A NEW ALGORITHM FOR MEASURING PULSE TRANSIT TIME FROM ECG AND PPG SIGNALS

Radjef Lilia and Omari Tahar

Department of Electrical Engineering Systems,
Boumerdes University, Boumerdes, Algeria

ABSTRACT

Pulse transit Time (PTT) is a physiological parameter that is based on characteristics of the pulse waveform, a direct indicator of Cardiovascular Diseases (CVD). The (PTT) is defined as the time taken for the arterial pulse to travel from the heart to a peripheral site. It is commonly derived from Electrocardiogram (ECG) and Photoplethysmogram (PPG) signal calculations and is calculated as the interval between the peak of the electrocardiogram (ECG) R-wave and a time point on the photoplethysmogram (PPG). In this study, we propose a new and low-complexity algorithm for the Pulse transit time (PTT) measurement, using these two signals and detecting (PTT- foot) and (PTT- peak). We built a 37 subjects dataset containing a simultaneous recording of the (ECG) and (PPG). The calculation of (PTT) consists of detecting the peak and foot points of a (PPG) and the R-peak of the (ECG) signal. Intermediate operations such as normalization and thresholding to detect the local maxima and minima, are processed on noisy signals, this algorithm is improved by a windowing temporal analysis. The obtained results are promising for the first step. The average sensitivity (SEN) and accuracy (ACC) obtained were (97.5%, and 96.82%) respectively for R-peaks detection and respectively (97.77%, and 97.64%) for (PPG-peak) detection. The sensitivity (SEN) and accuracy (ACC) of (PPG- foot) detection were (98.33%, and 94.14%).

KEYWORDS

Pulse transit time (PTT), Cardiovascular Disease (CVD), Electrocardiogram (ECG), Photoplethysmography (PPG), Algorithm, Peaks detection, Sensitivity (SEN), Accuracy (ACC).

1. INTRODUCTION

The World Health Organization (WHO) estimates that cardiovascular disease is the leading cause of death in the world. [1, 2, 3]. It is crucial to evaluate pulse transit time (PTT), which is a direct indicator of cardiovascular (CV) health [4], especially arterial stiffness (AS) [6], vessel compliance, and blood pressure (BP) [7, 8, 9, 10]. The earliest detection of vascular disease can be the key to the prevention of cardiovascular diseases. Several definitions of pulse transit time (PTT) exist. Originally, it refers to the time taken for the pulse wave to travel from a proximal to a distal point of the arterial tree. It is based on the Moens-Koertweg and Bramwell-Hill equations [5] and is inversely related to the pulse wave velocity (PWV), which is calculated as the pulse wave travel distance divided by time. The (PTT) can be measured using pulse wave transducers placed close together in a homogeneous arterial segment [19] (as shown in Figure 1).

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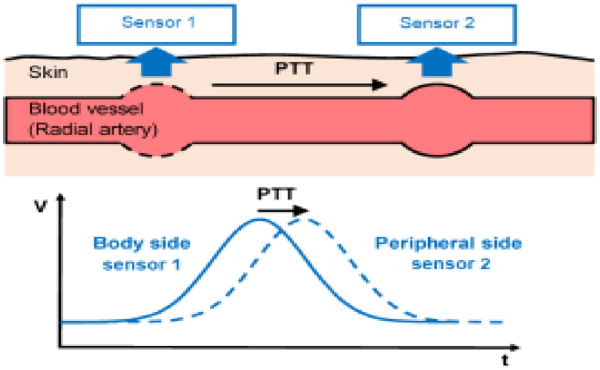

Figure 1. The pulse transit time (PTT)

Increases in (PTT) are related to changes that occur in the cardiovascular system, for example, a decrease in both systolic blood pressure (SBD), and arterial stiffness (AS), or on the contrary an increase in path length [11]. The (PTT) levels are affected by several factors including age, and the presence of atherosclerotic disease associated with risk factors [12]. Among the promising applications of (PTT) is the monitoring of ductus arteriosus closure in the neonatal setting [13] and the detection of sleep-disordered breathing [14] as well as stroke and myocardial infarction [15] Kounalakis et al. used pulse transit time that was related to cardiac output [16]. Smith et al. have used pulse transit time for a sleep disorder study [4]. To detect sympathetic nervous system (SNS) excitation, Fechir et al. used the pulse transit time [17]. Changes in (PTT) can be used as a measure of the smooth muscle relaxation that occurs when a functional endothelium is stimulated study reported by Maltz and Budinger [18]. There are different non-invasive techniques to measure PTT, such as arterial tonometry, Doppler ultrasound, electrocardiography-photoplethysmography (ECG signal represents the electrical activity of the heart, while PPG signal measures changes in blood volume), and pressure transducers [20, 21, 22, 23, 24]. Depending on the equipment used and the applications, the (PTT) can be defined as different time intervals: (1) The Time difference between the onset of cardiac ejection approximated by the R-peak in the electrocardiogram (ECG) and the arrival of the pulse at the fingertip as determined by the photoplethysmogram (PPG) as in [25. 26, 27, 28, 29, 30], which is the popular (PTT) estimation (shown in Figure 2).

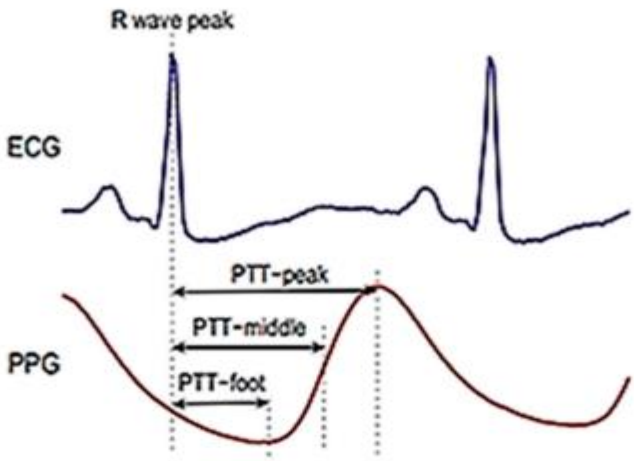

Figure 2. Graphical explanation of the (PTT) calculation using (PPG) and (ECG) signals

The use of (PTT) dates back to 1964 when Weltman et al [31] designed the PWV computer based on the use of the (ECG) complex and a downstream pulse signal to determine the pulse transit time over a known arterial length. A combination of the (ECG) and (PPG) signals leads to the measurement of another cardiovascular parameter called pulse arrival time (PAT). The (PAT) includes not only the desired (PTT) but also a rejection period (PEP). This approach has been extensively reported in the literature [32, 33, 34]. The (PTT) technique is reproducible, non-invasive, easy, and safe, it is therefore not necessary for specialized training required for medical staff to handle (ECG) and (PPG) signals. Another approach (2), the (PTT) can be acquired by observing two PPG waves distant from each other [35, 36], or by using only one (PPG) signal [37, 38, 39, 40], different measurement sites exist in the periphery including the finger, ear lobe, toe, and forehead although they are less practical. To measure the (PTT) (or PAT), various vital signals such as Photoplethysmograph (PPG), electrocardiogram (ECG), ballistocardiogram (BCG), gyrocardiography (GCG), impedance plethysmography (IPG), electrical bio-impedance (Bimp), the PPG/tonoarteriogram (TAG), impedance cardiography (ICG) and seismocardiogram (SCG) can be used [41]. The features obtained from the (ECG) and (PPG) signals depend on the purpose or type of disease and diagnosis to be estimated. To develop a good algorithm, it is necessary to know first how to define the relevance of a pulse wave for the calculation of (PTT). In the literature, several algorithms based on characteristics of the pulse waveform analysis have been proposed, mainly focusing on the determination of characteristic point's peak detection [42, 43, 44, 45], and located at the foot of the wave. This paper presents a new algorithm for non-invasive measurements of the pulse transit time (PTT), which is obtained by measuring the pulse time between the heart and the finger. The (PTT-Peak) and (PTT-Foot) are the time intervals between the wave peak (ECG-R) and the (PPG) peak and foot, respectively.

2. MATERIALS AND METHODS

In this study, the (ECG) and (PPG) signals were processed to measure the (PTT), which is estimated using the algorithm illustrated in Figure 3. The (PTTs) (PTT-foot and PTT-peak) values are obtained by the measurement of the differences between the (PPG) (foot; peak) locations and R-peak locations.

2.1. Training Dataset

We first built a 37 subjects dataset containing a simultaneous recording of the (ECG) and (PPG). All the participants have signed a voluntary agreement to participate in this study. The Authorization for data acquisition granted by the ethics committee of Tlemcen University.

2.2. The PTT Algorithm

The robust determination of characteristic points is still a difficult task in the PTT estimation due to motion artifacts, electrical interference noises, and signal crossovers among others, and also due to respiration. First, the (PPG) is normalized at the value of 1 according to the equation (1):

$$PPG(\text{normalized}) = (PPG(n)) / (\max(PPG)) \qquad (1)$$

Where n: is the normalization factor. In our case, it equals 1. PPG peaks were detected using a thresholding operation. The threshold was set at 0.5. After that, the first derivative was calculated and symmetrically thresholded (+0.5and -0.5) to detect the local maxima and minima. The subtraction of each peak location (in the PPG signal) with the difference between its minima and maxima location (in the derivative signal) detects perfectly the (PPG-foot). The (PPG-foot) detection process evolved mathematically from a Gaussian pulse (which corresponds highly to a (PPG) pulse) and its first derivative, all steps (shown in figure 4). The processing of the (ECG) signal starts with a normalization (at the value of 1) followed by a thresholding operation (at the value of 0.3) to detect the R-peaks. The threshold value is fixed at less than 50% of the normalized signal to avoid any loss in the detection, as well, as to avoid the misleading R-peaks detection resulting in some cases from high amplitude T waves. This algorithm is improved by a windowing temporal analysis, from which, the max value in each window locates perfectly the R-peak, (as shown in figure 5).

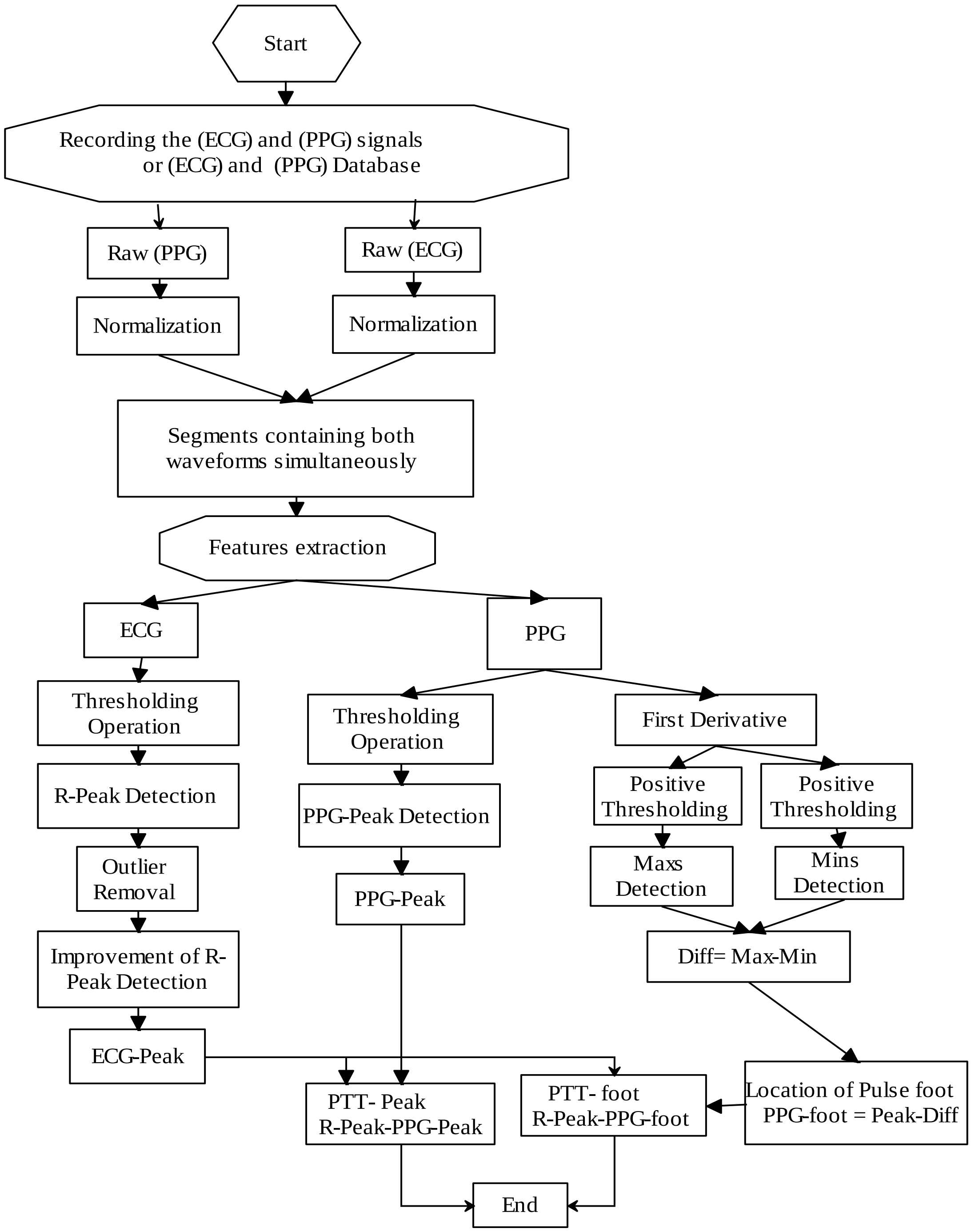

Figure 3. The algorithm developed for the (PTTs) (PTT-f and PTT-p) detection

3. RESULTS AND DISCUSSION

Peaks Detection

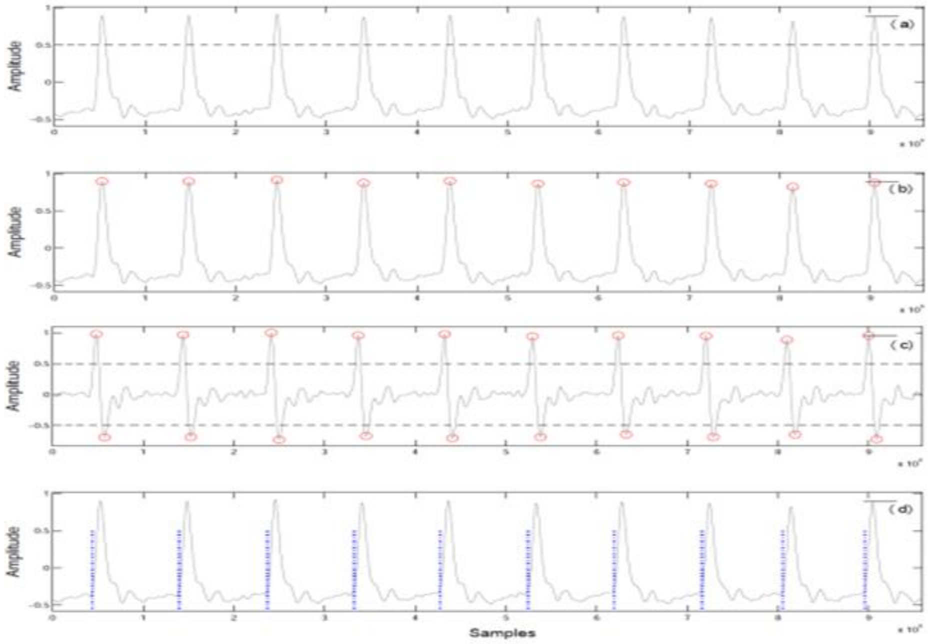

Figure 4. Localization result of (PPG-foot) and (PPG-peak). (a): normalization and thresholding operation, (b): (PPG-Peak) detection, (c): the first derivation of (PPG) signal and detection of local maxima and minima, and (d): (PPG-foot) localization

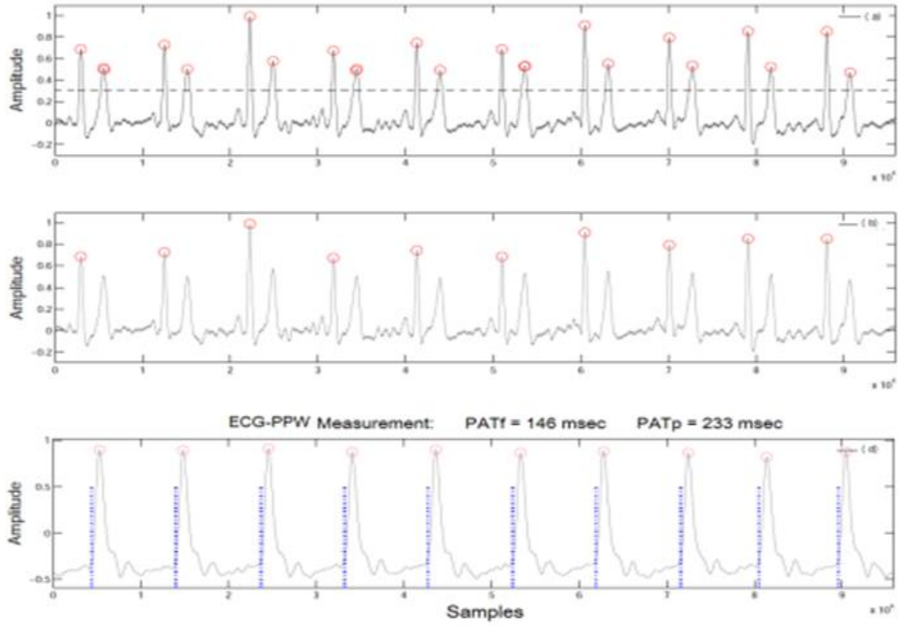

Figure 5. (ECG) processing and measurement of (PTT) foot and peak, (a): normalization, thresholding operation, and all local maxima detection, (b): improvement of R-peak detection, (c): measurement of (PTT-foot), and (PTT-peak)

Experimental results of the proposed algorithm are evaluated in terms of sensitivity (SEN) and accuracy (ACC) given by equations (2) and (3), respectively. Where TP (true positive) is the number of peaks (or feet) correctly recognized, FN (false negative) is the number of peaks (or feet) missed, and FP (false positive) is the number of false peaks (or feet) recognized as true.

$$SEN = TP/(TP + FN) \times 100\% \quad (2)$$
$$ACC = TP/(TP + FN + FP) \times 100\% \quad (3)$$

Where TP (true positive) is the number of peaks (or feet) correctly recognized, FN (false negative) is the number of peaks (or feet) missed, and FP (false positive) is the number of false peaks (or feet) recognized as true.

Table 1 shows the accuracy and sensitivity values of the algorithm. The total beats recorded over all subjects were 719 beats with an average of 24±9 beats. In the case of R-peak detection (ECG-p), the algorithm fails to detect 23 beats (18 FN beats and 5 FP beats) out of 719 beats. The average (SEN) and (ACC) of R-peaks detection were 97.5%, and 96.82% respectively. In the case of PPG-peak detection, the algorithm fails to detect 17 beats (16 FN beats and 1 FP beat) out of 719 beats. The average (SEN) and (ACC) of PPG-peak detection were 97.77%, and 97.64%, respectively. In the case of PPG foot detection, the algorithm mislocated 54 beats (12 FN beats and 32 FP beats) out of 719 beats. The average (SEN) and (ACC) of (PPG- foot) detection were 98.33%, and 94.14%, respectively. Obtained results show satisfactory performances on the records. We note that only the correct detections are used in this study.

Table 1. Detection results of the algorithm.

Total beats=719(Avg=24±9 beats)					
	TP	FN	FP	Accuracy%	Sensitivity%
ECG-p	701	18	5	96.82	97.50
PPG-p	703	16	1	97.64	97.77
PPG-f	707	12	32	94.14	98.33

4. CONCLUSIONS

In this study, we introduced a new algorithm (PTT) that is considered to be very useful for studying cardiovascular diseases. A parameter of major importance in the prevention of cardiovascular diseases, in particular arterial aging and hypertension. The collected data were processed for PTT estimation. We obtained the (PTT- foot) and (PTT- peak) from both (ECG) and (PPG) signals. A number of statistical measures were employed in the studies, with the objective of evaluating performance, the sensitivity of false positives (FP), false negatives (FN), and true negatives (TN), which produced good results.

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AUTHORS

Radjef Lilia PhD student in Biomedical Instrumentation at M'hamed BOUGARA University of Boumerdes, Department of Electrical Systems Engineering Member of the Biomedical Instrumentation Laboratory (Laboratoire de L'Iinstrumentation Biomédicale) research team