Wearable Diffuse Reflectance Sensor For Continuous Monitoring Of Cutaneous Blood Perfusion

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Abstract: A double-wavelength optical sensor for monitoring of cutaneous blood perfusion is presented. A simulation of partial differential pathlengths has been used for the optimization of source-detector distance. Hardware implementation and outpatient results are discussed.

OCIS codes: (170.1870) Dermatology; (170.1470) Blood or tissue constituent monitoring; (170.3660) Light propagation in tissues; (170.6510) Spectroscopy, tissue diagnostics; (170.3890) Medical optics instrumentation

1. Introduction

Non-invasive glucose monitoring (NIGM) is promising a great relief to many patients with diabetes for whom a tight glucose control is desirable in reducing the effects of long term complications associated with the disease. Previous approaches to NIGM have faced challenges due to complex perturbations that affect the measurement, such as natural physiological variations of the body conditions [1-3]. This has pointed towards the need not only to monitor glucose or the effects of glucose variations itself but also other parameters that can be impacted by changes in the biophysical characteristics of skin (such as temperature, blood perfusion or sweat and skin hydration). Correction of these parameters that can be considered as perturbing could improve the quality of NIGM. The multisensor platform under development at Solianis Monitoring AG is directed to address these challenges [4].

As indicated one of the important parameters to be monitored and hence of interest for a multi-sensor monitoring system is the variation in the blood concentration in skin or cutaneous blood perfusion (CBP). The skin is the largest and outermost organ of the body. It is actively employed for thermoregulation which is achieved by altering the amount of blood in the dermal layer of the skin. Perfusion changes can be also triggered by different extrinsic or intrinsic factors and can be short-term or prolonged.

In addition, CBP is itself an important physiological parameter which can serve as an indicator of body hemodynamic function. For example, in circulatory failure, blood flow is diverted from the less important organs such as the skin to the vital organs. Thus monitoring CBP can be an early marker of the hypoperfusion of vital tissues. Nevertheless currently, no measurement method for non-invasive and continuous CBP assessment has been implemented in a wearable device that has been shown not to be susceptible to the movements of patient [5].

2. System design

The double-wavelength spectroscopic system is designed for monitoring CBP in the upper skin layers. Since perfusion of blood is restricted to certain tissue compartments (such as the upper and lower net dermis), the geometry of the sensor was optimized based on an *a prioiri* knowledge of skin morphology. The geometry was optimized in order to ensure the monitoring of the probe light absorption in the volume of interest using a Monte-Carlo simulation of partial differential pathlengths (PDP).

The multi-layered Monte-Carlo simulation method was originally introduced by L. Wang [6] and the partial differential pathlength concept by M. Hiraoka [7]. A simulation algorithm based on both methods has been developed and used to optimize the source-detector distance (SDD) of the sensor. It has been found that the sensitivity to blood content in the skin model does not benefit from a larger SDD, after separation exceeds certain geometrical limit. At the same time the back-reflected intensity decays almost exponentially with SDD. Thus an optimal separation can be found which allows for high sensitivity to the blood content changes in the upper net dermis while preserving the sufficient intensity level of detected light.

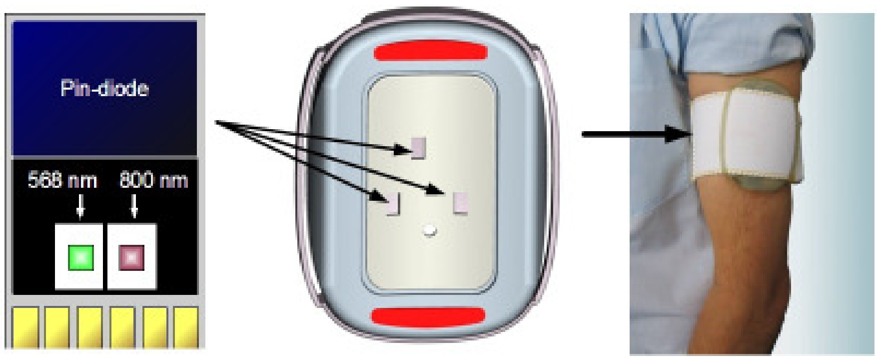

Figure 1 Hardware implementation of the optical module for non-invasive cutaneous perfusion monitoring in a wearable system

Based on the simulation results, the optical sensor has been designed and implemented as the part of multisensor platform developed by Solianis Monitoring along with dielectric, temperature, moisture and acceleration sensors (see Figure 1).

3. Experimental results

The sensitivity of the optical perfusion sensor has been tested in a laboratory setting by affecting the CBP with a venous occlusion protocol as well measurements in an experimental study on the subjects with Type I Diabetes Mellitus performing normal daily activities.

The perfusion index (PI) is calculated from the normalized back-reflected intensities measured at two isosbestic wavelengths:

$$PI = -10\log_{10}\left[I_N(568) / I_N(800) \right]$$

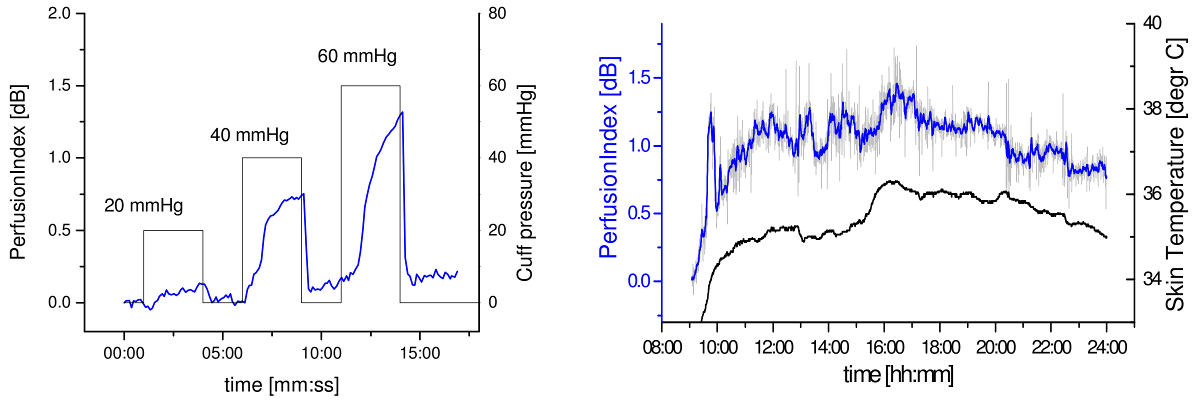

Figure 2 Left - Response of the sensor signal to venous occlusion of the upper arm for different levels of cuff pressure. Right - Typical daily pattern of PI changes. Blue line is the 10 minutes average of perfusion index. Black line is the skin temperature

In the laboratory tests, the high sensitivity of the CBP perfusion index has been demonstrated as it is shown in Figure 2(a). Higher cuff pressure results in more efficient blocking of the blood outflow and leads to the higher blood volume in the lower arm which is detected with the optical sensor. As we can see the perfusion index dependence on pressure is almost linear.

The outpatient experiments revealed significant general trends in the daily CBP pattern associated with circadian rhythms and sensor attachment causing pressure-induced vasodilation , which are of general importance for non-invasive physiological monitoring with wearable devices. Short-term changes are dominated by blood redistribution due to posture changes, which are also detected by the accelerometer of the multisensor system. **Figure 2**(b) shows a typical example of the PI changes during the day of the outpatient study together with the skin temperature measured simultaneously.

In conclusion, the optical sensor for non invasive monitoring of the skin hemodynamic has been designed with the help of Monte Carlo simulation and the testing results indicate a high sensitivity to CBP changes.

4. References

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