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Optical non-invasive methods for characterization of the human health status

Jens Kraitl and Hartmut Ewald
Institute of General Electrical Engineering,
University of Rostock, Rostock, Germany
jens.kraitl@uni-rostock.de

Abstract

The absorption of whole blood in the visible and near infrared range is dominated by the different haemoglobin derivates and the blood plasma. It is well known that pulsatile changes of blood volume in tissue can be observed by measuring the transmission or the reflection of light. This diagnostic method is called photo-plethysmography PPG. The pulsatile change of blood volume is caused by the heart-circulation system. The measured PPG time signals and the ratio between the peak to peak pulse amplitudes at different wavelengths and its dependence on the optical absorbability characteristics of human blood yields information on the human health status. A photometric device PMD will be described which is based on the realisation of a photoplethysmography measurement device developed for the German Space Agency DLR. The non-invasive in vivo multi-spectral method described here is based on the radiation of monochromatic light, emitted by laser diodes, through an area of skin on the finger. Deferrals between the proportions of haemoglobin and water in the intravasal volume should be detected photo-electrically by signal-analytic evaluation of the signals. The computed coefficients are used for the measurement and calculation of the relative haemoglobin and haematocrit concentration change. First results with this photometric method to measure changes in the haemoglobin concentration will be shown during measurements with healthy subjects. Additionally the Wigner-Wille distribution will be used for the analysis of PPG time series. This is a specific, sensitive method for the identification of heart-circulation and microcirculation patterns.

Keywords: photometric device, photoplethysmography, non-invasive

1 Introduction

The absorption of whole blood in the visible and near infrared range is dominated by the different haemoglobin derivates and the blood plasma that consists mainly of water [1,2]. It is well known that pulsatile changes of blood volume in tissue can be observed by measuring the transmission or the reflection of light. This diagnostic method is called photoplethysmography PPG [3]. The separation between arterial blood-absorption and background-absorption (mainly venous blood and tissue water) be obtained by evaluating the relationship between the pulse signal component (AC part – alternating current) and the DC-component (direct current) (figure 1). The DC-component is calculated by subtraction of the AC-component from the whole PPG-signal. The pulsatile change of blood volume is caused by the heart beat [4]. Besides measurement of oxidised (HbO_2) and reduced haemoglobin (Hb) for the calculation of oxygen saturation (SpO_2) in the arterial blood, the haematocrit value H (volume of red blood cells in whole blood) as well as the haemoglobin concentration are also important health status parameters.

The haematocrit absorption and scattering is influenced mainly by the total haemoglobin concentration. The absorption-coefficient μ_a (in mm^{-1}), the scattering-coefficient μ_s (in mm^{-1}) and the phase-function $p(s, s')$ are parameters necessary for the calculation of optical properties in turbid mediums like blood.

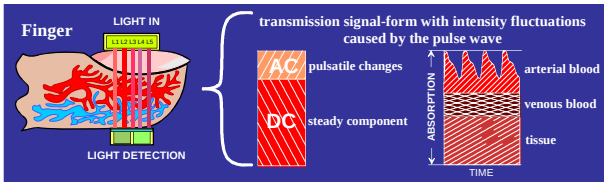

Figure 1: Principle- in vivo measurement on finger

The phase-function describes the probability of scattering for a photon travelling in direction s to be refracted in direction s'. Mathematical calculations can be simplified by using the anisotropy-factor $g = E(\cos(s, s'))$ instead of the phase-function and the reduced scattering-coefficient $\mu'_s = \mu_s(1- g)$ instead of the scattering-coefficient. To take the influence of light scattering into account, we assume that the measuring volume is composed of tissue (v_{tis} tissue volume, μ_a^{tis}, μ'^{tis}_s absorption and scattering coefficient tissue), arterial blood (v^{art} arterial blood

volume, μ_a^{art} , μ'^{art}_s absorption and scattering coefficient arterial blood), and venous blood (v^{ven} venous blood volume, μ_a^{ven} , μ'^{ven}_s absorption and scattering coefficient venous blood). The model assumes further that the measuring volume can be considered as a homogeneous distribution of scatterers and absorbers of the components mentioned [5]. Therefore, expressions for the coefficients are given in the following form:

$$\mu_a^{art} = H\, SaO_2 \mu_a^{HbO_2} + H(1 - SaO_2)\mu_a Hb + (1 - H)\mu_a^{H_2O}$$

$$\mu_a^{ven} = H(SaO_2 - deltaSO_2)\mu_a^{HbO_2} + H(1 - SaO_2 + deltaSaO_2)\mu_a^{Hb} + (1 - H)\mu_a^{H_2O} \quad (1)$$

$$\mu_a = v^{art}\mu_a^{art} + v^{ven}\mu_a^{ven} + v_{tis}\mu_a^{tis} \quad \text{and}$$

$$\mu'^{art}_s = \mu'^{ven}_s = \mu'^{blood}_s = H\mu'^{Hb}_s$$

$$\mu'_s = v^{bood}\mu'^{blood}_s + v^{tis}\mu'^{tis}_s \,. \quad (2)$$

2 Measurement Method

The optical parameters of blood and its components depend on many factors, e.g. the haematocrit value, the oxygen saturation, the flow-velocity, the osmolarity and haemolysis [2].

The objective of the photometric device (PMD) described here is the non-invasive continuous measurement of light absorbent blood components in the arterial blood of the human finger [6]. This non-invasive multi-spectral measurement method is based on radiation of monochromatic light, emitted by laser diodes in the range of 600 nm to 1400 nm, through an area of skin on the finger (figure 1).

The method takes advantage of the intensity fluctuations caused by the pulse wave. The ratio of the relative changes of the pulse sizes, when measured at different wavelengths after transmission through a finger is directly related to the absorbance characteristics of blood components (figure 2).

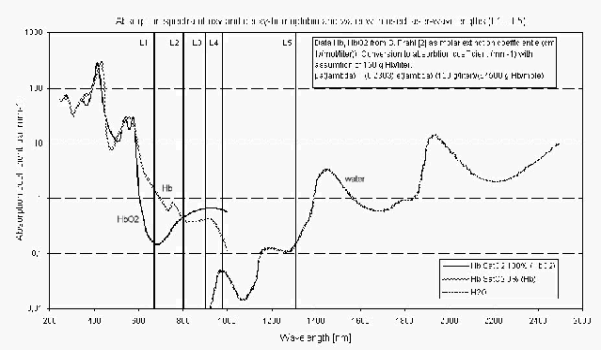

Figure 2: Absorption spectra for haemoglobin (Hb, HbO_2) and water [7]

After interaction with the tissue the transmitted light is detected non-invasively by photo-diodes. Figure 2 shows the absorption spectra for the main blood components and the wavelengths L1 to L5 of the five laser diodes of the PMD system. Suitable wavelengths were selected for the analyses of SpO_2 and relative haemoglobin/ haematocrit concentration change. Four of the five laser diodes emit light in the range of wavelengths between 600 – 1000 nm. This is the so-called therapeutic window region, in which the blood absorption is dominated by the haemoglobin derivatives [8]. At 980 nm besides the haemoglobin absorption a weak absorption band also exists for water. An additionally 1300 nm laser diode was integrated, at this wavelength the absorption of water is dominant (Figure 2). The measurement method evaluates the waveforms of peaks, troughs, DC averages, and pulsatile averages (AC-part). For a calculation of haemoglobin/ haematocrit, the wavelengths are chosen to suit the absorbance peaks of water in blood [9] where the two components of blood have differing amounts of water (980 nm, 1300 nm). To find a value corresponding to an isosbestic point for absorbance of oxyhaemoglobin and deoxyhaemoglobin, a wavelength of 800 nm is chosen. A second relationship for the measurement and correction of oxygen saturation is calculated with the 670 nm (absorbance of deoxyhaemoglobin greatly exceeds the absorbance of oxyhaemoglobin) and 905 nm (absorbance of oxyhaemoglobin greatly exceeds the absorbance of deoxyhaemoglobin) transmission signals.

3 PMD Photometric measurement device

A photometric device PMD was developed which is based on the realisation of a photoplethysmography measurement device developed for the German Space Agency DLR [10].

Inside the measurement device the laser diodes are integrated together with the required control electronics. The device electronics consists of the components required for signal amplification, digitalisation, and triggering of the laser diodes, which operate in a pulse mode. After software mean value calculations and subtraction of the dark-current inside the main unit, the transfer of the five photocurrents is achieved with a sample rate of about 100 Hz each. A main component of the measurement device is a high performance DSP-system with the floating-point processor TMS320C32, flash and memory. This enables DSP software-control and time-multiplexed operation of the 5 lasers and control of each of the 2 receive channels. The evaluation of the data and the operation of mathematical algorithms for pre-processing, e.g. digital filtering and averaging, are achieved by using the DSP-software. The data viewing and storing is achieved via the serial RS232 I/F connection on a Laptop or personal computer. The application software is LabView® programmed. The laser light is transmitted to a special optical

transmission head by means of optical fibres inside the sensor probe. Two Photo-detectors are also contained in the sensor head together with the required pre-amplifiers; the sensor signals detected here will be processed inside the measurement device. To detect the transmission signals of lasers 1 to 4 a Silicon Avalanche Photodiode is used with a spectral sensitivity of 400 nm to 1150 nm. For detection of the 1300 nm transmission signal an InGaAs- Photodiode is required with a spectral sensitivity of 1000 nm to 1700 nm. Figure 3 shows a photo of the PMD device PCB electronics.

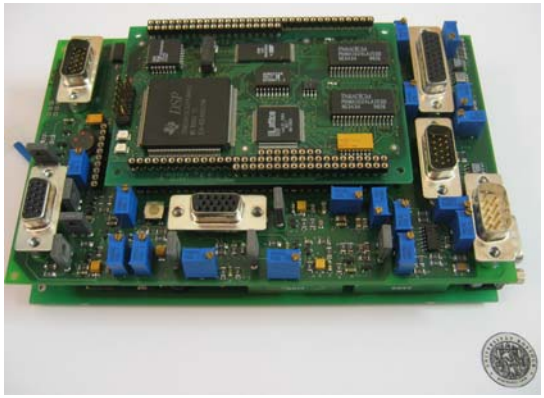

Figure 3: Photo PMD electronics

4 Applications and Results

Previous measurements of the transmission signals of the five wavelengths had shown an apparent variation of the arterial pulse. The signal quality was sufficient to analyse the signal components and to calculate relative attenuation coefficients of the arterial blood. With regard to the components at 1310 nm an evaluation of the relative portions of haemoglobin and water in the blood is feasible [11].

The measurement technique requires a pulse signal for the calculation of the relative attenuation coefficients. Vasoconstriction at the extremities can be a problem, as it decreases the signal amplitude, and therefore the signal to noise ratio. A small signal amplitude tends to give inaccurate results [12]. The PMD has therefore, a minimum signal amplitude below which no value for the calculated coefficient is displayed. The lower limit for the pulse amplitude with the 1310 nm laser is in the order of 0.2% of the measured intensity. This may be a limitation when using the system on various patient groups (vascular disease, Raynaud's phenomenon, shock etc.).

Figure 4 shows the PMD time signals after the passage of the laser light through the finger. The measurements were performed with a person lying calmly in a horizontal position at room temperature.

The transmission values of the pulse waves processed are constant with breath dependent periodical oscillations for all five laser wavelengths.

As external reference measurement, a POX10 Oximeter device (Medlab GmbH, Germany) was used.

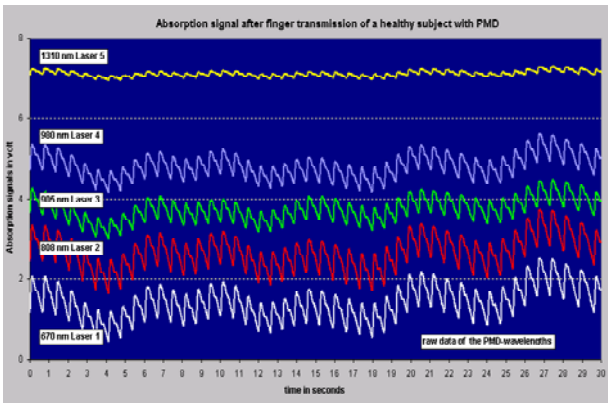

Figure 4: PPG signals of the five lasers from PMD

The PMD is suitable for non-invasive continuous on-line monitoring of one or more biologic constituent values. The objective of this development is to reduce the dependence on measurement techniques which require that a sample of blood be withdrawn from the patient for in vitro analysis. Any invasive method used on the patient to obtain blood is accompanied by problems of inconvenience, stress, and discomfort. The patient is also exposed to the normal risks of infection associated with such invasive methods. The non-invasive measurement method described in this paper might be applicable for clinical applications where an invasive method is undesirable or inconvenient. One particular application could be the monitoring of patients vital signs in Critical Care Medicine, Anesthesia. Another application might be in the monitoring of patients who are undergoing surgery, were presumably the loss of blood during surgery would produce a change of haemoglobin concentration. It may also be a useful tool during dialysis sessions for the monitoring of haemodialysis patients with end stage renal failure [11, 13]. By using a dialyser (haemofilter) the patient has dialysat (prevailing water) distracted. This deferral means a fluid reduction for the patient during the ultra filtration. The change in blood volume involves a change of the haematocrit status.

5 Measurements

The figure 5 shows a measurement during a hypoxia study for one subject. The arterial oxygen saturation was reduced to about 75%. Thereby the recorded data of the photometric device PMD was compared with the data of the blood-gas-analysis BGA from the A. radialis (arterial oxygenic saturation - SaO_2 in percent). The results for 4 subjects showed a high sensitivity and high reproducibility for all measurements with the photometric device [11].

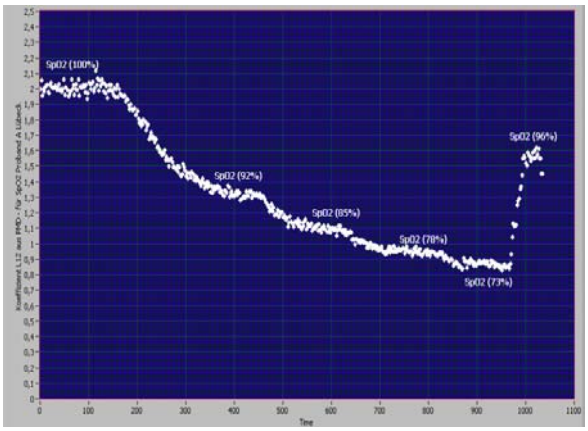

Figure 5: SpO2 measurement with PMD during a hypoxia study

The figure 6 shows the in-vivo measured and computed coefficients C_{Hb} from PMD device vs. the corresponding invasive haemoglobin values in mmol/l from a HemoCue^{TM} HB201^{+} hemoglobin analyzer for 19 healthy male and female subjects. The results for all 19 subjects showed a good correlation (R=0.92) with the invasive measurements.

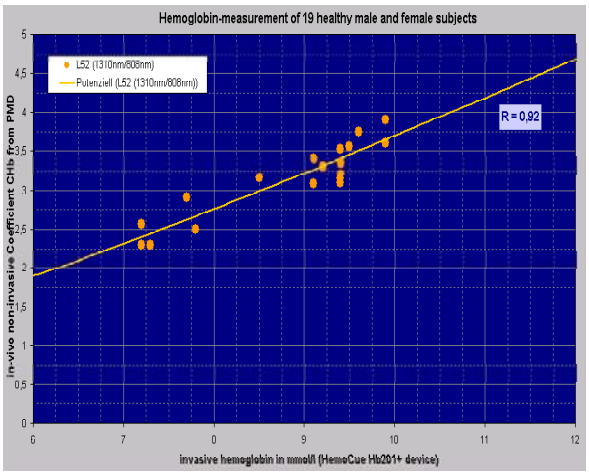

Figure 5: non-invasive Coefficient from PMD vs. invasive Haemoglobin measurements

A wigner-wille analysis of the non-stationary PPG time series allows an access to information about the human health status. The wigner-wille distribution is a specific, sensitive method for the identification of heart-circulation patterns. The PPG time series contains information of microcirculation patterns, pulse rate and variability, breathing rate and vasomotion, auto-regulation and thermoregulation frequencies. The figure 6 shows an analysed PPG signal in the frequency-time domain for a healthy subject. The figure shows a typical spectral power distribution between the pulse signal components caused by the heart beat and the heart circuit regulation patterns in the lower frequency range.

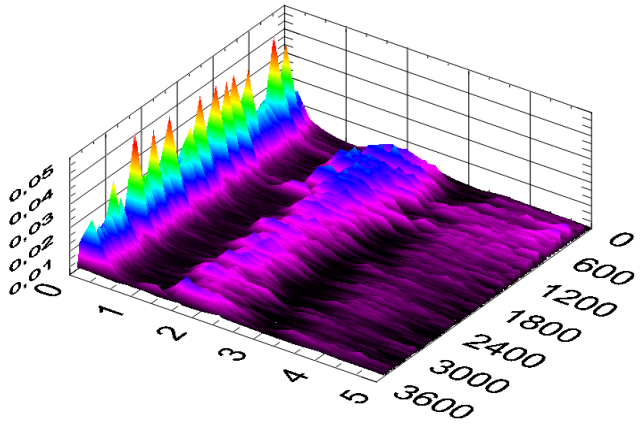

Figure 6: Frequency-time analysis of a PPG- time series for a healthy subject

The figure 7 shows an analysed PPG signal of a patient with a functional cutaneous microangiopathy which is associated with diabetic neuropathy.

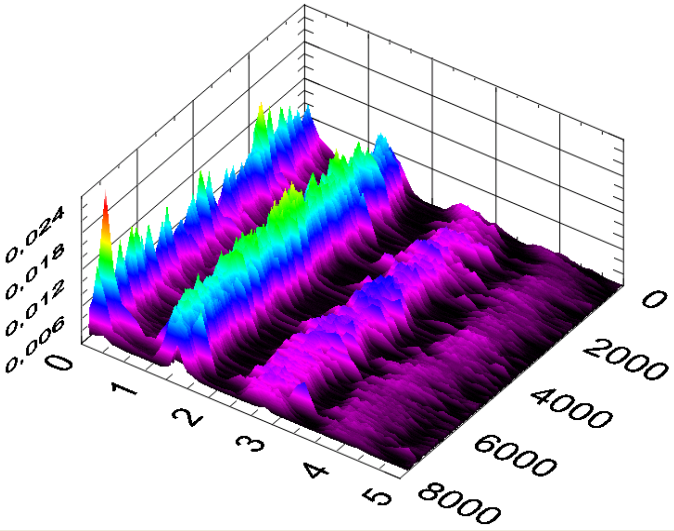

Figure 7: Frequency-time analysis of a PPG-time series for a microangiopathy patient

Figure 7 shows a very high spectral power signature in the frequency range of the heart beat. The variability of the pulse frequency is low.

6 Conclusions

In this paper a multi-wavelength photometric measurement method that provides non-invasive in vivo photo-plethysmographic and spectral measurements in human blood and tissue has been described. A newly developed PMD device has been introduced that is able to measure PPG-signals continuously at five different wavelengths from 600nm up to 1300nm. The fact that the absorption-coefficients μ_a and scattering-coefficients μ_s for blood differ at difference wavelengths has been exploited and is used for calculation of the optical absorbability characteristics of human blood yielding information on the blood composition.

In the first clinical measurements of the new measurement system, high sensitivity and spectral selectivity were demonstrated. A trial study to measure hypoxia showed that the sensitivity of the system for measurement of SpO2 levels was very good.

The possibility of non-invasive haemoglobin measurements with the system was shown. The analyses of the PPG time series gives the possibility for a monitoring of the human health status. Future work will involve further clinical studies, optimisation of the photometric measurement device, and evaluation of suitable statistical analysis algorithms.

7 References

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