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Improvements on Signal Processing Algorithm for the VOPITB Equipment

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Abstract. The pulse signal obtained non-invasively through an oscillometric method can accurately measure the Cardio-Ankle Vascular Index (CAVI) and Pulse Wave Velocity (PWV), two valuable physiological markers of arterial stiffness and cardiovascular health. The VOPITB device is designed to obtain these markers whose accuracy heavily depends on the correctness of feature extraction from pulse wave signals. Typically, a threshold method is obtained, leading to excessive detection success dependency on the established level. To overcome this limitation two signal processing methods are proposed, one based on a modified version of the Pan-Tompkins algorithm and the other centered on a Wavelet approach. A statistical study is presented assessing the accuracy of both methods. The new algorithms are presented as an alternative to the simple thresholding method.

Keywords: CAVI; Signal Processing; Pulse Wave Velocity; Wavelet Analysis

1 Introduction

In the last decades, the morbidity and mortality from Cardiovascular Disease (CVD) have been decreasing [1]. Despite this progress, CVD continues to be one of the main causes of death worldwide [2]. Strategies for the early detection of vascular disease may be the key to prevent CVD.

Arterial stiffness is an indicator of vascular disease and has been recognized as a crucial component in cardiovascular risk assessment since it precedes hypertension, target organ damage, and has been associated with cardiovascular mortality and morbidity [3]. The arterial stiffness can be evaluated with the Pulse Wave Velocity (PWV) and Cardio-Ankle Vascular Index (CAVI). The PWV is considered the gold standard for measuring arterial stiffness and has been recommended by the European Society of Cardiology and the European Society of Hypertension to evaluate asymptomatic organ damage in hypertensive patients [4]. CAVI is an alternative marker of arterial stiffness that overcomes some of the PWV disadvantages, due to its independence from the blood pressure level and its high reproducibility and sensitivity [5].

The VOPITB equipment (Velocidad de Onda de Pulso Índice Tobillo Brazo – Pulse Wave Velocity Index Ankle-Brachial) [6] has been validated to measure the PWV and CAVI indexes [7][8]. This device registers the pulse wave by placing cuffs and electrodes on the ankle and arm. The pulse wave is created by the interaction of the cardiac contraction and the distensibility of the arterial walls. The arteries expand due to the increased blood volume caused by the cardiac contraction and when the elastic energy produced throughout the distension is released, the arteries contract. For that reason, the arteries have a regular pulse called the pulse wave [9].

In the analysis of the pulse wave obtained from the VOPITB cuffs, it is crucial to have a correct identification of key points to accurately determine the PWV and CAVI. Some studies have been published regarding this subject. Jang *et al.* [10] developed a method for pulse peak determination that was tested in Digital Volume Pulse signals. A true detection rate of 97.32% was achieved with a normalized error rate of 0.18%. Vadrevu *et al.* [11] studied three pulse peak methodologies in photoplethysmogram (PPG) signals. An overall accuracy of 99.43%, 87.45% and 52.89% was achieved for the multiscale sum algorithms, Hilbert transform and pulse waveform delineator, respectively. Argüello-Prada [12] proposed the mountaineer's method for peak detection in PPG signals. Three datasets were analyzed in which the algorithm sensitivity ranged from 97.72% to 99.48% and presented a failed detection rate between 0.86% and 5.92%.

The goal of this work was to overcome the limitations of the previous VOPITB detector by combining a modified Pan-Tompkins algorithm and a wavelet-based detector.

2 Contribution to Life Improvement

One of the main objectives of CVD primary prevention should be the identification of asymptomatic individuals to decrease clinical symptoms and the progression of the disease. The evolution in technology is crucial to the development of new parameters for CVD assessment. The PWV and CAVI are non-invasive markers of arterial stiffness with promising clinical value that can be applied in risk population as well as in asymptomatic patients. The correct determination of these markers relies on the accurate identification of signal peaks.

3 Methods

The CAVI index calculation is given by [13]:

$$CAVI = \frac{2\rho}{\Delta P} \left(\ln \frac{Ps}{Pd} \right) PWV^2. \quad (1)$$

where ρ is the blood density, ΔP is the pulse pressure, Ps is the systolic blood pressure and Pd is the diastolic blood pressure. The PWV is given by [13]:

$$PWV = \frac{L}{T}. \quad (2)$$

$$T = t_b + t_{ba}. \quad (3)$$

where L is the length from the origin of the aorta to the ankle, T is the time taken for the pulse wave to propagate from the aortic valve to the ankle, t_b is the time between the rise of the brachial pulse wave and the rise of the ankle pulse wave, and t_{ba} is the time interval between aortic valve closing sound and the notch of brachial pulse wave [13]. The assessment of these parameters is achieved by the analysis of the pulse wave signal.

The Pulse Wave Signal (PWS) shown in Figure 1 contains the three points necessary to evaluate the PWV and CAVI. Those points are the onset mark, the systolic peak followed by a minimum notch. The accurate detection of these three points, which may be challenged by the natural PWS variations and motion artefacts, is crucial for the CAVI and PWV correct evaluation. Two methods are presented: the modified Pan-Tompkins ECG algorithm [14] and a Wavelet-based detector [15]. The Pan-Tompkins

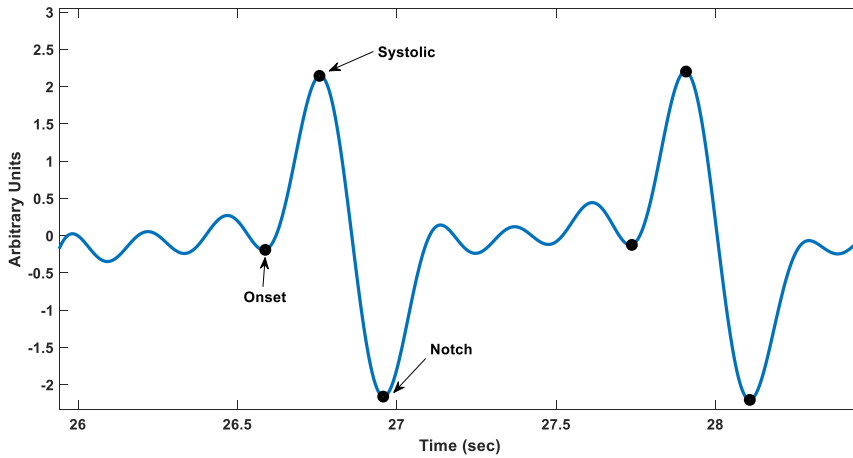


Fig. 1. A PWS showing the three relevant points to be detected: onset, systolic and notch.

algorithm has been successfully used in the R-waves detection of the ECG and is a de-facto standard method for this task. Adaptations were introduced to address the PWS parameters such as its lower frequency band [16]. The notch point was obtained as the local minimum between two successive systolic points, and the onset point was obtained using a slope detection methodology. Both the notch and the onset points correct localization depends on the detection accuracy of the systolic point. A signal pre-processing step is included with the application of a filter with passband between 0.4 to 4 Hz. A detrending and trimming procedure was then applied. The flowchart of the global process is shown in Figure 2. The Wavelet detector is based on an adapted version of the R-wave peak detector introduced by Sahambi *et al.* [17]. An adjustment in the calculation of the optimal wavelet level for the algorithm input is made by obtaining the respective wavelet scale using:

$$S = Fc / (Fp \times \Delta), \quad (4)$$

where Fc is the central frequency of the selected wavelet, Δ is the sampling period and Fp the central frequency of the PWS band. Having in consideration that the bandwidth of the PWS extends from 0.4 to 4 Hz a $Fp = 2$ Hz is selected which, with $\Delta = 1/200$ seconds produces wavelet scale equal to 25 equating to the closest wavelet level of 5. The selected wavelet was the Mexican hat given its similarity with the signal under study. An adaptive thresholding methodology is applied to the wavelet coefficients in level 5 of the transform after which the systolic point is obtained. The process is represented in Figure 3.

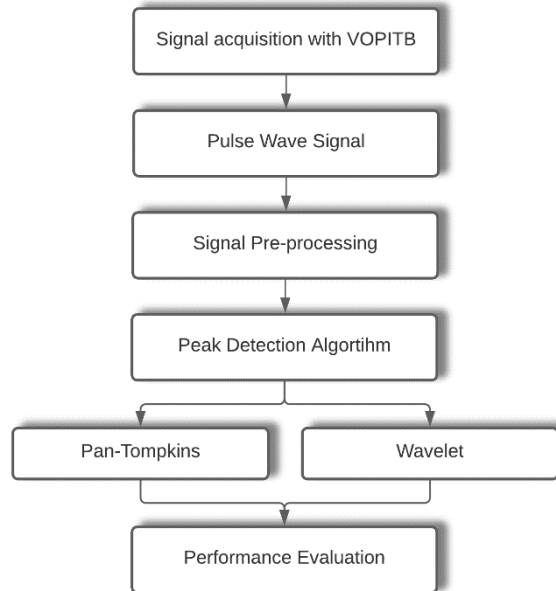


Fig. 2. Methodology description flowchart which includes the modified Pan-Tompkins and wavelet detectors.

For this study, a total of 39 PWS were analyzed from 30 men and 9 women. The Body Mass Index (BMI) ranged from 25.5 to 32.8, with mean of 29.7. All data were analyzed with MATLAB®.

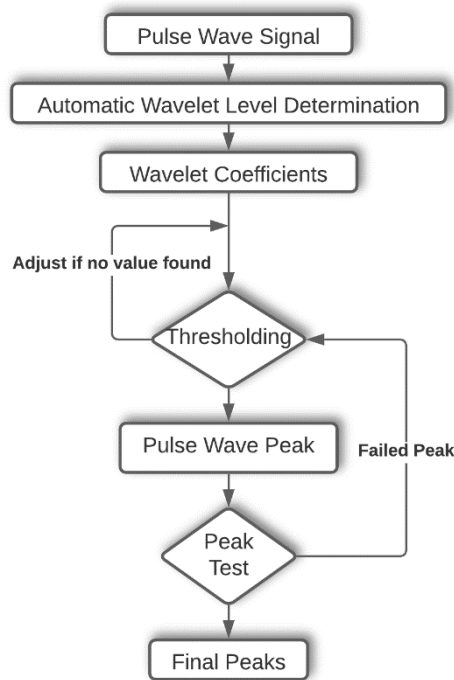


Fig. 3. Wavelet algorithm description flowchart. See text for details.

4 Results

The proposed algorithms were evaluated using the mentioned dataset. The results represented in Table 1 show that the wavelet algorithm outperforms the Pan-Tompkins' in all the detected points. Moreover, as expected, the similarity between the obtained sensitivities in the three studied points is patent since the fiducial systolic point is the key mark for the localization of the two other points. The better results in the wavelet algorithm can be explained by the good correlation between the Mexican hat used wavelet with the PWS and due to the denoising operation implied by the selection of one wavelet level only. Comparatively, the above-mentioned studies present better sensitivity outcomes. However, this comparison should be made with caution since different datasets may produce nonequivalent results due, for instance, different present

noise levels. Computationally both algorithms are equivalent as far as complexity is concerned. Regarding computational load the Pan-Tompkins algorithm is roughly 1.5 times faster than the Wavelet algorithm. For an AMD platform, 32 GB and Windows 10 the average processing time for a one minute record is 300 milliseconds. Figure 4 illustrates the detection results for a signal of the used dataset.

Table 1. Evaluation of Pan-Tompkins and the Wavelet-based algorithm performance in the PWS

	Pan-Tompkins Sensitivity (%)	Wavelet Sensitivity (%)
Systolic	84.06	93.67
Notch	82.89	93.32
Onset	83.15	91.65

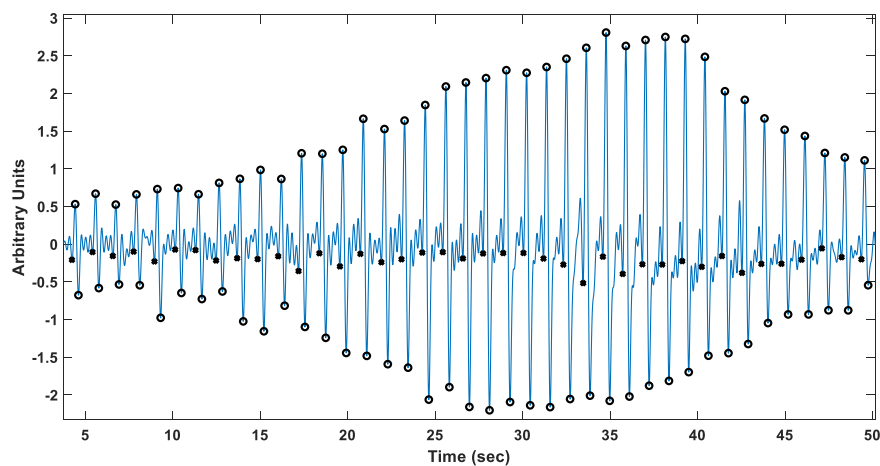


Fig. 4. Example of PWS from the used dataset where all the peaks are correctly identified using the wavelet-based algorithm.

5 Discussion and Conclusion

The calculation of the PWV and the CAVI rely on the accurate localization of three main features in the PWS: the onset, systolic and notch points.

Some studies [11] [12] presented different peak determination algorithms for the PPG signal, such as the mountaineer's method. The accuracy of the systolic peak detection presented in this work (93.67%) is comparable to the Jang *et al.* [10] and Argüello-Prada [11] results, 97.32% and 97.72%, respectively. Despite the similar

nature of the PWS and PPG, one must keep in mind that the recording sensor for these signals is different.

Commonly, a challenging thresholding technique is applied for the detection of these points with poor results due to the natural signal variability and amplitude between subjects. Two algorithms for the localization of these points are presented. The wavelet-based method demonstrated to produce more accurate localization points. The algorithm is adaptive by adjusting the detection rules to the signal amplitude and is also computationally light enough to be easily embedded in real-time systems.

The peak detection is essential for feature extraction in the several biomedical signals. In future work, machine learning methods, such as neural networks, could improve the accurate assessment of crucial futures for prevention and early detection of CVD.

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