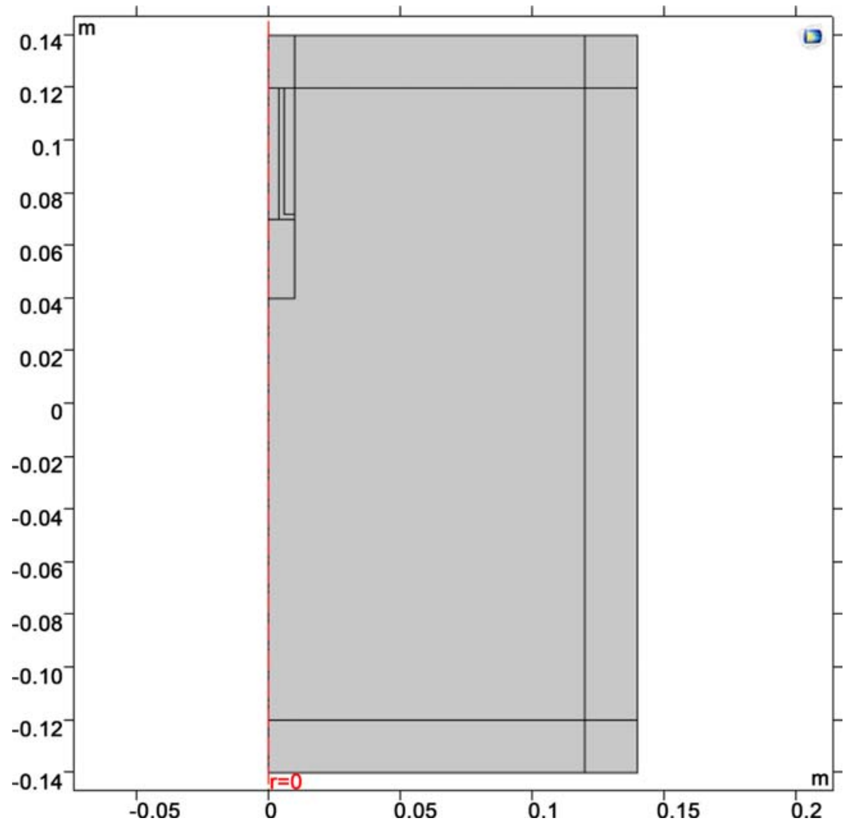

Figure 1. Simulation Model used for our EM Study.

$$\boldsymbol{n}\times(\nabla\times\boldsymbol{E})-jk\boldsymbol{n}\times(\boldsymbol{E}\times\boldsymbol{n})=0$$

The wave impedance η is given as $\eta=\sqrt{\frac{\mu}{\varepsilon}}$

The power density is estimated from E^2/η

The material properties for the blood and Lipoprotein used in the simulation are given in Table 1. The global definitions of the research parameters are given in Table 2, and the geometry parameters presented in Table 3.

3. Results and Discussion

The three parameters used in the simulation are frequency, SAR values, and lipoprotein density. Frequency values of 64 MHz, 0.5 GHz, and 1 GHz were chosen to investigate a range of possible frequency values. 64 MHz was chosen based on FDA approved frequency for MRI studies. Likewise, the 0.6 SAR was also based on approved values for MRI studies [18]. However, the testing time is short, thus minimizing the energy the tissue is exposed to. The simulation was conducted for three different lipoprotein densities, 1.0, 1.1, 1.2 g/mL. This corresponds to very low density lipoprotein (1.0), a mixture of LDL and HDL (1.1), and very high density lipoprotein (1.2) [19] [20]. The data received from COMSOL simulations addresses the impact of frequency and SAR on the three different density values. Figure 2 represents reference values for a frequency of

Table 1. Material properties used in the simulation.

	Material			
Property	Blood	Source	Lipoprotein	Frequency (Hz)/Density (g/mL)
Relative Permeability	1	1	1	64 MHz/1.00g/mL
Electrical Conductivity	1.21	6.0×10^7	2.5	
Relative Permittivity	86.4	1	1	
Density	1050	-	-	
Thermal Conductivity	0.52	-	-	
Heat Capacity at Constant Pressure	3617	-	-	
Relative Permeability	1	1	1	0.5 GHz/1.10g/mL
Electrical Conductivity	1.38	6.0×10^7	18.75	
Relative Permittivity	63.3	1	1	
Density	1050	-	-	
Thermal Conductivity	0.52	-	-	
Heat Capacity at Constant Pressure	3617	-	-	
Relative Permeability	1	1	1	1 GHz/1.20g/mL
Electrical Conductivity	1.58	6.0×10^7	35	
Relative Permittivity	61.1	1	1	
Density	1050	-	-	
Thermal Conductivity	0.52	-	-	
Heat Capacity at Constant Pressure	3617	-	-	

Table 2. Global Parameters Used.

Name	Expression	Value	Description
R_0	0.12	0.12	Plasma source radius
Z_0	0.24	0.24	Plasma source height
Psp (change this to change SAR)	6.51, 3.257, or 1.086 [W] (Based on SAR Level)	6.51, 3.257, or 1.086 [W] (Based on SAR Level)	Total power absorbed by the plasma set point
Rho_blood	1050	1050	Blood Density

Table 3. Geometry Parameters.

Label	Width	Height	R:	Z:	Description
Rectangle 1	R_0	Z_0	0	$-z_0/2$	Blood
Rectangle 2	0.01	0.03	0	0.004	Blood
Rectangle 3	0.004	0048	0.006	0.072	Wave Source
Rectangle 4	0.004	0.05	0	0.07	Blood
Rectangle 5	$R_0 - 0.01$	0.02	0.01	0.12	Blood
Rectangle 6	0.02	0.02	R_0	0.12	Blood
Rectangle 7	0.04	Z_0	$R_0 - 0.02$	$-z_0/2$	Blood
Rectangle 8	0.02	0.02	R_0	$-0.02 - z_0/2$	Lipoprotein
Rectangle 9	R_0	0.02	0	$-0.02 - z_0/2$	Lipoprotein
Rectangle 10	0.01	0.02	0	0.12	Lipoprotein

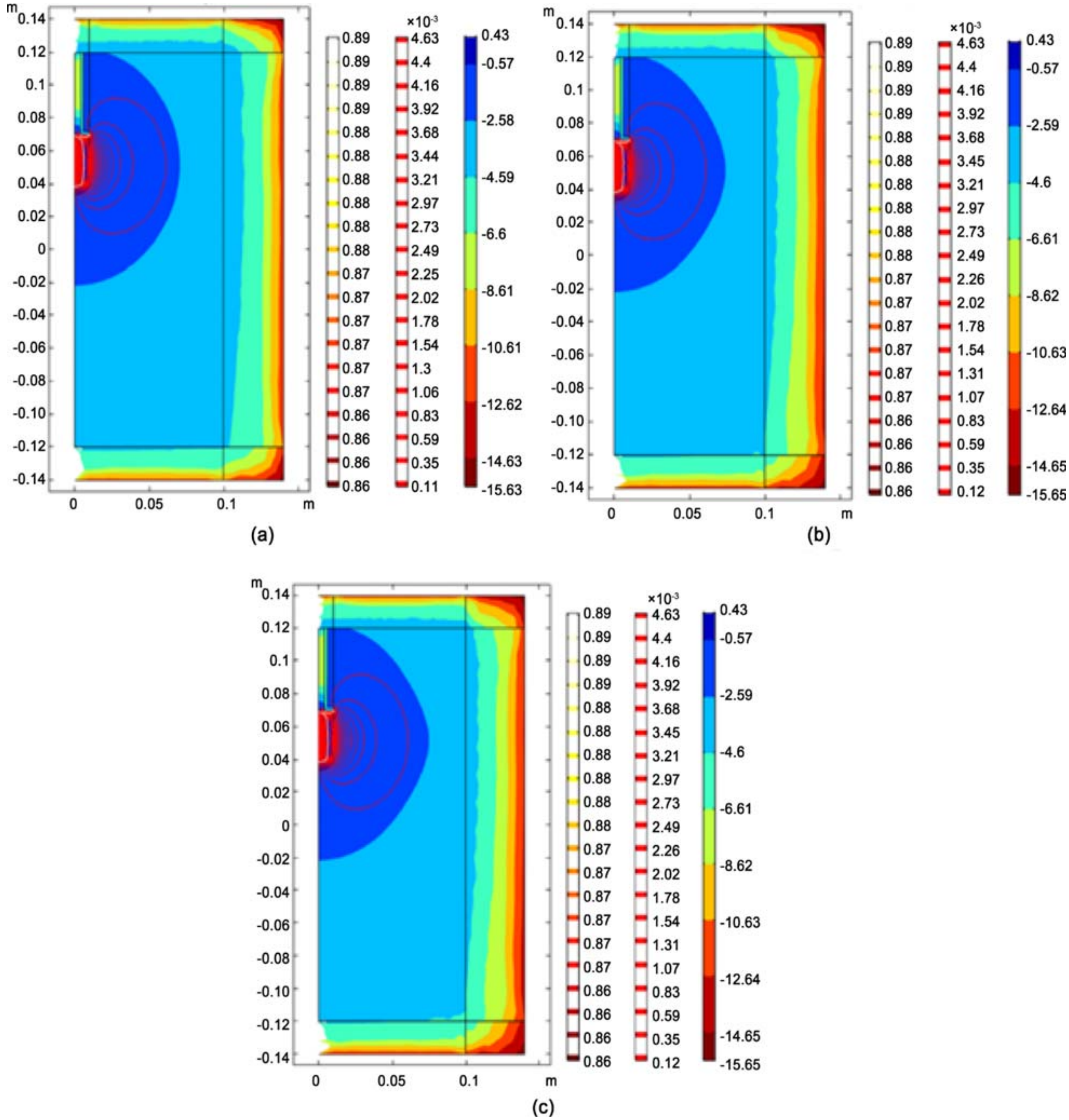

Figure 2. Magnetic Flux Graphs at 64 MHz, 0.6 SAR, and Lipoprotein density ranging from 1.00 (a), 1.1 g/mL (b) and 1.20 g/mL (c).

64 MHz, SAR of 0.6, and Lipoprotein density from 1.00 g/mL to 1.20 g/mL increasing to the right. Figure 3 presents Magnetic Flux values for 1 GHz, 0.3 SAR, and Lipoprotein density from 1.00 g/mL to 1.20 g/mL increasing to the right. Figure 4 presents Magnetic Flux values for 0.5 GHz, 0.6 SAR, and Lipoprotein density from 1.00 g/mL to 1.20 g/mL increasing to the right.

Figure 3 and Figure 4 show the magnetic vector potential, A, in Wb/m at 0.6 SAR for three different densities (1, 1.1, and 1.2 g/mL) and two different frequencies; 64 MHz and 0.5 GHz. The differential A values between the reference A (64 MHz) and the test A (0.5 GHz) given at different densities show different penetration depth within the blood material and near the interface with the lipoprotein tissue. The A value near the boundary differ at 1, 1.1, and 1.2 g/mL densities for the two frequency values. The change in A at the boundary layers are attributed to the impact of the density values. This differential potential can be tracked or monitored via magnetic sensor devices and the lipoprotein density may be estimated. The differential magnetic potentials are tabulated in Table 4.

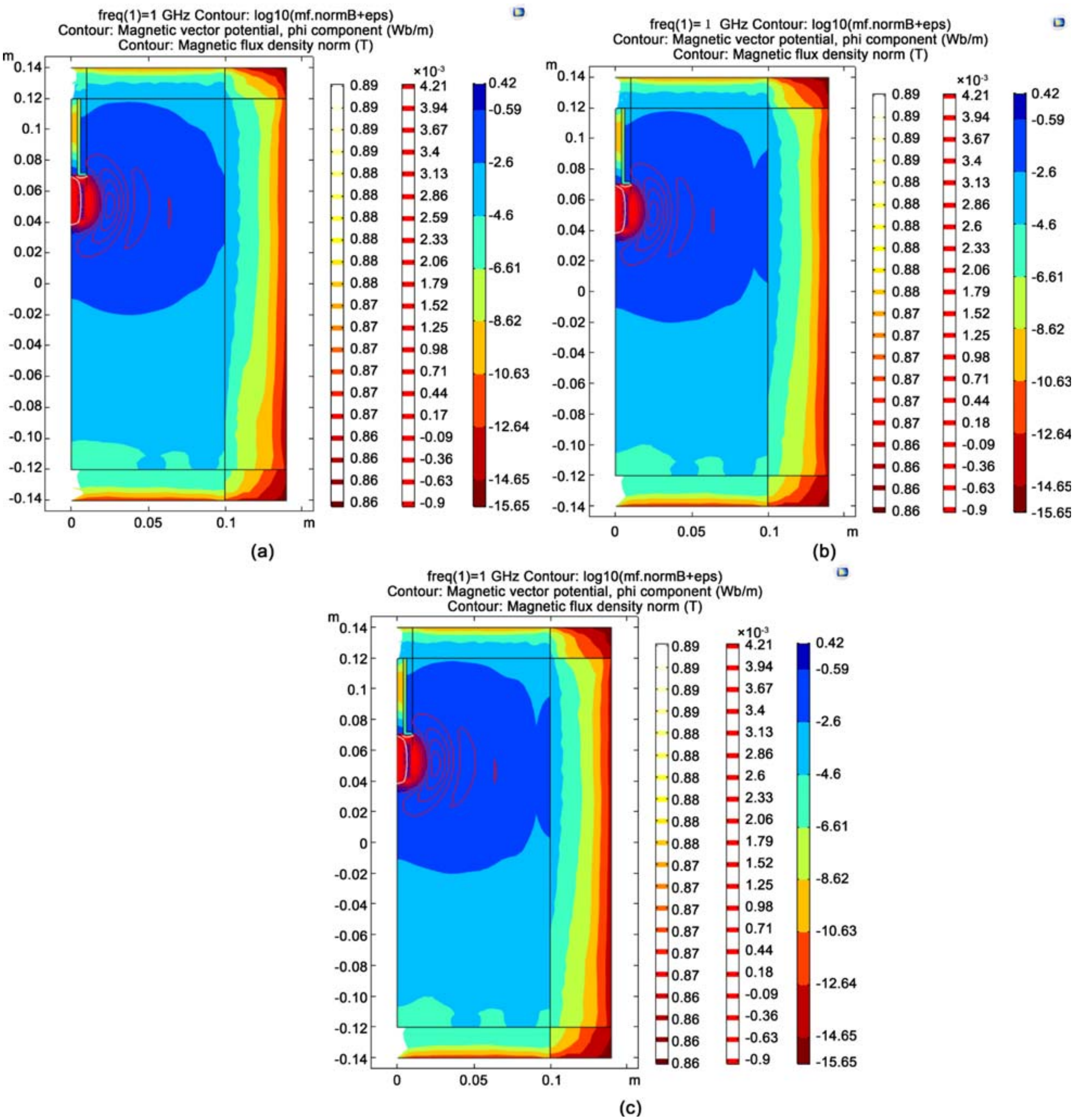

Figure 3. Magnetic Flux Graphs at 1 GHz, 0.3 SAR, and Lipoprotein density ranging from 1.00 (a), 1.1 g/mL (b) to 1.20 g/mL (c).

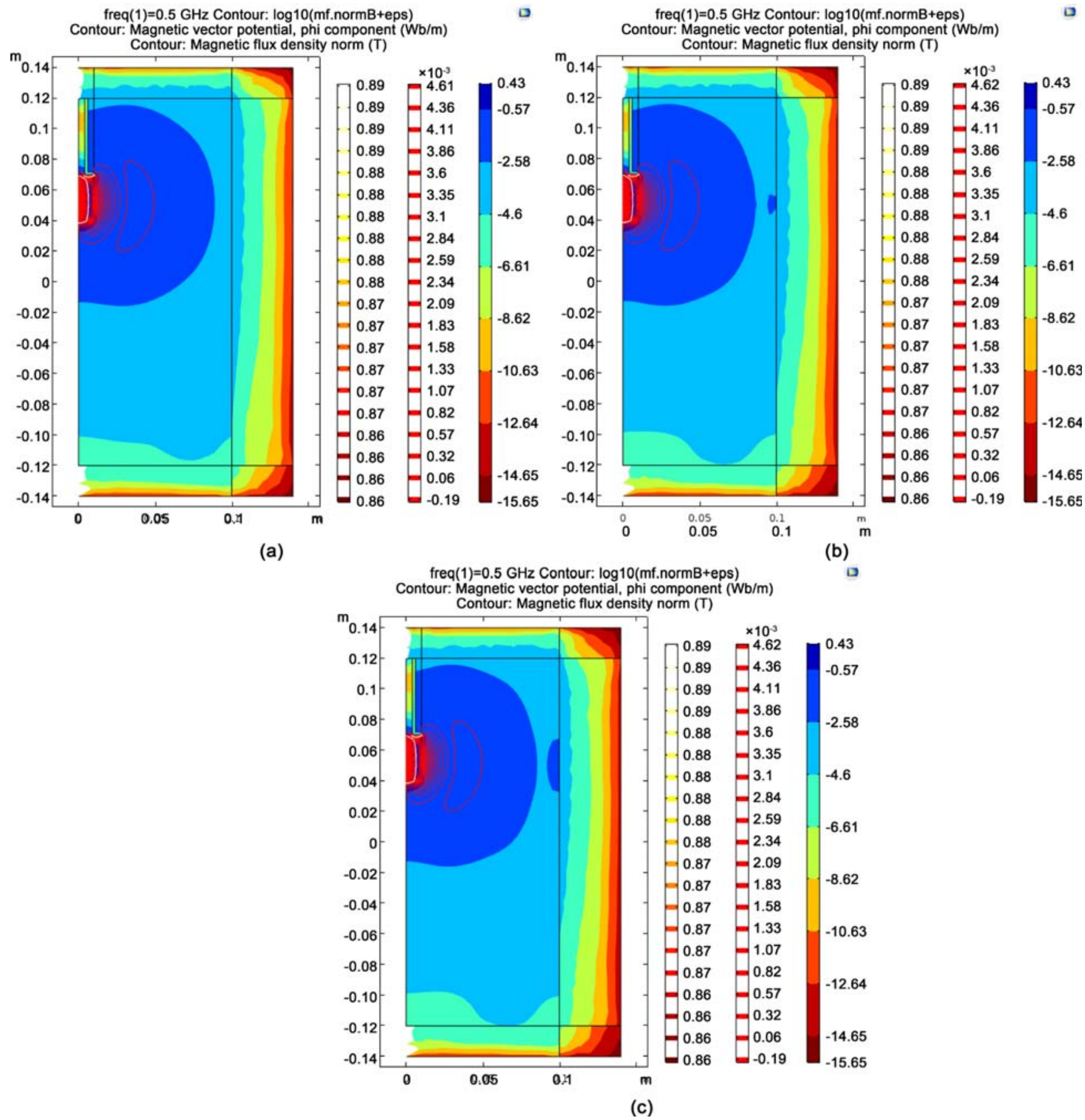

Figure 4. Magnetic Potentials at 0.5 GHz, 0.6 SAR, and Lipoprotein density ranging from 1.00 (a) 1.1 g/mL (b) to 1.20 g/mL (c).

Table 4. Penetration of EM magnetic potentials for 64 MHz and 0.5 GHz at 0.6 SAR.

	64 MHz			0.5 GHz		
Lipoprotein Density	Penetration of (>−2.58) Wb/m values into Blood	Penetration of (−2.58 to −4.6) Wb/m values into Lipoprotein	Presence of (>−2.58) Wb/m values at Boundary	Penetration of (>−2.58) Wb/m values into Blood	Penetration of (−2.58 to −4.6) Wb/m values into Lipoprotein	Presence of (>−2.58) Wb/m values at Boundary
1.00 g/mL	7 cm	1.5 cm	No	8.5 cm	0.5 cm	No
1.10 g/mL	7.5 cm	1 cm	No	8 cm	0.5 cm	0.5 cm
1.20 g/mL	7.5 cm	1 cm	No	7.5 cm	0.5 cm	1 cm

4. Conclusions and Future Work

Using range values for magnetic flux generated via simulation, we observed no useful differential values for the diagnosis of lipoprotein density. However, the distribution of these magnetic flux values across these ranges varied greatly when parameters were changed, as presented visually in Figures 2-4. The total summation of magnetic flux over a defined area will therefore also vary when parameters are changed and could be used to properly diagnose the density of lipoprotein tissue. The simulation given at 64 MHz was considered the reference value for the estimation of the differential potentials at different frequencies for various densities. 64 MHz was chosen as it is commonly used in medical applications such as MRI studies and has been FDA approved [18].

We envision a wearable wristband system similar to that of previous studies into non-invasive glucose monitoring [11] [12]. Our current models suggest the usage of RF sources for both 64 MHz and 0.5 GHz at corresponding locations on the skin tissue. Possible materials for these wristbands include highly flexible bismuth Hall sensors on polymeric foils [16]. These sensors were designed with such applications in mind and could be adapted to fit either the inserted catheter or external source models we envision for future studies. Magnetic sensors with analog devices may be utilized for monitoring the change in magnetic vector potentials at 8 locations shown in Figure 5 for the 12 cm size layers, covering both the blood and lipoprotein tissue.

The current model does not incorporate skin moisture, skin tissue, muscle tissue, and bone. As such, a comprehensive model will be needed that takes into account the transmission properties of these parameters. The addition of these parameters may cause an EM power attenuation. In such a case, a higher transmitted EM power may be considered in order to reach 0.6 SAR within the blood.

Following the data presented in Table 4, a comparison of the magnetic field at different locations for both 64 MHz and 0.5 GHz is necessary. This may be accomplished by implementing complementary magnetic sensors arranged in matrices on flexible substrates at suitable locations. Four (4) by two (2) sensor metrics, as shown in Figure 5, allowing for comparison of sensor information in

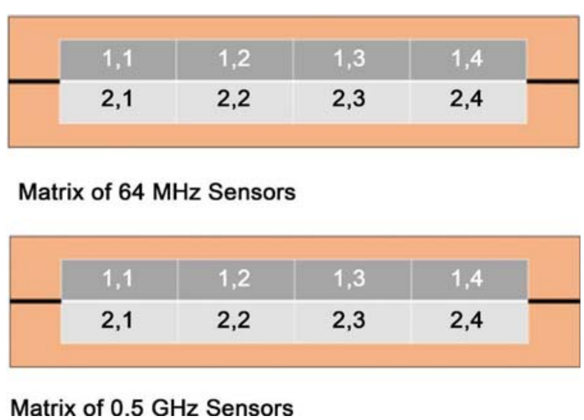

Figure 5. Proposed Practical Model for the Lipoprotein Density Monitoring System.

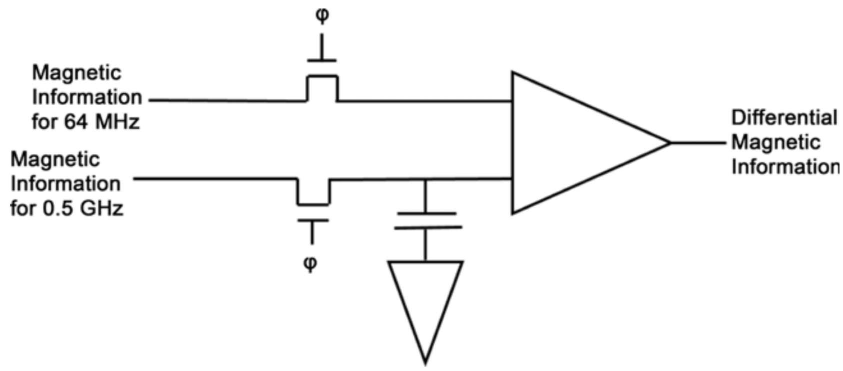

Figure 6. Proposed Sample and Hold off Circuit Model.

location 1,1 for instance at 64 MHz with location 1,1 at 0.5 GHz are suited to this task. A differential sample and hold off circuit, as shown in **Figure 6**, may be utilized to provide a comparator that compares the two magnetic field patterns at both frequencies in corresponding locations. In this figure, a MOSFET switching device will enable the passing of the sensor information into the comparator circuit. The magnetic sensing information from the 64 MHz is used as a reference potential. **Figure 5** and **Figure 6** give a proposed idea for the practical model of the system. The details of the system hardware and its implementation are reserved for future considerations.

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