Influence of Subcutaneous Fat Thickness upon the Activation Volume in Transcutaneous Electrical Stimulation to a Thigh Simulation Model

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Abstract

Activation Volume, which is calculated from the Activating Function, describes the spatial location of nerve activation, thus is useful in optimizing stimulation electrodes geometry and waveform for improving selectivity and comfort in transcutaneous electrical stimulation. For example, the discomfort due to the fat thickness has been studied before, but the effect of fat thickness on selectivity, which could be studied through the Activation Volume, needs to be further analyzed. In this study, we implemented a human thigh model using the Finite Element Method to study the effect of fat thickness on the Activation Volume in terms of penetration and volume. The thigh model was represented by a multiple layer cylinder composed of superficial stimulation electrodes, skin, subcutaneous fat, muscle, and bone. We found out that the selectivity under the electrode is better for smaller fibers close to the electrode, because the activation volume for those fibers do not spread out the area under the electrode.

Keywords*: Activation Volume, Fat Thickness, Transcutaneous Electrical Stimulation, Finite Element Method.*

Introduction

The analysis of the spatial location of nerve activation (Activation Volume) is useful in optimizing stimulation electrodes geometry and waveform for improving selectivity and comfort in transcutaneous electrical stimulation (TES). One aspect that affects comfort is the subcutaneous fat thickness because higher stimulus currents are required for an action potential (AP) in obese subjects than in subjects with healthy-weight [1].

An AP can be predicted when an activating function (AF), which is a function of the second derivative of the extracellular potential along a nerve fiber, is positive and over a threshold [2]. The threshold varies with fiber diameter, pulse duration and electrode location [3].

Many models have been developed to examine the excitation phenomena in nervous tissue [1], [4], [5]. For instance, a "two-step" calculation method has been adopted for superficial stimulation. The first step is the calculation of potentials induced in the extracellular medium. The potentials may be obtained either analytically or numerically and the electrical properties of skin, fat, and muscle should be taken into account. The second step is the determination of the response of nerve or muscle fiber due to the extracellular potentials. The AF has been used for the second step to obtain a 3D spatial distribution of the nerve activation.

The discomfort due to the fat thickness has been studied in [1] by evaluating the stimulating current and the AF. Also, the influence of electrode size and anode position on spatial nerve activation have been investigated [6]. However, the effect of fat thickness on selectivity needs to be further analyzed; for example, using Activation Volume [6].

The aim of this study is to investigate the influence of fat thickness on the Activation Volume and penetration distance for nerve fibers with different diameters, in order to quantify the selectivity of nerves. For this purpose, we implemented a human thigh model using the Finite Element Method to study the effect.

Material and Methods

An idealized human thigh is modelled using the Finite Element Method (FEM). The software package used for the analysis is the AC/DC module of COMSOL Multiphysics.

Model Considerations

The thigh model is represented by a multiple-layer cylinder, composed of superficial stimulation electrodes, skin (1.5mm), subcutaneous fat (2-60mm), muscle (64.2mm), and bone. For simplification, the electrical parameters are isotropic and frequency independent for each domain (Table 1). The cylindrical dimensions were obtained from cross section areas of MRI data for an average thigh, as described in [7]. The electrodes were modelled as a 1 mm thick electrode-skin boundary layer (hydrogel) with a square shape of 4cm of length, and separated by a distance of 5cm. The fiber diameters inspected were 6um, 10um, and 14um.

The effect of fat thickness (0.2cm-6cm) was studied employing a current stimulation with an amplitude of -100mA (a monophasic square pulse of 1ms).

Table 1 Model input parameters of the 3D Thigh [1],[4],[7]

Layer	Electrode	Skin	Fat	Muscle	Bone
Conductivity (10^{-4}S/m)	33.33	4.3	300	4000	200
Relative Permittivity (10^{4})	10^{-4}	0.6	2.5	12	0.3
Dimension (mm)	40 (length)	1.5 (radial)	2-60 (radial)	64.2 (radial)	13.6 (radial)

Governing equation

The potential (φ) within the thigh was calculated using (1), taking into account the conductivity (σ) and permittivity (ε) of the tissues, and the quasistatic condition.

$$0 = -\nabla \bullet (\sigma + iw\varepsilon)\nabla\phi \qquad (1)$$

Activation Volume

The activation volume (AV) is the region inside the muscle where AP may occur [6]. The AV space is limited by an Activating function over a threshold, as described in equation 2, and the fat-muscle layer, as shown in figure 1. The Activating Function is the second derivative of the extracellular potential with respect to x (along the fiber). The threshold value for activation depends on the fiber diameter and stimulation pulse duration [3]. The thresholds used in this study were defined for 1ms of stimulation time and a fiber diameter of 8um, 10um, 12um, and 14um, as explained in [4]. The threshold needs to be positive in order to evoke an AP; otherwise, hyperpolarization will occur in the fiber.

$$\frac{\partial^2\phi}{\partial x^2} > Threshold \quad (2)$$

We evaluated the Penetration Distance (PD), the Volume of the AV (V_{AV}) and the Volume under the electrode (V_{elec}) to study selectivity under the electrode and quantify the AV.

The PD is the distance between a point at the fat-muscle interface and another point with minimum AF value. Both points are in a line normal to the stimulation electrode surface and intersect with the surface at the center of the electrode.

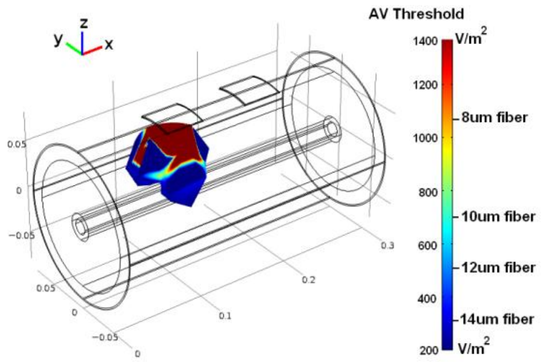

Figure 1. Thigh model and AV within the muscle. The AF thresholds for fibers of different diameter are presented (8, 10, 12, and 14um). The fat thickness is 1.4cm for a cathodic stimulation of –100mA, pulse duration of 1ms.

The PD is an index of the penetration within the muscle (without fat thickness), and calculated for each specific fiber [6].

The V_{AV} could be used to compare the change of the volume for different fat thickness and fiber diameters. Also, the V_{elec} is the V_{AV} limited by the electrode size (the volume under the electrode area). We defined fiber selectivity under the electrode as the ratio of V_{elec} to V_{AV}. It quantifies a percentage of the AV that is under the electrodes with respect to the total AV. Furthermore, it is a measurement of how much of the AV may activate a fiber outside the electrode (1- V_{elec}/ V_{AV}). In this case, selectivity is used to indicate selectivity under an area.

Results

Figure 2 shows the V_{AV} versus subcutaneous fat thickness, for different activation threshold corresponding to a fiber diameter. As expected, V_{AV} decreases as fat thickness increases. Figure 3 shows the penetration distance for different subcutaneous fat thickness. Clearly, the penetration distance shows a similar pattern as V_{AV}. The average of selectivity under the electrode over the values of fat thickness is calculated for each fiber (Table 2). For deeper activation, the selectivity decreases indicating that the activation outside the area under the electrode increases.

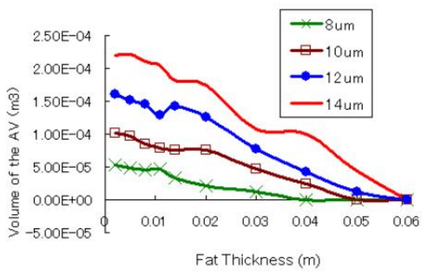

Figure 2. V_{AV} versus fat thickness.

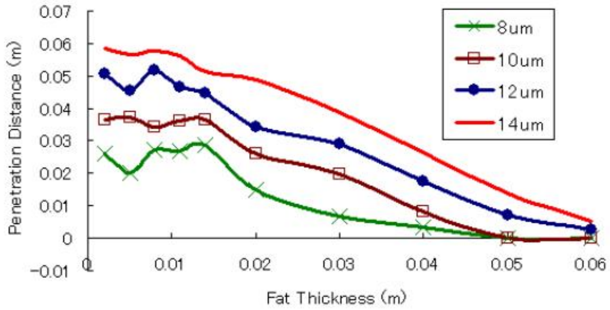

Figure 3. Penetration distance versus fat thickness.

Table 2 Average of the selectivity (V_{elec} /V_{AV}) over different values of fat thickness for each fiber diameter.

Fiber Diameter (um)	Average of V_{elec} /V_{AV} (%)	SD
8	62.21	4.73
10	49.22	9.41
12	44.63	4.62
14	38.54	3.42

Discussion

We studied the effect of fat thickness on the AV and penetration distance to evaluate selectivity under the electrode of transcutaneous electrical stimulation. This investigation could contribute to the understanding of the exact location where nerves may be activated.

According to figure 2 and 3, the V_{AV} and PD, decreases with the increase of fat thickness for each fiber activation threshold, as expected. The reason is that the current density spreads over the fat domain, and part of it does not penetrate into the muscle domain when the fat thickness increases [8].

Also, as shown in figure 2 and 3, the small fiber (thinner) cannot be activated in deeper regions like larger fiber (thicker) for the same fat thickness. However, the selectivity under the electrode is better for smaller fiber activation threshold because higher values of AF are concentrated near the electrode, and low values of AF spreads farther from the electrode (table 2). Therefore, forceful fiber (large) may be activated not only outside the electrode, but also in deeper regions than small fibers, which make more difficult control of fine motions using transcutaneous electrical stimulation.

Conclusions

In this paper, we studied the effect of fat thickness on the nerve fiber selectivity during transcutaneous electrical stimulation. We defined the fiber selectivity under the electrode as the ratio of volume under the electrode area and the total Volume of the Activiation Volume, and found out that selectivity under the electrode is better for high values of Activation Function because they are concentrated close to the electrode. However, small fibers cannot reach deeper distance as large fibers.

References

[1] Emer P. Doheny, Brian M. "The effect of subcuataneous fat thickness on the efficacy of Transcutaneous Electrical Stimulation", IEEE EMBS, pp. 5684-7, 2008

[2] F. Rattay, "Analysis of models for extemal stimulation of axons," IEEE Trans. Biomed. Eng., vol. BME-33, pp. 974-977, 1986.

[3] E. N.Warman,W. M. Grill, and D. M. Durand, "Modeling the effects of electric fields on nerve fibers: Determination of excitation thresholds," IEEE Trans. Biomed. Eng., vol. 39, pp. 1244–1254, Dec. 1992.

[4] Andreas, Kuhn. *Modeling Transcutaneous Electrical Stimulation*. Thesis. ETH ZURICH, 2008. 2008. .

[5] Reichel M, Mayr W, Rattay F. Computer simulation of field distribution and excitation of denervated muscle fibers caused by surface electrodes. *Artif Organs* 1999;23:453–6.

[6] A. Kuhn, T. Keller, "A model for transcutaneous electrical stimulation using activation volumes to describe the influence of the electrode placement and size," in *Proc. Vienna Int. Workshop Functional Electrostimulation*,2007, vol. 9, pp. 151–4.

[7] Fuller NJ, Hardingham CR. "Predicting composition of leg sections with anthropometry and bioelectrical impedance analysis, using magnetic resonance imaging as reference". Clinical Science 96, pp 647-57, 1999

[8] Gomez J, Gonzales J, Wenwei Y. "Preliminary Simulation Of The Current Distribution Across The Skin During Surface Stimulation Using Finite Element Analysis" CCCA 2011, pp 495-8, 2011.

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