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# Novel wearable VCSEL-based sensors for multipoint measurements of blood perfusion

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## ABSTRACT

A novel non-invasive, wearable VCSEL-based system for multipoint $in - vivo$ measurements of blood perfusion was introduced. The system operates on the basis of the laser Doppler flowmetry (LDF) method and allows for microcirculation studies. The sensors developed were used to analyse the skin blood flow synchronization in homologous regions of the contralateral limbs, both in the basal state and during various functional tests. A high synchronisation of blood flow rhythms in the contralateral limbs of healthy volunteers was shown in the studies presented.

**Keywords:** Laser Doppler flowmetry, blood perfusion, wearable sensors, VCSEL lasers

## 1. INTRODUCTION

Microvasculature is a subtly organised important part of our cardiovascular system. The microcirculation system plays a crucial role in the life support for all types of tissues in every part of our body. Changes in skin microcirculation precede the clinical manifestations of different pathological processes.[1–3]

There are several methods to measure the blood microflow.[4] One of them is Laser Doppler monitoring, which is closely related to the Dynamic Light Scattering technique. It is a well known technology for non-invasive measurements in living tissue, which is based on laser sensing of tissue and further analysis of scattered light, reflected from moving red blood cells (RBCs). Such devices use a single mode fibre coupled near an infrared laser and one or two photodetectors with appropriate signal processing of both photocurrents to evaluate intensity of the blood perfusion.[5]

The theory behind the laser Doppler flowmetry method relies on the Fourier analysis of the photocurrent from the detectors giving an estimation of the Doppler spectrum, produced by the scattering of the single mode laser radiation in the moving red blood cells.[6] Using that information it is possible to evaluate an integral parameter which is at a first approximation proportional to the concentration of the scattering particles as well as to their averaged velocity.[7–9] To prove the assumption that the LDF records are really proportional to the RBCs velocity, joint application of the LDF and the high-speed videocapillaroscopy (VCS) methods were considered recentrly. The latter provides the direct measurement of the RBCs velocity into a capillary. An essential correlation between blood flow velocity oscillations in a separate human capillary and the integral perfusion estimate obtained by the LDF method has been found both in a basal state and during arterial occlusion.[10,11]

Records of the blood perfusion carry an important information about many vital processes in human body such as cardiac activity, Traube-Hering respiratory waves, as well as different types of vascular regulation.[12] Therefore,

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continuous monitoring of the blood perfusion parameters could be used, for example, for early prediction of the cardiovascular diseases,[3] diabetes[13] and insulin resistance.[2] Recent emergence of new extra-compact single mode power-efficient VCSEL lasers has opened completely new opportunities for such measurements.[14]

The purpose of this work was to investigate the possibilities of using the set of wearable VCSEL-based sensors for multipoint measurements of blood perfusion.

## 2. MATERIALS AND METHODS

Experimental studies were conducted using four FET-1 (Aston Medical Technology Ltd., Birmingham, UK) wearable wireless devices for the measurements. Each device featured the blood perfusion sensor implementing the laser Doppler flowmetry method, accelerometer and thermosensor to measure skin temperature.[15] Blood perfusion sensors can demonstrate the same quality of blood perfusion signal as a conventional LDF monitor does and are sensitive to both the blood volume fraction in the diagnostic volume and the blood flow velocity. All devices were combined in a single network to record the results of simultaneous measurements at several points on the human body.

All studies were carried out in accordance with the Declaration of Helsinki principles and approved by the Ethics Committee of the Orel State University. All volunteers participating in the studies have given their full written consent on measurements and were informed of their right to discontinue participation at any time.

The studies included several types of measurements with different sensor locations at basal state (at rest) and during occlusion or breath holding tests. Healthy volunteers involved in the studies were screened to avoid pernicious habits (such as an alcohol or drug dependence) and cardiovascular and other serious chronic diseases that can affect the blood circulation system. All measurements were performed in a sitting position in conditions of physical and mental rest about 2 hours after a meal.

## 3. RESULTS AND DISCUSSION

In the first part of the study, the measurements were carried out in a basal state. The volunteers' hands were placed on the table at the heart level. Sensors were attached symmetrically without applying any pressure on the study area: 2 on a palmar surface of the middle fingers distal phalanges and 2 on a dorsal side of the wrists. Blood perfusion signals were recorded continuously for 10 minutes.

An example of synchronous registration of blood perfusion in the fingers is shown in Fig. 1

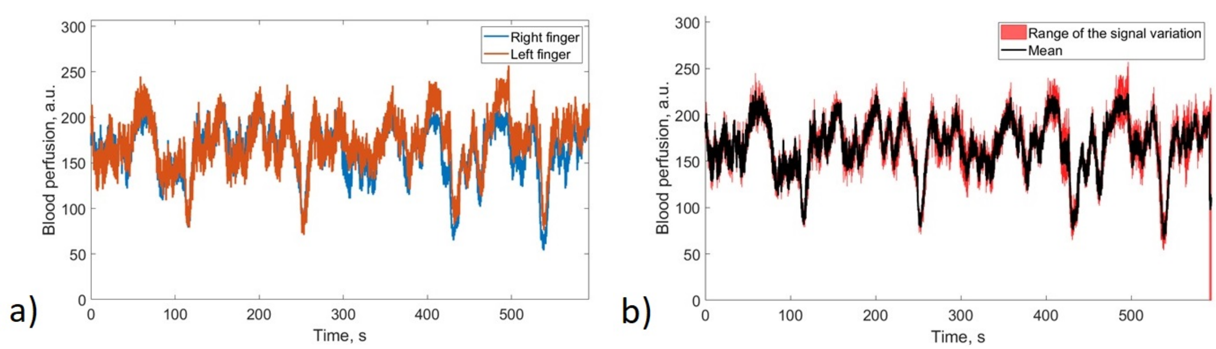


Figure 1. Example of synchronous registration of blood perfusion in the fingers: (a) - measurements of blood perfusion in the right (blue line) and left (red line) middle fingers; (b) - black line is the point-by-point averaging of two signals; red area is a variation area.

As can be seen from Fig. 1 a high level of blood perfusion rhythms synchronisation has been observed in the fingers. By the simultaneous measurements we have the potential to distinguish system and local impacts of the vascular regulation. A similar result is demonstrated in Fig. 2, which shows an example of synchronous registration of blood perfusion in the fingers and wrists.

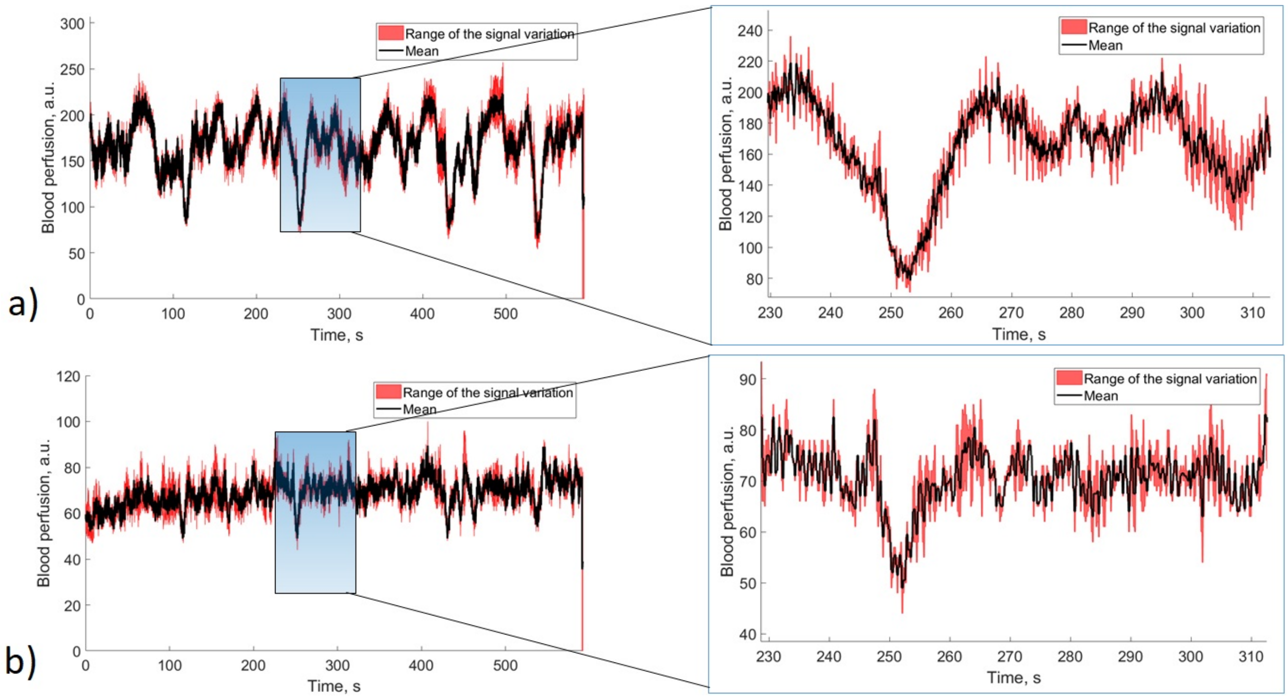


Figure 2. Example of synchronous registration of blood perfusion in the fingers (a) and in the wrists (b). Black line is the point-by-point averaging of two signals from contralateral limbs; red area is a variation area.

As shown in Fig. 2 the variation can be very low, especially in symmetrical homologous points.

The measurements in the second part of the study were carried out during the occlusion test. The location of the sensors was similar to the first part of the study. During the measurements, a 3-minute arterial occlusion was performed by creating excess pressure in the occlusive cuff. Before and after the occlusion the difference in blood perfusion was low as well as in previous part of the studies. During arterial occlusion the difference between records in contralateral limbs was high, but there was a short period of time after the start of the occlusion when the perfusion drops simultaneously in right and left arms. The third part of the study consisted of the measurements carried out in the same way during a breath holding test. The volunteers held their breath for 15 seconds several times during the experiment. The records of vasoconstrictions provoked by taking a deep breath demonstrated high synchronisation in both fingers and wrists. In the fourth part of the study, the sensors were attached on a dorsal side of the wrists and on front side of lower third of shins. The symmetrical points had quite the same signals.

## 4. CONCLUSIONS

The paper presents the results of blood perfusion measurements using wearable VCSEL-based sensor system. Blood perfusion signals were recorded of symmetrical areas of the human body both at rest and during functional tests. Studies have shown a high synchronisation of blood flow rhythms in the contralateral limbs of healthy volunteers.

Demonstrated wearable sensor system have many advantages that open new horizons for new type of experiments. Power efficient VCSEL-based devices allow performing of long-term blood perfusion monitoring. Portability and low sensitivity to motion artefacts make them more mobile and capable of use outside the clinic. Furthermore, sensors demonstrate high repeatability of measurements at rest and in physiological tests that increases the diagnostic value of measurements.

The presented pilot tests of the wearable VCSEL-based sensors demonstrated great opportunities to be applied in future clinical studies.

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