An Experimental Measurement Complex for Probable Estimation of Arterial Stiffness

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Abstract—Current work is a part of long term research, which aim is to study the possibilities to diagnose the atherosclerosis in early stadium by using pulse wave velocity and its waveform analysis. The mobile experimental measurement complex is built and technically tested for the long term study in hospital. Measurement complex consists of ten physiological signal recording channels and reference devices: Sphygmocor, Arteriograph, Finapres. The measurements with this complex are planned to carry out during six month on patients with different severity of coronary disease and diabetes.

I. INTRODUCTION

Atherosclerosis is pathology, which causes the most of the early deaths in Europe. In case the atherosclerosis is diagnosed in early stadium, the pathogenesis can be stopped with right treatment. Before the fats are buildup on walls of artery, the first changes are taking place in the walls of blood vessels. The walls become stiffer and thicker. In this stadium the pathogenesis of atherosclerosis can be stopped.

Numerous methods and devices have been developed to assess the stiffness of the arteries, including pulse wave velocity (PWV) measurements and pulse waveform analysis. Arterial stiffness rise causes the PWV increase [1-2]. The stiffness of arteries can be estimated easily and non-invasively with recognized devices as Sphygmocor and Arteriograph. With both devices it is possible to estimate the PWV in aorta.

Our study aim is to analyze the physiological parameters, which can be used for the early diagnosis of atherosclerosis. In our previous research there have been studied the relationships between PWV and the depth of atherosclerosis on patients with the coronary heart disease. It showed that patients with coronary heart disease had increased PWV in aorta, leg and arm arteries compared with healthy subjects.

In following wider research the PWV is planned to measure from different arteries simultaneously and to investigate the changes in parameters of pulse waveform, which are caused by the arterial stiffness. In addition the other physiological signals and parameters are measured from subject, which describes the cardiovascular system, such as electrocardiographic (ECG) signal, blood pressure, etc. The experiments are planned to carry out on larger number of patients with coronary disease and diabetes.

For the synchronous measurement of the physiological signals, which are originated from different devices, the measurement complex is needed built. As the experiments are carried out in hospital, the system needs to be mobile, compact and easy to use. The types of sensors should be selected according to body location, where the pulse waveform is registered.

II. METHODS

During the experiment different physiological signals are recorded with measurement complex from subject (Figure 1). Pulse wave signals are registered from index finger, wrist, elbow, neck, earlobe, temple of the head, knee and the big toe. Enumerated pulse wave signal registration locations are on arteries and also in periphery. In addition to pulse wave signals the electrocardiographic, phonocardiographic and peripheral blood pressure signals are registered synchronously.

The pulse waves from index finger, earlobe, temple of the head and neck are registered by using photoplethysmographic (PPG) method. PPG is a non-invasive optical technique for measuring changes in a blood circulation and has been used mainly for monitoring blood perfusion in skin [3]. The pulsating AC component of the registered PPG signal corresponds to pulse wave.

There are two main PPG sensor design modes: the reflection and the transmission mode. In the reflection mode, a photodiode is placed adjacent to the LED and directed towards the skin. The photodiode measures the reflected and scattered light intensity from the skin surface. In the transmission mode, the photodiode and the light source are placed on opposite sides of the measured volume. The photodiode measures the transmitted light intensity. The transmission sensor measurement sites are limited, because of geometrics, whereas a reflection mode sensor can be placed at any point on the skin surface.

The PPG signal is registered from index finger and from earlobe by using commercially available transmission sensors. Due to the clip type of construction the sensors can
be easily fixed to measurement location. For temple of the head and neck the reflection mode sensors are used. In this research have been used Nellcor Max-Fast reflectance sensors and Nellcor finger and ear clip transmission mode sensors. The registration of PPG signal may be difficult during poor perfusion. Before the signal recording process the blood circulation can be stimulated in those locations.

PPG signals are easily obtained from previously described peripheries. PPG signal registration is difficult from wrist, elbow, knee, because the arteries are hidden under other type of tissues. Also the big toe may have poor perfusion and the signal is hard to obtain with high signal-to-noise ration (SNR). For those locations the piezoelectric method is used.

With piezoelectric sensor it is possible to register mechanical pulsation of arteries. It is relatively simple method for the detection of the pulse wave. By placing the piezoelectric sensor above the artery and applying the additional pressure on it, the pulse wave signal can be obtained. On the same time the applied pressure can affect the pulse wave velocity and its waveform. Still under the critical pressure level the influence is not noticeable [4]. In this research have been used ADInstruments MP100 transducers.

Besides the pulse wave signals the ECG and phonocardiography signals are registered synchronously during the whole experiment. ECG signal describes the electrical activity of the heart. In addition it is easy to determine the beginning of heart contraction period from the R-peak of the signal. As the ECG signal is more stable and less influenced by movements of subject, than registered pulse wave signals are, it can be used as reference for the offline signal processing. For example to remove the motion caused noises from the PPG signal, which is registered from neck [5].

Phonocardiographic signal characterizes the heart related processes, which are measurable through acoustic signals. In frequency spectrum from 70 up to 300Hz are situated the frequencies, which are describing the movement of aortic valve [6]. By using ECG and phonocardiographic signals it is possible to measure directly the pre-ejection period and ejection duration during the heart cycle. It is also possible to measure the PWVs starting from opening of the aortic valve.

To measure in online the blood pressure changes the Finapres is used as reference device. It is possible to get the estimation of blood pressure during the whole experiment. On the same time it has to be taken account that Finapress gives the information about blood pressure in periphery. It can be assumed, that similar changes in blood pressure are also taking place in arteries, while the subject is lying down.

In addition to Finapres the Arteriograph and Sphygmocor are used as reference devices to estimate the arterial stiffness. By using Sphygmocor the pressure wave is registered from radial artery with tonometer. Arteriograph closes with cuff the blood flow in brachial artery and the pressure waves on different pressures are registered. With both devices the registered pressure wave shape is analyzed and the two main parameters are estimated: augmentation index and PWV in aorta; which characterize the stiffness of arteries. The measurements with Sphygmocor and Arteriograph are carried out separately from general synchronous signal recording process.

On Figure 2 the block diagram of measurement complex is given. The raw PPG signals are registered with lab-built modules. The current of the PPG sensor LED and registered PPG signal gain can be set manually from the module. This way the PPG module is adjusted for the patient skin parameters and the signal is registered with high SNR. Similarly the raw piezoelectric signals are registered with lab-built amplifier, which has adjustable gain.

The output signals from modules are digitalized with
National Instruments PCI MIO-16-E1 data acquisition card with sampling frequency 1kHz. Similarly the Finapres analogue output was connected to data acquisition card to register the peripheral blood pressure wave.

The PPG, piezoelectric and Finapres signals are monitored in online and recorded through program, which is written in LabVIEW environment. On Figure 3 is given program outline for two signal tracks. For better monitoring all the signals are displayed on the screen during experiment. All the signals are recorded raw without using any additional filter or algorithm. Still for monitoring every signal can be filtered with low and high pass filters, which cut-off frequency can be set manually. In addition the power line interference can be eliminated with 50Hz notch filter. For the recorded data validation the maximal, minimal and amplitude of the signal are displayed online for every five seconds. Every track of the signal has quality indicator, which turns into red in case the signal is out of range, with too low or too high amplitude. As there are 11 signals to monitor the indicator helps operator to get fast overview the quality of the signals.

For the hospital environment the measurement complex is fixed on cart, which enables to carry it easily from one patient to another. On Figure 4 is given built measurement complex.

III. RESULTS

The measurement complex was firstly tested with sine wave to ensure that the two monitoring programs are working synchronously. Inputs of PowerLab 4/20T and piezoelectric signal modules were connected to the sine wave generator output. The generated signal frequency was 5Hz. The recording process was started in LabVIEW program,

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Fig. 3. LabVIEW program outline for signal monitoring and recording. For easier monitoring every signal track has adjustable filters, signal quality parameters and signal quality indicator.

Fig. 4. Built experimental measurement complex.

Fig. 5. Experimental results for synchronous test. A) Sine wave, which is recorded with Chart Software. B) Sine wave, which is recorded with LabVIEW program.
which also started the recording process in Chart Software through trigger signal. As follows the signal generator was switched on. After recording the signals were monitored offline in MATLAB. On Figure 5 is given the results of this test. The dotted line is put through sine wave maximal point, which is recorded with Chart Software. The dotted line also goes through sine wave maximal point, which is recorded with LabVIEW program. It is visible, that recorded signals are aligned and the systems are synchronous with each other.

The first experiments were carried out on four volunteers to test the measurement complex. The subject was lying down and the signals were registered for about 60 seconds. In addition the reference measurements were carried out with Arteriograph to obtain the PWV in aorta.

The signals were post-processed in MATLAB and the average PWVs were calculated. On Figure 6 are given results. For every volunteer are given three PWVs. The $PWV_{\text{ref}}$ is measured by using Arteriograph. $PWV_1$ and $PWV_2$ are calculated from the recorded signals, which are obtained with measurement complex.

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The signals were post-processed in MATLAB and the average PWVs were calculated. On Figure 6 are given results. For every volunteer are given three PWVs. The $PWV_{\text{ref}}$ is measured by using Arteriograph. The $PWV_1$ was calculated as the ratio of the distance travelled by the pulse wave from elbow to index finger and the time delay between the two pulse waves. The $PWV_2$ is calculated similarly to $PWV_1$ by using distance between knee and big toe and the time delay between pulse waves. On Figure 6 is visible that PVWs, which are calculated for the hand and leg arteries ($PWV_1$ and $PWV_2$), are comparable with reference device measured PWV ($PWV_{\text{ref}}$). In case the $PWV_{\text{ref}}$ is higher, also the $PWV_1$ and $PWV_2$ are increased. It corresponds to the results, which were presented also in our previous research [2].

IV. CONCLUSIONS

The experimental measurement complex for physiological signals registration was built and tested to study the possibilities to diagnose the atherosclerosis in early stadium. The experimental complex enables to register the signals from different locations of body including pulse waves from periphery and arteries. In addition the physiological signals, which are originating from different devices, are recorded synchronously. The measurement complex was technically tested on volunteers. The results were similar with our previous study outcome, which ensures that our experimental complex can be used for experiments with larger group of patients. The complex is planned to use in hospital, where the patients with coronary heart disease and diabetes are examined.

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