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Contactless Measurement of Pulse Transit Time Between Upper Extremities During Simulated Stenosis

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Abstract: This paper proposes a novel approach for the non-invasive assessment of different degrees of stenosis by remote photoplethysmography (rPPG) using an RGB camera. A proof-of-concept study was performed on 20 healthy participants simulating different levels of perfusion in the upper extremities. The rPPG signals from both arms were extracted and the pulse transit time (PTT) was analyzed using cross correlation. The results show that the PTT time can be used for both the detection of stenosis and the differentiation of two degrees of stenosis. These findings have the potential to contribute to the development of a low-cost and non-invasive diagnostic approach for peripheral arterial disease (PAD).

Keywords: remote photoplethysmography, rPPG, stenosis, peripheral artery disease, camera, contactless, cross correlation, pulse transit time

1 Introduction

PAD is a perfusion disorder that affects more than 200 million people worldwide, particularly those over the age of 40 [1]. Current diagnostic methods include the ankle-brachial index (ABI), which has low sensitivity for early-stage PAD [9], and digital subtraction angiography, which is invasive.

A reliable and cost-effective method is needed to detect the disease early and prevent complications. One potential solution is the use of rPPG. It offers a non-invasive and cost-effective alternative for detecting and monitoring perfusion disorders. Using an RGB camera, changes in the absorption of light in the skin caused by blood flow can be detected, allowing the non-contact measurement of vital parameters such as heart rate and oxygen saturation [2]. rPPG has previously been used to create spatially resolved perfusion maps of the skin to assess perfusion [13, 14]. It has been shown that changes in rPPG amplitude [12] or changes in correlation with a reference rPPG [14] can be used to detect different perfusion states and stenoses.

Numerical simulations have shown that a local stenosis causes blood to flow more turbulently after passing through the stenosis, resulting in a decrease in blood pressure and lower blood flow [3]. Studies have demonstrated this relationship by measuring an altered pulse wave distal to the stenosis in an artery with a stenosis. Using a dual PPG setup on a cartoid artery, Horrocks et al. found that changes in PTT can indicate the presence of stenosis and provide insight into the degree of stenosis [10]. In addition, Du et al. demonstrated that the calculated PTT between both arms, measured using bilateral finger PPG sensors, changes in the presence of unilateral stenosis [11].

The purpose of this study is to build on these findings by investigating whether rPPG can be used to measure PTT between both arms and to detect and distinguish different degrees of applied stenosis in one arm. To achieve this, a study is conducted with 20 healthy participants in which rPPG signals of the upper extremities were extracted from RGB videos and PTT is determined by cross correlation of the signals. The aim is to determine whether stenoses can be identified and different degrees of stenosis can be distinguished, as an important step towards a low-cost diagnostic method for perfusion disorders.

2 Methods

2.1 Data Acquisition

A study of 20 healthy participants was conducted to investigate the effects of an applied stenosis on the pulse transit time (PTT) of the rPPG signal. During the study, videos of the upper extremities were recorded using an Allied Vision Manta G-201C RGB camera at a frame rate of 30 fps and a resolution of $1234 \times 1624\,px^2$. A cuff was placed around the right upper arm to induce three different degrees of stenosis based on the systolic blood pressure BP_{sys} of the subject (see Tab. 1), which was measured beforehand. The left arm served as a reference.

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Tab. 1: Performed measurements **A-D** during the study with the respective cuff pressures.

Measurement	Scenario	Cuff Pressure
A	Baseline	$0\,\text{mmHg}$
B	Full Stenosis	$\text{BP}_{\text{sys}} + 20\,\text{mmHg}$
C	Moderate Stenosis	$2/3 \cdot (\text{BP}_{\text{sys}} + 20\,\text{mmHg})$
D	Light Stenosis	$1/3 \cdot (\text{BP}_{\text{sys}} + 20\,\text{mmHg})$

The study consisted of four measurements **A-D** that lasted three minutes each. During measurement **A**, both arms were recorded under baseline conditions. Measurements **B**, **C** and **D** were divided into a two-minute *stenosis phase* during which pressure was applied to the right arm, followed by a one-minute *reperfusion phase* during which the cuff was deflated. Between each measurement, the subject rested for two minutes. For the following analysis, measurement **B** was discarded because the external pressure was above the subject's systolic blood pressure. Therefore, there was no rPPG signal from the right arm. This resulted in a total of 9 minutes of data for each subject.

2.2 Image and Signal Processing

To extract the rPPG signals and significantly reduce the size of the data, skin pixel detection is performed for each image. An algorithm is created that first applies a bilateral filter to the raw image, followed by Otsu's method [4] to create a binary image that distinguishes skin from background pixels. This filtering minimizes noise and helps to accurately classify slight shadows and dark lines on the skin. The result of this algorithm is a Boolean matrix $M[x, y, t]$ that functions as a skin mask. This matrix is multiplied with each raw image to remove all background pixels and retain only the skin pixels.

To extract the rPPG signal, only the green channel of the RGB videos is considered, since hemoglobin has the strongest absorption properties in this spectral range [5]. The color values of the green channel are filtered using a 5^{th}-order Butterworth bandpass filter with cutoff frequencies of $0.5\,\text{Hz}$ and $4.0\,\text{Hz}$. Lastly, the individual measurements of the subjects are segmented into equal-sized windows of 300 frames each, corresponding to ten seconds. This resulted in 12 windows for each subject, as only the *stenosis phase* is considered for the following analysis of PTT.

2.3 Pulse Transit Time Analysis

The resulting signal windows are used to investigate the effects of applied stenosis on the PTT between both arms. The PTT is determined by calculating the cross correlation $R_{\text{px}}[x, y, \tau]$ of the rPPG signal from each skin pixel $S_{\text{px}}[x, y, t]$ with the averaged rPPG signal from the left $S_{\text{left}}[t]$ arm as a function of the lag τ, according to Eq. 1:

$$max(R_{\text{px}}[x, y, \tau]) = \sum_{x=1}^{1234} \sum_{y=1}^{1624} \sum_{t=1}^{300} S_{\text{left}}[t]\, S_{\text{px}}[x, y, t-\tau] \quad (1)$$

This results in a lag τ, representing the PTT, for each skin pixel of each signal window, where there is a maximum correlation between $S_{\text{px}}[x, y, t]$ and $S_{\text{left}}[t]$. To visualize the results, the numerical values of τ are used with the coordinates of the skin pixels to create a heatmap. The entire range of values of τ is ordered, and each τ is assigned a color value.

As a second method of evaluating PTT, instead of using the individual rPPG signals from the skin pixels, the averaged rPPG signals from both arms are considered. The cross correlation $R_{\text{avg}}[\tau]$ is calculated between the averaged rPPG signal of the right arm $S_{\text{right}}[t]$ and the averaged rPPG signal of the left arm $S_{\text{left}}[t]$, as detailed in Eq 2.

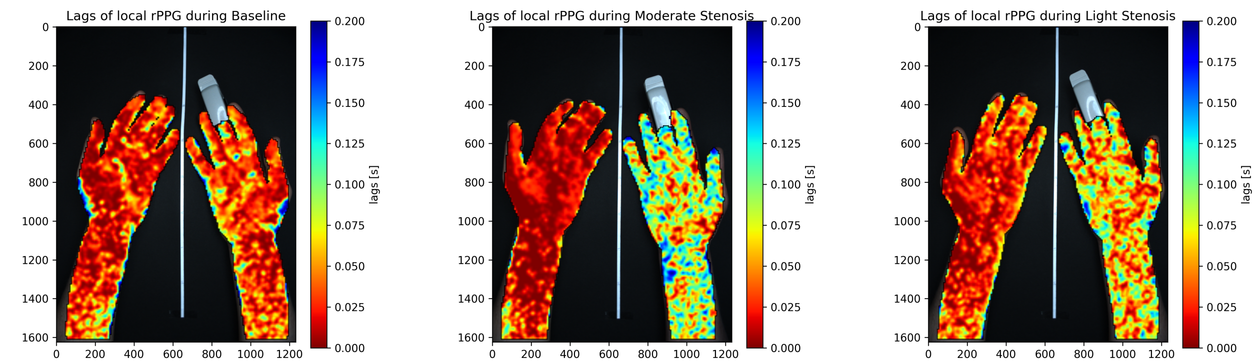
$$max(R_{\text{avg}}[\tau]) = \sum_{t=1}^{300} S_{\text{left}}[t]\, S_{\text{right}}[t-\tau] \quad (2)$$

This yields a single value of τ, representing the mean PTT, for each signal window that can then be compared during different degrees of stenosis.

3 Results

The heatmaps that were obtained from the local PTT analysis are shown for a representative subject in Fig. 1. During the baseline measurement (a), a high agreement of the color values of both arms is observed. In addition, there is no significant qualitative difference between the fingertip and the forearm. In moderate stenosis (b), there are significantly higher PTT values in the right arm, which are reflected in a significantly altered color distribution. The right arm during light stenosis (c) is visually different from the baseline and moderate stenosis. The heatmap of the left arm shows no noticeable changes between the different measurements.

The mean PTT values for the examined measurements are presented as boxplots in Fig. 2, illustrating the distribution of values for all participants. The black boxplot shows has a median PTT of $0\,\text{s}$ during the baseline measurement, as marked by the yellow line. In addition, the narrow interquartile range shows that there were only small deviations between the participants. The boxplots for moderate (orange) and light (green) stenosis show strong similarities in both distribution and interquartile range. However, the median PTT for moderate stenosis is



(a) Heatmap of reference arm (left) and stenosis arm (right) during baseline measurement.

(b) Heatmap of reference arm (left) and stenosis arm (right) during moderate stenosis.

(c) Heatmap of reference arm (left) and stenosis arm (right) during light stenosis.

Fig. 1: Heatmaps showing the local lags τ that were obtained from cross correlating the rPPG signal from each pixel $S_{\text{px}}[x, y, t]$ to the averaged rPPG $S_{\text{left}}[t]$. (a): baseline; (b): moderate stenosis; (c): light stenosis.

0.12 s, while for light stenosis it is 0.06 s seconds.
A significance test of the mean PTT values using a paired t-test showed high significance between baseline and moderate stenosis ($p < 0.001$) and between baseline and light stenosis ($p < 0.01$). The difference in mean PTT between moderate and light stenosis was also moderately significant ($p < 0.05$).

4 Discussion

The study found that reduced blood flow induced by a simulated stenosis from external pressure in the upper extremities results in altered PTT between both arms. These differences in PTT indicate that the stenosis causes delay in pulse arrival time in peripheral vessels distal to a stenosis.

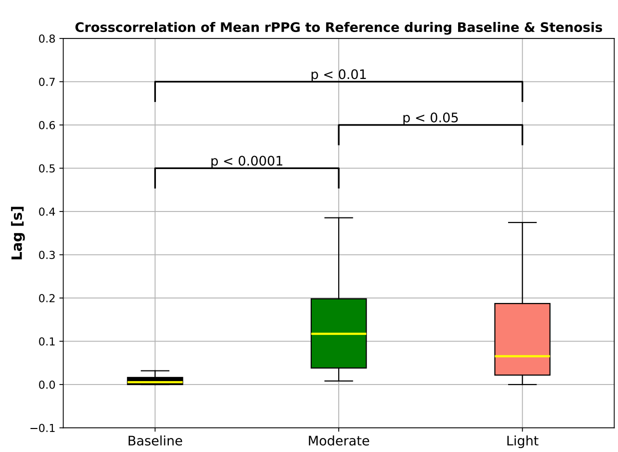


Fig. 2: Boxplots of the distribution of lags τ after cross correlation during baseline, moderate and light stenosis.

In an initial investigation, qualitative heatmaps are presented where the local PTT of each skin pixel is visualized with respect to the averaged rPPG signal of the left arm. This results in a different color representation of the right arm, indicating that changes in local PTT occurred, with all three measurements showing different patterns. The color changes observed in these heatmaps are consistent with the findings of previous studies analyzing spatially resolved perfusion maps under various perfusion conditions [13, 14]. Furthermore, the heatmap of the baseline measurement shows that both arms had a very high similarity in local PTT values, allowing the left arm to be used as a reference in the following analysis.
In the subsequent step, the averaged rPPG signals of both arms are used to calculate the mean PTT, allowing a generalized assessment during the different perfusion levels. The averaging of the signals is possible because the camera frame rate of 30 fps does not allow the measurement of a pulse wave delay within an arm. With an average pulse wave velocity in the radial artery, the main artery of the forearms, ranging from 4.5 to 9.0 m/s [6], an occuring PTT within an arm falls outside the temporal resolution of the camera used. This is also supported by the heatmap of the baseline measurement in Fig. 1a, where no change in PTT is observed at different locations on the arm.
Analysis of the averaged signals using a paired t-test shows that all three measurements result in significantly different PTT values. In particular, the baseline measurement can be distinguished from the two degrees of stenosis, indicating that simulated stenosis can be detected with high significance on the basis of the mean PTT using rPPG. The distinction between the two degrees of stenosis is also possible with a moderate level of significance, however not as clear as for the base-

line measurement. These results are in agreement with previous studies of changes in PTT associated with both simulated and actual stenoses [10, 11].

The reasons for the altered PTT can be attributed to a reduced pulse wave velocity in the artery distal to the stenosis. Studies have shown that in the case of a local stenosis, an increase in flow turbulence can lead to a slight decrease in velocity [7, 8]. Another reason may be the decrease in blood pressure distal to the stenosis, resulting in delayed pulse arrival time in peripheral vessels. The drop in pressure can affect both the volume and velocity of blood in small-diameter vessels because of changes in blood viscosity [8].

5 Conclusion

This study demonstrated that locally applied stenosis results in delayed PTT between the rPPG signals of both extremities distal to the stenosis and that this delay can be measured using an RGB camera. This was shown in a study of 20 healthy participants, where different degrees of stenosis were simulated using a pressure cuff on the upper arm. By cross correlating the averaged rPPG signals from both arms, the PTT between the two arms could be determined, demonstrating that this PTT can be used to detect a stenosis with high significance and differentiate between two degrees of stenosis with moderate significance.

This investigation showed that a simple camera-based setup, along with appropriate analysis of the rPPG signal, can effectively detect and identify different degrees of stenosis in the presence of a healthy rPPG reference. In the future, it may be possible to apply these findings to perfusion disorders such as PAD, providing a low-cost, non-invasive and accessible method for detecting these conditions.

- Author Statement

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