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Original article

Comparison between ambulatory measurement of effective thermal conductivity and laser Doppler flowmetry method to assess skin microcirculatory activity

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Abstract

The main objective of this paper was to assess the performance of the ambulatory device μHematron to measure indirectly skin blood flow relative to the well-established Laser Doppler flowmetry method. The μHematron device is dedicated to the non-invasive measurement of effective thermal conductivity of living tissues, based on the thermal clearance method. Its major advantage is its ambulatory functionality, as available methods for evaluation of microcirculatory activity are non-ambulatory methods. An experiment was conducted on ten healthy women exposed for one hour in three different thermal environments (22 °C, 25 °C and 30 °C). Skin microcirculatory activity was analyzed after an acclimatization period of 30 minutes. The time between each exposure was at least one hour. Performances of the μHematron device were assessed and a comparative study with a laser Doppler perfusion monitor (LDPM) was performed. Good correlation coefficients between the two devices ($r = 0.71$ at T1 = 22 °C, $r = 0.77$ at T2 = 25 °C and $r = 0.83$ at T3 = 30 °C) were obtained while the LDPM signal was filtered by a low pass filter (0.1 Hz). These results showed that continuous monitoring of effective thermal conductivity was possible in neutral and warm ambiences. Then, the μHematron device could be considered as a complementary tool to Doppler techniques for the investigation of skin blood flow, when ambulatory conditions are required.

Keywords: Ambulatory device; Effective thermal conductivity; Thermal clearance; Microcirculatory activity; Non-invasive sensor; Laser Doppler flowmetry

1. Introduction

The present trend in healthcare technology is to design miniaturized, non-invasive sensors and their associated instrumentation in order to make the systems convenient to carry or wear and thus suitable for ambulatory monitoring applications. Non-invasive measurements are desirable for several reasons: they are generally painless, they tend to avoid problems of infection, and they are relatively simple and easy to use.

In this context, the miniaturized device presented in this paper has been designed to facilitate the monitoring of effective thermal conductivity under ambulatory conditions, in ecological experimental conditions. Effective thermal conductivity can be considered as an indicator of metabolic activity and microcirculation activity. Indeed, Gibbs [1] demonstrated that thermal methods can detect changes in blood flow and Grayson [2] found a linear relationship between blood flow and thermal conduction of tissues, allowing quantitative measurement. These thermal methods, based on a thermistor probe, have been used to evaluate blood flow, in particular skin blood flow [3]. Several methods, as in our case, use isothermal devices: they keep the heated thermistor at a constant temperature above that of the tissue and measure the power required to maintain the heat, which is proportional to the effective thermal conductivity of the tissue [4]. This method investigates local changes in heat transfer by conduction (characterized by the intrinsic thermal conductivity of tissue) and convection (characterized by tissue perfusion). The sum of these two transfers is characterized by effective thermal conductivity of the tissue, which depends on the hydration of the tissue and irrigation. Thus, effective thermal conductivity of tissue is used as an index of metabolic activity and microcirculation activity.

Regarding the evaluation of microcirculatory activity with non-invasive devices, others methods exist, such as capillaroscopy, laser Doppler flowmetry (LDF), and laser Doppler perfusion imaging (LDI). These optical methods are used in many clinical applications such as in diagnosis of diabetic

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microangiopathy [5], peripheral vascular disease such as Raynaud's phenomenon [6] and chronic venous inefficiency [7,8]. LDF method is appropriate for measuring and monitoring punctually temporal changes in tissue perfusion. LDI has no contact with the skin and gives quantitative or qualitative measurement. These methods are non-ambulatory, have arbitrary units and are generally sensitive to movement artefacts [9,10]. To overcome these limitations, more recent techniques have been developed such as the laser speckle imaging (LSI) [11], used for imaging skin blood flow, with a short time of image acquisition, high image resolution and a linear response of blood flow changes.

The non-ambulatory version of Hematron has been compared to plethysmography and Laser-Doppler (LDF) technique during changes in skin blood flow on six subjects [12]. They observed that heat clearance method correlated well with the forearm blood flow ($r = 0.69–0.97$) and with LDF measurements ($r = 0.86–0.92$) for the 6 subjects.

In this paper, the performance of the μHematron instrumentation is evaluated and compared with a standard method, the laser Doppler flowmetry. The LDF has been chosen because it is an established method, largely employed in clinical investigations. During one day, a subject was exposed to three different ambient temperatures (22 °C, 25 °C and 30 °C). Simultaneous measurements of skin microcirculation activity were performed using the μHematron device and a laser Doppler perfusion monitor (LDPM). Both methods provide continuous and non-invasive measurements. Measurements with LDPM are related to changes in microvascular perfusion, in terms of relative changes of blood volume and velocity, whereas measurements of Hematron are related to changes in effective thermal conductivity of tissues. We investigate mean values (obtained over the 30 min period after acclimatization) of skin perfusion measured by LDPM and effective thermal conductivity measured by μHematron. A descriptive study of temporal signals is proposed in order to explore variations of microcirculation activity and a comparative study between μHematron and LDPM is presented.

2. Materials and methods

2.1. Instrumentation

First, the μHematron device and the working principle of the probe are presented. Design, realization and validation of the miniaturized electronics associated with the existing Hematron probe, enabling effective thermal conductivity ambulatory monitoring have already been presented by Toumi et al. [13,14]. The miniaturization, achieved thanks to a programmable component and the reduction of power consumption had no adverse consequence on the system's performances. Secondly, we present briefly the LDPM device used in this experiment, as the principle of laser Doppler flowmetry is well known.

2.1.1. μHematron device

2.1.1.1. Effective thermal conductivity of perfused tissues. Effective thermal properties include the contribution to heat transfer due to intrinsic conduction and the contribution caused by the transport of blood through the tissue. The heat transfer by conduction depends on the nature of tissue involved. Three compounds are principally involved in living tissues: proteins and lipids with a thermal conductivity of 1.8 mW.cm^{-1} °C^{-1} and water with a thermal conductivity of 6 mW.cm^{-1} °C^{-1} [15,16]. Consequently, without blood flow perfusion, thermal conductivity of a tissue depends mainly on its water content. The second mode of heat transport is convection, via microcirculation activity. This mode transport is more significant when tissue blood supply is increased. In living tissues, heat convection transfer occurs principally in the smallest vessels of the vascular system as a result of their large surface for exchange. Thermal conductivity has units of mW.cm^{-1} °C^{-1} and values range from 2 to 10 mW.cm^{-1} °C^{-1} for biological tissues.

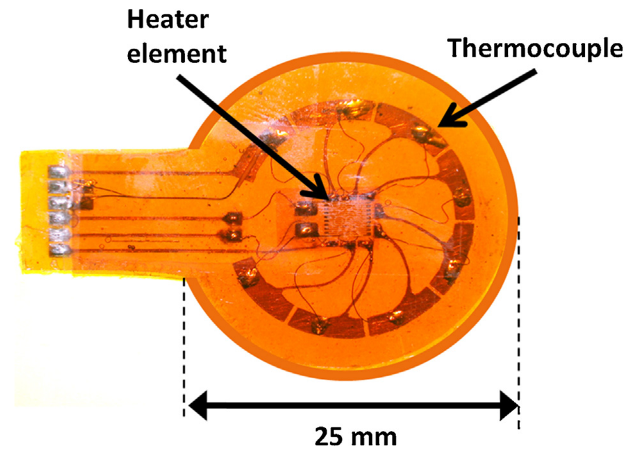

Fig. 1. Hematron probe: the heater element is at the centre of the disc, 8 thermocouple junctions are located at the periphery of the disc.

2.1.1.2. Hematron probe. The Hematron probe (Fig. 1) consists of a disc of 25 mm in diameter and 4 mm thick. The measurement process is as follows: at the beginning of the measurement, the probe, placed on the epidermis, heats its centre to establish an increment of 2 °C between the centre of the sensor and its periphery. This heating stage is necessary to establish the thermal field under the heater element. Hematron is an active sensor, based on a Proportional Integral (PI) regulator which controls the heating power of the central heater so that the increment of 2 °C is maintained between the measuring and reference components, and then, ensures that the volume explored by the thermal field is constant. Geometry of the sensor was designed so that the thermal field generated spreads mainly to the smallest vessels in the circulatory system. Thus the electrical power required to maintain the probe's increment is proportional to the effective thermal conductivity of tissues [17].

The measuring surface, which is in contact with the skin, is composed of two parts: the reference part at the periphery of the disc and the measuring part at the centre of the disc. A flat planar thermal heating element is located in the central part of the sensor, consisting of a 120Ω constantan resistor. The temperature difference between the measuring part and the peripheral part is measured by means of 8 copper-constantan thermocouple junctions with a sensitivity of 320 μV.°C^{-1}. The copper-constantan