Computers in Biology and Medicine 61 (2015) 144–149

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

A human-phantom coupling experiment and a dispersive simulation model for investigating the variation of dielectric properties of biological tissues

Jose Gomez-Tames*, Yuto Fukuhara, Siyu He, Kazuyuki Saito, Koichi Ito, Wenwei Yu

Medical System Engineering Department, Graduate School of Engineering, Chiba University, Yayoi Chou, Inage Ku, 1-33, Chiba 263-8522, Japan

ARTICLE INFO

Article history:
Received 15 December 2014
Accepted 30 March 2015

Keywords:
Electrical stimulation
Simulation model
Human-equivalent phantom
Dielectric properties
Motor threshold

ABSTRACT

Variation of the dielectric properties of tissues could happen due to aging, moisture of the skin, muscle denervation, and variation of blood flow by temperature. Several studies used burst-modulated alternating stimulation to improve activation and comfort by reducing tissue impedance as a possible mechanism to generate muscle activation with less energy. The study of the effect of dielectric properties of biological tissues in nerve activation presents a fundamental problem, which is the difficulty of systematically changing the morphological factors and dielectric properties of the subjects under study. We tackle this problem by using a simulation and an experimental study. The experimental study is a novel method that combines a fat tissue-equivalent phantom, with known and adjustable dielectric properties, with the human thigh. In this way, the dispersion of the tissue under study could be modified to observe its effects systematically in muscle activation. We observed that, to generate a given amount of muscle or nerve activation under conditions of decreased impedance, the magnitude of the current needs to be increased while the magnitude of the voltage needs to be decreased.

1. Introduction

Simulation of electrical stimulation is required to adequately represent physiological, stimulation, and anatomical factors. Variation of the dielectric properties of the tissues (physiological factors) can happen under natural processes, like aging [1], or under natural conditions, such as moisture in the skin [2]. Muscle conductivity can be changed after acute denervation injury [3], and temperature can increase or decrease blood flow, which directly affects the impedance of the body [4]. Several experimental studies compared different stimulation schemes (stimulation factors), such as pulse stimulation (PS) and burst-modulated alternating stimulation (BMAS), to investigate which elicits greater muscle torque while keeping discomfort low and whether modulations in frequency facilitate current transmission deeper into the muscle. However, contradictory results have been reported regarding whether PS or BMAS produces more force while maintaining comfort [5–10]. As tissue's conductivity changes according to the pulse duration of the stimulation waveform, the effect of the tissue's conductivity variation may explain the outcomes of the experimental studies mentioned. In addition, in a previous study, we evaluated different morphologies to investigate their limitations and advantages for model implementation [11].

The study of the effect of the dielectric properties of biological tissues in nerve activation presents a fundamental problem, which is the difficulty of systematically changing the dielectric properties of the subjects under study and controlling tissue thickness variability, especially fat thickness. This can be tackled by simulations or experimental studies.

Simulation studies can be used to investigate the effect of the conductivity variation on the extracellular medium and neuronal excitation. Livshitz et al. [12,13] presented a model with three tissue layers to study the current density distribution through the tissues and force production; however, that study did not consider nerve model or muscle conductivity variation or anatomical characteristics.

In our previous simulation study [14], we investigated the effect of the conductivity of the tissues in nerve activation by implementing a non-dispersive 3D multi-layer (skin, fat, muscle, and nerve) model of the thigh during current stimulation. The result showed that the variation of the skin conductivity did not modify muscle recruitment (without considering the effect of the electrode's moisture or perspiration), and an increment of fat's conductivity decreased the recruitment for current stimulation. We also presented a novel method that combined a fat-equivalent phantom, with known and adjustable dielectric properties, coupled with a human thigh [15]. In this way, the dispersion of the tissue under

* Corresponding author: Tel.: +81 090 6018 7532; fax: +81 043 290 3231.
E-mail address: dagothames@chiba-u.jp (J. Gomez-Tames).

http://dx.doi.org/10.1016/j.compbiomed.2015.03.029
0010-4825/

study could be modified to systematically observe its effects in muscle activation.

In this study, we investigated the effect of tissue conductivity in a larger number of subjects using current- and voltage-controlled stimulations. An improved model is used to account for the effect of a larger range variation of the dielectrically dispersive properties of the tissues.

2. Method

2.1. Human-phantom coupling experiment

2.1.1. Tissue-equivalent phantom

The tissue-equivalent phantom has a relative dielectric constant and conductivity similar to biological tissues, primarily in the study of the effect of electromagnetic field for high-frequency applications [16–18]. A customized fat-equivalent phantom was fabricated to match low-mid-frequency for electrical stimulation, presented in detail in [15]. Three different conductivity dispersions were designed for the fat-equivalent phantom: σ_L, σ_M, and σ_H, as shown in Table 1. Relative permittivity and conductivity of the fat-equivalent phantom were verified using an LCR meter (HIOKI, IM3533-01, Nagano, Japan) within a frequency range from 1 Hz to 200 kHz, showing a similar frequency response in the literature [19,20], Fig. 1.

Measurements of the dielectric properties in multiple phantoms confirmed the robustness of the recipe. In addition, storage in a refrigerator and measurements during one week showed that the phantom retained its dielectric properties across one week. In a previous study, the distribution of the voltage in the phantom was measured to verify the model; then a two-layered plate, composed of two phantoms, was used to measure the voltage distribution within the two layers to investigate the interface effect, which is similar to the one between the human thigh and the tissue-equivalent phantom [15]. The phantom was used 20 min after refrigeration and a sample of the employed phantom was always measured to verify its properties before each experiment. The room temperature was kept around 20 °C during the experiment and the skin was cleaned with alcohol.

2.1.2. Experimental setup

Eleven healthy subjects (age 23.7 ± 3.4, height 174.3 ± 5.7 cm, weight 65.9 ± 10.9 kg, BMI 21.7 ± 3.2, mean ± SD) participated in the study. All subjects were informed of all experimental procedures and signed a statement of informed consent, as approved by Chiba University.

In order to analyze the effect of the conductivity variation of the tissues in muscle recruitment, a semicircular fat-equivalent phantom, coupled with a human thigh, was used to mimic a variable tissue's conductivity during nerve activation. The phantom's distal edge was placed 10 cm from the knee, and two square electrodes of area 25 cm^2 were spaced 3 cm edge-to-edge and 7 cm over the middle of the phantom. An accelerometer was placed on the electrodes to determine the smallest detectible contraction that current or voltage stimulation produced (hereafter referred to as Motor threshold, MT), as shown in Fig. 2.

Table 1
Composition of the fat-equivalent phantom.

Material	Amount (g)	Effect
Deionized water	400	Base material
Glycerol	400	Base material
Polyethylene powder	80	Relative permittivity
Agar	24	Forming
Sodium chloride	0	Conductivity (σ_L)
	0.8	Conductivity (σ_M)
	3.2	Conductivity (σ_H)

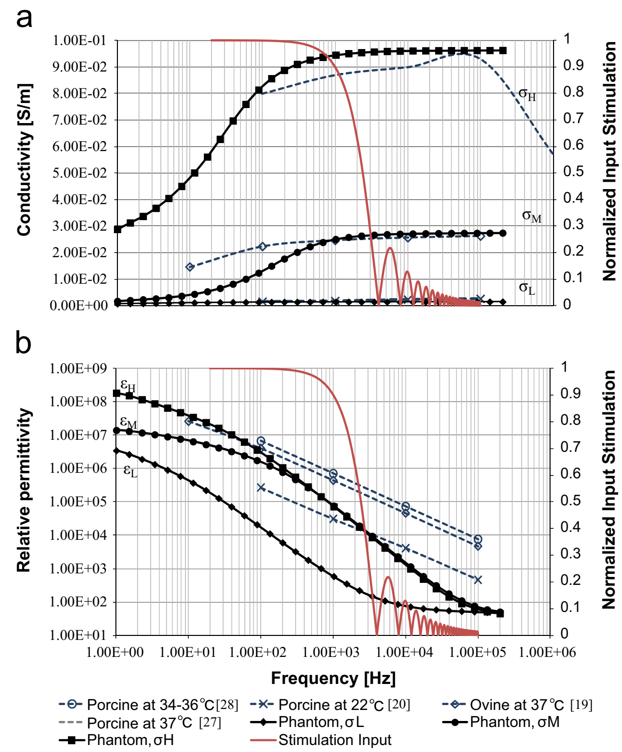

Fig. 1. Dispersive response of three different (a) conductivities and (b) permittivities of the fat-equivalent phantom based on experimental data in the literature. The spectrum of a pulse of 250 μs is shown (median frequency of 1082 Hz) [19,20,27,28].

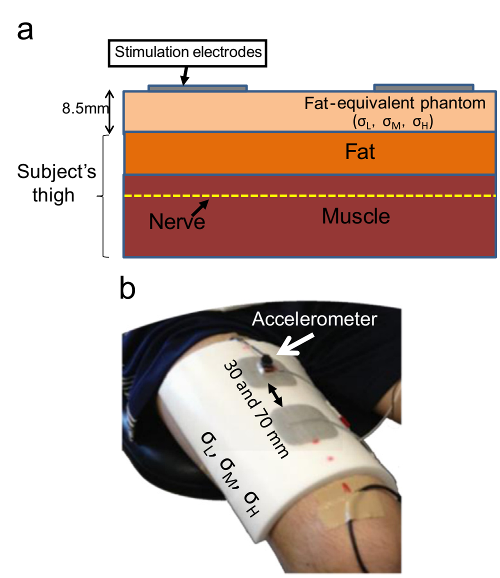

Fig. 2. Human-phantom coupling experiment. A semicircular fat-equivalent phantom was coupled with the subjects' thighs (thickness of 0.85 cm, length of 20 cm, and three different conductivity dispersions: σ_L, σ_M, σ_H). The phantom was tightly adjusted to the thigh using two straps at the level of the electrodes without causing a considerable stress in the thigh (the straps were omitted for clarity).

A monophasic voltage-controlled and a current-controlled stimulation were employed with a square pulse of 250 μs with a period of 266 Hz, using a purpose-built device for voltage stimulation and a Trio 300 device (ITO Co., Ltd, Tokyo) for current stimulation. The duration of the stimulation pulse was chosen to be small enough to introduce high harmonics, to take into account