Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 82 (2011) 483–493
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Intelligent multichannel sensors for pulse wave analysis

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Received 26 February 2010; accepted 14 October 2010
Available online 25 October 2010

Abstract

Aortic pulse wave velocity is an independent predictive indicator for all cause mortality and cardiovascular morbidity. Unfortunately it is only invasively accessible and thus the A. carotis–A. femoralis pulse wave velocity (cfPWV) is recommended as a non-invasive substitute. This work presents a model based analysis method for the beat-to-beat online determination of an arbitrary, peripheral pulse transit time (PTT). The method is based on the recording of a three lead electrocardiography (ECG) and of pulse waves (PW) at a peripheral site such as the A. carotis by means of a multiple sensor array. The two modules for the signal acquisition work autonomously but time-wise simultaneously and transmit the data via a radio unit to the central processing unit. There the algorithms for the pulse transit time determination exploit these signals. In doing so the main focus is on an efficient implementation to assure real-time usability. The evaluation of the developed modules and algorithms was done in two separate trials. First the algorithms were tested offline against manual signal annotation using invasive data previously recorded to proof their accuracy. The resulting mean differences in PTT for pulse waves assessed at the aortic root and the aortic bifurcation are 2.86 ms (4.72 ms SD) and 2.00 ms (2.28 ms SD). To evaluate the whole system integrity in a second step online measurements on probands were carried out and compared to data from literature. The trials resulted in a mean PTT of 174.6 ms (17.7 ms SD) for the A. radialis and of 81.9 ms (13.2 ms SD) for the A. carotis. The results suggest that the method may be useful and deployable at general practitioners (GP) and in ambulatory care of (chronic) cardiovascular diseases.

Keywords: Pulse transit time; Pulse wave velocity; Arterial stiffness; Cardiovascular risk; Electrocardiography

1. Introduction

The medical research regarding hypertension has changed considerably during the last two decades. Around the year 1990 the diastolic blood pressure has been the most important value to look at [18] and about ten years later the focus has been on the systolic blood pressure. With the beginning of the new millennium the topic of arterial stiffness of major vessels related to hypertension has slowly arisen in clinical practice. Arterial stiffness and its indicators have

Abbreviations: BP, blood pressure; cfPWV, A. carotis–A. femoralis pulse wave velocity; dBP, diastolic blood pressure; ECG, electrocardiography; FIR, finite impulse response filter; ICA, independent component analysis; Idx_{ao}, index of the artificial onset point; Idx_s, index of the maximum slope; Idx_o, index of the onset point of the pulse wave; INA, instrumentation amplifier; LED, light-emitting diode; $p(Idx_s)$, pulse wave signal at the maximum slope point; $p(Idx_o)$, pulse wave signal at the onset point; $p'(Idx_s)$, differentiated pulse wave signal at the maximum slope point; $p'(Idx_o)$, differentiated pulse wave signal at the onset point; PTT, pulse transit time; PW, pulse wave; PWV, pulse wave velocity; sBP, systolic blood pressure; SD, standard deviation.

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0378-4754/$36.00
doi:10.1016/j.matcom.2010.10.023

been mentioned for the first time in the ESH-ESC guidelines for hypertension treatment in the year 2003 [8]. As parameters to measure arterial stiffness primarily the methods of pulse wave analysis (PWA) and pulse wave velocity (PWV) have been proposed.

Ageing and pathological changes (e.g. arteriosclerosis or subclinical organ damage) are the main factors for the stiffening of vessels and as a result an increase of PWV may occur. As a consequence increased and premature pressure reflections emerge, which superimpose the generic pulse wave ejected by the heart earlier and more intensely. The superposition may cause a pathological increase of the aortic systolic blood pressure and subsequently an increase of the cardiovascular risk [22,25,32].

Meanwhile aortic PWV has been shown to have an independent predictive value for all cause mortality and cardiovascular morbidity, coronary events and strokes in patients with uncomplicated essential hypertension [4], with impaired glucose tolerance [5] and with renal failure [3], in elderly individuals [20] and in the general population [34]. In the update of the ESH-ESC guidelines for hypertension treatment in the year 2007 [19] the consequences of arterial stiffness on cardiovascular mortality play a major role. These guidelines additionally claim widely suitable measuring devices for the measurement of arterial wall stiffness and describe the influence of arterial stiffness on the aortic blood pressure. The authors have recently introduced a simple method for PWA based on an inverted simulation model to be used in oscillometric devices [29]. The aim of this work is the presentation of a model based approach for simple PWV measurements.

2. Aims and goals

As aortic pulse transit time (PTT) cannot be measured non-invasively, an estimate is assessed using the time difference of pulse wave arrival at the carotid and at the femoral artery, respectively. In clinical routine this measurements can easily be performed using ultrasound. Beyond the clinical environment cheaper solutions with applanation tonometry based on piezo technology are used. The disadvantage of such technical approaches is their sensitivity to artefacts motivated by the operator and the resulting moderate reproducibility due to non-specialist use. This work introduces a model based analysis method using multichannel optical sensors for pulse wave acquisition. Such an approach avoids operator interaction and overcomes the common problems with piezo applications on human bodies.

3. Methods

The presented method for the desired beat-to-beat real-time determination of the pulse transit time (PTT) and subsequently of the pulse wave velocity (PWV) is based on simultaneously recorded electrocardiogram (ECG) signals and peripheral pulse waves (PW). Thus an ECG module and a PW module have been developed, which transmit their recordings wirelessly to a central processing unit. This processing unit works as a signal selecting and merging platform. The process of the signal selection is necessary for choosing the optimal channel providing the best signal quality and strength for both modules. Thereafter the R-waves and the artificial onset point of the pulse wave at the peripheral recording site are determined. Hence the PTT can be calculated by means of the points in time of the detected points of interests of the observed signals. In Fig. 1 the whole process is depicted.

3.1. Hardware

The ECG acquisition is realized by a universally usable ECG module which transmits the data to the signal processing unit wirelessly. The module is equipped with an input protection to secure the patient from dangerous electrical current and the electrical circuit from high input voltages. It is necessary for the approval as a medical measurement device. Furthermore it consists of an instrumentation amplifier (INA), which eliminates any undesirable source loading, equalizes the source impedances of the inputs and removes the drifting baseline that is common in ECG recordings, and a driven-right-leg-circuit, which helps to arrange the different potentials of the human body and the ECG device itself and to reduce electromagnetic influences. The input circuit is followed by a hardware filtering and an amplification unit. Thereafter the pre-processed signal is transmitted by the radio unit.

The pulse wave module is similarly designed as the ECG module and also transmits the recorded data to the signal processing unit via the radio unit. It is based on photoelectric plethysmography, which is a well-known method to acquire peripheral, arterial pulse wave signals. Photoelectric plethysmography realizes data acquisition with a minimum of