Non-invasive Technique for Determining Local Pulse Wave Velocity in Humans Ascending Aorta

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Abstract

Background: Pulse wave velocity (PWV) is a measure of arterial stiffness and widely used as a predictor of cardiovascular risk. Local PWV (lPWV) can be calculated non-invasively using the ln(D)U-loop method.

Aim: To develop a novel non-invasive technique for the determination of lPWV in human ascending aorta.

Methods: 13 healthy volunteers (19-33 years, 6 females) were studied using ultrasound (GE, Vivid E95) with a 1.5–4.5 MHz phased array transducer.

M-mode in the parasternal long axis view was used for diameter measurements, Pulsed Wave Doppler ultrasound in the apical 5 chamber view was used for blood velocity measurements in the ascending aorta. Diameter and flow were measured sequentially.

The ln(D)U-loop method was used to determine lPWV, and the SphygmoCor Xcel (AtCor Medical, Australia) was used to measure carotid-femoral PWV (cfPWV).

Results: Mean lPWV using ln(D)U-loop was 3.6±0.7 m/s with higher values for men compared to women. The results showed that lPWV was systematically lower than cfPWV.

Conclusions: lPWV can be measured non-invasively at the ascending aorta by ultrasound with sequential recordings of diameter and velocity using the ln(D)U-loop method.

1. Introduction

High pulse pressure resulting from increased arterial stiffness is an important risk factor for cardiovascular disease. Arterial stiffening occurs not only with age but also with cardiovascular diseases.

Arterial stiffening is commonly assessed by measuring pulse wave velocity (PWV). PWV has traditionally been measured non-invasively using the foot-to-foot method which principally relies on detecting the pressure pulse at two different arterial locations that are at a known distance apart, such as carotid-femoral PWV [1]. More recent techniques allow the measurement of PWV locally [2], although they require invasive measurements of pressure and flow. Recently, a non-invasive technique was developed which requires the measurement of diameter deformation and blood velocity [3].

Experimental testing of this method using ultrasound measurements of diameter and velocity have only been carried out in the superficial arteries such as carotid and femoral [4].

The aim of this study was to show the feasibility of measuring non-invasively local PWV in the ascending aorta of humans, a location that comprises a substantial part of total arterial compliance [5].

2. Methods

Ultrasound images were obtained from healthy volunteers. Off-line analysis of the images was used to determine the PWV.

2.1. Study population

13 volunteers, 6 females, aged 19 - 33 years old, were scanned in the echocardiography laboratory at Brunel University London, with an ultrasound system, GE Vivid E95. Healthy volunteers were recruited from university students and staff. The study protocol was approved by the local ethics committee and written informed consent was obtained prior to measurements.

2.2. Data acquisition

Ultrasound images were obtained with a phased array transducer, 1.5–4.5 MHz, in the parasternal long axis view (PLAX) for diameter measurements and apical 5 chamber view (A5CH) for velocity measurements. The ascending aorta (AO) was scanned by placing the M-mode scanning line just downstream of the sino-tubular (ST) junction. The blood flow velocity was measured with pulsed wave Doppler (Doppler PW) by placing the sample volume in

the ascending aorta's location.

The ECG was recorded with both measurements. The volunteers were scanned in left lateral decubitus position. Each recording was acquired for ~20s and the measurements were repeated 3 times with the operator resting their hand between acquisitions. Dicom images were exported for offline analysis.

cfPWV was measured with SphygmoCor Xcel where the cuff was providing the femoral waveform while the tonometer, hand-held by the operator, provided the carotid waveform. The measurements were repeated 3 times and the values averaged.

2.3. Image analysis

An in-house algorithm was developed in Matlab to read the dicom recordings, analyze the images and obtain the continuous waveforms of flow velocity and wall diameter at the measurement location, ascending aorta.

After reading the dicom files, the frames were concatenated to have one image that included all the heart-beats recorded.

The R-wave of the ECG was automatically detected by finding the peaks in the signal. The timing of the R-waves was used to separate individual heart-beats.

To detect the lumen diameter waveform over a single cardiac cycle the code used an initial grey-scale thresholding based on brightness. Because the brightness for each recording and each person scanned can vary due to different machine settings (i.e. optimized image gain), a user-defined threshold was allowed to ensure appropriate tracing of the walls. The thresholds used for diameter are independent of each other for top and bottom vessel walls. The subtraction of the position of the two walls yielded the diameter waveform (fig. 1).

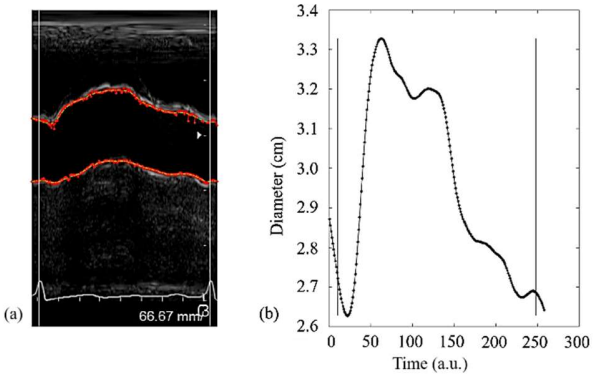

Fig. 1. (a) M-mode ultrasound image of the ascending aorta over one heart-beat showing the tracing of the luminal side of the near and far wall that the code achieves (red points) and concurrent ECG, vertical white lines. (b) The resultant diameter waveform and the peaks of the successive ECG R-waves shown as vertical black lines.

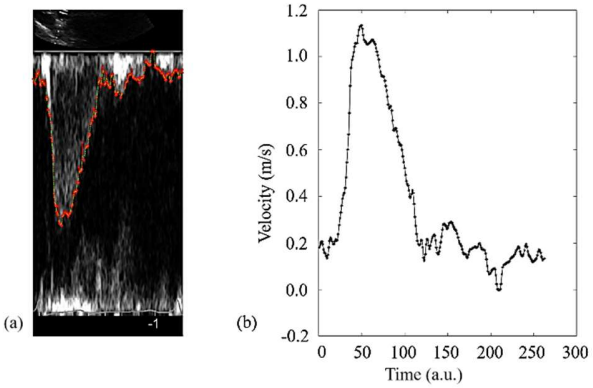

Fig. 2. (a) PW Doppler echocardiographic image of one heart-beat of the velocity in the ascending aorta and the tracing that the code achieves (red points). (b) The blood velocity tracing.

Similarly, the user-defined thresholding technique was used for determining the velocity (fig. 2).

After thresholding, the code displayed both the diameter and the velocity images next to the resulting waveforms (figs. 1, 2). The user was asked to decide if the images were traced appropriately and if so, these were used for further analysis.

The next step of the algorithm was to compute ln(D)U-loops for all the accepted diameters and velocities and to extract the PWV from the initial linear part of each loop (fig. 3). The upstroke for both the velocity and diameter (red points in fig. 3 on both diameter and velocity waveforms) was determined as described previously [6]. The slope of ln(D)U-loop was automatically calculated from the upstroke of the two waves up to 2/3 of the maximum velocity. This duration was chosen to ensure the absence of reflected waves during this period.

$$PWV = \frac{1}{2}\frac{dU}{dln(D)} \qquad (1)$$

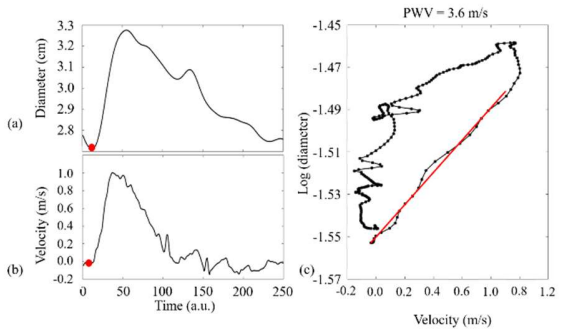

Fig. 3. (a) Diameter waveform as extracted from M-mode images as described in fig.1. (b) Velocity waveform as extracted from pulsed wave Doppler images as described in fig.2. The red points represent the starting points of D and U where the upstroke is, aligned for a best estimate of PWV. (c) ln(D)U-loop and the linear part fitted (red line) from which the PWV is extracted.

Each 20s recording of accepted diameters matched with each 20s recording of accepted velocities yields a matrix of PWVs. A mean PWV is calculated from all these matrices.

3. Results

Table 1. Age, mean and standard deviation for lPWV and cfPWV of each participant included in the study.

	Age	Sex	lPWV	cfPWV
Participant 1	26	F	3.7±0.79	4.6±0.09
Participant 2	30	F	3.2±0.12	5.7±0.21
Participant 3	29	F	4.0±0.62	4.6±0.14
Participant 4	29	M	4.2±0.64	6.3±0.28
Participant 5	20	F	3.2±0.51	4.8±0.05
Participant 6	32	F	3.7±0.97	5.2±0.25
Participant 7	23	M	3.8±0.63	6.3±0.09
Participant 8	24	M	3.2±0.55	5.9±0.08
Participant 9	22	M	3.8±0.64	7.3±0.05
Participant 10	25	F	3.4±1.0	5.5±0.21
Participant 11	28	M	5.2±1.36	5.7±0.12
Participant 12	28	M	3.6±0.59	6.0±0.08
Participant 13	33	M	2.0±0.12	7.2±0.28

lPWV measured non-invasively in the ascending aorta of 13 young healthy volunteers has an average value of 3.6±0.7m/s with an average value for women of 3.5±0.3m/s (age range 19 to 32) while for men 3.7±1m/s (age range 22 to 33 years old). cfPWV was 5.8±0.9m/s with (5.2±0.4m/s for women and 6.4±0.6m/s for men; fig. 5). The individual values as well as the volunteers' age are shown in Table 1.

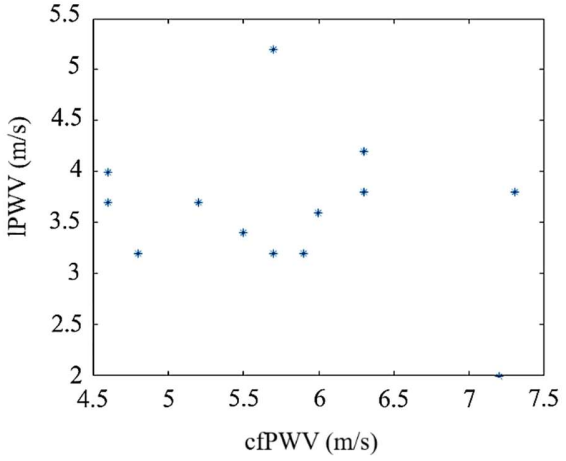

Fig. 4. lPWV plotted against cfPWV.

Bland-Altman plots (fig. 6) showed a bias between the two measurements of 2.16 m/s and limits of agreement of 4.64.

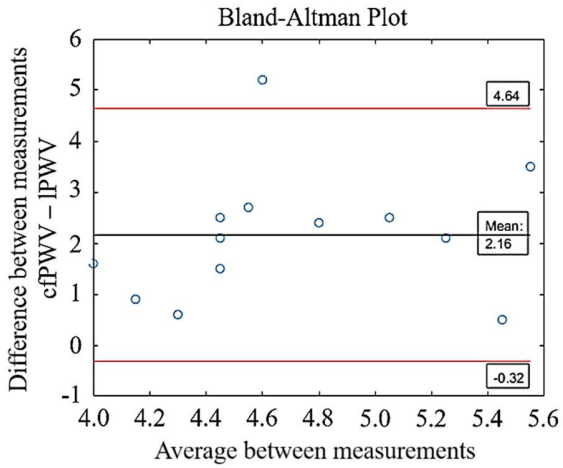

Fig. 5. Bland-Altman plots of the two measurements, lPWV and cfPWV with limits of agreement.

4. Discussions

PWV, as a measure of arterial stiffness, can be measured locally and non-invasively in the ascending aorta of humans. This can be achieved by recording diameter and velocity waveforms in echocardiographic images, then, by the use of ln(D)U-loop, in early systole, when it is assumed reflected waves are absent, the slope of the initial linear part of the loop can be used in Equation 1 to determine PWV.

The lPWV values determined in this study are in in good agreement with previous studies using MRI [7].

As expected, values of cfPWV are higher than those of lPWV. This is because cfPWV is an average velocity of the wave over the distance between the two measurement sites. Usually wave speed is higher in the more distal circulation, where the arterial bed has smaller diameters and different wall characteristics from the ascending aorta.

Diameter and velocity were recorded sequentially due to the limitations imposed by the anatomy and requirement for the ultrasound probe: being in line with the flow for velocity and perpendicular to the vessel for diameter. Simultaneous recordings of diameter and velocity would be preferred to avoid the heart rate variation during the recordings of diameter and velocity. This is because the interpolation of one signal to match the length of the other one may affect the slope of the ln(D)U-loop. To overcome this limitation, the heart beats with similar length can be chosen in future analysis.

In this study, the PWV is calculated as the mean value when all accepted diameters are matched with all accepted velocities. Another way of calculating PWV is to ensemble average the diameter and the velocity for each recording and calculate mean PWV from ln(D)U-loops. In future analysis both methods can be used for comparison.

The small number of participants as well as the narrow age range where few significant changes are noticed conventionally, makes the change of PWV with age unclear. Further data should be added to the study and the age range increased for a proper evaluation of the trends with age. Also, comparison of ultrasound data with MRI data will follow for validation.

5. Conclusions

lPWV can be measured non-invasively in the ascending aorta of humans by assessing the diameter deformation and the flow velocity waveforms. ln(D)U-loops match the two parameters to extract the PWV. The results of the technique described in this work are comparable to those reported in the literature, indicating the potential use of the presented technique for aortic stiffness assessment.

Acknowledgements

The authors would like to thank BHF (grant no PG/15/75/31748) for financial support.

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