Determining the State of Cardiovascular System Using Non-invasive Multichannel Photoplethysmography

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Abstract. The cardiovascular system is one of the most important system in human body and it is necessary to oversee its right function. Clinicians would benefit from the evaluation of the state of the cardiovascular system without using invasive entrance and to have information about state of all main parts of cardiovascular system. Pulse wave measurement could be one possibility of how to noninvasively evaluate the state of cardiovascular system and its individual parts. The paper introduces methodology of pulse wave measurement from several sites on the human body and the ECG signal simultaneously. Hardware and software materials developed for the solution are described and preliminary results are presented.

Keywords: ECG · Multichannel photoplethysmography · State of cardiovascular system · PWV · Labview

1 Introduction

Cardiovascular diseases are the most frequent causes of death in the world. This is very known and discussed problem, and yet many people underestimate risks connected to the formation of these diseases. Clinicians, together with engineers, try to find some reliable and noninvasive methods which help to evaluate the rate of cardiovascular problems. One of possible methods could be pulse wave measurement.

Parameters of pulse wave provide relevant information about heart rate and also about the good functioning of heart thanks to the information about start and end of systole and, what is very important, information about pulse wave velocity. Pulse wave velocity could be used for the evaluation of the stiffness of blood vessel or for the evaluation of blood pressure which is a complex indicator about state of cardiovascular system [1, 2].

Pulse wave results from the work of the left part of heart. From this part, the blood is ejected into the aorta, and the heart provides energy to make the blood circulate. A single pulse wave is generated during each cardio cycle, defined by the interval

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between two successive systoles. Each pulse wave consists from a forward wave and a backward wave, the latter arising arises thanks to reflection of forward wave from the division of artery, and its shape is affected by elasticity of blood vessel. Decrease of stiffness of artery makes the forward wave smaller and backward wave bigger and vice versa [3, 4] (Fig. 1).

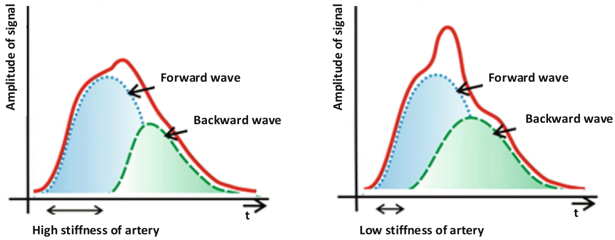

Fig. 1. Comparison of the shape of pulse wave based on stiffness of artery. High stiffness leads to faster waves and backward wave makes blood pressure higher. Low stiffness leads to a slower backward and positively affects blood flow.

Most of the time, Pulse wave is measured from periphery like fingertip or from places showing good blood perfusion like ear lobe, nose or forehead. This measurement is noninvasive and relatively comfortable for the patient. This is why the diagnostic methods based on processing of pulse wave could end up being a good candidate for the prevention of cardiovascular failure.

2 Problem Definition

Both pulse wave velocity and pulse transmit time depend on the properties of blood vessels and from heart mechanisms. Thus it is possible to evaluate non-invasively the state of cardiovascular system. From pulse wave it is also possible to evaluate the right functioning of heart because of its anacrotic and catacrotic parts. Anacrotic part is the increasing part of pulse wave which is produced by systole and catacrotic part is the slowly decreasing part which captures moving of artery wall during diastole.

Pulse waves which are measured on different places of human body has different properties. Differences of state of cardiovascular segments can then be identified (Fig. 2).

Pulse wave is affected by arterial stiffness which is also the reason why its shape is different on different places. The pulse wave velocity increases along with arterial stiffness for both forward and backward wave. In this case backward wave can affect the next forward wave already in anacrotic part which causes increasing of blood pressure [4–6].

It is possible to measure the pulse wave as a pressure wave, thanks to invasive pressure sensor, or as a volume wave, thanks to plethysmography. From plethysmography measurement, it is possible to obtain relevant information about shape and properties of pulse wave while this non-invasive method remains comfortable for the patient [7, 8]. Clinicians would from the use of a noninvasive system to help them with the evaluation

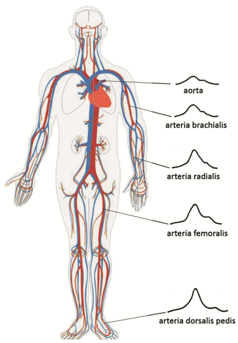

Fig. 2. Different shape of pulse wave based on location of measurement. For diagnosis not only the changes in shape of the wave are important, but also the time delay of pulse wave propagation from heart to the periphery.

of the state of cardiovascular system. The assessment of pulse waves from different parts of human body seems to be a relevant indicator. For the monitoring of cardiovascular system, it is necessary to use an accurate multichannel photoplethysmograph which can provide more complex information [9].

3 Implementation of New Solution

Our main objective was to develop a measurement device which would be able to non-invasively measure pulse wave from several parts of human body simultaneously and synchronously. Our solution consists from two parts; hardware part for analog preprocessing of measured signal and for AD conversion, and a software user interface for the display of measured signal and digital signal processing.

The hardware designed includes 6 channels for PPG measurement one channel for ECG measurement and an AD convertor. Software part includes digital filtering of measured signals and signal processing which is needed for evaluation of state of cardiovascular system.

3.1 Measurement Device

The whole hardware was developed as an independent device for the measurement of biological signals. For our purpose, it was mandatory to ensure a proper synchronous measurement between the channels in order to avoid time delay between the samples, and also a higher sampling rate than usual was required (Fig. 3).

PPG and ECG signals were preprocessed by an analog frontend for better conversion to digital form.

We used standard reflexive and transmission PPG sensors. All of these sensors were photoplethysmography sensors so they included one IR LED as transmitter and one photodiode as receiver, from which a small current is measured through a transimpedance amplifier to provide a voltage that can be converted by the ADC. Directly after

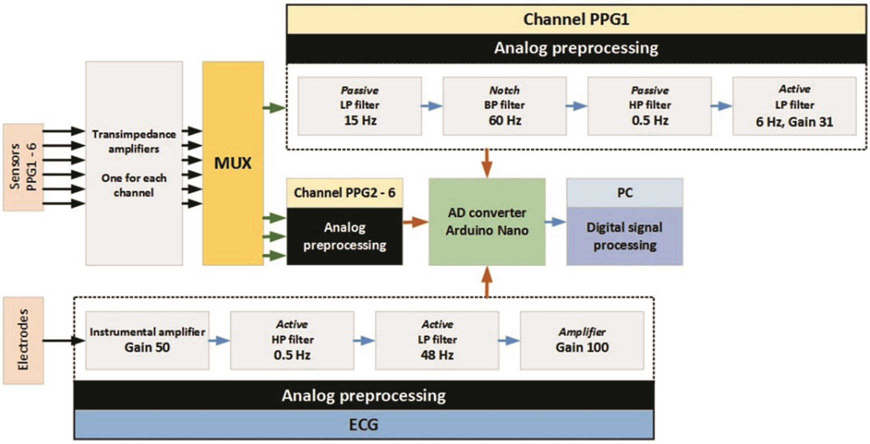

Fig. 3. Block scheme of the hardware part developed. The device includes six PPG channels and one ECG channel. Signal from each channel is processed analogically for better digital conversion. A software-controlled multiplexor enables to connect the output of the same amplifier to all channels to evaluate the delay between samples of different channels.

this amplifier the signals are sent through a multiplexor. This multiplexor enables to connect the output of one transimpedance amplifier to all measurement channels, while disconnecting other amplifiers. Having the same signal on every channel enables the evaluation of time delay between the different channel after analog processing and analog to digital conversion. A software compensation is then applied to cancel the delay during future measurements.

The analog preprocessing chain for PPG sensors consists of a series of filter for the removal of undesirable frequency components of the signal. Active and passive filters are used to preserve the 0.5 Hz–6 Hz frequency band which contains the relevant variations of the signal.

An Arduino Nano was used for digital conversion. This module includes a microcontroller which provides an 8-channel, 10-bit ADC. This microcontroller is also used to synchronously control the multiplexor using PWM.

The device is connected and powered by a host computer using USB (Fig. 4).

Fig. 4. Multichannel photoplethysmography device with three connectors for ECG electrodes. ECG in this device is used for time synchronization of all of pulse wave during one cardiac cycle.

3.2 Developed Software

The software developed consists of two parts. Acquiring and visualization of measured signals is made with LabView (National Instruments Corporation) for real time measurement. Digital signal processing of signals is made with Matlab (The Mathworks, Inc.) with the implementation of online processing tools (Fig. 5).

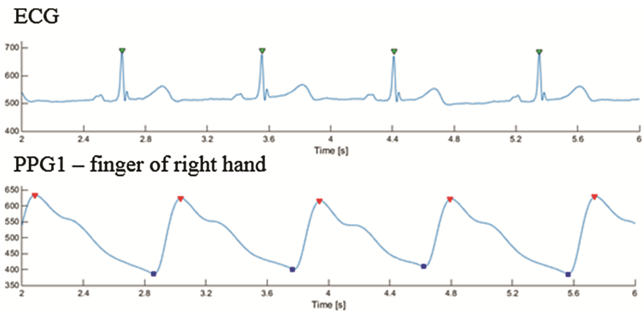

Fig. 5. Detection of significant points on signals measured. R-peak of ECG is detected as point of heart's systole, and subsequent valley and peak of pulse wave are detected on each channel. All of these point are used for statistical analysis and evaluation of relationship between parameters of pulse wave and state of cardiovascular system.

It is supposed that heart's systole can be determine as R wave from ECG. It means that for processing of ECG signal, an algorithm for detection of R waves based on adaptive threshold was implemented to determine which peak should be taken.

Digital processing of measured signals is focused on the computation of main parameters of PPG signals. Parameters evaluated are: the length of anacrotic and catacrotic part, and the length of each pulse wave and time delay between heart's systole and arriving of pulse wave at periphery. For the determination of these values it is necessary to determine peak and valley of each pulse wave. This detection is based on first derivation of the PPG signal [5].

4 Signal Analysis

Preliminary tests were conducted on a group of 6 individuals. The group was composed of men and women from three categories of age. The youngest category was composed of two healthy sportsmen without any chronic disease. The second category was composed of middle-age man and woman with adequate body. The woman has been treating hypertension for a long time. During the tests, measurements have shown that the man was also subject to hypertension. The oldest category of patients were two people with cardiac problems. The man has been subject to heart attacks and received twice bypass surgery. The woman did also have heart attack and she has a stent in coronary venous (Table 1).

Table 1. Group of measured patients.

Gender	Age	Smoker	BP	bpm
Male	24	No	121/80	74
Female	22	No	117/77	64
Male	52	Occasional	210/134	84
Female	51	Yes	134/81	80
Male	66	No	134/81	80
Female	67	Yes	103/63	61

All measurements were made at rest. Each subject was sitting on a chair and at the same time wasn't measured only pulse wave and ECG signal but also noninvasive blood pressure was measured by standard automatic tonometer.

Pulse waves were measured from index finger of right hand (PPG1); index finger of left hand (PPG2); second finger of right foot (PPG3); second finger of left foot (PPG4); right temporal bone (PPG5); left temporal bone (PPG6).

The length of anacrotic part of pulse wave was determined as the time duration between valley and peak of pulse wave; the length of catacrotic part was determined as the time duration between peak of one wave and valley from next wave. The duration of the whole pulse wave, and the time delay (PTT) between pulse wave and R wave from ECG were also measured. The Pulse wave velocity is calculated thanks to equation [6]:

$$PWV = \frac{D}{PTT} \tag{1}$$

Where D is the distance between heart and the place where the pulse wave was measured. This distance was measured by tape.

The expandability of blood vessels was also evaluated thanks to equation [6]:

$$Expandability = \left(\frac{3.57}{PWV}\right)^2 \tag{2}$$

After the evaluation all of parameters, a statistical analysis was made based on linear regression. Length of anacrotic part of pulse wave and age of patients were compared (Fig. 6).

It can be seen that anacrotic phase duration increases with age of. It can be interpreted as an effect of stiffness of blood vessel and also of heart mechanisms.

Another analysis was made on the relationship between expandability of blood vessel and age of patient (Fig. 7).

It can be seen that with increasing of age of patient, the expandability of blood vessel decreases.

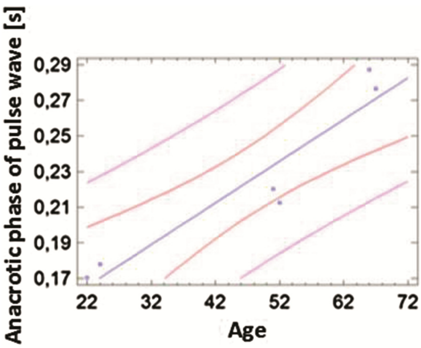

Fig. 6. Relationship between anacrotic phase of pulse wave, which corresponds to systole of heart, and age of patient. With increasing of age of patient; time of anacrotic phase of pulse wave decreases. Picture shows analysis which was made on signals from PPG1 (index finger of right hand).

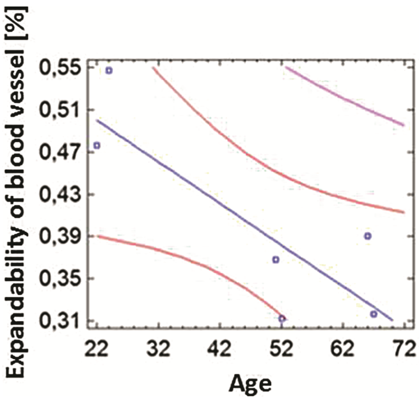

Fig. 7. Relationship between expandability of blood vessel and age of patient. With increasing of age; expandability of blood vessel decreases. Picture shows analysis which was made on signal from PPG1 (index finger of right hand).

Expandability of blood vessel and duration of the anacrotic part of pulse wave can be relevant of the actual state of cardiovascular system. These parameters affects blood pressure and heart's function. Table 2 shows comparison between all of these parameters all of patients. Interestingly, the third patient had hypertension during measurement. These preliminary results tends to confirm that stiffness of blood vessels has strong effect on blood pressure.

Table 2. Group of measured patients. Comparison between all of patient and main evaluating parameters.

PPG1				
Gender	Age	Expandability [%]	Anacrotic part [ms]	BP [mmHg]
Male	24	0.63	0.18	121/80
Female	22	0.61	0.17	117/77
Male	**52**	**0.38**	**0.21**	**210/134**
Female	51	0.52	0.22	134/81
Male	66	0.50	0.29	131/85
Female	67	0.48	0.28	103/63

5 Conclusion and Summary

It is very important to monitor state of cardiovascular system. There are many parameters which can bring significant information about its condition. A relevant indicator is the value of blood pressure. This value gives global information about state of cardiovascular system but many times it is more useful to know information about each part of cardiovascular system. A possibility to evaluate parameters of each parts is to measure pulse wave which gives information about state of blood vessel reflecting state of cardiovascular system.

Our main objective was to develop a system which could be used for evaluation of each part of cardiovascular system and gives complex information about state of cardiovascular system. This system should be accurate and comfortable for patient because of possibility of continuous long time monitoring.

Our measurements were made using a developed multichannel photoplethysmograph which was tested on group of six people. Six photoplethysmography signals from different places on human body were measured and analysis of these signals were conducted to study the impact of age on the duration of anacronic part of pulse wave and the expandability of blood vessels. Moreover the study has confirmed that this expendability has a direct impact on blood pressure.

Our device and methodology have thus shown promising results. This has been tested in laboratory conditions and now and the next step will be to integrate testing within clinical trials. Indeed for the validation of this method it is necessary to confirm the preliminary results obtained on a bigger group of patients and compare them to standard methods for evaluation stiffness of blood vessels or blood pressure.

Multichannel photoplethysmography is thus a promising method for long time monitoring of state of cardiovascular system which will bring better information about treatment of this system and it could prevent heart failure or; in the worst case, premature death.

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