A Computational Tool for Quantitative Assessment of Peripheral Arteries in Ultrasound Images

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Abstract

Blood velocity vs. time graphic images, that are based on ultrasound Doppler technique, can be used to reveal relationships between data within them and the presence of cardiovascular diseases, among other applications. In clinical protocols, this kind of study involves, typically, hundreds of patients and a manual and tedious segmentation of the blood velocity curve from the images. In this paper we present a computational tool designed to extract quantitative data from these graphics. The algorithm detects the baseline and the spectrum envelope to calculate peak velocity and velocity-time integral (VTI). A comparative analysis between commercial ultrasound systems and the present methodology included measurements of carotid and brachial arteries and echocardiographic exams. The results showed small bias and high correlation for both: systolic peak velocity (bias = 0.02 m/s; r > 0.998; p < 0.001; n=102) and VTI (bias = 1.25 cm; r > 0.998; p < 0.001; n=75).

1. Introduction

Ultrasound signals have been extensively used in clinical sites, by exploiting Doppler effect to measure vascular blood velocity and flow, among other applications [1,2]. Typically, a spectrum of frequencies related to the different velocities of the blood cells is presented as a curve of velocity vs. time (Figure 1). This information can reveal important relationships between the frequency spectral pattern along the cardiac cycle and the presence of cardiovascular diseases [3,4], among other examples [5,6,7].

Since commercial ultrasound systems are primarily dedicated to get instantaneous data for individual patients, they have, in general, low flexibility to perform large-scale researches. Thus, to make easier this kind of study in clinical protocols involving hundreds of patients, a user friendly computational tool was developed to extract quantitative data from spectral display of Doppler images.

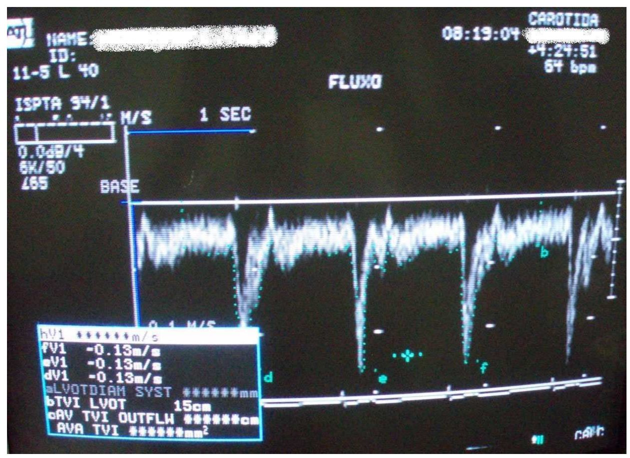

Figure 1. Typical screen of an ultrasound system showing a graphic of vessel's blood velocity vs. time, including amplitude and integral measurements.

The aim of this paper is to describe and evaluate the semi-automatic methodology to detect the spectrum envelope and to measure blood velocity, flow and velocity-time integral (VTI).

2. Methods

The spectral images displayed in the form of blood velocity vs. time graphics were acquired from four different ultrasound system models: a) Apogee 800 Plus (ATL, Bothell, WA, USA) equipped with a 11-5L40 linear transducer (5-11 MHz); b) Cypress™ (Acuson, Mountain View, CA, USA) - 7L3 (5.22 MHz); c) HDI 5000 (Philips/ATL, Bothell, WA, USA) – P4-2 (2-4 MHz) or P5-3 (3-5 MHz); d) Sonos 5500 (HP/Philips, Bothell, WA, USA) – S3 (1-3 MHz) or S4 (2-4 MHz).

To extract blood velocity and flow a new module was added to a previously developed computational tool [8,9], which, given B-mode ultrasound images as input data, was specialized for arterial wall thickness and lumen diameter measurements. An overview of the methodology used in this new module is presented below.

After two steps defined by the user: calibration and selection of the region of interest (ROI), a Gaussian filter (σ=1 pixel, precision$\geq$ 90%) is applied to the grayscale input image to attenuate high frequency noise.

The detection process of the time axis (‘X’) considers that it is exactly in the horizontal direction and their pixel intensities have small variation. Thus, equations (1), (2) and (3) calculates the ordinate ‘y’ expected for the axis ‘X’, which will be the reference (0 m/s) to the velocity calculation.

$$g(i,j)=\begin{cases}\dfrac{1}{\left|I(i,j)-I(i+1,j)\right|+1}, & I(i,j)>z\\ 0, & I(i,j)\leq z\end{cases} \quad (1)$$

$$f(j)=\sum_{i=0}^{m-2} g(i,j), \quad j\in\left[y_{\min},y_{\max}\right] \quad (2)$$

$$y=\left\{j\in\left[y_{\min},y_{\max}\right] \;\middle|\; f(y)=\max f(j)\right\} \quad (3)$$

where:
I(i, j) is the image intensity (grayscale level) at i and j coordinates; m is the image width (in pixels); y_{min} and y_{max} are, respectively, the ordinates of the superior and inferior lines that delimit the rectangular ROI defined by the user; and z = 40 is an empirical pre-defined threshold to reject the graphic background which, in general, has darker colors.

The image is, then, converted to binary values depending on a threshold level (default: 40) that can be adjusted by the user according to his criterion. A Median filter (size: 3 x 3 pixels) is applied to the binary image for edge smoothing and spurious suppression.

The envelope detection step is initialized with horizontal lines at the top and at the bottom of the ROI. Each point of these lines is moved down or up to the border of the binary curve. At last, the algorithm holds either the superior or the inferior contour (Figure 2), assuming that, in general, the desired one has higher amplitude variation.

Finally, after peak detections, the algorithm computes the mean peak velocity, the mean envelope velocity and the VTI. They are displayed in a bar measurements of the tool (Figure 2) and can be exported to a text file.

In addition, if B-Mode images are available, an arterial wall interface detection module determines the vessel diameter and the blood flow can be estimated.

A comparative analysis between ultrasound systems operated by specialists and the present methodology included systolic peak velocities (102 samples) and VTIs (75 samples) of common carotid and brachial arteries under basal condition, brachial arteries in the reactive hyperemic response and echocardiographic exams.

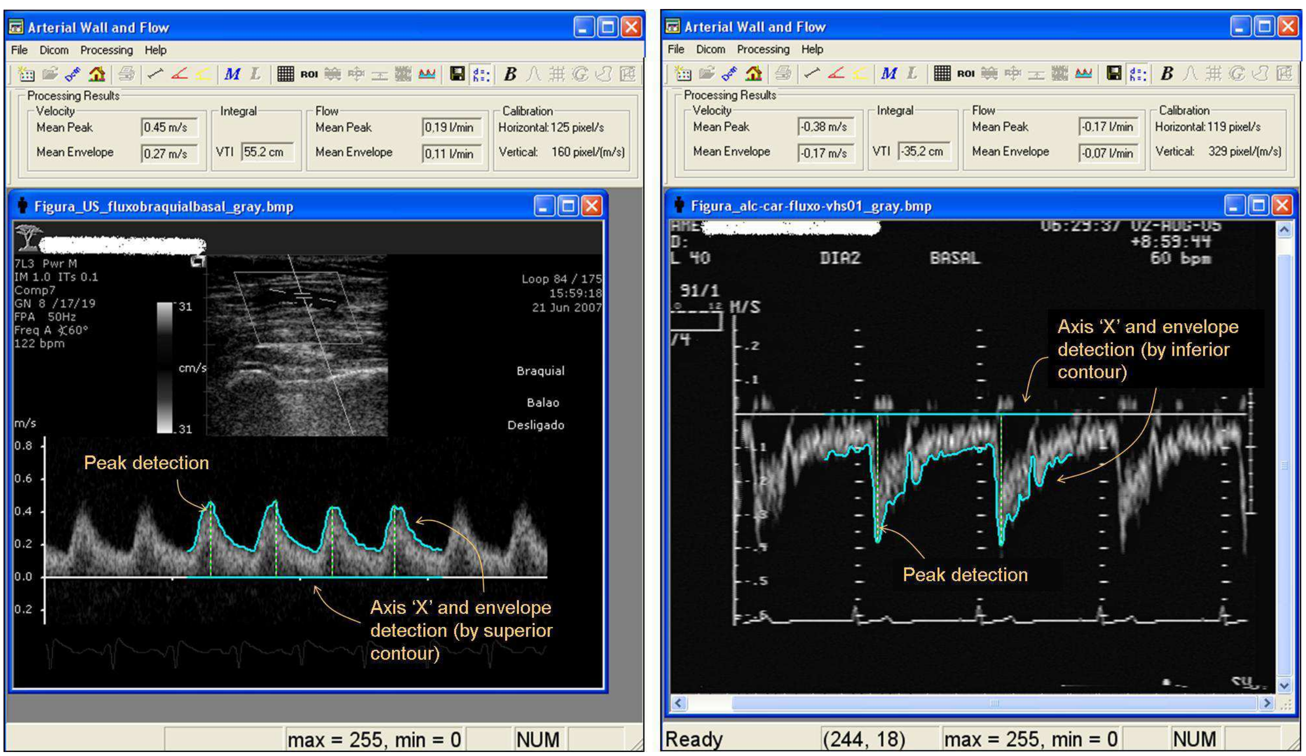

Figure 2. Detection of the axis ‘X’, envelope (by superior or inferior contour) and peaks.

3. Results

According to the adopted procedure, the peak velocities measured from the carotid artery were negative (average: -0.59 m/s), while from the brachial artery under basal condition as well as in the reactive hyperemic response, the peak velocities were positive (averages: 0.63 m/s and 1.18 m/s, respectively). In the echocardiographic images the measurements were either positive or negative and the average of the absolute values was 1.48 m/s.

Similarly, positive or negative VTIs were dependent on the exam type. However, the number of cardiac cycles used to get these measurements was not standardized, leading to a range of the samples, from -150 to 91 cm.

Figure 3 shows Bland-Altman's [10] and Linear Regression graphics for the systolic peak velocity analysis, where 'A' refers to the measurements done with a commercial ultrasound system and 'B' refers to the proposed methodology.

Bias, standard-deviation, correlation coefficient, and linear equation results are presented in Table 1. Like peak velocity, Figure 4 and Table 2 were obtained for VTI's analysis.

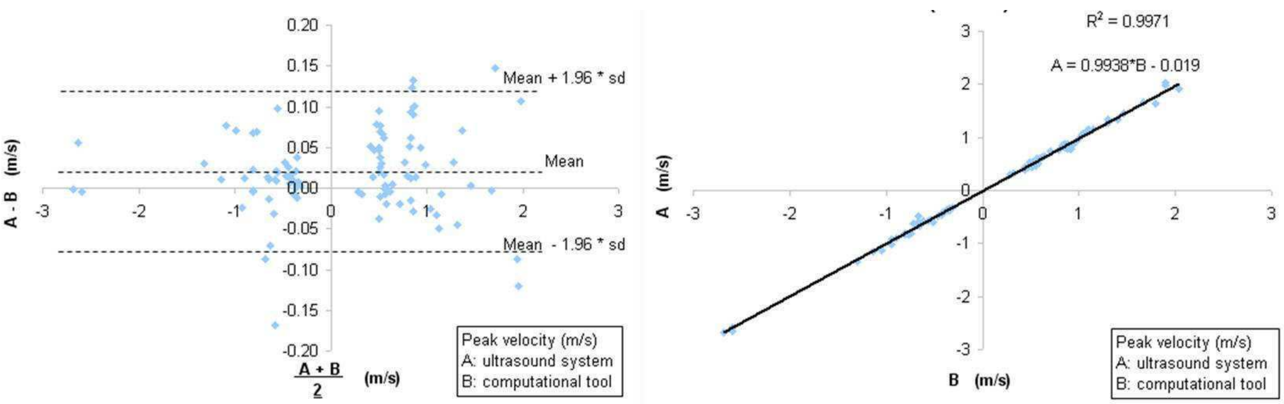

Figure 3. Bland-Altman's (left) and Linear Regression (right) analysis of the systolic peak velocity (102 samples) measured by the ultrasound system and by the proposed methodology.

Table 1. Summary of systolic peak velocity statistics.

Systolic Peak Velocity (N=102)			
Bias (m/s)	sd (m/s)	r_{AB} ($p<0.001$)	Linear Regression Equation
0.02	0.05	0.9985	A = 0.9938*B – 0.0190

Table 2. Summary of VTI statistics.

VTI (N=75)			
Bias (cm)	sd (cm)	r_{AB} ($p<0.001$)	Linear Regression Equation
1.25	3.86	0.9984	A = 1.030*B – 0.9287

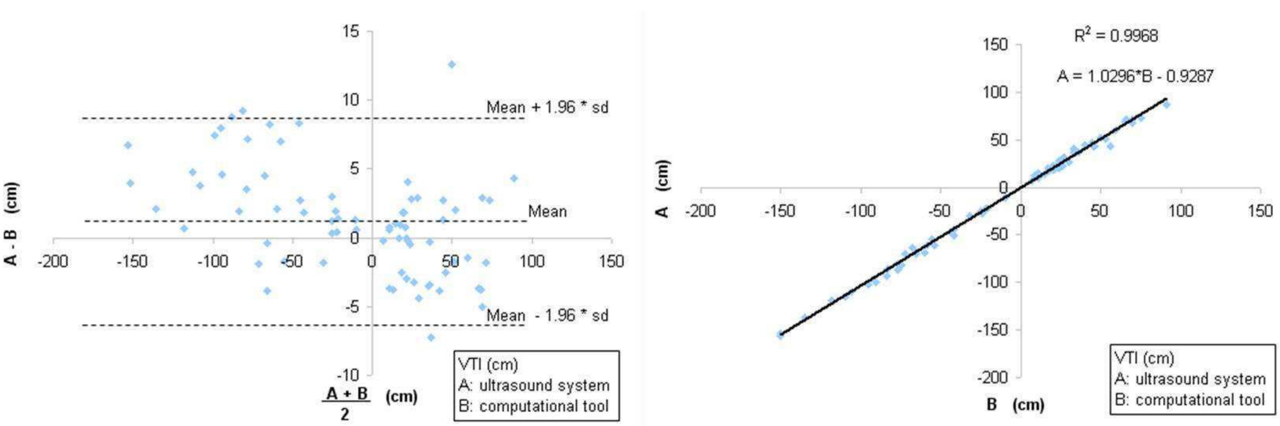

Figure 4. Bland-Altman's (left) and Linear Regression (right) analysis of the VTI (75 samples) measured by the ultrasound system and by the proposed methodology.

4. Discussion and conclusions

The small bias and high correlation for both, peak velocity and VTI, indicate the reliability of this methodology and these findings are better than those presented by Tschirren et al. [11] (bias: 0.40 m/s for peak velocity and 7 cm for VTI), though their results refers to a dilatation study of the brachial artery, where data values were about ten times higher than the present study.

It is important to note that for VTI statistics shown in Table 2, the threshold used to get the binary image was 60, instead of the default 40 used to extract the systolic peak velocity. This change was motivated by the higher bias (1.70 cm) and standard deviation (6.78 cm) obtained with the default value for VTI.

Despite these numerical results, it is not possible to conclude that the threshold of 60 is more appropriate than 40, since the human operation to get measurements using the ultrasound equipment may also be subject to systematic errors and deviations. For instance, visual results showing the envelopes drawn on the blood velocity graphics point that, by using the proposed methodology (Figure 2), the envelope line is more refined than that obtained by manual operation of an ultrasound system (Figure 1), because in the latter, the user does not notice or, simply, disregards small image brightness variations, which means that this procedure is highly dependent on the user's subjective evaluation and it is hardly reproducible.

By processing diversity of common carotid, brachial and echocardiographic Doppler image samples, collected from four different commercial ultrasound systems, the methodology implemented in this tool to measure velocity and VTI was validated by the Bland-Altman's analysis and by the correlation coefficient. Visual analysis also confirmed that the spectrum envelope detection is very satisfactory.

The user friendly graphical interface combined to the semi-automatic characteristic of this tool intends to help the clinicians for their studies based on Doppler ultrasound images, with the following advantages: to save operational time, to lower subjective results, and to support measurement reproducibility.

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