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Pulse Arrival Time Estimation from the Impedance Plethysmogram Obtained with a Handheld Device

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Abstract—**This paper describes a novel method to estimate pulse arrival time (PAT) from the electrocardiogram (ECG) and the impedance plethysmogram (IPG) obtained by using a compact and easy-to-use handheld device with only four electrodes. A proof-of-concept has been carried out where PAT values obtained with the proposed device have been compared to PAT values measured between the ECG and the photoplethysmogram (PPG) during three experiments of paced respiration to induce controlled PAT changes. The results show that both methods yield equivalent PAT values in within ± 7 ms (95 % confidence interval), which is less than typical deviations reported for common PAT measurements.**

I. Introduction

Time intervals between physiological waveforms have been widely used to assess cardiovascular function [1]–[3]. One of these time intervals is the pulse arrival time (PAT), which is defined as the time between a characteristic feature of the electrocardiogram (ECG), typically the R wave, and a fiducial point of an arterial pulse waveform [4]. The term PTT (pulse transit time) has sometimes been used as an alternative name for PAT [5], but the PTT is most commonly defined as the time delay between two arterial pulse waveforms simultaneously detected at different distances from the heart [4]. Conventionally, as one detection point is proximal and the other one is distal to the heart, the term pulse wave velocity (PWV) has also been used; it is calculated by dividing the distance between the two points, measured over the skin, by the difference in time between two analogous points in the pulse waveform [6] such as the foot or the point of maximal slope [7]. The main difference between PTT and PWV with respect to PAT is that the first two involve the delay due only to the propagation of the pulse along the arterial tree whereas PAT includes the pre-ejection period (PEP), which provides information about mechanical heart function. Because of that, the performance of different time intervals depends on the cardiovascular parameter being assessed [8].

The above mentioned time intervals are commonly measured by using arterial pulse pick-ups such as applanation tonometers and Doppler ultrasound devices, whose use is tedious and time-consuming, and whose repeatability depends on the positioning of the sensors, hence on the operator. Oscillometric-based detection is faster and more reproducible [9] but cannot detect beat-to-beat changes. More recently, photoplethysmography (PPG) is being used as an alternative method to pick the pulse waveform because it can reliably detect beat-to-beat changes and is easy to apply [10]. But PPG sensors are bulky and must be properly placed.

Electrical bioimpedance signals have also been used to detect arterial pulse waves. They only need inexpensive electrodes, are easy to apply, and the agreement between PWV estimated by Doppler ultrasound and impedance methods such as whole-body impedance cardiogram (ICG), which measures mainly PEP, and impedance plethysmogram (IPG) near the aorta and popliteal arteries has been found to be good, and the repeatability and reproducibility, excellent [11]. However, several points of the body must be exposed to place the electrodes, which is not practical in non-clinical settings. Recording impedance signals at various limb locations is easier as they are more accessible but needs electrode arrays for accurate positioning [12] or up to seven electrodes if the ECG and IPG are separately obtained [13].

In this work we propose to measure PAT by using a device able to simultaneously obtain the ECG and the IPG that uses only four electrodes in contact with two fingers of each hand. The current injected to obtain the IPG signal flows along the arms and through the thorax, hence the IPG signal is contributed by the sum of all the pulsatile components of each body segment in the current path. Therefore, given that the impedance of fingers and hands is larger than that of the arms or the thorax [14], we expect that the IPG signal measured between fingers will be mostly contributed by local impedance changes in the hands. This means that the IPG delay measured with respect to the ECG will include not only the PEP as does the ICG signal, but also a delay due to arterial pulse propagation, the same as the common PAT.

As a first step towards the experimental assessment of this hypothesis, we compare PAT measurements simultaneously obtained with the proposed method, which we will call PAT_{HH} (from PAT handheld), with the traditional approach based on ECG-PPG intervals. The measurements have been obtained during paced respiration at several rates in order to generate controlled and repeatable PAT changes due to the well-known blood pressure changes produced by respiration

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effort [5].

II. Materials and Methods

A. The handheld device measurement

Fig. 1 shows a block diagram of the system to measure PAT_{HH}. There are four metal electrodes on a flat surface, which are intended for the index and middle finger of each hand to contact them. The electrodes are used respectively for current injection (A), reference (signal common) for current injection and voltage measurement (B), and voltage detection for both ECG and IPG signals (C, D). This configuration yields great repeatability because it implies a highly repeatable position of the contact points between the hands and the electrodes.

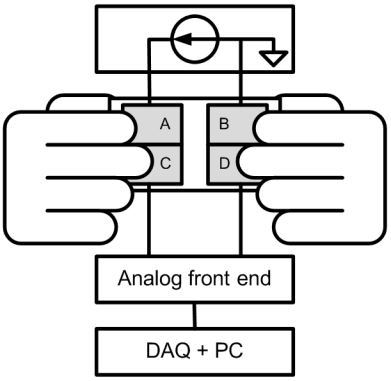

Fig. 1. Block diagram of the system proposed to obtain the ECG and the IPG using only four electrodes in contact with the fingers.

B. ECG and IPG acquisition

The ECG acquisition system is based on the circuit design described in [15] with the common ac-coupled input stage replaced by a band-pass filter to reject high-frequency interference from the IPG system (see Fig. 2).

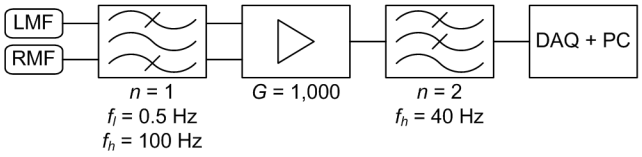

Fig. 2. Block diagram of the system for ECG acquisition.

The system inputs are connected to dry electrodes intended to be contacted by the left middle finger (LMF) and the right middle finger (RMF), whereas amplifier common is intended to be contacted by the right index finger (RIF). The left index finger (LIF) is not connected to this system. The first stage is a fully-differential, first-order band-pass filter based on the design in [16] with corner frequencies 0.5 Hz and 100 Hz, followed by an instrumentation amplifier (INA118) with gain set to 1,000. The final stage is a second-order low-pass filter with corner frequency 40 Hz. This filter bandwidth fulfills the standardized requirements for QRS detection in ECG monitors.

Fig. 3 shows the block diagram for the IPG acquisition system. There is a current source based on a Wien bridge and a current conveyor which applies 10 kHz, 0.5 mA peak current between RIF and LIF. The drop in voltage is measured between LMF and RMF by using a fully-differential ac-coupled filter [16] with corner frequency 1 kHz connected to an instrumentation amplifier (INA118) with gain set to 1. The output signal is demodulated by a coherent detector based on an amplifier with gain +1/-1, and band-pass filtered between 0.5 Hz and 15 Hz by a second-order filter with gain set to 14,000.

Both systems are supplied by a 12 V rechargeable battery, and the outputs are connected to a 12 bit, 10 V range data acquisition system (μDAQ Lite, Eagle Tecnhology). Data is acquired by LabVIEW® running on a battery supplied laptop PC hence the whole system is electrically isolated from power lines and ground.

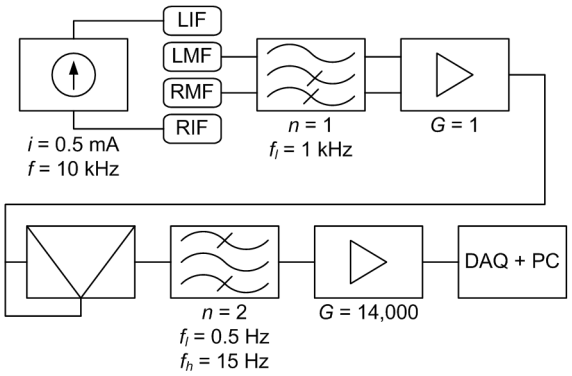

Fig. 3. Block diagram of the system to acquire IPG between the fingers.

C. Signal processing

PAT is defined as the time delay between the R peak and the systolic upstroke (foot) of pulse signals such as the PPG. But this last fiducial point is sometimes difficult to determine because of waveform variability due to the confluence of incident and reflected waves [17]. Because of that, several algorithms have been proposed to detect the foot of the pulse wave [18].

The algorithm implemented for PAT_{HH} measurements suits the detection of R waves in ECG signals whose EMG noise is higher than usual [15], which is the case for ECGs recorded with the proposed device. The time arrival of the pulse in the IPG signal is computed by locating the mid-raise point (50 % amplitude) between the foot and the maximum of the pulse in the impedance signal. This fiducial point has experimentally shown an acceptable performance against signal variations produced by mechanical motion.

D. Experimental methods

Some common methods to induce hemodynamic changes that result in PAT variations are the Valsalva maneuver [19], holding breath [20], and changing the body position from laying down to upright [21]. Here we use paced respiration because of its simplicity [5]. During inspiration effort, blood pressure increases proportionally, which increases tension

(stiffness) in the arterial walls and this makes the pressure pulse to travel faster, hence shortening PAT.

Three consecutive 50 s measurements have been taken from a single (healthy) subject (male, 28 years old) with paced respiration, at 0.1 Hz, 0.2 Hz and 0.4 Hz, by synchronizing his respiration with an on-screen bar graph.

The results were compared against a traditional PAT measured from the same ECG signal and a PPG signal obtained from the ring finger by a commercial device (ChipOX® from Corscience GmbH). PAT has been calculated as the distance between the R peak and the 10 % of the PPG pulse [18]. All signals have been offline processed with Matlab®.

III. Results and Discussion

Fig. 4 shows a sample record of signals acquired with the handheld system and the PPG device.

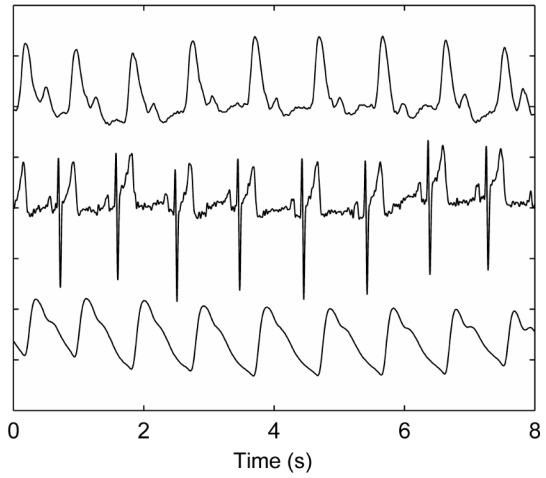

Fig. 4. Sample signals acquired using the handheld device: IPG (top), ECG (middle) and PPG (bottom)

Each R-wave from the ECG is followed by an impedance decrease in the IPG (represented as a positive peak, as usual in impedance plethysmography) and later a PPG peak (whose delay is due in part to an offset that arises from internal signal processing.) The time interval between ECG and IPC is longer than that usually measured between ECG and ICG. This, together with the sharpness of the IPG signal suggest that the measured IPG is more related to local changes in the hands than to those in the thorax.

The correlation coefficients between PAT_{HH} and PAT, and the straight line fitted according to the least squares criterion are shown in Table 1. The total PAT has been estimated from PAT_{HH} and named PAT' by fitting a straight line to the results from the three records. The correlation coefficients on Table 1 indicate that there is a good correlation between the two PAT measurement methods (statistical significance $p < 0.001$).

TABLE I
Correlation Coefficient and Best Straight Line

Respiratory rate	r	Least squares adjustment
0.1 Hz	0.930	$PAT = 0.769 \times PAT_{HH} + 119$
0.2 Hz	0.833	$PAT = 0.806 \times PAT_{HH} + 110$
0.4 Hz	0.775	$PAT = 0.820 \times PAT_{HH} + 103$
Total	0.855	$PAT = 0.769 \times PAT_{HH} + 117$

Fig. 5 shows both the measured (ECG-PPG) and estimated (ECG-IPG) PAT for the three records at different respiration frequencies. Both signals evolve in a similar way in response to respiration cycles. The worse correlation when the respiratory rate increases can be attributed to the fact that the number of heart beats during each respiratory interval becomes smaller, hence worsening the resolution of changes induced in the PAT. Further, motion artifacts and the uncertainty in identifying the foot of the IPG signal have a larger relative effect on shorter time intervals [18].

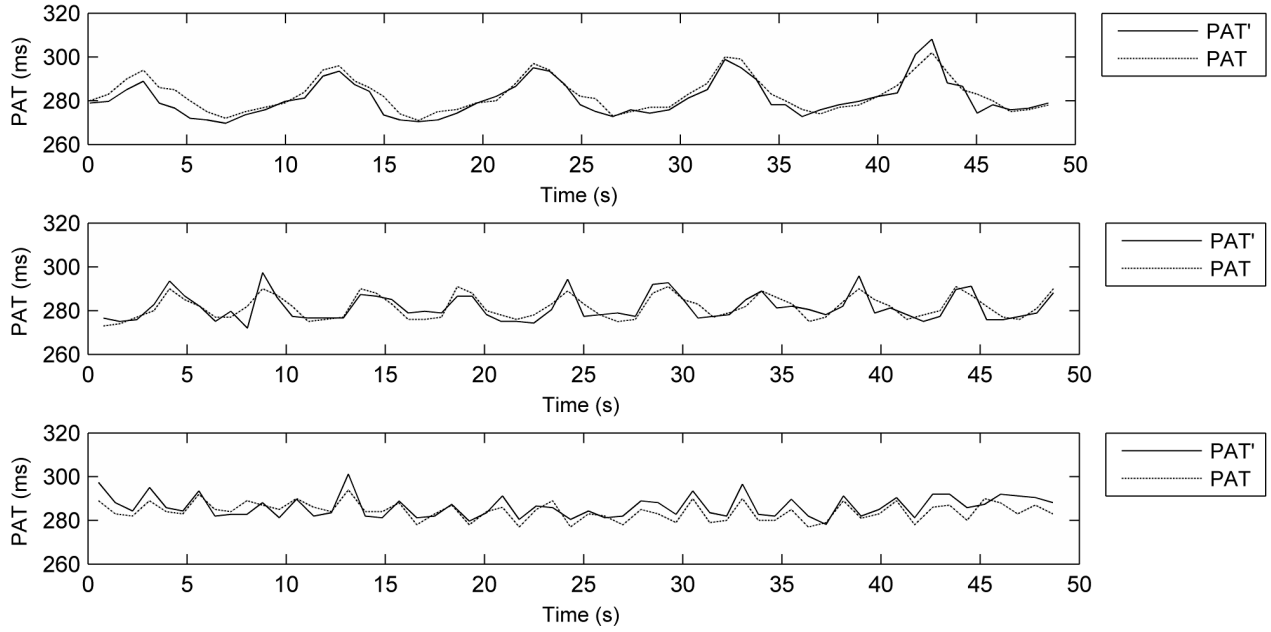

Fig. 5. PAT measured and estimated from ECG-IPG for respiratory rates 0.1 Hz (top), 0.2 Hz (middle), and 0.4 Hz (bottom)

The mean deviation of the difference between PAT and PAT' is 0 ms and the standard deviation (σ) is 3.6 ms, the agreement being better al lower respiratory frequencies. The Bland-Altman plot is depicted in Fig. 6. For a 95 % confidence interval, the deviation is ± 7 ms, which is far below typical deviations for PPG-based PAT values and PAT-based parameters reported in other studies (for example, an average deviation of ± 30 ms for a 95 % confidence interval in [8]).

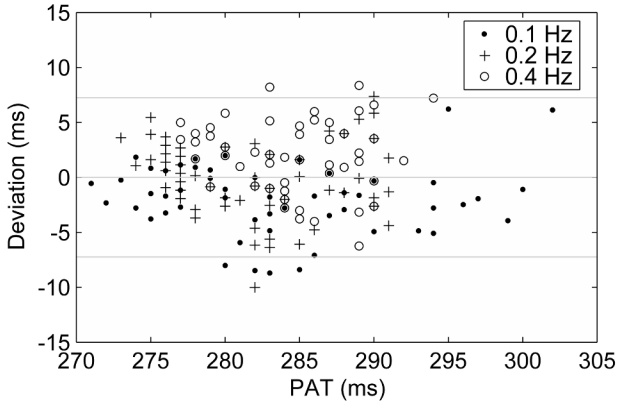

Fig. 6. Bland-Altman plot of the two methods used to estimate PAT.

IV. Conclusions

A novel method to estimate PAT from IPG measurements obtained with a handheld device has been presented. This method allows us to acquire ECG and IPG signals between the two hands and compute PAT by using only four dry electrodes touched by two fingers of each hand. No bulky PPG sensor, no need for skilled operators.

Preliminary experiments performed in a single healthy subject at different respiratory rates show that there is a good correlation with PPG-based PAT measurements ($r = 0.855$) and time deviations of ±7 ms for a 95 % confidence interval, which are relative small as compared to typical deviations of PPG-based PAT values.

Further developments of this work should include studies on a wider group of test subjects and under different kinds of hemodynamic changes.

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