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Microwave Power Absorption in Human Body for Non-invasive Glucose Monitoring

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Abstract— The main objective of this contribution is to explore the absorption of electromagnetic microwaves in different human body regions for non-invasive glucose monitoring (NGM). Recently, the use of dielectric measurements for the purpose of NGM has been an area of much interest. However, currently no existing report can explore the power dissipation of electromagnetic waves for the NGM. This work is based on established empirical models of human tissue and standard human body models of the Electromagnetic (EM) simulation tools, such as CST Voxel Model. The Specific Absorption Rate (SAR) is investigated for various frequencies and different regions of the human body to estimate the optimum real-world scenarios for non-invasive glucose monitoring (NGM). Empirical models of dielectric properties for estimating the blood glucose concentrations are applied at frequency range from 1 GHz to 10 GHz and blood glucose concentration of hyperglycemia (300 mg/dl), hypoglycemia (40 mg/dl) and euglycemic (100 mg/dl). A comparative evaluation of SAR measurements for blood in free space and blood in body's vessels is presented in context of investigating the effect of power dissipation for dielectric NGM measurements.

1. INTRODUCTION

Diabetes mellitus is a disorder of the metabolic homeostasis controlled by insulin, resulting abnormalities of carbohydrate and lipid metabolism. According to the International Diabetes Federation, the current diabetic population of 366 million diabetics is estimated to increase up to 552 million by 2030, with the Middle East hosting the fastest growth [1]. Diabetic patients require frequent self-monitoring of blood glucose (SMBG), which is conventionally performed via painful finger-pricking using electrochemical glucose sensors. To overcome the trauma of invasive SMBG, non-invasive glucose monitoring (NGM) devices externally sense glucose without perturbing an external membrane or sampling a body fluid [2].

The feasibility of dielectric measurements for NGM has been demonstrated by Feldman et al., whom demonstrated that the specific cell capacitance of erythrocytes is in uenced by changes in the concentration of D-glucose within physiologic range [3, 4]. Building on Feldmans work, Caduff et al. developed the first NGM device based on impedance changes of the skin and underlying tissue [5]. Other attempts have also demonstrated dielectric NGM devices [6–10], however a successful commercial dielectric NGM device is yet to be developed. A recurrent problem in all dielectric NGM attempts was to translate successful results under controlled conditions in the laboratory to real-life clinical scenarios [11].

Despite the established correlation between blood glucose and blood dielectric properties, few models have been proposed for quantification of the correlation [12, 13]. An interesting model has been proposed by Venkataraman et al. [12], whom modified the Cole-Cole model relating blood dielectric properties with frequency to include glucose concentration. The model is important not only because it demonstrates feasibility of dielectric NGM, but it also enables the simulation of various effects in NGM using standard human body models of the Electromagnetic (EM) simulation tools, such as CST Voxel Model. The current contribution explores the specific absorption rate (SAR) of microwaves for major blood vessels of thigh, arm and neck. Furthermore, comparison of blood in free space to that in body's vessels enables the critical analysis of laboratory measurements compared to real-life scenarios. To mimic the conditions investigated by Venkataraman et al., the simulations were conducted utilizing 1–10 GHz frequencies and hyperglycemia (300 mg/dl), hypoglycemia (40 mg/dl) and euglycemic (100 mg/dl) concentrations.

2. MATERIALS AND METHODS

CST Human Body Voxel model (Figure 1(a)) was utilized for simulations, where blood voxels in selected slices in the thigh, arm, and neck were selected for pertinent calculations (Figure 1(b)). These locations were selected because they contain major systemic blood vessels, such as the femoral

artery & vein (thigh), brachial artery & vein (arm), and carotid artery & jugular vein (neck). A near-field solution was obtained for an antenna placed closest to major blood vessels in the inner thigh, outer arm, and neck surface. Permittivity and conductivity values of blood were calculated using the Cole-Cole equation [14]:

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{n=1}^{2} \frac{\Delta\varepsilon_n}{1-(j\omega\tau)^{1-\alpha_n}} + \frac{\sigma_s}{j\omega\varepsilon_o} \tag{1}$$

where $\omega = 2\pi f$ is the angular frequency, $\Delta\omega = \varepsilon_s - \varepsilon_\infty$ is the relaxation strength, ε_s and ε_∞, τ is the relation time constant, α is an emperical measure of frequency broadening, σ_s is the static (DC) conductivity, and ε_o is the permittivity of free space.

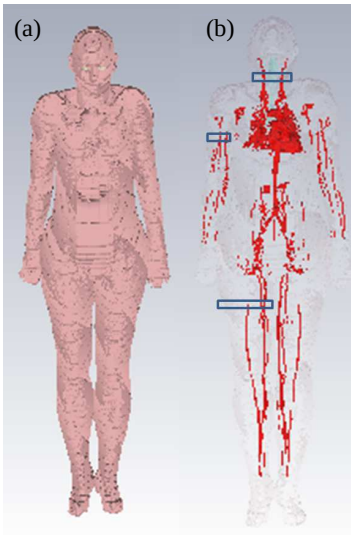


Figure 1: (a) Complete CST human Voxel body model; (b) associated blood vessels of body model, where simulations were conducted on major blood vessels in selected slices in the thigh, arm, and neck.

Model parameters of Equation (1) were used as established by Gabriel et al. [15], and the corresponding permittivity and conductivity of blood for 1–10 GHz were fed into CST. Furthermore, to simulate the effect of variation of blood glucose in NGM, a modified Cole-Cole equation [12] was used to calculate permittivity and conductivity values for use by CST:

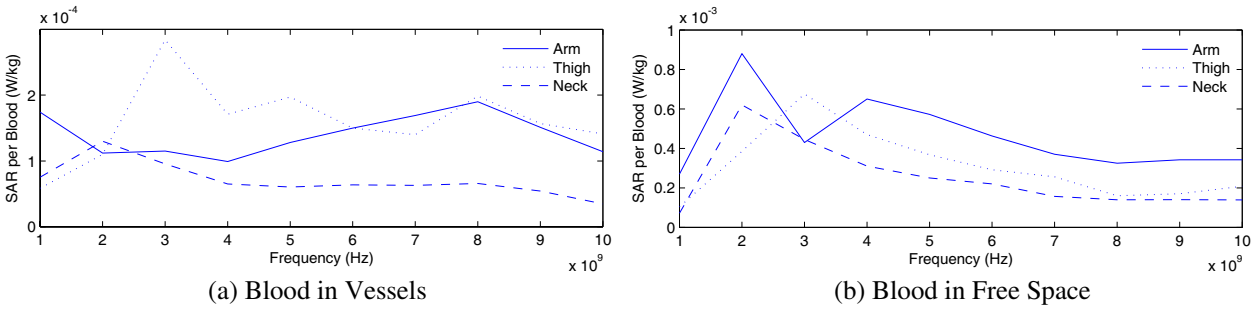
$$\varepsilon(\omega) = \Re\left(\varepsilon_\infty + \sum_{n=1}^{2} \frac{\Delta\varepsilon_n}{1-(j\omega\tau)^{1-\alpha_n}}\right) \times (-0.001445g + 1.145882) + \Im\left(\varepsilon_\infty + \sum_{n=1}^{2} \frac{\Delta\varepsilon_n}{1-(j\omega\tau)^{1-\alpha_n}} + \frac{\sigma_s}{j\omega\varepsilon_o}\right) \tag{2}$$

where g is the blood glucose concentration, and the parametric values utilized in Equations (1) and (2) are displayed in Table 1.

Simulations were carried out for blood in the body's blood vessels and blood in free space to calculate SAR values using permittivity values from Equations (1) and (2).

3. RESULTS AND DISCUSSION

Several body locations have been studied for electromagnetic NGM, including the wrist [5, 8], arm [16], fingertip [7], and ear lobe [17]. However, no comparative evaluation of the optimum body compartment for dielectric NGM has been conducted. SAR values of blood in the thigh, neck and arm demonstrate that the highest power loss is in the thigh (Figure 2(a)). This suggests that the thigh might not be the optimum location for NGM because of high SAR values of thigh major blood vessels. electrogmagnetic NGM exploits reflected power to calculate the relative pertivities of blood and hence blood glucose concentration. As a result, maximum reflected power and minimum absorbed power would yield optimum Signal to Noise. Although the neck has the lowest SAR value, the arm presents a reasonable choice that balances between patient convenience and moderate power absorption of incident EM wave.



(a) Blood in Vessels (b) Blood in Free Space

Figure 2: Specific absorption rate (SAR) of blood voxels for selected slices in arm, thigh and neck within (a) the human boday, and (b) in free space.

Many dielectric NGM studies perform their tests utilizing blood samples in the laboratory. Therefore, it was important to compare the SAR calculations for blood in the body's vessels relative to free space for the same voxels, which are presented in (Figure 2(b)). The differences between calculated blood SAR in vessels relative to free space can be attributed to the effect of various body components (other than blood) on the electric field patterns, as shown in (Figure 3).

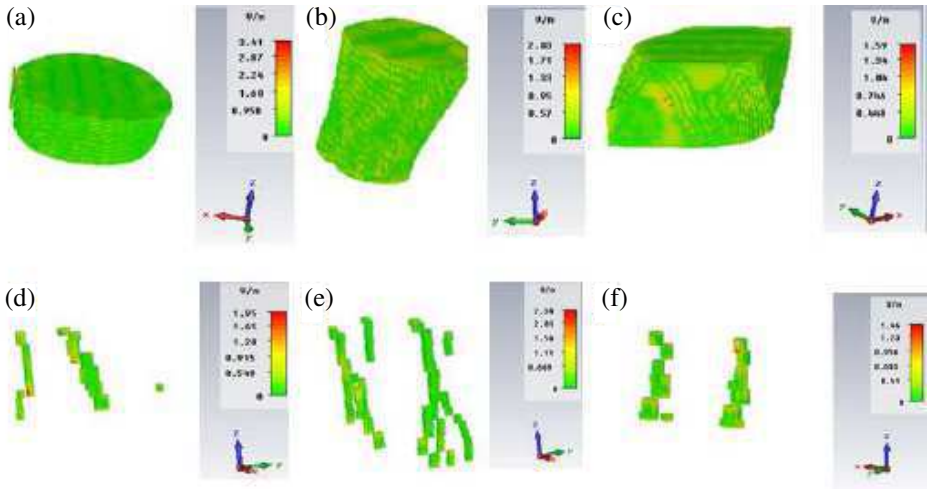
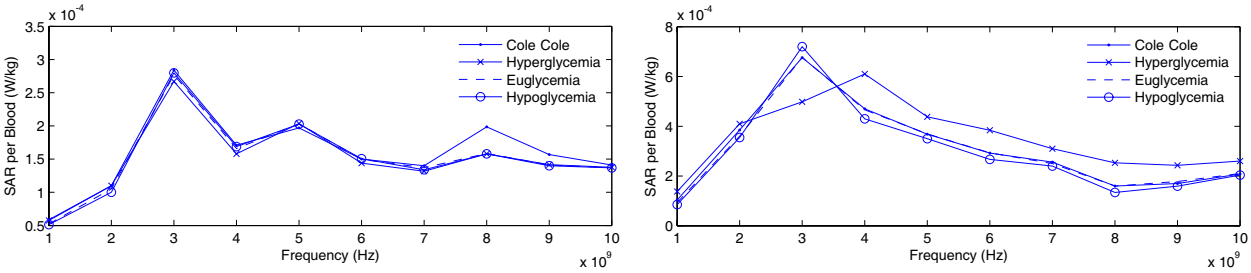


Figure 3: Calculated electric fields of selected slices in (a) thigh, (b) arm, (c) neck, (d) thigh blood in free space, (e) arm blood in free space, and (f) neck blood in free space.

Simulations for the blood SAR values using permittivity and conductivity values calculated using Equations (1) and (2) has shown no significant difference for simulated glucose concentrations, i.e., hyperglycemia (300 mg/dl), euglycemia (100 mg/dl), and hypoglycemia (40 mg/dl) (Figure 4(a)). This may have been expected because SAR is largely a funcition of conductivity, while the modification of the Cole-Cole model only affected the real component of the complex conductivity and did not include the imaginary component [12]. Other models have modified the Cole-Cole model to account for glucose concentration using both the real (ε') and imaginary parts (ε'') of the complex permittivity [13]. On the other hand, some differences may be observed for hyperglycemia calculations for blood in free space (Figure 4(b)). In the case that the dimensions of the object becomes small compared to the wavelength (i.e., wavelength inside the material is greater than ten times the dimensions of the object), Electric field becomes inversely proportional to relative permittivity [17]. Under such conditions, SAR becomes inversely proportional to relative permittivity [19]. This was the case for blood in free space, where the object's dimensions were an order of magnitude less than the wavelngth at 10 GHz (3 cm). These results are in agreement with previous reports demonstrating the dependence of the localized SAR value of organs in EM Human Body simulations on both the real and imaginery values of complex permittivity [20].



(a) Variable Blood Glucose in Thigh (b) Variable Blood Glucose in Free Space for Thigh

Figure 4: SAR of blood voxels for selected slices in thigh using Cole-Cole model and hyperglycemia, euglycemia, & hyperglycemia in modified Cole-Cole model within (a) the human boday, and (b) in free space.

4. CONCLUSION

The results of this contribution suggests that the arm or neck may be better locations for NGM measurements than the thigh, although the arm is naturally more convenient. Differences between blood in vessels and in free space indicate the importance of considering the effect of other body tissues on dielectric measurements of blood glucose. Last but not least, contributions of both real and imaginery components of complex permittivity should be considered when conducting or modelling dielectric NGM measurements.

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