PULSE WAVE ANALYSIS BASED ON INTELLIGENT, MULTICHANNEL SENSORS FOR PERIPHERAL BIOSIGNALS

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Abstract. The development of sensors recording peripheral biosignals and algorithms evaluating these signals plays an important role in future prevention of cardiovascular diseases. The combination of the electrocardiogram and simultaneously registered pulse waves at different peripheral sites offers the possibility to determine the pulse wave velocity, which can be used as a cardiovascular risk indicator. Therefor an ECG Modul and a Pulse Wave Modul have been developed. The modules work autonomously and provide on the one hand information about the start of the cardiac cycle, the ejection of the blood and thus the emission of the pulse wave and on the other hand information about the point in time of the arrival of the observed pulse wave at the peripheral sites. These information are extracted by reliable and robust algorithms running on a digital signal processor, which is used as the computational unit and to control the whole process of the determination of the pulse wave velocity. In the future the recorded signals shall be used as an input for mathematical models for the derivation of the aortic pulse wave and hence the aortic pulse wave velocity to improve cardiovascular risk assessment.

1 Background

The risk to suffer from various cardiovascular diseases increases dramatically. These diseases are jointly responsible for around 50% of deaths in the developed countries [22, 15]. Current statistics show that mortality motivated by cardiovascular complications like cardiac infarction, stroke or renal dysfunction is much higher than mortality caused by cancer [17].

At the moment about 1 billion people are suffering from hypertension worldwide and the number will increase to approximately 1.6 billion in the next 20 years with its main focus on the OECD[1] and emerging countries like China or India [1]. Demographical changes and prosperity influence the appearance of this disease. As you can see in the figure 1, the probability to be faced with hypertension over the years is very high.

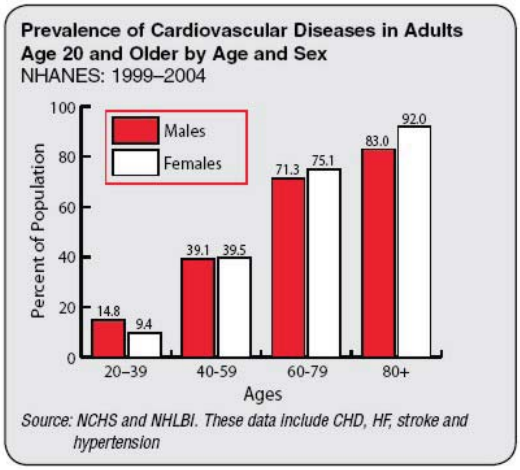

Figure 1: Prevalance of Hypertension [17]

In combination with other risk factors (e.g. physical inactivity, greasy food, alcohol, tobacco, etc.) this leads to vascular diseases, myocardial infarction, stroke, renal failure or dementia with a finally death end [17, 1].

In order to characterize the cardiovascular risk several parameters are used. High blood pressure and Hypercholesterolemia are the most popular ones. But epidemiological data present that only 40% of the diseases can be described with these two risk factors [13]. Thus, there is a need for additional relevant and independent risk indicators.

[1]Organisation for Economic Co-operation and Development

In the current treatment guidelines of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH) the view is held that hypertension (high blood pressure) is not an isolated disease but rather a combination of cardiovascular syndromes [4]. A mix of several risk factors enhances the cardiovascular risk.

The parameters pulse wave velocity (PWV) and central aortic blood pressure are independent and significant marker to detect an acute problem [2]. Therefore, the guidelines indicate the need for observation of the cardiovascular system by means of pulse wave analysis and the synthesis of values, such as blood glucose or lactate in the diagnosis in outpatient or stationary field. In combination with these additional parameters multiple pathologies can be early identified. Within the guidelines a lack of certain technologies is also complained [4].

2 Motivation

The aim of this work is the development of a sensor whereby peripheral biosignals can be acquired non-invasively as a tool for the calculation of the central aortic pulse wave velocity. Current commercial solutions concentrate on the measurement of the peripheral pulse wave velocity. It is basically measurable with available sensor systems, but two major problems for determining the cardiovascular risk arise:

1. The peripheral measured pulse wave velocity is not a significant cardiovascular risk indicator.
2. Unsatisfactory signal quality by limited scope of available sensors.

As a solution for the first problem new research has been done on the basis of peripheral waves. It could be shown that a joint assessment of several peripheral measured pulse wave transit times can be a conclusive statement on the possible cardiovascular risk [19]. This method is named *brachial-ankle pulse wave velocity*. Its drawback is the influence of measured values, which are mainly dominated by the peripheral vascular system. As a compensation an assessment of the Windkessel function of the Aorta based on non-invasive peripheral pulse waves is desirable. Therefor a precisely recorded peripheral pulse wave is important.

The second problem, the unsatisfactory signal quality, is a result of the restrictions of the existing technologies for pulse wave recording such as air pressure cuffs, applanation tonometers based on piezos or extinction methods. These restrictions are

- the site of application (especially the lower extremities),
- influence by the examiner and
- technological and economical usability.

Invasive measurements, which are partially state of the art, cannot be used in the outpatient area. In the intensive care field the use of invasive products is also critically observed. It should be noted that there are currently no satisfactory commercial sensor solutions available for the non-invasive, synchronous and objective measurement of multiple pulse waves at various human limbs. On the basis of such measurements a new calculation system could be built up, which allows a direct statement on the situation of the Aorta.

Thus the aim has to be the development of intelligent, multichannel sensors for the recording of synchronous, peripheral biosignals and the evaluation of these.

3 The measurement system

Basically, mean pulse wave velocity is defined as distance over time. As shown in figure 2 the starting point of the measurement is the left ventricle, as the cardiac activity is the origin of the pulse wave signal. The ejected pulse wave travels through the vascular system and the onset point of the peripheral pulse wave, which is acquired at the A. carotis, A. femoralis or A. radialis, subsequently defines the travelled transit time.

Consequently the R-peak of the derived ECG, which characterises the moment of the blood ejection from the heart into the Aorta, can be used as reference point for time measurements. Based on the peripheral signals (A. radialis, A. femoralis, A.carotis) a Texas Instruments Digital Signal Processor computes the pulse transit times and pulse wave velocities.

The development of intelligent, active sensors for synchronous, non-invasive measurement of haemodynamic parameters in the blood circulation based on two or more peripheral signals and their joint evaluation in diagnosis and therapy, is a unique possibility in ambulatory treatment to estimate the arterial status and individual cardiovascular

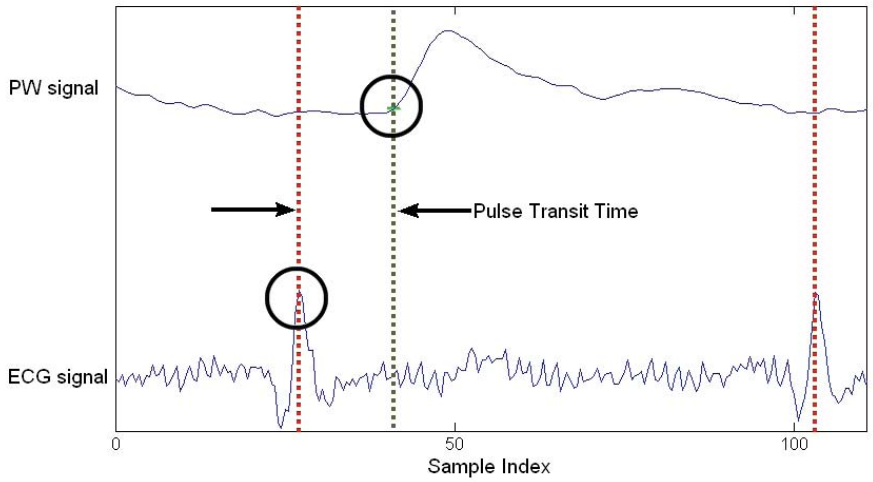

Figure 2: Determination of the pulse transit time

risk. The described method is so simple that the functional status of the arteries can be estimated without special efforts by each doctor at each ambulatory patient. Thus, the developed tool can be a major contribution to the prevention of cardiac death.

3.1 The ECG Modul

The ECG Modul is used to determine the R-peak of the electrocardiogram as a starting point of the pulse wave velocity measurement. To interpret and calculate the claimed point of the electrocardiogram algorithms are applied. A schematic structure of the problem is shown in figure 3, where the use of the ECG module is demonstrated. The ECG is determined with four electrodes applied on the right arm (RA), left arm (LA), left leg (LL) and right leg (RL). The sampled data is transmitted with a proprietary radio module with a frequency of about 2.4 GHz to a receiver, which is placed on the main module (includes the digital signal processor). The electrocardiogram usually has a magnitude in the range of 1 mV, so a reasonably high gain, high quality biopotential amplifier is needed. The ECG is derived using four electrodes (Ag/AgCl). The Einthoven leads are measured directly with the hardware and the Goldberger leads can be calculated if necessary.

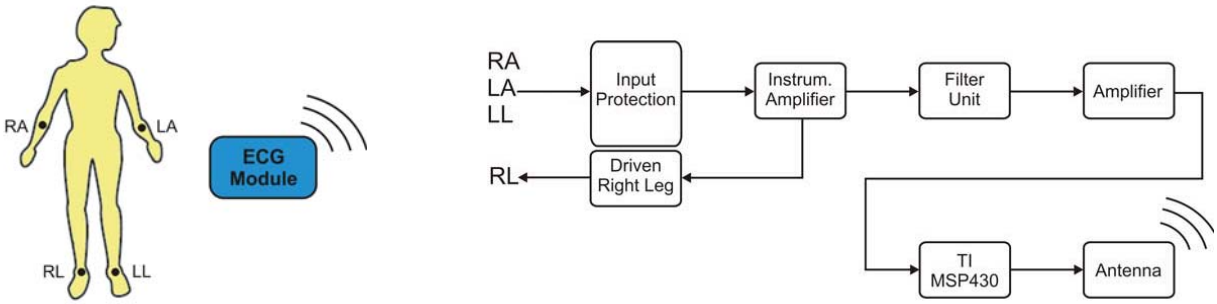

Figure 3: Schematic structure of the ECG recording

The ECG's R-peak is a good estimator for the starting point of the measurement of the pulse transit time. In contrast to the pulse waves this point is especially prominent and very easy, quick and reliable to identify. Many different detection algorithms exist in literature, for instance based on Artificial Neural Networks, signal derivatives, digital filters and the Wavelet Transform. For a detailed description of algorithms using these methods see [10] and [5]. These solutions have several drawbacks, e.g.:

- They have a high computational complexity.
- The degree of accuracy based on the error rate of the algorithm is not as high as possible.
- Its performance is not very satisfying (noise artefacts).
- They are not appropriate for this application (memory consumption, desired speed of algorithm, real-time application).

For this application a very easy, real-time usable and fast algorithm is necessary to ensure real-time usability, because this algorithm has to run on a Digital Signal Processor from Texas Instruments (TMS320C28x).

3.2 The Pulse Wave Modul

Generated by the contraction of the heart, the pressure pulse travels with a finite speed through the arterial system. The pulse wave contour is also changing as it propagates downstream due to interaction between the forward travelling and backward moving waves reflected at bifurcations in the arterial system and the attenuation of these waves. In figure 4 one can see a schematic presentation of the arterial pressure pulse.

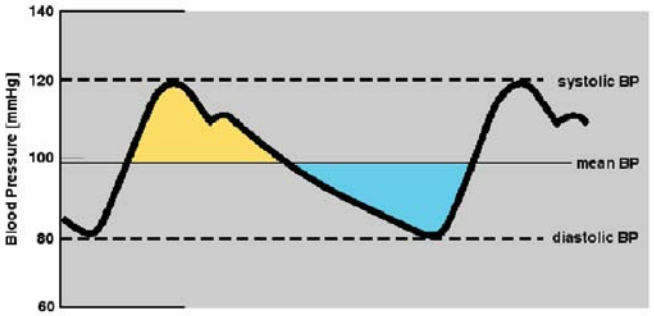

Figure 4: Schematic presentation of the arterial pulse pressure - reproduced from [18]

The pressure wave in the arterial system shows clear pulsations according to the chronology of systole and diastole of the left ventricle. After the ejection of the stroke volume, a steep increase of pressure can be observed, which ends at a maximum, the systolic blood pressure P_S. The closing of the aortic valve leads to the so called incisure, a decrease in pressure. After a second small pressure increase (dicrotism), caused by the reflection of the pressure wave in the peripheral vascular system, pressure decreases to a minimum (diastolic blood pressure P_D) due to the outflow of blood. The amplitude of the pressure pulse for healthy young people in physical rest is about 40 mmHg (P_S approx. 120, P_D approx. 80 mmHg).

The shape of the pressure pulse in the Aorta (figure 4), which propagates as a pressure wave through the peripheral vessels, changes due to reduction of distensibility of the vascular walls and due to superposition with reflected waves from the circulatory system. The pressure amplitude rises in the large muscular arteries (A. femoralis, A. subclavia, ...), while it is damped in the peripheral arteries. Furthermore, in the capillaries the pulsatory pressure variations are very small. The pressure wave, which is generated from the left ventricle, travels with a velocity of about 3-5 m/s in the Aorta and with about 5-10 m/s in the large arteries, but only with about 1-2 m/s in the veins through the vascular system [18].

To register these pulse waves several technologies can be used. A schematic structure of the problem is shown in figure 5. The pulse wave signal will be obtained at three locations of the body as illustrated in the same figure. Like in the electrocardiogram module, the recorded data is transmitted by means of a proprietary radio module with a frequency of about 2.4 GHz to a receiver, which is placed on the main module.

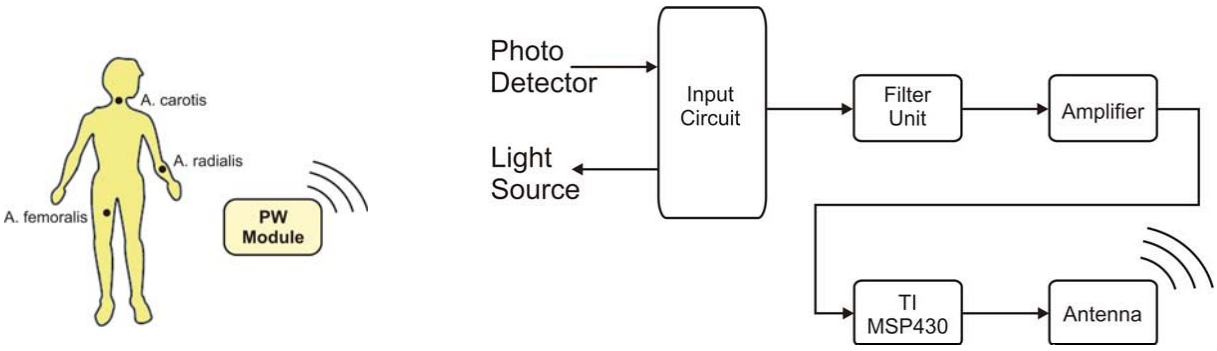

Figure 5: Schematic structure of the pulse wave recording

For the recording of the signal optical sensors are used. These optical sensors work in accordance with the procedure of photoplethysmography (PPG) [7]. These sensors include a source of infrared light and a photo detector. Blood vessels expand or contract depending on the blood pressure conditions. Since infrared light is strongly attenuated by blood, one can measure the brightness changes at the receiver to determine the change of the quantity of blood under the sensor. Considering the geometrical placement of these components, there are two methods in

use. In transmission mode the light source and the detector are fixed on opposite sides of the measured area. It is only possible to register the pulse at locations of the body with low tissue thicknesses (e.g. the finger, earlobe, toe). By operating in reflection mode the arterial wave signal can be obtained almost everywhere on the body.

For the use in a biosignal monitoring system several requirements are noted. A reliable measurement of the volume pulse should be done with respect to low disturbance. For example the sensor system must be insensitive to day light influences. Another important thing is the effect of the contacting force on the photoplethysmographic signal [20]. Hence a minimum of body contact with the sensor should be ensured. The greater the pressure of the sensor system on the tissue and the underlying blood vessels, the more unreliable are the registered signals. Because of this external applied pressure the vessel cross-sections are changed, which results in major haemodynamic changes. It is therefore necessary that the sensors are small, lightweight and easy to apply on the human body in order to reduce these effects.

For the design of a photoplethysmographic sensor the following parameters are considered:

- the peak wavelength and the angle of intensity of the light source,
- the distance between the light source and the photo detector (PD),
- the optical and electric characteristics of the components and
- the optical properties of the tissue.

The signal, which is detected by the photodetector, can be separated into two parts [3]: a direct-current signal, the DC-signal, and an alternating current signal, the AC-signal. The level of the DC component is primarily related to the attenuation in the structures of the tissue like tissue bed, bone, venous blood, capillary blood and non-pulsatile arterial blood [21]. It is therefore correlated to the blood volume (relative vascularisation of the tissue) [8, 9]. The AC component is a cardiac synchronous signal (heart rate), which is directly related to the pulsating arterial blood.

The AC component changes, whereas the variation depends on the light scattering and the reflection caused by the orientation of the erythrocytes, axial aggregation and their deformation [12]. When blood flows, erythrocytes deform and orient themselves in the direction of flow [6]. The expansion of the vascular walls plays also an important role during the blood volume pulsation [16].

Considering the geometric design of the sensor system the focus should be on the penetration depth in connection with the change of intensity. The gap between a decrease of intensity (direct proportional to the LED/PD distance) and the high distance between the light source and the detector has to be considered. Beside the decrease of the AC/DC amplitudes with increasing LED/PD distance, Mendelson [14] has shown that by increasing the separation distance from 4 to 11 mm, results in a twofold increase in the pulse amplitude of the infrared photoplethysmographic signal. Furthermore, the PPG signal becomes progressively more stable as the LED/PD separation increases.

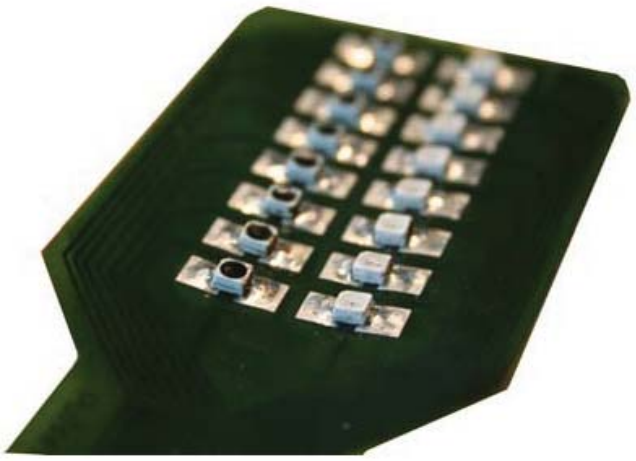

Figure 6: Picture of the flexible part of the pulse wave module with IR Led's and photodetectors

To record undisturbed signals, one needs to think about the placement of the sensors to find the desired artery. This problem can be reduced by placing multiple sensors on a special cuff (figure 6). An implemented control algorithm is polling the individual sensors and finds the one, which should be used for the pulse wave recording

by checking the signal quality. For obtaining the end point of the above described pulse transit time measurement, an algorithm is applied on a peripheral pulse wave. To determine the onset point of the pulse wave a method with low computational effort, but high accuracy is needed for a pulse-to-pulse real-time detection.

For this real-time detection the identification of artificial onset points is considered as the best solution because this method has the advantage that the artificial onset point utilises the information from two points and therefore it is robust against interference. Moreover, this method has a significantly low computing effort. As illustrated in figure 7 two points of the pulse wave are detected - the onset point (Idx_{onset}) and the point of maximum slope (Idx_{slope}). The intersection of the tangents at both points provides the artificial onset point. From the pulse wave signal $p(x)$ (with x ... sample index) and its derivative, this artificial point is calculated by means of the maximum slope point and the onset point.

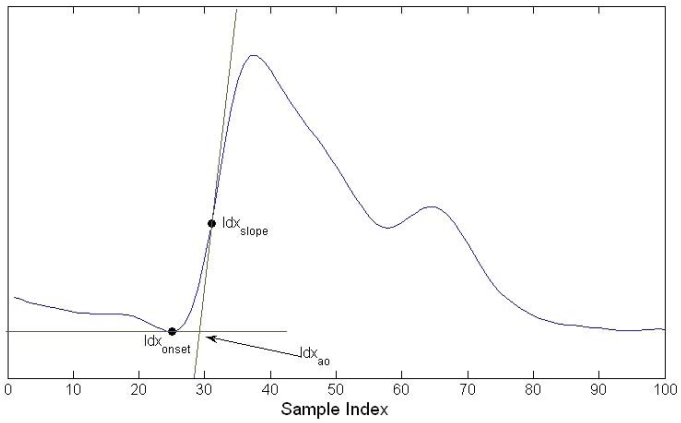

Figure 7: Determination of the artificial onset point

For the calculation of the pulse transit time the strongest peripheral pulse wave signal should be found to get an accurate measurement. The algorithm uses the amplitudes of the signals to detect the one with the highest signal strength. For these purposes one needs the maximum and the onset point of a peripheral wave.

These computed amplitudes of the miscellaneous LED/PD combinations are filtered to reduce the influence of interference. Then, the processed amplitudes are compared to find the largest one. With the detected R-peak of the ECG and the artificial onset point of the chosen peripheral signal, the pulse transit time (PTT) can be calculated. To determine the pulse wave velocity (PWV), which is defined as the ratio of the propagating path (PGP) to the pulse transit time, the propagating path of the pulse wave has to be known.

4 Conclusion and Outlook

Considering the current situation for doctors and in the ambulatory care of (chronic) cardiovascular diseases, there is a need for cheap, easy-to-use, efficient treatment solutions. The above described modules and algorithms are part of a flexible designed, multifuntional platform for biosignals. The platform is the carrier for new technologies and the central element of a biomedical sensor network.

The developed modules for acquiring the pulse wave and ECG signals provide reliable and usable results. Thus, the developed technology can be applied to record continuous and synchronous signals of the human body to derive haemodynamical risk indicators. With the pulse wave module it is possible to achieve pulse wave signals without applying any pressure to the measurement site and therefore the module does not influence the arterial signals. Hence, a good analysis of the recorded pulse waves is feasible.

Furthermore the central aortic pulse waves can be obtained by means of an already developed tool [11] based on the peripheral pulse waves in order to calculate the central aortic pulse transit times and pulse wave velocities. The pulse wave form is recorded at two sites of the human body - the right carotid and the left radial artery. The transformation of the radial and carotid pulse waveform to the central aortic contour (at the Ascending Aorta) is based on frequency and phase transformation by means of the Womersley equations [11]. The simultaneous recording of two pulse curves enables to calculate an accurate pulse wave shape at the Aorta.

5 References

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