CONTINUOUS BLOOD PRESSURE MONITORING USING PULSE WAVE DELAY

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Abstract-**Proposed paper is a part of a research to develop a convenient method for continuous monitoring of blood pressure by non-invasive and non-oscillometric way. The method is based on a presumption that there is a singular relationship between the velocity of pulse wave and blood pressure for a person. The detection of the velocity of pulse wave is based on the registration of the mechanical movements of blood vessel's walls and computing the time delay in different regions of the human body using an ECG as a reference signal. Additional information about the blood pressure evaluation is gotten from the photoplethysmographic (PPG) channel. Used optical method, which is able to detect pulsation profiles of the blood vessels, is based on the self-mixing that occurs in the diode laser cavity when the radiation, scattered back by the skin into the laser, interferes with the field inside it and causes the changes of the laser pump current. National Instruments software LabView for Windows is used for output signal digitalization and processing purposes.**
Keywords- **Diode laser, continuous monitoring, blood pressure, optical self-mixing, time delay.**

I. INTRODUCTION

Along with blood pressure, the arterial pulse has long been known as one of the most important medical signs. Conventional non-invasive techniques to detect cardiovascular pulsation and blood pressure, such as different oscillometric methods, stethoscopes, phonocardiograms, or manual palpation of superficial arteries, are non-convenient for continuous monitoring, especially in state of physical activity. An optical method for non-touch measurement of skin surface vibrations, which can reveal the pulsate propagation of blood pressure waves along the vasculature, is promising. Typically, expansion and shrinkage of the vessel wall results in movement at the skin surface, which contains useful parameters, such as period of pulsation, blood pressure and pulsation profile. Laser Doppler for cardiovascular applications was introduced in late 1970s [1]. Unlike the conventional optical Doppler techniques that have been used to measure blood perfusion in skin layers, such systems may be optimized to pick up skin vibrations. As an example, an optical interferometer with a 633nm HeNe laser was used to detect micrometer displacements of the skin surface, which means that motion velocity profiles of the skin surface near each superficial artery and auscultation points on a chest were measured [2]. Theoretical and experimental results of the same authors demonstrated that the velocity of skin movements was proportional to the time derivative of the blood pressure profile within the underlying vasculature.

Another useful and convenient parameter for continuous monitoring of calculating blood pressure is pulse wave velocity. In a scientific paper pulse wave transit time (PWTT) of the toe, finger and nose was measured and the difference between each site's PWTT was calculated. The slope of PWTT against systolic blood pressure was calculated and the result was that PWTT was found to be a useful parameter to estimate cardiovascular instability [3]. In another paper a narrow-band filtering method was explored to improve the correlation between systolic blood pressure and pulse arrival time. The results suggested that although it may be difficult to estimate systolic blood pressure from pulse arrival time with acceptable accuracy, possibilities still remain to utilize changes of pulse arrival time as an indicator of changes in systolic blood pressure [4].

Today many scientific teams in the world are working to find a way to use such parameters as pulse wave profile, velocity of pulse wave and PPG to calculate blood pressure for continuous monitoring. An adaptive fuzzy logic system was developed that continuously estimates cardiac output (CO) from the blood pressure waveform with mean error of 5.9%. The system will be developed in the future by modeling human data and including real-time digital signal processing software [5]. A measurement system has been designed for blood flow velocities in carotid, brachial and femoral arteries simultaneously with ECG. It was found from the results that the slower maximum blood flow velocity and the faster wave propagation time were observed for standing posture as compared with those for supine [6]. Pulse waves of subjects over a wide range of age were measured at the brachial artery, and their embedding dimensions and the numbers of active degrees of freedom of the dynamics were calculated using global and local false nearest neighbor (FNN) methods [7]. To develop a non-invasive measurement method of circulatory parameter by analyzing waveforms of digital PPG, mathematical modeling of input (ventricular ejection) / output (observed PPG waveforms) relations were performed [8]. A new method for cuff-less blood pressure monitoring was presented, where signals from plethysmographic sensors were integrated with a hemodynamic model to estimate beat-to-beat blood pressure waveform. On authors opinion more experiments are needed for further verifications [9].

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Abstract

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During many years our research team has studied optical coherent detection based on self-mixing inside a laser active medium to realize more simple and effective methods for coherent receiving. These methods enable to simplify optical scheme of such devices, as they require the consideration of only one optical axis, in addition to the use of fewer optical components. They are self-aligning as well as self-detecting. A fiber-coupled self-mixing system will be more attractive, because it is quite easy to reflect the light back into the cavity of the laser and this presents maximum advantages in compactness, simplicity, robustness and ease of alignment in comparison with conventional methods [10, 11, 12].

II. METHOD

A simple optical coherent method using a photodetection in a diode laser may be used for blood vessels profile registration. An experimental device with pigtail laser diode has been developed. This device is able to detect pulsation profiles of major arteries with potentially useful information, including pulse wave velocity and profile of pulse pressure. The basis of the registration is the self-mixing that occurs in the diode laser cavity when the radiation, scattered back by the skin into the laser, interferes with the field inside it and causes the changes of the laser pump current. These changes are registered in two different ways simultaneously: with using a photodiode accommodated in the rear facet of the diode laser package and with a help of small resistance resistor from the chain of laser pump current. The delay of a pulse wave in different regions of the human body is measured relatively to the ECG signal. Registered signals are stored after digitalization and pre-processed using LabView for Windows environment.

Experimental arrangement for pulse wave velocity and PPG signal registration is represented in Fig. 1. The probing ray was guided via an optical fiber of 1m length, which consists in a package of pigtail laser diode to the skin surface (Mp2 close to neck artery). A special clamp was attached to the end of the fiber to minimize interfering signal due to involuntary body tremor (position of fibre tip relative to the skin was fixed). As a reference signal for pulse wave velocity measurements we used ECG signal recorded by 4 leads system with standard ECG clinical device Mingograf-
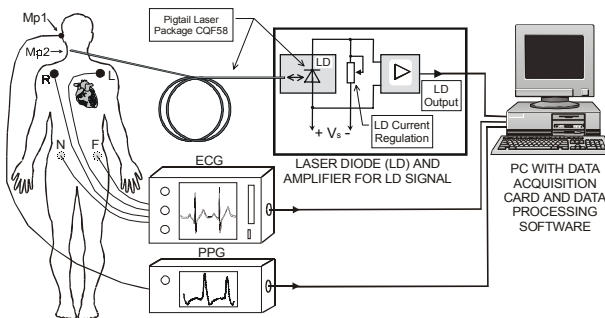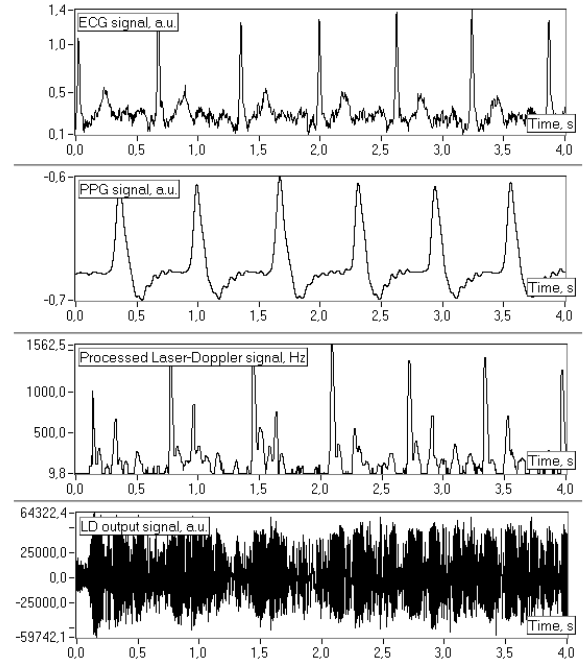

Fig. 2 Recorded ECG as a reference signal, Photoplethysmographic signal (PPG), processed Laser-Doppler signal and Laser Diode output signal before processing.

4, produced by Siemens-Elema. Additional channel for PPG signal consists of optical sensor, connected to ear (Mp1) and standard amplifier with high input impedance. Blood pressure was measured with standard device Omron IC using oscillometric method. Heart rate was calculated from recorded ECG signal.

The signals were recorded with a sampling rate of 10 kHz, which gives a bandwidth of 0-5000 Hz, duration of recording was 10 seconds. Recorded signals are given in Fig. 2. Here the first signal (upper curve) is ECG as a reference signal, then PPG and processed Laser-Doppler signals and signal from Laser Diode as input signal (without processing). Recorded signals were pre-processed (Fig. 3) using sliding window, the length of the Hanning windowed signal was 256 points and power spectrum was calculated after every 8 points (resolution 0.8 ms) using FFT algorithm. From every calculated power spectrum the frequency with maximum amplitude was detected, which gives us time dependent
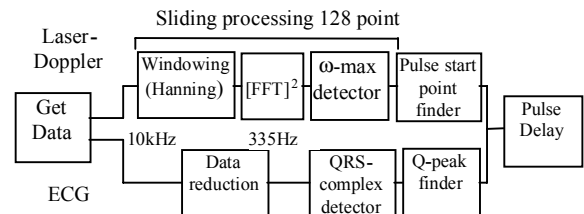

Fig. 1. Experimental arrangement

Fig. 3. Block diagram of digital signal processing algorithm for pulse wave and PPG signal delay measurements.

Doppler frequency. Every pulse beat was detected using adaptive level peak detector, after which the pulse vibration rising point was detected finding maximum of the first derivative of the signal. Laser-Doppler pulse signal never goes exactly to the zero because of noise and this makes it problematic to determine the exact starting point of the pulse vibration. In this work the starting point of the pulse wave was fixed to the point where tangent of the maximum absolute value of the derivative of pulse profile and zero frequency converge.

Frequency of discretization of ECG was reduced, because there is no relevant information above 200Hz. Thereafter QRS complexes were detected and from this the Q-points were calculated finding the first local minimum inside QRS-complex. Pulse delay was calculated as a time difference between Q-point of ECG and following pulse start point of laser Doppler or PPG signal.

III. RESULTS

Registered pulse wave signals time delay to ECG signal in different workloads and simultaneously in two channels represented in Table 1. To get a different blood pressure

TABLE1
Measured systolic and diastolic blood pressure (BP) in different work loads with corresponding heart rate (HR) and time delay of pulse wave in Laser Doppler (Mp2) and photoplethysmographic (Mp1) channels simultaneously.

Load, a.u.	BP systolic, mmHg	BP diastolic, mmHg	Delay, s Laser-Doppler (Mp2)	Delay, s PPG (Mp1)	HR, sycle/min
First measurement					
0	151	86	0,112	0,365	95
5	158	80	0,118	0,348	89
6	163	84	0,099	0,353	92
7	184	89	0,077	0,295	108
8	186	88	0,087	0,305	123
9	186	93	0,080	0,296	134
10	199	88	0,074	0,281	148
10	182	86	0,074	0,282	151
10	183	84	0,083	0,287	175
Second measurement 3 hours later					
0	167	91	0,117	0,350	78
5	158	92	0,120	0,345	82
6	176	90	0,102	0,327	84
7	179	96	0,096	0,329	90
8	186	92	0,095	0,323	94
9	181	93	0,096	0,319	93
10	216	95	0,068	0,296	124
10	217	100	0,066	0,298	133
10	181	93	0,072	0,298	175

rates a bicycle test with 9 different steps of workloads was used. This test was done in two different series with 3-hour time delay between the measurements. Time delay of pulse wave to ECG signal was measured in two channels simultaneously (Laser-Doppler and PPG).

In Fig. 4 a comparison of time delays between Laser-Doppler and PPG signals in different heart rates and in
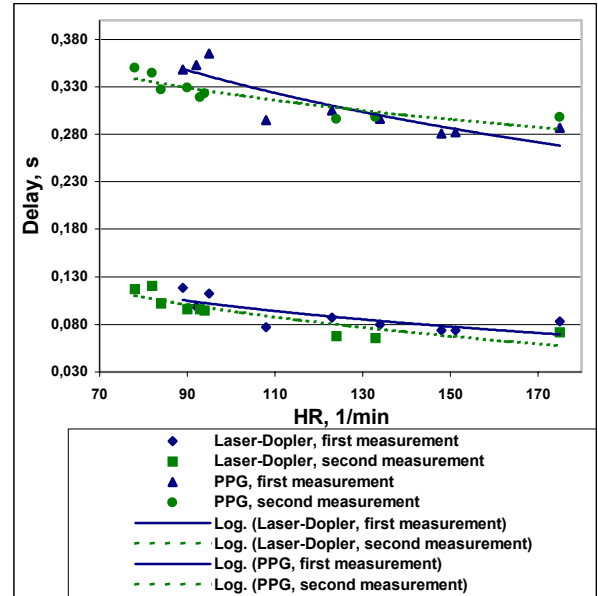

Fig. 4. Changes of pulse wave time delay to ECG signal in different heart rates measured in two channels (Laser-Doppler and PPG) simultaneously.
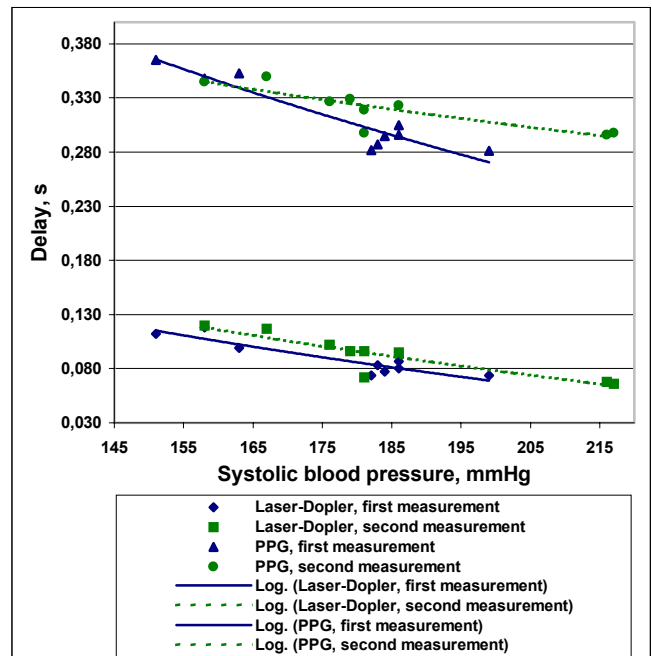

Fig. 5. Changes of pulse wave time delay to ECG signal in different systolic blood pressures measured in two channels (Laser-Doppler and PPG) simultaneously.

different measurement series is represented. There is a longer time delay for PPG signal because the distance for pulse wave is longer (measurement point in ear versus neck artery). In Fig. 5 is a comparison of time delays between Laser-Doppler and PPG signals in different systolic blood pressures and in different measurement series.

IV. CONCLUSIONS

It is shown that both Laser-Doppler and photoplethysmographic methods presented in this paper can be used for the non-invasive registration of pulse wave time delay in different regions of human body in comparison with ECG signal. Used methods are simple and compact. Photoplethysmographic method is more known but there are some advantages and disadvantages for both, for example a larger dispersion of time delay using PPG because of the specific shape of the signal or more complicated process to get the Laser-Doppler signal from different regions of the human body.

As we have a very large dispersion in our measurements, it is impossible to use this time delay directly for calculation of blood pressure. But such method gives us information about blood pressure changes for the same person in different conditions. For more precise results it is better to use both methods simultaneously and probably additional information about pulse profile would be useful.

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