Functional Venous Diagnostics: Spatial Acquisition of Hemodynamic Behavior during Muscle Pump Tests

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Abstract. Nowadays, to meet the needs of an aging society, customization of medical diagnostics becomes more and more important. Therefore, medical devices should be simple-to-use and low in price. Thus, we propose a method that enhances the evaluation capability of the Muscle Pump Test (MPT), a classical functional test for venous diagnostics. Instead of a classical functional test for quantification of venous vessel function that has the potential to meet the requirements of homecare.

The focus of this paper is a quantitative measurement method for the venous refilling, which is affected by venous diseases. Therefore, we propose an advanced method for the measurement of venous refilling properties. The Muscle Pump Test (MPT) is a classical examination, where quantified measurements are usually performed with Photoplethysmography (PPG). Our method is a camera-based measurement technique that represents a further development of the classic PPG to a spatial resolved dermal perfusion measurement of larger skin areas, called Photoplethysmography Imaging (PPGI).

2. Basics

2.1 Classical Photoplethysmography

A PPG probe consists of a light source and a photodetector. Typically, an LED is used to irradiate light of a distinct wavelength into the tissue. A photo diode measures the reflected light component. By this means, the changes of optical dampening caused by blood volume variations in the underlying tissue can be quantified. One of the advantages of using this technology is its low costs. Moreover, it is non-invasive, fast to apply and easy to use though practical experience is required to place the sensors in the right area in order to get a result of informative value [4]. On the downside, direct skin contact of sensors is required. This is problematic when sensors cannot be attached, e.g. when facing ulcers. A method to measure the venous hemodynamics in open wounds would be desirable.

2.2 Photoplethysmography Imaging

A contactless method for non-invasive quantifying of blood volume changes is available in the form of PPGI: Instead of single contact based light sensors, a CCD camera is used for remote measurements. Either ambient light or adapted light concepts with a distinct wavelength can be used for irradiating the tissue under test. The sensor array of the camera measures the reflected light. Besides being
contactless, the main advantage of this method is its spatial resolution. More informative value is achieved by the possibility to analyze multiple regions simultaneously. In case of application in MPT measurements, the whole inner side of the leg can be monitored and, hence, can be considered for diagnostics.

2.3 Muscle Pump Test

For the MPT the subject is seated with a 110°-angle between lower legs and thighs as shown in Fig. 1. The test is a movement procedure including eight dorsal extensions during a 16-second time interval. In this manner, the muscle flexions pump the blood upwards. In healthy veins, a backflow is prevented by venous valves, so the refilling is by the arterial blood flow only [5]. In case of defective venous valves, the vessels are refilled faster, see Fig. 2. Furthermore, an insufficient muscle pump or venous obstructions like a deep vein thrombosis decrease the venous return to the heart. These characteristics of blood flow can be examined by measuring the changes of venous blood pressure in the legs or a proportional parameter [6]. In case of the PPG technology, this is the change of light absorbance of the skin, which increases as the light absorbing blood fills the vessels close to the surface.

![Fig. 1. Posture during standardized movement maneuver of the Muscle Pump Test. Eight dorsal extensions are executed during a 16-second interval. Afterwards, the subject rests relaxed until the venous refilling is finished.](image)

![Fig. 2. In healthy veins, a blood flow in distal direction is prevented by the venous valves (left) whereas varices with insufficient venous valves allow blood flow in both directions (right).](image)

An exemplary PPG signal is shown in Fig. 3. One can see the rise of the curve during the muscle pump movements. It is followed by the refilling phase with a slow decrease down to about the base level, the measurement started with. The two main parameters extracted from this curve are the venous refilling time \( T_0 \) and the venous pump power \( V_0 \). Internationally, the refilling time is used for classification in three stages of the pump insufficiency, but also the venous pump power can be used [5].

![Fig. 3. Normalized PPG signal: during the movement maneuver blood is pumped upwards and more light is reflected by the tissue. As the veins are refilled, the signal decreases. The main parameters, the venous refilling time \( T_0 \) and the venous pump power \( V_0 \), can be extracted.](image)

3. Methodology

In this section, a setup for contactless, camera-based MPT measurements is presented. Furthermore, algorithms for extracting time-varying signals from the image sequences are described.

3.1 Experimental Setup

The subject sits comfortably on a chair to minimize unwanted leg movement as shown in Fig. 1. A scientific CCD camera (AVT Pike F-210B) is placed on a tripod and flipped 90°, so the long side of the sensor is aligned with the leg. The distance between leg and camera is adjusted such that the leg can be recorded from the knee downwards.

Room light from neon lamps is used for illumination. Daylight influences are minimized by shading the experimental setup.

We conduct the test with a Matlab graphical user interface on a computer connected to the camera. The program controls the camera, gives movement instructions to the subject, saves and processes the data and visualizes the results in graphs and functional images.

![Fig. 4. Measurement setup consisting of a scientific CCD camera mounted on a tripod in front of the subject’s leg. The setup is screened from daylight influences.](image)

The subject performs the MPT consisting of eight dorsal extensions during a 16-second-time-interval [5]. The camera records the test with a fixed framerate of 10 Hz. The test is visualized in Fig. 4.
3.2 Signal processing and analysis

Each time-varying sensor value of the CCD camera sensor array can be interpreted as a PPG signal.

However, the extracted PPG signal quality is strongly influenced by pixel noise. To minimize this noise, we used the concept of binning and spatial convolution, basically merging the information of adjacent sensor elements. Binning is an internal function of the camera, which conflates adjacent sensor values, so one pixel value equals the average of a 2x2-, 4x4- or 8x8-matrix of sensor values into a virtual sensor. Our chosen 2x2-binning increases the signal-to-noise ratio by factor 2. The use of binning has the positive side effect that the data record requires less memory space than without binning. The images were further smoothed by low pass filtering with a Gaussian 5x5-kernel (σ = 1.2) to further decrease the effects of noise.

A PPGI signal curve as shown in Fig. 5 is comparable to one measured with PPG. Same as for the PPG signal, the signal analysis determines the two quantitative parameters refilling time \( T_0 \) and pump power \( V_0 \) by the start and end point of the refilling phase as well as the static signal component, which is necessary to calculate a quantitative value for the pump power \( V_0 \). However, there is one difference between PPGI and PPG signal which has to be considered: The legs moving in front of the camera during the muscle pumps might come to rest in a changed position than at the beginning of the sequence. A skin area, originally captured by one virtual sensor, shifts away and is captured by another nearby virtual sensor of the camera. That is the reason why the signal amplitudes during the movement maneuver are much higher and the nearly static signal at the beginning and end of the measurement might differ. This is due to adjacent skin areas having different lighting intensities or surface orientation to the light source or the camera. Therefore, the static signal component has to be determined by the signal after the end of refilling instead of before the muscle pumping.

![Fig. 5. The example of a recorded PPG signal curve resembles the one of typical PPG signals. Movement artefacts influence the signal especially during the muscle pumps. The signal in normalized form is achieved by subtracting the direct component \( dc \) and dividing by it.](image)

The analysis starts with the determination of \( P_{\text{max}} \), which marks the beginning of venous refilling. The high signal changes during the muscle pump movements are used by detecting high peaks in the gradient of the signal, see Fig. 6. Thereby, the end of the movement maneuver can be found. A light smoothing of the noise in the next 5 seconds of the signal with a Butterworth low pass filter of the 8th order and cut-off frequency \( F_c = 2 \) Hz is performed in retrospect. On the smoothed curve section the maximum \( P_{\text{max}} \) can be determined.

![Fig. 6. The gradient of the PPGI signal from Fig. 5 has high peaks during the movement maneuver. A peak detection is used to determine the start of \( P_{\text{end}} \).](image)

For the identification of the end of refilling time \( P_{\text{end}} \), two approaches have been tested and evaluated. The first method uses low pass filtering to prepare the signal section from \( P_{\text{max}} \) to the end of measurement for an analysis of the declining curve’s gradient. The second one interprets the signal section by a curve fitting.

The low pass filtering is supposed to eliminate not only the signal noise but also oscillations caused by the pulse and especially respiratory movements. As smoothing filter, a Butterworth low pass filter of 8th order is used. \( P_{\text{end}} \) is defined by the point where the absolute modulus of the gradient has decreased to 1/10 of the maximum gradient value.

In Fig. 7 two signals are shown, one with a short and the other with a long refilling time. Filters with varying smoothing factors, set by the cut-off frequency \( F_c \), were applied to those signals. The resulting gradients are presented graphs below. The calculated \( P_{\text{end}} \) is marked for each case. The figure visualizes why different signal curves need different smoothing factors to achieve a reliable and exact value for \( P_{\text{end}} \).

Usually, the longer the refilling time, the flatter is the curve, such that the respiratory movement artefacts have a relatively greater impact on the gradient. This can lead to a false determination of \( P_{\text{end}} \) as displayed in Fig. 7. In this case, we get a false result for cut-off frequencies \( F_c \geq 0.34 \) Hz, which is a reasonable value as the respiratory frequency averages less than that with about 0.3 Hz. A smoothing filter with \( F_c = 0.1 \) Hz makes the determination of \( P_{\text{end}} \) robust. However, for signals of a shorter refilling time, such a strong smoothing is not necessary and results in a bad resemblance of original and smoothed signal. The bend in the curve at the end of refilling is smoothed, such that \( P_{\text{end}} \) is determined for a later point in time, see the left graphs in Fig. 7.
4. Results

After analyzing a video in the above manner, the results can be visualized in spatially resolved form as functional images. Therefore, the calculated value of $T_0$ or $V_0$ for each pixel is displayed in false-color. In Fig. 8 and Fig. 9 this is exemplarily done for every fifth pixel in both image directions.

In Fig. 8 the refilling times are mapped. The spatial variations are evident, e.g. the surrounding of the dilated Vena saphena magna along the shin shows shorter refilling times than other regions. A relation between the visible varices and the observed refilling times could be assumed. The displayed signal curves for three virtual sensors show varying refilling characteristics. The distribution of the venous pump power is uneven, as well.

Finally, the relative reflection increase $R(t)$ and the quantified venous pump power $V_0$ are determined as:

$$R(t) = \left( \frac{\text{signal}(t)}{dc} - 1 \right) \cdot 100 \text{ PPG}$$  \hspace{1cm} (1)

$$V_0 = R(t P_{\text{max}}).$$  \hspace{1cm} (2)

5. Discussion

Classical PPG allows the evaluation of functional parameters of the venous hemodynamics in the MPT. We developed an experimental setup for a contactless measurement by PPGI. The functional images can be used for analyzing the variations of venous refilling time and venous pump power; now, it is possible to locate regions with especially low refilling times by visual inspection of the functional image. The initial examination can be executed even easier and faster than with the classical PPG method because there is no positioning of sensors needed. Currently, the equipment costs are higher but the expense factor might be relativized if it can be shown that consumer-grade cameras are sufficient for the test.

The classification of venous pump insufficiency by the refilling times only is less recommended because the refilling time is influenced by physiological variations. Instead, bilateral measurements are advised for a mutual agreement of the PPG signals due to physiological differences between the legs [4]. These recommendations...
can be applied to PPGI, too. The capability not only to compare between the two legs but also between skin areas should be explored.

For future studies, both the determination of refilling time and consequently the classification of venous pump insufficiency need to be further investigated for the PPGI method in relation to the classical PPG.

6. Outlook

The promising results obtained from the setup described in the previous sections encouraged us to further improve the setup.

As was observed, the changes of daylight might affect the measurement. Therefore, a lighting setup, which is less influenced by these changes, is tested. We follow the approach as described in [8] and [9] using near-infrared illumination. The CCD camera is flanked by a near-infrared LED panel (wavelength 840 nm), see Fig. 10. To diffuse the light, tracing paper is used. In this manner, undesired light spots are minimized. A second near-infrared panel is placed on the floor to better illuminate not only the leg but the foot, too. Visible light up to 720 nm is blocked by an optical filter in front of the lens.

Fig. 10. Hybrid camera setup for the functional multispectral measurements: scientific CCD camera with optical filter (1), IRT camera (2) and near-infrared illumination (3).

The described PPGI method is used to evaluate blood volume changes. These changes are accompanied by heat transport, which can be made visible with another imaging modality. Therefore, an infrared thermography (IRT) camera (Infratec VarioCAM hr head 400) is supplemented to the CCD camera. Whereas the CCD camera depends on illumination, IRT measures thermal radiation passively. The modified setup is described in the following section: the IRT camera is coaligned with the CCD camera on a slide bar mounted on a tripod. This hybrid system is tilted by 90°, like in the setting described above.

The foot is positioned on a dark fabric, which is also used as the background: in the first place, it simplifies contrast-based image segmentation techniques in both spectral bands. With regard to the visible band, the contrast between leg and fabric is obvious (see Fig. 11). Similar results are achieved with near-infrared lighting, whereas in thermal images the contrast is given by the different temperatures of the recorded objects. Secondly, the fabric is used to reduce the cooling of the foot, which is due to thermal conduction amongst other causes. This way, we try to achieve a flat temperature gradient on the foot which is easier to segment.

Images recorded by the hybrid system are shown in Fig. 12. The left image shows the leg recorded by the CCD camera. Small vessels at the foot, as well as bigger vessels, e.g. near the knee, are visible. On the other hand, in the image recorded by the IRT camera bigger varices are visible, only.

In further studies, we plan to use the image information of the IRT-camera to complement the information extracted by the CCD camera.

Fig. 11. Complete setup showing the hybrid camera system, a subject’s leg and a black background used for a segmentation of the leg.

Fig. 12. Comparison shots by the hybrid camera system: In near-infrared (left) vs. thermal image (right).

Acknowledgements

All authors thank financial support by the German Ministry of Economic Affairs and Energy within the research program “Zentrale Innovation Mittelstand” (ZIM). We also would like to thank for the committed support of the supervisors, Univ.-Prof. Dr.-Ing. Dr. med S. Leonhardt and Prof. Dr.-Ing. Dr. h.c. V. Blazek, Philips Chair for Medical Information Technology, Helmholtz Institute for Biomedical Engineering, RWTH Aachen University, Germany.
References


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