Measurement of the Aortic Pulse Wave Velocity in MRI: Comparison of Transit Time Estimators

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Abstract

The efficiency of a new transit time (Δt) estimator (MSeg) for Pulse Wave Velocity (PWV) estimation is compared with three previously described methods (MUpslope, MFoot, MPoint), in terms of correlation with aging and reproducibility. SSFP and PC acquisitions from 40 subjects (42±15 year), recorded at the level of the aortic arch were studied. Δt was defined as the time shift between the flow curves in the ascending (CA) and descending (CD) aorta and calculated with: 1) MSeg, by minimizing the area delimited by two sigmoid curves fitted to the systolic up-slope of CA and CD, 2) MUpslope, by minimizing the area between the systolic up-slope of CA and the CD curve, 3) MFoot using CA and CD feet, 4) MPoin,t using the half maximum of CA and CD. The MSeg estimator resulted in a higher reproducibility (6%), better correlation of pulse wave velocity with aging (r=0.85), and less overlap between the <40 and ≥40 years groups.

1. Introduction

Magnetic resonance imaging (MRI) is increasingly used for the assessment of the aortic wall stiffness. One of the most reliable indices of the aortic stiffness is the pulse wave velocity (PWV); the speed of propagation of the flow wave in the aorta. The PWV is higher on a stiffer wall and its increase leads to cardiac pressure overload, myocardial hypertrophy [1], and enhance the risk of coronary heart disease [2]. Furthermore, PWV increase with age [3-6]. Indeed, aging is an accepted factor of cardiovascular risk [3], and it is associated with a loss of elasticity of the aortic wall in adulthood even in healthy subject [6-9].

The aortic PWV is commonly calculated in MRI as the ratio between the distance separating two locations of the aorta and the transit time needed for the flow wave to cover this distance. Although the estimation of the distance can be quite easily calculated from MR cine Data, the determination of the transit time is somewhat more difficult. Indeed, due to the wave reflections and damping by aortic wall, the profile of the velocity waves extracted from PC MR data can change and bias the transit time measurements [10]. Several studies described different methods for the aortic PWV estimation using MRI [6, 11-15]. However, the main difference between the proposed methods was the determination of the transit time, and even if the foot-to-foot method is commonly used to calculate the transit time there is no standardized method for the PWV determination.

The aim of this study was to describe a new method (MSeg) for Δt estimation and to compare it with three previously described methods (Mfoot, MPoint, MUpslope), in terms of correlation with aging and reproducibility.

2. Material and methods

2.1. Acquisitions

For this study, 40 volunteers (age: 42 ± 15 years) were recruited. None of the volunteers had any history of cardiovascular event or hypertension. All MR examinations were performed on a 1.5T scanner (Sigma Excite; General Electric Medical Systems, Milwaukee, Wisconsin, USA) using a cardiac phased-array coil and ECG-gated sequences. SSFP and PC cine acquisitions were acquired during apneas for each subject.

For the flow wave extraction, the PC slice was set perpendicular to the axis of the aorta at the level of the bifurcation of the pulmonary trunk. Hence, the ascending and descending aorta could be studied simultaneously. The PC data were acquired using an ECG-gated breath-hold gradient sequence with a velocity encoding gradient in the through-plane direction, which provided phase-related pairs of modulus and velocity-encoded images. The average scan parameters were: repetition time = 9 ms, echo time = 3.5 ms, flip angle = 20°, inter-phase delay = 19 ms, pixel size = 1.58 mm × 1.58 mm, slice thickness = 8 mm, and encoding velocity = 200 cm/s.

For the 3D aortic length measurements, axial and coronal sequences covering the whole aortic arch were acquired according to the SSFP sequence using the following average scan parameters: field-of-view = 370 mm ×370 mm, repetition time = 3.2 ms, echo time = 1.4 ms, flip angle = 50°, slice thickness = 8 mm, pixel size = 1.65 mm × 1.92 mm, and inter phase delay = 33 ms. Fig. 1 shows an example of the acquired sequences.

2.2. MR image analysis

To extract ascending and descending aorta flow curves, aortic lumen contours were segmented along the cardiac cycle from the modulus of the PC images using the Art-FUN software package as described in a previous work [16]. Contours were then superimposed on the velocity-encoded images.

The aortic arch PWV was calculated as the ratio between the 3D length of the aortic arch, and the transit time (Δt) between the velocity waveforms in the ascending and descending aorta. To estimate the 3D length of the aortic arch, the centers of the aortic lumen were first selected by the user on each cine axial and coronal slices in a 3D Coordinate-System. Six to eight markers were defined for the ascending and the descending segment using axial slices, and three markers were defined for the top of the aortic arch using coronal slices. The 3D coordinates of the selected centers were computed from the DICOM headers of the MR images, and were interpolated with a 3D Bezier curve. The length of the 3D Bezier curve comprised between the ascending and descending aorta planes defined from the PC images was considered for the estimation of the PWV. The transit time (Δt) was calculated automatically from our method MSeg, and from three different methods MFoot, MPoint and MUpslope described and used in previous MRI studies: in [6, 10]; in [5, 11] [17], and in [18]; respectively.

MFoot method: the MFoot estimated the Δt from the foot of the flow waveforms of the ascending and descending aorta. The foot of the curve was determined by the point yielded by the intersection between the horizontal line passing through the minimum point and the linear regression modelled from the initial systolic up slope of the velocity wave. The regression line was modelled from the velocity values between 10% and 30% of the total range. This method was based on the foot to foot technique which is the most commonly used for the transit time estimation in tonometric studies [19].

MPoint method: the MPoint estimated the Δt from the points where the flow wave of the ascending and descending aorta reached its half maximum.

MUpslope method: the MUpslope estimated the Δt by minimizing the area between the normalized systolic up-slope of the ascending aorta flow curve, and the whole normalized descending aorta flow curve, using a method based on the least squares minimization approach. The flow waveforms were re-sampled to a temporal resolution of 1 ms using a cubic interpolation, and the systolic up-slope was defined as the portion of the flow curve delimited by the minimum and maximum of flow values. Δt was calculated as being the time shift for which the likelihood between the profile of the systolic up-slope of the normalized ascending aorta flow waveform (E_A^*), and the whole normalized descending aorta waveform (E_D) was maximal. This was obtained by shifting E_D by successive temporal translations with a unitary step of 1 ms.

MSeg method: our MSeg method estimated the Δt by using a sigmoid model. First, the systolic up-slope of the normalized flow waveforms in the ascending and descending aorta were respectively fitted to sigmoid model using the least squares minimization approach as shown in Figure. 2. Then, the transit time Δt was calculated as follow:

$$\Delta t = \Delta t_k \,/\, Er(\Delta t_k) = 0 \,.$$

Where:

$$Er(\Delta t_k) = \int_{t_1}^{t_2} \left(Seg_A(t) - Seg_D(t - \Delta t_k) \right) dt. \; \Delta t_k \in \Re$$

Here, Seg_A and Seg_D are the sigmoid models fitted respectively to the systolic up-slope of the flow waveforms in the ascending and descending aorta; t_1 and t_2 are the bounds of the systolic up-slope ascending aorta flow curve.

In our approach, the systolic up-slope was defined as the portion of the flow curve comprised between the point of maximum curvature preceding the systolic peak, and the point of maximum flow.

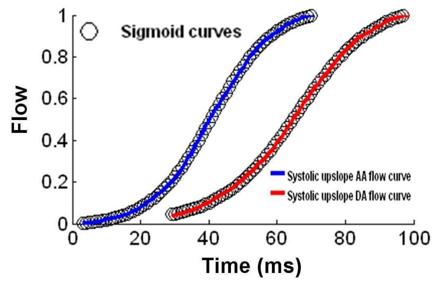

Figure 1. Results of fitting the sigmoid curves to the systolic upslope of both flow waves in ascending and descending aorta.

The estimation of the transit time with the above methods was repeated by two independent operators to assess inter-observers variability.

2.3. Statistical analysis

Comparisons were performed using linear regression and mean +/- standard deviation (SD). For regression analysis Pearson's correlation coefficient (r) was provided. The inter-observer variability was studied using the coefficient of variation defined as the mean of the absolute difference between the two series of measurements divided by the mean of both measurements.

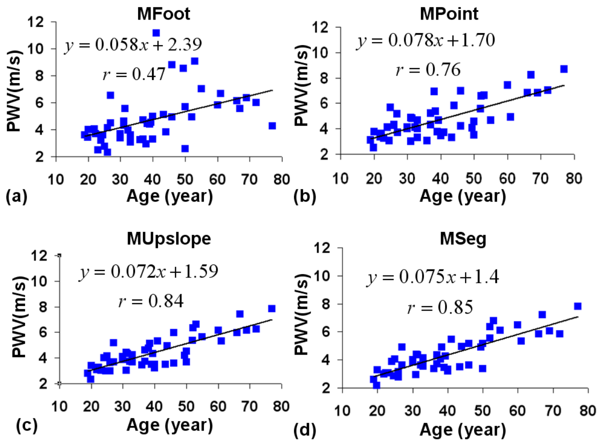

Figure 2. Results Variation of PWV according aging estimated by MFoot (a); MPoint (b); MUpslope (c); and MsSeg (d).

3. Results

Figure1 shows that the regional aortic PWV, calculated with the four estimators of transit time, increased linearly according to aging: the older subjects had the highest values of PWV.

Table. 1 shows the results of the corresponding Pearson's coefficients, as well as the mean +/- SD values of PWV for the two groups: subject <40 years and subject≥40 years. Transit time estimation by two operators demonstrated a variability of 7.45% (MFoot), 6.67% (MPoint), 6.17% (MUpslope), and 6.07% (MSeg).

Table 1. Pearson coefficient and Mean±SD PWV.

		Mean±SD PWV (m/s)		
		Subjects		
Methods of Δt	r	All (n=40)	<40years (n=21)	≥40years (n=19)
MFoot	0.47	4.81±1.78	3.86±0.7	6.11±2
MPoint	0.76	4.97±1.52	4.26±0.94	5.93±1.65
MUpslope	0.84	4.62±1.26	3.89±0.56	5.62±1.28
MSeg	0.85	4.53±1.29	3.74±0.54	5.6±1.25

4. Discussion

The aim of this study was to describe a new method (MSeg) for Δt estimation and to compare it with three previously described methods (MUpslope, MFoot, MPoint), in terms of correlation with aging and reproducibility. Although, all the Δt estimators provided the expected trend in PWV according to aging, our MSeg method resulted in a better correlation with aging, a higher reproducibility, and less overlap between the <40 and ≥40 years groups.

The complex geometry of the aorta with the multiple branches of different mechanical properties along the aortic path generates wave reflections and attenuation that may corrupt the transit time estimation [10], and thus the PWV. Indeed, the shape of the velocity waveform can change due to the wave reflections and damping by the aortic wall. Therefore, velocity waveforms have a physiological widening and a decreasing slope along the aorta tending to artificially lengthen the transit time interval. This could partly explain the differences in the aortic PWV values, assessed by the four methods, and their different evolution with aging.

As the MUpslope method, the MSeg estimated the Δt from the systolic up-slope portion of flow waves. The up-slope portion was preferred to the entire flow curve because of the unidirectional and reflectionless nature of the flow wave during the systolic phase [12]. However, our method differed from MUpslope on two points. First, the systolic up-slope portion was defined using the curvature of the flow curves instead of its minimum. The curvature approach provided a more accurate characterization of the beginning of the systolic phase, and more reproducible results. Second, the MSeg used a sigmoid model, and thus the transit time was analytically calculated. This approach provided a more precise estimation of Δt than by shifting flow curves with a temporal step of 1 ms. The MSeg and MUpslope methods were less sensitive to noise since they avoided the restriction of the analysis to a few characteristics points of the flow curves. Indeed, it minimizes the variability of MFoot and MPoint measurement inherent to low temporal resolution on flow curves. Similar methods for the transit time estimation in MRI have previously been described in [5, 6, 12-14]. The studies as in [6], and in [14] used the foot-to-foot methods. However, these methods differed in the determination of the foot of the systolic upslope of the velocity wave: in [6] the feet of the flow waves was determined from the upslope of the flow waves at the beginning of the systole as in the MFoot method, whereas in [14] the feet of the waves was determined from the systolic upslope between 20% and 80% of the maximum velocity value. The mean value of PWV was found in [6] equal to 4.3±0.7 m/s (age 10-19 years, n=16) and to 7.2±0.2 m/s (age 50-59 years, n=4). Whereas in [14] the mean value of PWV was found to 4.3±0.5 m/s (age: 29±8 years, n=10). The work presented in [5] used the MPoint method for the transit time estimation, and the PWV was found to 3.8±0.7 m/s (age:28±6 years, n=26). Study [13] presented a method for the transit time estimation based on the least squares minimization in considering the whole shape of the flow curves, the mean value of PWV was found to 3.6±0.64 m/s (age: 25±5 years, n=21).

In our study, a 3D approach was used to assess the aortic arch length from both the coronal and axial slices, rather than the traditional 2D measurement which is usually performed from a single sagittal oblique section by a manual definition of the centerline of the aorta [5, 6, 11, 12].The advantage of our 3D technique is its ability to better take into account the 3D geometry of the aorta. Indeed, the curvature of the aortic arch is not always aligned in a specific plane regarding to the position of the ascending and descending aorta.

Age is considered as an important determinant of cardiovascular risk and is an essential factor of aortic stiffness even in healthy subjects [6-9], the results of the PWV measurements were compared to aging. In the present work, aortic PWV increased linearly according to aging, and the results were in good agreement with previous work: the linear correlation coefficient between PWV and age found [6] r = 0.8 (age 10-59 years, n = 20), in [5] r=0.55 (age: 28±6 years, n = 23), and in [7] r = 0.76 (age: 54±15 years, n = 24).

In the present study, the physiological criterion of aging provided a separation between the different estimators of Δt. However, it was also possible to use others criterion for comparison, as the stiffness indices of aortic distensibility and carotid-femoral PWV assessed by tonometry. These studies will be investigated in future works.

In conclusion, the PWV was assessed non-invasively from morphological and hemodynamic MR data using four different estimators of transit time. Our estimator MSeg provided the better correlation of PWV with aging and higher reproducibility.

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