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EIS measurements for characterization of muscular tissue by means of equivalent electrical parameters

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ABSTRACT

The objective of this work was to study the use of electrical impedance spectroscopy (EIS) measurement to characterize muscle electrical properties in different conditions.

In vivo EIS measurements were carried out in the range 1–60 kHz on 32 forearm flexor muscles of healthy volunteers. Each subject underwent to a protocol consisting of three trials: rest condition, isometric contraction, 4 min relaxation. Measured data were fitted with Cole–Cole equivalent electrical circuit using the complex nonlinear least square method. Finally, the relative variations from the steady state of the electrical parameters of the equivalent electrical circuit were estimated.

Results obtained are in agreement with the hypothesis that, in the frequency range considered, the current preferentially flows through the extracellular fluid, being the component of intracellular resistance negligible. Among circuital parameters, in fact, the relative variations from steady state of R_0 changed highly significant ($p < 0.001$) both during contraction and after 4 min relaxation.

1. Introduction

The human body, like any conductive material, provides some impedance to the passage of electric current. The measure of this impedance is a field of engineering research, already employed also in medical practice. This technique is applied to muscle tissue, sometimes named Electrical Impedance Myography (EIM), is a poorly invasive tool for neuromuscular evaluation. Generally speaking in EIM an alternating current is injected via surface electrodes and the resulting voltage drop over a selected muscle or muscle group is measured [1–5]. Many applications concerning analysis of muscular tissue can be found in literature, in particular with the issue to characterize different physiological or pathological conditions [1–3,5]. As the impedance of biological tissue is frequency dependent, important information can also be obtained measuring tissue in a range of frequencies; this technique is generally referred to as electrical impedance spectroscopy (EIS) [5,6]. EIS measures have already produced interesting results in different clinical applications [1,7–10]. For example, the method has been successfully employed for characterizing in vivo changes in skin electrical properties due to drug delivery or for monitoring the osteointegration process of metallic implants for auditory recovery; this technique has been used also for studying changes in electrical properties of muscular tissue at low levels of contraction or for testing health condition of muscles in elderly subjects. However, additional investigations are needed to better highlight complex mechanisms involved in tissue's intrinsic changes [7–9]. Muscular impedance depends in fact on different factors, such as biochemical changes, structure and geometry of the muscle itself, direction of

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the applied current, kind of electrodes used and inter electrode distance [9,10]. Moreover there is a lack of standards in measurement parameters, lay out and protocol [10–12].

In biomedical engineering, it is common to model systems and particular electrical measurement of biological tissues by means of equivalent electrical circuits which provide a simplified description of the properties of the measured organs [6,13,14]. An opportune choice of the model makes possible to correlate the circuit elements to underlying physical and physiological processes [7,13]. Muscular tissue, such as any other biological tissue, is formed by cells whose structure can be represented by considering extra cellular fluids (blood and interstitial fluid), cell membrane and intra cellular components [14]. From the electrical point of view, intra and extracellular media can be considered as a liquid electrolyte (represented by a resistive component) and the cell membrane, being characterized by a double layer of lipids, behaves as a capacitor [6,7]. Thus it is possible to study the modifications in muscular tissue, related to different conditions, analyzing the correspondent changes in the equivalent electrical parameters. Recently, it has been demonstrated that those changes are large enough to be considered as sufficiently sensitive, reproducible and hence appropriate for clinical use [11,12]. However, on the basis of our knowledge, except some isolated case [4,12,13], not many research works there exist specifically concerning the relationship between electrical circuits and muscle tissue.

The objective of this work was to study the variation of muscle electrical properties in three different muscle conditions, rest, sustained contraction and phase after contraction; of which the last two conditions are poorly studied in literature. To this aim, an equivalent electrical model was adopted to analyze the forearm flexor muscles and in vivo EIS measurements were employed to estimate changes in the equivalent electrical parameters of the tissue impedance in order to evaluate their sensibility to the variation of the muscular state.

The paper in the following considers different aspects of the study. The methods section includes impedance measurement background, instrumentation and lay out and protocol for muscular tissue measurement; moreover this section describes the used equivalent electrical model, the fitting and data analysis procedure. The result section shows raw data analysis according to the previously described approach which are examined in Section 4.

2. Method

2.1. Impedance measurement for biological tissue characterization

For this study, the logical scheme represented in Fig. 1 was adopted. This scheme follows the general approach employed to define the procedures to test new in vivo measurement methods [7].

In this application the impedance of the tissue under measurement was evaluated by means of the equation:

$$Z = \frac{|V|}{|I|} e^{j(\theta_V - \theta_I)}$$

where $|V|$, θ_V and $|I|$, θ_I represent, respectively, modulus and phase of the acquired sinusoidal voltage and of the injected current signal. In order to implement the impedance measure, an appropriate measurement system must be designed and utilized [11,15].

2.2. Measurement system

2.2.1. Hardware

The prototyped proof demonstrator, based on a battery-powered notebook PC implemented with an AD/DA board and an analog interface, has been described elsewhere [7,16,17]. It was used, in a clinical tool, for EIS measurements of transcutaneous implants during the osseointegration process [17] and for a preliminary evaluation of muscle tissue [11,16].

The digital I/O board was a PCMCI DAQCard-6062E (National Instrument™, Austin, Texas), with a two DACs and 16-channels ADC, all ones with a 12-bits resolution. One of the DACs was used to generate the low voltage sinusoidal stimulus [18]. The analog output of the DAC was amplified by a high-accuracy instrumentation amplifier and applied between the A+/A– electrodes. The current value was measured by a transimpedance amplifier. The tissue drop voltage was gathered between the V+/V– electrodes by means of another high-accuracy differential amplifier (chosen to guarantee high noise immunity and common-mode rejection). The output voltages of the differential amplifiers were sampled by the two channels of the ADC and processed by the software (described in the following sub-section) for impedance evaluation.

2.2.2. Software

The software, derived from [15] and detailed in [11], was designed in LabVIEW environment (National Instruments). It was developed for (i) managing the acquisition board; (ii) setting and controlling the stimulus, by means of a loop procedure, in order to maintain constant the voltage drop, at a value here called Vp, over the portion of tissue under measurement (in accordance with the typical procedure employed in EIS measurements [18]); (iii) checking the amplitude of current stimulus (kept within safety levels) [8,17]; (iv) implementing a sine-fitting technique [20], to reduce the influence of noise in the final impedance computation; (v) averaging modulus and phase of five measurements for impedance evaluation and (vi) generating and saving an ASCII file with all the impedance parameters.

All the operations can be easily executed by the operator using a front panel interface developed in LabVIEW, which allows also to see, in real time, frequency-courses of modulus and phase of the measured impedance.

2.3. Measurement lay out

EIS measurements were carried out by employing tetra polar measurements, since it is known that the use of four electrodes can help to isolate an area of interest and, mainly, to reduce the effects of electrode polarization [6].