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Impedance plethysmography as a tool for assessing exertion-related blood flow changes in the lower limbs in healthy subjects

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ABSTRACT

Impedance plethysmography, also known as the impedance test, the blood flow test, or impedance phlebography, is a non-invasive test that measures blood flow in the vessels of the peripheral vascular system by monitoring changes in electrical resistance (impedance) to detect deep thrombosis (blood clots or thrombophlebitis).

The aim of our study was to use this technique for assessing changes in blood flow in the lower limbs in healthy subjects wearing protective footwear while walking.

The test was performed on a group of 30 professional firefighters (age 30.7 ± 4.5, BMI 25.1 ± 3). Blood flow was monitored in the peripheral vascular system of the lower limbs during walking on a treadmill. The testing protocol consisted of the following three phases: warm-up, exercise, and rest.

In order to identify differences between the three phases of the study, analysis of variance (ANOVA) with repeated measures was conducted. The statistically significant parameters of blood flow in the lower limbs were the impedance ratio (IR) ($p < 0.001$), slope ratio (SR) ($p < 0.001$), crest width (CW) ($p < 0.001$), and alternative blood flow (ABF) ($p < 0.001$). All of them showed an upward trend.

The study confirmed the validity of impedance plethysmography as a non-invasive technique for measuring blood flow changes in the lower limbs in healthy subjects, especially under non-steady-state conditions, such as walking. This technique provides valuable quantitative data.

Therefore, impedance plethysmography may be considered a reliable research method enabling evaluation of local blood flow in healthy subjects under different conditions.

1. Introduction

Rheography, a method used to study the filling of a part of the body with blood by graphically recording fluctuations in its resistance (impedance), is a non-invasive method as impedance is measured externally to the tested tissue area. For this purpose, electrodes are placed on the patient's body according to the examination algorithm. The diagnostic device used is equipped with 4 electrodes. Two outer electrodes supply a small amount of high frequency alternating current (AC), which is imperceptible to the patient. The current running through tissues generates a voltage, which is measured by the inner (detecting) electrodes, which delimit the tested area. In comparison with two- and three-electrode systems, the impedance system based on four electrodes exhibits the lowest measurement error [1].

The basic assumption of impedance plethysmography is the observation that the examined limbs demonstrate

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constant and alternating electrical impedance. Therefore, a particular tissue segment is a source of constant impedance signal. The characteristics of this signal depend on the shape of the organ studied as well as the volume of liquid and its relocation [2].

Measurement is enabled by the fact that the resistance of blood is much lower than that of the skin, muscles, or bones. That is why changes in blood volume correspond to changes in electrical impedance. Different factors can modify the measured flow, such as the filling of an organ with blood, increased capillary blood volume, blood flow, temperature changes in the examined tissue segment, and significant changes in hematocrit [3,4].

The beginnings of the plethysmographic method are connected with the research of Nyboer [5] who coined the term impedance plethysmography. The final results of that research were published in the 1950s. The theoretical model of blood flow assessment was made possible by establishing a mathematical relationship between changes in impedance and blood volume, based on the electric field theory by Geselowitz and Mortarelli [6,7]. In Poland, the impedance method of assessing blood flow in the extremities was initiated by Pałko et al. [8] and Pawlicki [9].

In the last decade, research on the use of impedance plethysmography for evaluation of blood flow in peripheral blood vessels has been conducted in various clinical settings, usually associated with cardiovascular diseases. The research conclusions confirm that impedance plethysmography is a method of assessing local blood flow that enables the identification of risks and therapeutic decision making. It also facilitates the planning of activities preventing disorders directly related to blood flow in peripheral circulation.

It should be noted that, to date, research into impedance plethysmography has been carried out in static systems involving patients after interventional treatment of atherosclerosis and those chronically immobilized at risk of bedsores [10]. Siebert et al. [11] conducted a study on a group of patients after radial artery extraction for heart revascularization by means of arterial by-pass grafting. They used impedance plethysmography for evaluation of blood flow in limbs following graft extraction and observed very good correlation between results obtained using measurement setups with different distances between electrodes on the forearm. This shows that it is possible to use impedance plethysmography for evaluation of blood flow changes in patients between and after radial artery extraction [11].

A cause-and-effect relationship between changes in the blood volume in the tested area and changes in electric impedance is at the root of the method, enabling blood flow assessment [12]. It should be emphasized here that the flow parameters tested with the plethysmographic method characterize the behavior of blood flow in a given area across the entire tissue containing many vessels; therefore, the results of a test cannot be related to one specific vessel.

While there exist many good methods of testing arterial blood flow, in some situations (under dynamic conditions) it may be necessary to assess blood flow in the peripheral vascular system.

Although the obtained assessment is related to many vessels in the tested area, contemporary physical models allow one to obtain a signal which can be used in clinical practice. Kubicek et al. [13] and Mohapatra et al. [14] modified a mathematical model of impedance in a way that makes it possible to assess blood flow in the tested segment within a minute. The study of Jindal et al. [15] has contributed to estimating changes in blood volume in the limbs throughout the cardiac cycle. Moreover, this has provided the basis for building calculation algorithms for modern diagnostic devices which enable evaluation of impedance parameters excluding the influence of some physiological factors such as respiration [16].

Currently there are no research tools enabling the objective assessment of the impact of protective footwear design on healthy workers [17–22]. Therefore, it is important to develop a new method for evaluating this impact by means of techniques used in medical diagnostics. The authors of this study attempted to use for this purpose a non-invasive technique that uses objective indicators of vascular flow. The method takes advantage of typical vascular reactions involving contraction and dilation of vessels depending on physical activity. During the use of heavy protective footwear the diffusion of heat and humidity to the environment is hindered due to its unconventional design and the materials used. This undoubtedly affects blood circulation in the legs. Impedance plethysmography was used in this study to assess this effect [23].

The present research efforts are the first step in understanding the impact of the construction of protective footwear on healthy workers. The study group in this study consisted of healthy professional firefighters wearing all-rubber protective footwear.

2. Objective

The objective of this study was to use impedance plethysmography as a technique for assessing changes in blood flow in the peripheral vascular system of the lower limbs under dynamic conditions in healthy subjects wearing protective footwear.

3. Materials and methods

3.1. Human subjects

The study group consisted of 30 healthy active men working in fire and rescue units (firefighters). The subjects were qualified for the tests on the basis of valid certificates consistent with the health and safety regulations in their workplace. The group was homogeneous in terms of age (25–35 years), body mass index (BMI = 20.1–32.6), and work experience (5–10 years). The subjects underwent an additional medical examination which ruled out cardiovascular diseases, metabolic diseases, and diseases of the locomotor system associated with the skin of the lower extremities.

3.2. Equipment

The tests were performed on all-rubber firefighter footwear equipped with protective elements, i.e., internal steel toecaps and steel insoles placed in the sole, providing