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Blood Pressure Estimation based on Pulse Transit Time and Compensation of Vertical Position

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Abstract

A chronically high blood pressure (BP) may lead to arteriosclerosis and consequently is a risk factor for apoplectic stroke and cardiac infarction – the main death causes in industrial countries. Hence, blood pressure recently has become one of the most relevant parameters for the assessment of a patients' health status. For the purpose of a continuous monitoring of cardiovascular patients, we have investigated a non-invasive and continuous (beat-by-beat) blood pressure estimation model, which is not based on the occlusion of arteries (like i.e. the auscultatory or the oscillometric method), but on the so called pulse transit time (PTT). In two studies, on the one hand we have evaluated the assumed linear relationship between pulse transit time and blood pressure and on the other hand we have examined the correlation between heart-rate and pulse transit time respectively the influence of the measuring arm position on the measured PTT.

Introduction

Blood pressure (BP) measurements have become one of the most relevant and cost effective methods for the assessment of a patients' health status. Since a chronically high BP may lead to arteriosclerosis and consequently is a risk factor for apoplectic stroke and cardiac infarction – the main death causes in industrial countries – a continuous monitoring of cardiovascular patients is highly recommended. Besides conventional techniques (like i.e. the auscultatory or the oscillometric method), another continuous and non-invasive, model-based approach to determine blood pressure values exists, which is not based on the occlusion of arteries but on the so called pulse wave transit time (PTT) [1]. A pulse wave in this context is defined as a pulse pressure wave, which is caused by the contraction of the heart and which is propagating through the vascular system from the heart to the periphery. Due to the vascular systems' properties (arterial diameter, vascular wall elasticity, blood viscosity and damping) there is a strong dependency between the transit time of the pulse wave (from the heart to a peripheral site) and its pressure, which is the arterial blood pressure (BP). The PTT is calculated as the temporal difference between the R-peak in an electrocardiogram (ECG) and the front slope of the following pulse wave measured by a finger photoplethysmograph (PPG) (see **figure 1**). In this way, one is able to form a beat-by-beat blood pressure estimation on the basis of pulse wave transit time.

To evaluate the approach and the correlation between PTT and BP (which is assumed linear by many publications [2, 3, 4]), and to investigate the influence of additional parameters (in this case *heart-rate* and the *vertical arm-position* wearing the finger PPG in relation to the heart), two separate studies [5] have been carried out.

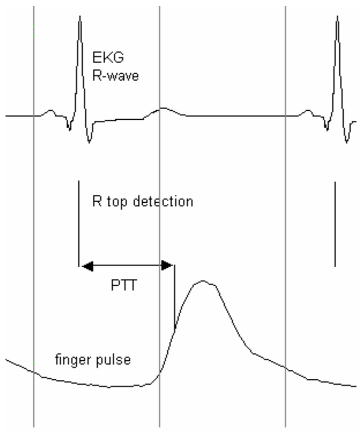

Fig. 1 The definition of pulse wave transit time

Evaluation of PTT/BP Model

The purpose of the first study, with 15 healthy volunteers (10 males and 5 females of ages 23 – 56), was to evaluate the assumed linear PTT/BP model.

Here, the test subjects' blood pressure (and so the pulse wave transit time) was steadily altered by an ergometric exercise of about one hour. During this time, the PTT as well as the corresponding reference BP were measured every 1 – 2 minutes. For the calculation of the beat-by-beat transit times an ECG with a sampling frequency (fs) of 1 kHz and a finger PPG with fs = 200 Hz synchronously were recorded. The corresponding reference blood pressure was measured with an auscultatory cuff. Furthermore, the ECG signal served as the source for heart rate (HR) calculation.

Examination of PPG-Position/PTT Relationship

The purpose of the second study, with six healthy male volunteers (of ages 26 – 31), was to investigate the relationship between the vertical position (relative to the heart) of the arm wearing the finger PPG and the pulse wave transit time. For gravity reasons, the mentioned position has a significant impact on the PTT.

Here, the test subjects have changed the finger PPG sensors' vertical position every two minutes by raising the according arm (which was the left) from "beneath heart-level" (arm down) to "heart-level" to "above heart-level" (arm up). For every arm-level the PTT was determined by averaging the corresponding recorded transit times. The calculation of the pulse transit times was realized as explained above.

Results of Measurements

In our first study, we have observed a strong correlation between PTT and systolic blood pressure with a mean correlation coefficient of $r = 0.83$ (range: 0.61 – 0.98). In comparison, the correlation between PTT and diastolic blood pressure with mean $r = 0.36$ (range: 0.01 – 0.53) was rather weak (see **figure 2**). The blood pressure estimation error standard deviation in our study was in the interval *5.8 – 8.3 mmHg* for systolic BP and in *5.9 – 6.7 mmHg* for diastolic BP. Besides, there was also a very strong correlation between heart-rate and pulse transit time with mean $r = 0.95$ (range: 0.92 – 0.96). In our second study, as expected we have observed very significant differences in pulse transit time at different finger PPG sensor positions (see **figure 3**). There was a mean PTT difference (i) of *25 ms* (STD: 17 ms) between "heart-level" and "beneath heart-level" and (ii) of *85 ms* (STD: 53 ms) between "heart-level" and "above heart-level".

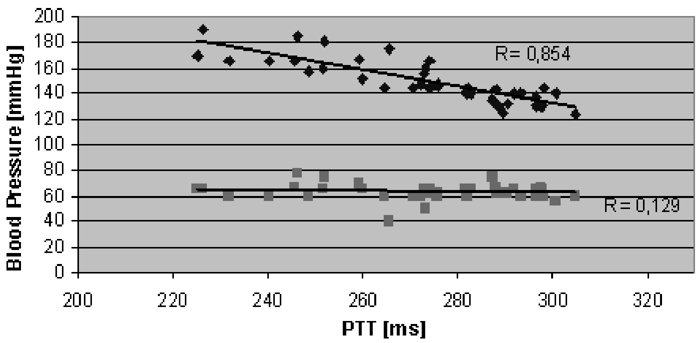

Fig. 2 Correlation between PTT and systolic BP (above) / diastolic BP (below)

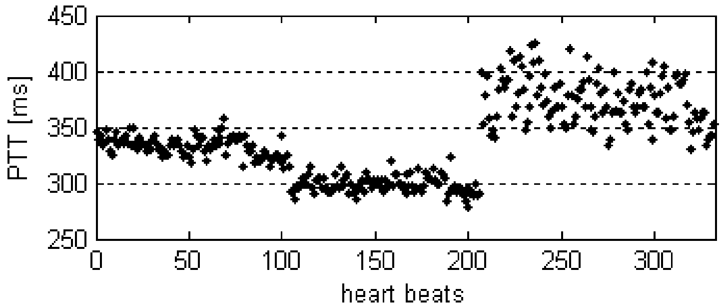

Fig. 3 PTT at different arm-levels: “heart-level (HL)” (left); “beneath HL” (middle); “above HL” (right)

Discussion

In our investigations the correlation between pulse transit time and (at least) systolic blood pressure could be confirmed. So, with respect to a certain error (5.8 – 8.3 mmHg) the linear model turned out to be an appropriate estimator for systolic BP.
To improve accuracy and reliability of the method, heart-rate has to be integrated in future model developments, since next to the PTT it was proved high correlation to the systolic blood pressure.
In order to avoid severe blood pressure estimation errors, it is recommended to detect or better compensate PTT changes caused by a vertical finger PPG sensor displacement, because gravity effects in this case falsify the quantitative relationship between PTT and BP.
Due to the small number of subjects these results are preliminary and have to be confirmed by studies with representative number of persons or even patients. To achieve the reliability and accuracy in blood pressure estimation sufficient for medical use additional studies have to be conducted. Especially the variance of blood pressure values over days and weeks for one person, the variance within day profiles, sex and age specialities and the influence of drug delivery should be subject to investigations.

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