Kalpa Publications in Engineering
Volume 3, 2020, Pages 262–269
Proceedings of International Symposium on Applied Science 2019

Simulation Of Impedance Measurements At Human Upper Arm Within 10 Khz To 1 Mhz With The Vary Of Fat Layers From 10mm To 25mm

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Abstract

The work presents a simulation analysis of the bioimpedance at the human upper arm using the finite element method (FEM). Comsol Multiphysics has been used to create the 3D model with four domains of dielectric behavior: skin, fat, muscle and bone. The main objective of this paper is studying the effect of the fat thickness and frequency on three parameters: resistance, reactance, and phase. The impedance values were calculated as the ratio of the output voltage at the electrodes and the applied current (1 mA). The measurements were done at four different values of fat layer (10mm, 15mm, 20mm, and 25mm) and electrical properties of the upper arm were used. The results clarify that the fat layer has significant impact on the upper arm impedance across the frequency spectrum, resistance and phase appear to be more affected than reactance.

1 Introduction

Neuromuscular diseases are those that affect the muscles and their direct nervous system control, problems with central nervous control can cause either spasticity or some degree of paralysis (from both lower and upper motor neuron disorders), depending on the location and the nature of the problem. In humans, examples of such diseases would include amyotrophic lateral sclerosis (ALS) and spinal muscular atrophy (SMAs). SMAs are disorders of lower motor neurons, while ALS is a mixed upper and lower motor neuron condition. There are various way to diagnose the neuromuscular disease such as using MRI [1], Ultrasound [2] and Electromyography (EMG) [3]. Each method has its own advantage and disadvantage.

Electrical Impedance Myography (EIM) is a fourelectrode bioelectrical impedance-based technique for the assessment of diseases affecting nerve and muscle. The advantages of EIM over standard approaches are a painless, non-invasive, quantitative technique. This method bases on applying high-frequency, low-intensity electrical current injected via the surface electrodes and measuring resulting voltage [4]. The outer electrodes apply and measure an alternating sine-wave current stimulus in the kHz to MHz frequency range. As a result of the current applied, the tissues generate a response in the form of an alternating voltage signal that is sensed by the inner electrodes. The ratio and normalization of the voltage and current amplitudes and phase delays provide a simple approach to measuring the impedance magnitude |Z| and phase angle θ at any particular frequency.

The impedance, Z, measures the obstruction to the flow of electric current through tissues and is defined as $Z= R + jX$. Where muscle resistance (R), representing the resistivity to the current flow in the extracellular and intracellular fluids; muscle reactance (X), illustrating how the current flow is affected by cell membranes and by the various fascia of the body; and phase (θ), which is defined as θ= arctan(X/R) [5]. In order to conform to the standard R bioimpedance convention, all reactance and phase values are plotted as positive values rather than negative. In this study, the impedance values were calculated as the ratio of the output voltage at the electrodes and the applied current (1mA) A tissue electric behavior mainly cause because tissue consist of membrane separating the intracellular an extracellular fluids. Which cause a variety of change in the impedance when the frequency increase.

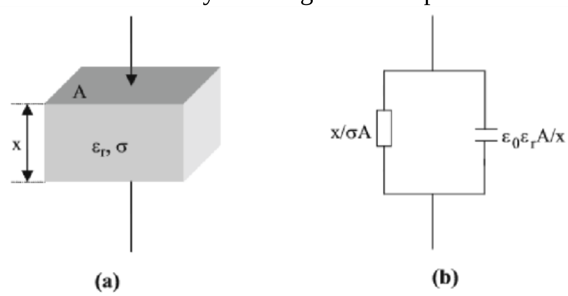

Figure 1. (a) Idealised slab of tissue, where A is the area, x is the thickness, ε r is the relative permittivity and σ is the conductivity. (b) Equivalent circuit of the slab of tissue represented by a resistance in parallel with a capacitance, where ε 0 is the permittivity of free space (8.85 × 10-12F/m) [6]

The model below will give us a clear sight how cell membrane affect the resistance.

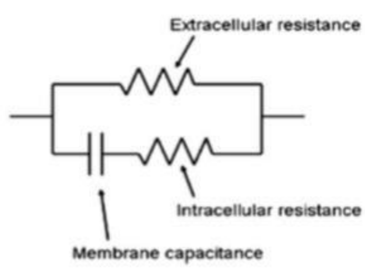

Figure 2. Muscle Tissue Circuit Diagram [7]

The capacitor represents the reactance of cell membranes and the resistors represent the extra and intracellular resistance of a skeletal muscle. Moreover, the capacitance varies on the frequency of the applied current, which in turn fluctuate the reactance of each muscle tissue. At lower frequencies, the current will flow initially through all three elements until the capacitor is fully charged. Once charged, the current will only flow across the extracellular resistor, but at higher frequencies of alternating currents, the current will be able to penetrate both the extra and intracellular resistors.

2 Methods

The main objective of this paper is studying the effect of the fat thickness and frequency on the EIM parameters. To do so, the finite element model of human upper arm model was developed using the AC/DC Module, Electric Current Physics, in Comsol Multiphysics software. The model included several layers: skin layer, subcutaneous fat layer, muscle fiber layer, bone, and four electrodes.

The thickness of skin and muscle is 3mm and 22mm respectively. There are four different values of fat layer (10mm, 15mm, 20mm, and 25mm). In this model, the circular shape of electrodes was applied with the radius 7mm and covering 154 mm^2 of skin area. In this model, the skin-subcutaneous fat and bone were all assumed to be isotropic, while the muscle fiber was anisotropic. The baseline inter-electrode distances were 15mm-30mm15mm (edge to edge). The two inner electrodes are for voltage measurement whereas the two outer ones are for excitation current source applied 1mA and a ground. The electrodes conductivity and relative permittivity values were set to 5.0e5 S/m and 1.0 respectively.

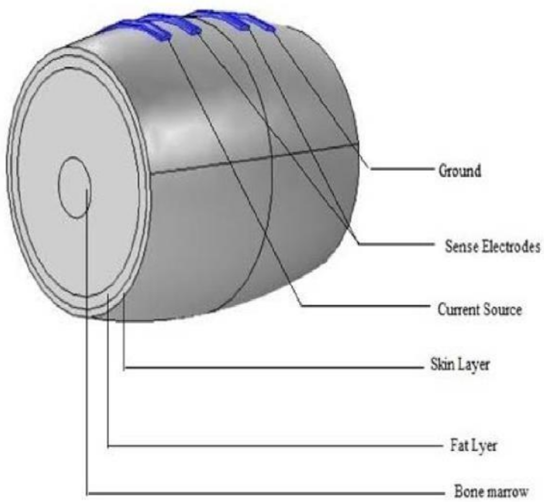

Figure 3. FEM model of the human upper arm [6]

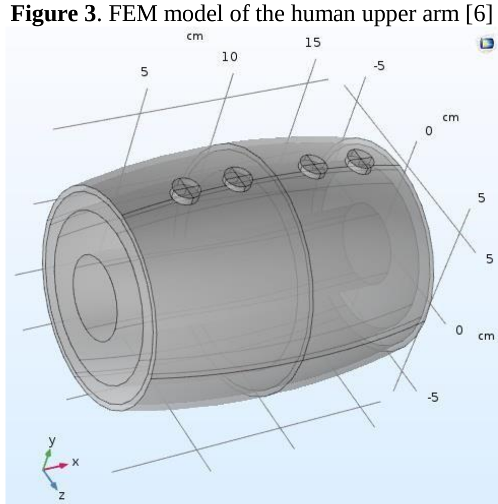

Figure 4. The 3D model of the human upper arm was designed

The value of conductivity and relative permittivity fordifferent layers at each different frequency were set according to the below table [7].

Frequencies	Tissue	Conductivity	Relative Premittivity
10k	Skin	0.0002	1150
	Fat	0.025	1000
	Muscle	{.4, .17, .17}	{120E3, 86E3, 86E3}
	Bone	0.002	675
50k	Skin	0.0002	1150
	Fat	0.03	500
	Muscle	{.55, .3, .3}	{40E3, 36E3, 36E3}
	Bone	0.0035	110
100k	Skin	0.0002	1150
	Fat	0.03	300
	Muscle	{.55, .3, .3}	{40E3, 36E3, 36E3}
	Bone	0.0035	110
1M	Skin	0.02	990
	Fat	0.05	150
	Muscle	{.65, .4, .4}	{4E3, 3E3, 3E3}
	Bone	0.004	40

Table. Dielectric Properties of different layers at different frequencies.

3 Results

The simulation was performed to evaluate the effect of the fat thickness and 10kHz to 1MHz frequency on the EIM parameters. The simulation gives us the result in the form of electric field distribution (an example shown in *Figure 3* and *4*) . By using the COMSOL we can evaluate the electric potential at the position of sense electrodes. Through that, we have calculated the electric impedance as the ratio of the voltage and the applied current. The impedance was plotted as the resistance, reactance and phase angle (shown in *Figure 5*, *6* and *7*). The %RSD of the 4 thickness of the fat respectively is 24.25%, 23.28%, 24.05% and 25.28% for the resistance and 52.06%, 33.21%, 18.65%, 22.67% for the reactance.

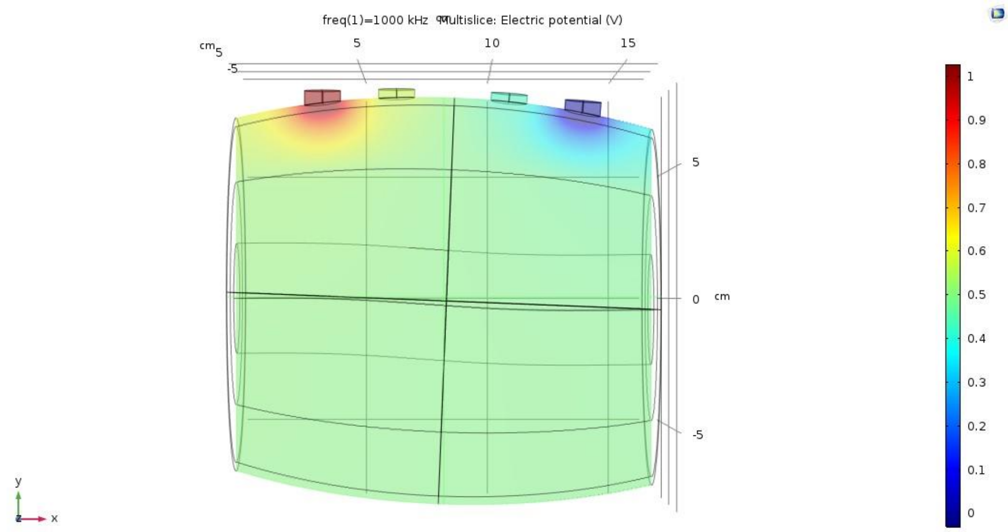

Figure 5. Electric distribution in XY view of the model simulated at 1MHz and 24mm of fat thickness

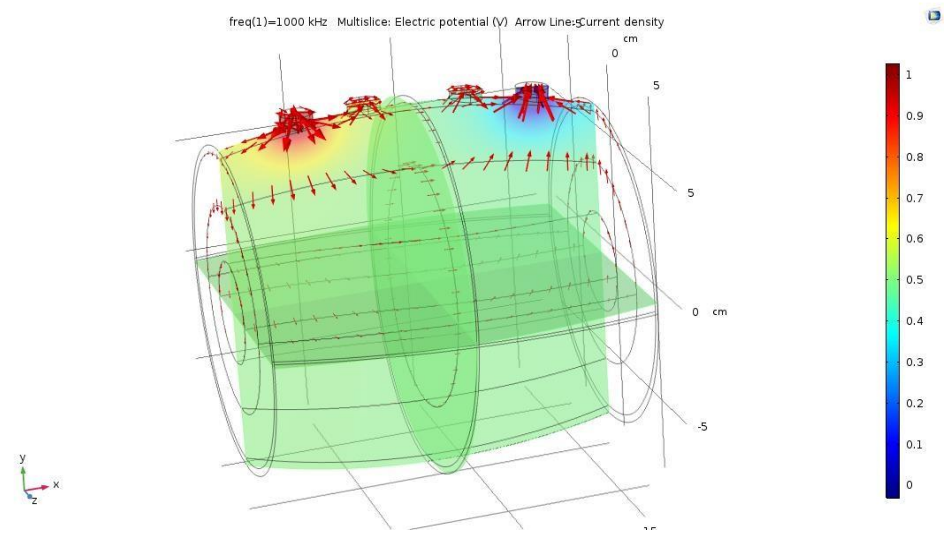

Figure 6. Electric distribution and the current density of the model simulated at 1MHz and 24mm of fat thickness

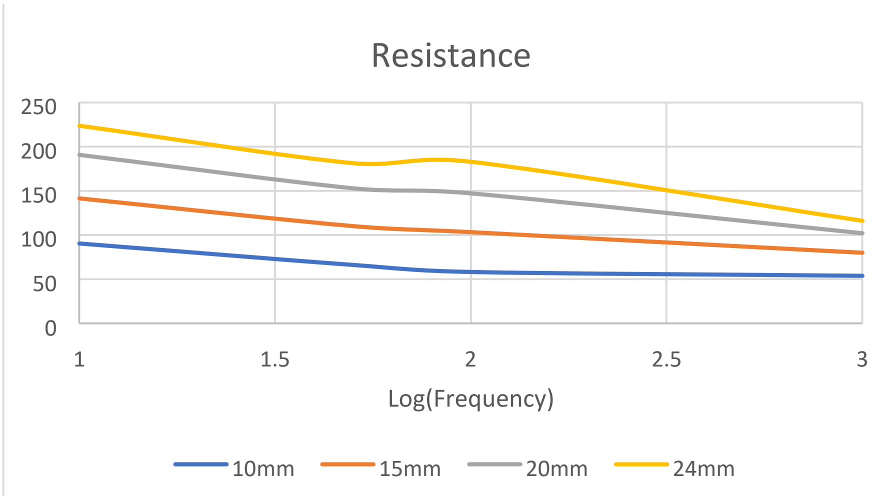

Figure 7. The resistance of upper arm at 4 different thickness of the fat layer in the simulation

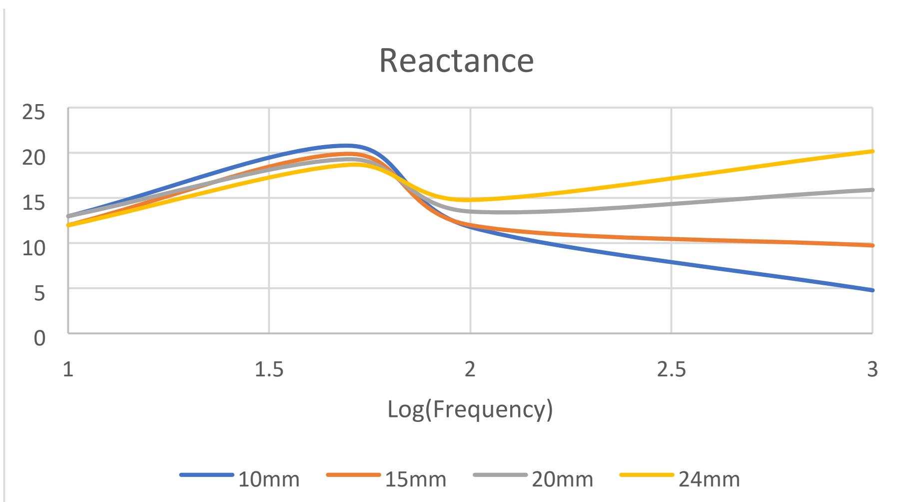

Figure 8. The reactance of upper arm at 4 different thickness of the fat layer in the simulation

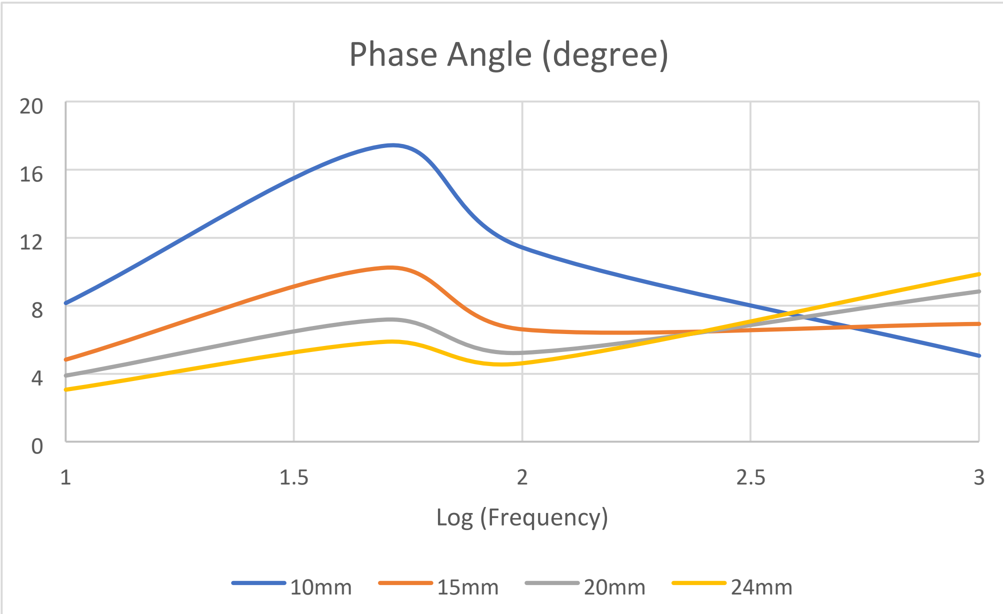

Figure 9. The phase angle of the upper arm at 4 different thickness of the fat layer in the simulation

4 Discussion

The results show the remarkable effect of frequency and fat thickness on EIM parameters which reactance and phase have demonstrated the most influence.

It is clear from figure 5 that the increase of frequency led to the decrease of resistance while the growth of the adipose layer caused resistance to rise. It can be considered that conductivity of fat varies slightly than the one of other tissue. Thus, as fat thickness increased, the current going through the tissue reduced, then resistance values went up. It is also noted that at high frequency, current could easily go across cell membranes into inner tissue, as a consequence, resistance decreased. In general, both frequency and fat thickness did not affect much to the shape of resistance graph.

On the other hand, reactance showed a clear dependence on frequency and adipose thickness. Figure 6 has indicated that reactance had a significant change from 50kHz to 100kHz as it started to felt at the point 50kHz and rose again at 100kHz. This could be explained that at 50kHz current started to go across the cell membranes in a more easy way, leading to the transition of reactance. By the side of it, the %RSD of reactance showed in the results, which felt dramatically from 52.06% to 18.65%, has pointed out that as adipose thickness rose, reactance had the potential to rise rather than felt when the frequency rose. This shows us that the thickness of fat layer caused a complex influence on the reactance since reactance can be considered the same for 4 thickness in the range of 10 to 50kHz.

In addition, phases were also strongly influenced by these two factors. Following the increase of frequency we can see that the thinnest fat layer (10 mm) witnessed the drop of phase from the highest value 8 degrees to the lowest point (approximately 5 degrees) while the thickness adipose layer (24 mm) experienced the jump of phase from the smallest value to the greatest point (10 degrees).

To have a closer look in the %RSD shown in the results, we can see that for the 4 thickness of fat, %RSD of the resistance was nearly the same. It proves that the fat layer did not affect much on the resistance when the frequency increased, whereas reactance was affected more clearly when the thickness of adipose tissue rose. Consequently, we can conclude that the influence of adipose is mainly to the reactance.

5 Conclusion

This simulation study aimed to evaluate the effect of frequency and fat thickness on EIM parameters. The results show that frequency and adipose thickness have significant effect on resistance and phase value. This will provide good support for future investigating the EIM. The study highlights a basic understanding of the frequency dependent electrical behavior of human upper arm tissues and presents an efficient simulation tool to analyze the effects and individual contributions of different tissues to the bioimpedance measurements.

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