The Effects of Subcutaneous Fat, Electrode Size and Inter-Electrode Distance During Transcutaneous Electrical Stimulation

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Abstract

Transcutaneous electrical stimulation (TES) is used as an adjunct therapy for obesity, where it can enable increased levels of voluntary exercise. Due to the high resistivity of subcutaneous fat tissue, however, high stimulus currents are required to evoke muscle contraction in obese subjects, possibly leading to patient discomfort. In this study, a three-dimensional finite element model of the human thigh, including skin, fat, muscle and bone, was developed to examine the effects of fat thickness, electrode size and inter-electrode distance on the level of evoked muscle activation, examined using the activating function, during monopolar and bipolar stimulation. The results indicate that increased electrode size may reduce patient discomfort while maintaining the efficacy of the electrical stimulation in obese patient populations. Additionally, muscle activation appeared to be less sensitive to inter-electrode distance as fat thickness increased.

1 Introduction

Transcutaneous electrical stimulation (TES) is a widely used technique, used to relieve pain, improve cardiovascular fitness and increase muscle strength. It may be used as an adjunct therapy for obesity, where significant voluntary exercise is not possible, to improve muscle strength, thereby physically enabling and psychologically encouraging increased levels of voluntary exercise. However, due to the high resistivity of fat tissue, high stimulus currents are required to evoke muscle contraction in obese subjects, leading to patient discomfort and intolerance of the therapy.

Previous experimental studies have examined the effect of varying electrode size and shape [1, 2], stimulus waveform [3, 5], skin blood flow [14] and subcutaneous fat thickness [14, 15] in order to reduce patient discomfort and to optimise stimulus parameters. Fat thickness is an important consideration in the conduction of current from the skin to the muscle, due to its high electrical resistivity and low blood flow. However, the effect of fat thickness on the current required to elicit muscle contraction during TES has received little attention to date, having been examined experimentally in only a small number of previous studies [14, 15], in which the variation in fat thickness has been limited to 1 cm between subjects. Examination of a wider range of fat thicknesses is required to extend the conclusions to an overweight or obese subject population.

The use of modelling studies to examine the mechanisms of electrical stimulation is well established. Previously, issues such as current and electric field distribution [12, 13, 9, 18, 19], electrode size, configuration and inter-electrode distance (IED) [10, 8] and the excitation of denervated muscles fibres [11] have been investigated. However, the effect of subcutaneous fat tissue thickness on the efficacy of TES has not been systematically examined to date. In this study, a three-dimensional mathematical model of the human thigh was developed to investigate the effect of fat thickness, electrode size and IED on the efficacy of TES by examining the properties of the resulting activating function (AF) [17].

2 Methods

The finite element (FE) method was used to calculate the electric potential in three-dimensional idealised cylindrical models of the human thigh due to monopolar and bipolar TES. The thigh was modelled as a set of nested cylinders, representing bone, muscle, subcutaneous fat and skin, as illustrated in Fig. 1. Circular electrodes were positioned along the midline of the thigh, Fig. 1. A series of models were constructed using Comsol Multiphysics (Hertfordshire, UK), with varying fat thicknesses, electrode sizes and IEDs.

![Figure 1: The geometry of the model, with 20 mm fat thickness and bipolar electrodes.](image-url)
of a fibre in response to changes in the extracellular potential [17]. It is calculated as the second spatial derivative of the electric potential along the fibre. The resulting AFs were lowpass filtered using a fourth order Butterworth filter with cutoff frequency 0.2 samples/mm. The conductivity of each material [6] is presented in Table 1.

Electrical ground was located at both ends of the central cylinder. Cathodic 100 mA monopolar stimulation, located 300 mm along the model (y = 300 mm), was simulated. 100 mA bipolar stimulation, with the cathode located as in the monopolar model and the anode positioned a fixed distance along the y-axis, was also simulated. Six fat thicknesses (5, 10, 15, 20, 35, 50 mm) were examined for both monopolar and bipolar stimulation. The effect of electrode size was first examined during monopolar stimulation: three electrode diameters (30, 50, 70 mm) were simulated at each fat thickness. The effect of IED was then investigated during bipolar stimulation: four IEDs (10, 20, 30, 50 mm) were examined at each fat thickness, with the electrode diameter held at 50 mm. The voltage along a sample fibre at the surface of the muscle tissue directly below the stimulating electrodes was examined and the AF of that fibre was then calculated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Model length</td>
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</tr>
<tr>
<td>Model radius</td>
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<td><strong>Thicknesses</strong></td>
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<tr>
<td>Skin</td>
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<td>[7]</td>
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<tr>
<td>Fat</td>
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<td>Muscle</td>
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</tr>
<tr>
<td>Bone</td>
<td>25 mm</td>
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<tr>
<td><strong>Conductivities</strong></td>
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</tr>
<tr>
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<td>Fat</td>
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<td>Muscle (longitudinal)</td>
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<td>[6]</td>
</tr>
<tr>
<td>Bone</td>
<td>0.02 S/m</td>
<td>[6]</td>
</tr>
</tbody>
</table>

3 Results

3.1 Monopolar stimulation

The peak amplitudes of the AFs due to 100 mA monopolar stimulation are presented in Fig. 2, and the corresponding AFs are presented in Fig. 3 for a range of fat thicknesses and electrode diameters. The peak amplitude decreased as both fat thickness and electrode diameter increased, Fig. 2, as expected. The AFs also broadened with increasing electrode diameter and fat thickness, Fig. 3. The relative decrease in peak amplitude with electrode diameter was greatest for low fat thicknesses (85% decrease for 5 mm fat thickness), while a relatively small decrease for higher fat thicknesses was observed (15% decrease for 50 mm fat thickness).

3.2 Bipolar stimulation

The peak amplitudes of the AFs due to 100 mA bipolar stimulation are presented in Fig. 4, and the complete AF are presented in Fig. 5 for all fat thicknesses and IEDs. The peak amplitudes of the bipolar AFs decreased with increasing fat thickness and with increasing IED. The effect of IED was greatest at low fat thickness levels. A variation in the shape of the AF was also observed with IED, due to the overlapping contributions from the anodic and cathodic electrodes, Fig. 5.
4 Discussion

In this study, the effect of fat thickness on the efficacy of TES was investigated, using the concept of the activating function [17]. The AF provides a close approximation to the source excitation, and also allows comparison between the relative efficacy of different electrodes to excite a nerve [20]. The effect of electrode diameter, IED, and their interaction with fat thickness were examined during monopolar and bipolar TES. The long-term aim of this study is to improve the impact of TES as an adjunct therapy for obesity.

Larger electrodes result in lower current density at the skin, which should improve the discomfort reported clinically during TES, as suggested by previous experimental studies [1, 2]. The peak amplitude of the AF decreased with both increasing electrode size and fat thickness, Fig. 2, as expected. However, the effect of electrode size was more notable at low fat thicknesses. The AFs also broadened as electrode size increased, Fig. 3, which may compensate for the reduction in amplitude. These results indicate that the use of larger electrodes could be preferable during TES for regions with high subcutaneous fat thickness, and particularly in obese patients.

The shape of the AF altered for the largest electrode tested, Fig. 3(c). The electric potential along the neuron becomes almost constant beneath the centre of the stimulating electrode. As the electrode size increases, this area enlarges and begins to affect the AF. This effect was most pronounced at lower fat thicknesses. The relative magnitude of the virtual anodes, the hyperpolarised regions on either side of the main polarised region of the monopolar AF [4], also increased as electrode size increased. These phenomena suggest that larger electrodes may not be preferable for use in a non-obese population.

Finally, the effect of IED on the peak amplitude of the AF decreased with increasing fat thickness, Fig. 4. The shape of the AF was also relatively insensitive to IED at higher fat thicknesses, Fig. 5. These results indicate that evoked muscle activity is relatively insensitive to IED at higher fat thickness. However, smaller IEDs would result in more focal stimulation with higher amplitudes when applied to a non-obese population.

The models developed here were used to simulate TES of an idealised human thigh. They were implemented under quasistatic conditions, hence neglecting capacitive and inductive effects, in accordance with previous models [10, 13]. The high capacitance of the electrical double layer and the details of the stimulus waveform are likely to further affect the results of this study. Furthermore to fully predict the electric field applied to a motor neuron a model of neural excitation would be required. Nevertheless, the AF provides a valuable insight into the behaviour of the system.

5 Conclusion

Higher currents are necessary to evoke muscle activation in obese subjects, leading to patient discomfort. The results of this study indicate that muscle activation is less sensitive to IED as fat thickness increased. Additionally, the results suggest that by increasing electrode size, patient discomfort could be reduced while maintaining the efficacy of the electrical stimulation in obese populations.

Literature