Blood Flow Quantification in the Aorta from MRI

Amjad Khan, Zafar Toshpulatov, Natalia Herrera and Alain Lalande

University of Burgundy

January 16, 2018

Abstract

The pulse wave velocity (PWV) is a significant parameter in blood flow quantification to conduct cardiovascular examinations. For instance, the aortic stiffness can be estimated by measuring PWV; the first one being an important indicator to detect cardiovascular events such as myocardial infarction and stroke, that are two leading causes of death. At present, the blood flow quantification is determined by utilizing the MRI technology. This non-invasive diagnostic technique not only reduces the examination time but also provides higher accuracy in diagnostic and monitoring of a certain cardiovascular event. In this project, two different methods of blood flow quantification by measuring PWV are studied. A detailed analysis has been conducted on the given MRI data of the aortic region. In order to understand the blood quantification process, the PWV measuring part in both methods have been re-implemented in MATLAB environment with help of other image analysis software products and results have been compared.

I. Introduction

Pulse wave velocity (PWV), the rate at which the systolic wave of blood propagates through the vasculature of the body, is a validated indicator for evaluating aortic stiffness over a certain arterial length [1] [2]. A faster PWV is associated to a stiffer aorta [3], therefore, to an increased risk of cardiovascular complications.

Although aortic wall stiffness is mainly an age-related phenomenon, there are also various diseases or disorders which can impact it significantly. In recent years, a great deal of emphasis has been placed on understanding different patient's cardiovascular conditions and help to plan appropriate therapies for their treatment. [4].

This measure of stiffness, PWV, can be obtained non-invasively through cardiac magnetic resonance imaging (MRI). MRI is a non-ionising imaging technique which use strong magnetic fields, radio waves, and field gradients to generate high spatial resolution images of the area of interest. In the case of cardiac MRI, it is used for both morphological assessment as well as the assessment of heart function, providing high level of accuracy and reproducibility [5]. Most of MR studies on PWV are achieved using 2D phase contrast acquisition with plane velocity encoding; in the most basic form, it is calculated as the ratio of distance between two locations (ascending and descending aortic regions) and the arrival of the pulse at these levels [3] [6] [7]. The aim of this project is to analyze and compare two different MRI-based approaches of measuring PWV for blood flow quantification in aorta. The rest of the document is divided into three sections. Section-II is discussing about methodology and implementation. Section-III is presenting the results and comparison. Finally, the document is concluded in Section-IV.

II. Methods and Implementation

In this section two different approaches (as given in the two assigned articles [3] [6]) for PWV calculations are described along their implementation steps.

i. Methodology

In the first article [6], the authors determined two parameters pulse wave velocity (PWV) along the entire aorta and distensibility in four specific points of this artery. Subjects of the study were a group of patients with the Marfan syndrome and a group of healthy volunteers, for comparison purposes. Studies were performed twice, before and after applying a beta blocker therapy; which has shown the ability to reduce the rate of aortic root dilation. To detect significant changes caused by this medication MRI was used. As part of the imaging protocol, patients were placed supine in a 1.5 Tesla magnetic scanner. The parameter of interest, aortic PWV was calculated as $\Delta x/\Delta t$, where Δx is the length between two imaging levels of the aorta and Δt is the time difference between the arrival of the pulse wave. To determine the aortic segment length between the two aortic levels, a sagittally angulated view of the aortic arch was acquired. As mentioned in [6][8], a freehand line tool is used to measure the aortic arch as shown in Figure 1.

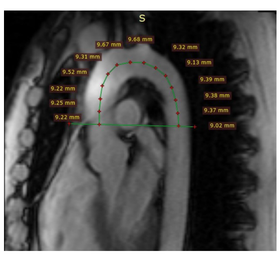


Figure 1: *Sagittal angulated aortic image with manually measured segments for aortic arch length calculation.*

In an axial plane, aortic contours of the ascending and descending aorta are drawn on the modulus images of all cardiac phases, in order to calculate the mean velocity and aortic flow as shown in Figure 2. Flow versus time curves from phase-contrast images were obtained to determine the time delay between the two imaging levels.

In the second article [3], the authors conducted a study on young patients with mutation of the smooth muscle myosin heavy chain to detect early aortic impairment. The study assessed three major parameters, the aortic compliance, aortic distensibility and PWV with the help of MRI. All three parameters were measured semi-automatically from MRI data. As the PWV is the focus of the this project, therefore, the rest of the section will be discussing about the adopted method to calculate PWV in the provided article [3]. For PWV study, the MRI data was acquired using 1.5 Tesla magnetic resonance. The aorta was imaged in the transverse plane at the level of the bifurcation of the pulmonary trunk such that both ascending and descending aortic regions can be studied simultaneously. In order to perform the PWV study in this project, the 60 slices of each velocity encoded and phase encoded images are provided, each one containing both aortic regions as shown in Figure 2.

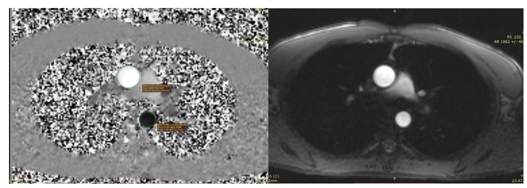


Figure 2: *Velocity encoded image (left) with contoured ascending and descending aortic region of interests with their mean values and phase encoded image (right).*

Each frequency and phase encoded image has repetition time [TR] 28.4 ms, echo time [TE] 2 ms, matrix size 132×192, field of view 68.75 mm, flip angle 30, slice thickness 7 mm, encoding velocity 150 $cm.s^{-1}$. Another single shot consisting of 30 slices of phase encoding images with transverse plane is also provided to calculate the aortic arch length between ascending and descending aorta. It is imaged on transverse plane with TR 269.5 ms, TE 1.4 ms, matrix size 132×192 and slice thickness 6 mm. From the first 60 images, contours of ascending and descending aortas were manually drawn on a selected velocity encoded images where the ascending and descending aortas were clearly defined (Figure 2). These contours defined two regions of interest that were realigned on each velocity encoded image if necessary. The mean signal was calculated within each region of interest, this value being associated to an instantaneous flow velocity.

By considering the whole series of images, we generated a mean velocity waveform versus time for the ascending and descending aortas. The relationship between the mean signal SI in gray level and the instantaneous flow velocity (IF) is provided by Equation [1] for the ascending aorta and Equation [2] for the descending aorta.

$$IF(m.s^{-1}) = ((NV - SI) \times MV)/NV \quad (1)$$

$$IF(m.s^{-1}) = ((SI - NV) \times MV)/NV \quad (2)$$

where NV is the pixel gray value associated with null flow velocity and it is determined as 2048, MV is the maximum flow velocity and 1.5 $m.s^{-1}$ is used. From the IF values, transit time Δt is calculated. In order to calculate the transit delay Δt, the IF values related to ascending aortic region are considered as input signal $x(t)$ and descending IF vector as output $y(t)$. Then both $x(t)$ and $y(t)$ are transformed to Fourier domain by taking FFT for group delay calculation as mentioned in [9] [10].

Similarly, from the given single shot 30 images, the length of the aorta was calculated by manually indicating the center of the aortic region on each slice as shown in Figure 3. The sum of the lengths of the segments defined by the center points (x,y) and slice orientation (z) provide the total length of the aortic arch between the ascending aorta at the level of the pulmonary trunk and the descending aorta at the same level. The total aortic arch length (AL) is calculated using Equation [3].

$$AL(mm) = \sum_{i=1}^{n} [\sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2)} + (z_i - z_{i+1})^2] \quad (3)$$

Finally, the PWV is measured by taking the ratio of aortic arch length (AL) to the transit time Δt as given in Equation [4].

$$PWV(m.s^{-1}) = AL/\Delta t \quad (4)$$

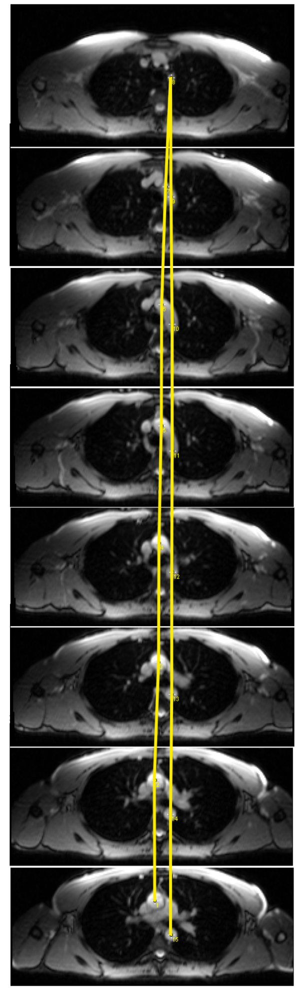


Figure 3: *Indicated points of centers of the ascending and descending aortic regions for aortic arch length calculation as mentioned in [3].*

ii. Implementation

In order to explain the implementation of both methods for PWV measurement, the steps are written in tabular form as shown in Algorithm 1. The steps are explaining to measure two important parameters for PWV calculation, transit time (Δt) and aortic arch length (AL). For the contours generation, the RadiAnt DICOM viewer is used. This software is freely available online to perform DICOM image analysis. On all 60 velocity encoded images of aortic region, the contouring is performed for both ascending and descending aorta (Figure 2). Then in each contoured region, the mean signal values are recorded in the excel sheet as shown in Figure 4. From the mean signal values, instantaneous flow velocity curves for both regions are obtained as in given in Figure 5. In the implementation, the ascending aortic flow curve is considered to be input signal $x(t)$ and descending aortic flow curve as output signal $y(t)$. From the discrete signal analysis, it is observed that each signal is obtained on each trigger time (*tr*). Therefore, *tr* is considered as sampling time of the signal and sampling frequency is calculated. Based on Nyquist theorem, the maximum frequency of the signal is also calculated from sampling frequency. Then both input and output signals are transformed into frequency domain using Fast Fourier Transform (FFT) in MATLAB by considering the total number of samples in each signal.

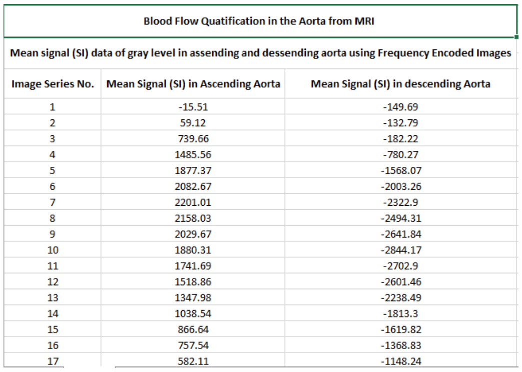
From the transformed version of the input and output signals ($X(j\omega)$ and $Y(j\omega)$) the transfer function ($H(j\omega)$) is obtained. The group delay is calculated after unwrapping the phase of the transfer function. The group delay is the negative first derivative of unwrapped phase with respect to maximum frequency. The ratio of the squared magnitude of the input signal in the frequency domain times group delay and sum of squared magnitude of the input signal gives the transit time (Δt).

In order to calculate the length of aortic arch (AL) for second method, second set, consisting of 30 MRI images of transverse view with both the aortic regions is used. The aortic regions are pointed carefully in the sequence then 8 slices in a sequence are selected based on the visibility of the aortic region. Then (x, y) points are extracted manually with the help of ImageJ software. Also, the orientation of each slice is obtained from the DICOM information and considered as z point (see Figure 6). Euclidean distance between each point gives the segment length and then summation of all the lengths results in the aortic arch length (AL). For the first method, manually drawn length is passed to the function. Finally, PWV is calcuated by taking the ratio of the aortic arch length (AL) to the transit time (Δt).

Algorithm 1 : Calculation of PWV

Get contours in the two ROI (ascending and descending aorta)
Get mean signal (SI) within each region of interest
Calculate instantaneous flow velocity (IF) $x(t)$ *using equation (1) and* $y(t)$ *using equation (2)*
$x(t) \rightarrow$ *IF for ascending aorta*
$y(t) \rightarrow$ *IF for descending aorta*
Perform Δt *calculations:*
    Calculate FFT for $(x(t), y(t))$
    $x(t) \rightarrow X(j\omega)$
    $y(t) \rightarrow Y(j\omega)$
    Determine $H(j\omega) = Y(j\omega)/X(j\omega)$
    Determine $H(j\omega) = Y(j\omega)/X(j\omega)$
    Determine $\angle H(j\omega) = angle(H)$
    $Mag(H(j\omega)) = abs(H)$
    Unwrap $\angle H(j\omega)$
    Get $GD = \frac{-d\angle H(j\omega)}{d\omega}$ *(GD=Group Delay)*
    Calculate $\Delta t = \frac{|X|^2 * GD}{\Sigma |X|^2}$
Perform AL (aortic arch length) calculations:
    Procedure employed in article 1 [6]:
    Manually place the segments to measure AL along a midline through aortic arch
    Procedure employed in article 2 [3]:
    Manually get center points in ascending and descending aorta (x and y)
    Get z = slice orientation
    Get each segment length (SL)
    Calculate $AL = \sum_i (SL_i)$
Calculate $PWV = \frac{AL}{\Delta t}$

The above implementation results in two different MATLAB functions for each method, $getPWVforM1()$ for first method and $getPWVforM2()$ for second method. Each function returns PWV in $m.s^{-1}$ by passing through arguments. For instance, $getPWVforM1()$ requires maximum flow velocity (*mv*, $m.s^{-1}$), pixel gray value associated with null flow (*nv*), trigger time (*tr*, ms) and aortic arch length (AL, mm) whereas $getPWVforM2()$ requires maximum flow velocity (mv, $m.s^{-1}$), pixel gray value associated with null flow (nv) and trigger time (tr, ms) to calculate the PVW.



Blood Flow Quatification in the Aorta from MRI		
Mean signal (SI) data of gray level in assending and dessending aorta using Frequency Encoded Images		
Image Series No.	Mean Signal (SI) in Ascending Aorta	Mean Signal (SI) in descending Aorta
1	-15.51	-149.69
2	59.12	-132.79
3	739.66	-182.22
4	1485.56	-780.27
5	1877.37	-1568.07
6	2082.67	-2003.26
7	2201.01	-2322.9
8	2158.03	-2494.31
9	2029.67	-2641.84
10	1880.31	-2844.17
11	1741.69	-2702.9
12	1518.86	-2601.46
13	1347.98	-2238.49
14	1038.54	-1813.3
15	866.64	-1619.82
16	757.54	-1368.83
17	582.11	-1148.24

Figure 4: *A screen shot of few mean signal values as recorded within each aortic region.*

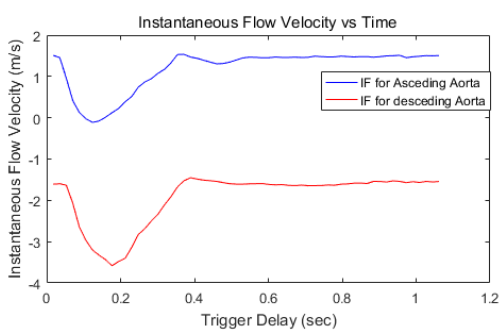
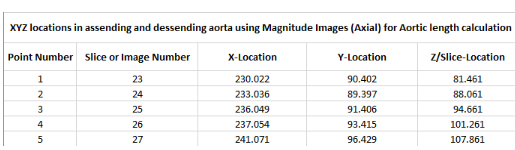


Figure 5: *Instantaneous flow velocity curves of both ascending and descending aorta.*



XYZ locations in assending and dessending aorta using Magnitude Images (Axial) for Aortic length calculation				
Point Number	Slice or Image Number	X-Location	Y-Location	Z/Slice-Location
1	23	230.022	90.402	81.461
2	24	233.036	89.397	88.061
3	25	236.049	91.406	94.661
4	26	237.054	93.415	101.261
5	27	241.071	96.429	107.861

Figure 6: *A screen shot of few extracted x,y and z points for aortic arch length calculation.*

III. Results and Comparison

Upon implementation of both methods in Matlab, the PWV is calculated as shown in Table 1. The only major difference in both methods was to measure the aortic arch length (AL) through different techniques. As described

Table 1: *Calculated parameters in both methods.*

	Implemented Methods	
Parameters	First [6]	Second [3]
Aortic arch length (AL,mm)	121.30	125.12
Transit Time (Δt,ms)	34.30	34.30
Pulse wave velocity (PWV, m.s^{-1})	3.5382	3.6497

in the Section-II, both methods involved in manually measurement of AL. In the first method, it was more straightforward due to the sagittal angulated image, in which user can easily measure the arch length by using the freehand drawing tool with the help of image analysis software. So in the first case the AL is measured around $121.30mm$. Whereas in the second method, AL measurement was a bit complicated procedure. It involved to extract points from each of the aortic regions of interest as well as each slice orientation. Then euclidean distances between the points resulted in total aortic arch length. Therefore, in the second case, the measured AL is around $125.12mm$ which is very close to the value obtained in the first method with a difference of $\pm 3.82mm$. However, the transit time (Δt) calculations were similar in both methods, therefore, $34.3ms$ was calculated as transit time. As the PWV is based on both transit time and aortic arch length, therefore a slight change in the aortic arch length reflected a small change in the PWV value. In the first method the PWV is calculated around $3.5382m.s^{-1}$ while second method resulted in $3.6497m.s^{-1}$. The PWV in both methods has a difference of $\pm 0.1115m.s^{-1}$ that is very close to the value obtained in first the method.

IV. Conclusion

In this project, two different methods to measure the pulse wave velocity in the aortic region using MRI have been studied. Both methods have been implemented successfully in the

MATLAB environment with the help of two other image analysis software such as RadiAnt DICOM viewer and ImageJ. The comparison analysis has been conducted on the results obtained through two different methods. The analysis showed that almost identical parameters have been obtained in both methods with less error.

Acknowledgement

Authors would like to thank Dr. Alain Lalande for his guidance and support to accomplish this project and other faculty members as well as the University of Burgundy for facilitating to learn new techniques and technologies in medical imaging and sensors. Authors are also very much grateful to the European Union for funding MAIA studies under the Erasmus Mundus scholarship program.

References

[1] E. Lehmann, "Biophysical properties of the aorta," *The Lancet*, vol. 344, no. 8939, p. 1763, 1994.

[2] J. L. Cavalcante, J. A. Lima, A. Redheuil, and M. H. Al-Mallah, "Aortic stiffness: Current understanding and future directions," *Journal of the American College of Cardiology*, vol. 57, no. 14, pp. 1511 – 1522, 2011.

[3] A. Lalande, P. Khau Van Kien, P. Walker, L. Zhu, L. Legrand, M. Claustres, X. Jeunemaitre, F. Brunotte, and J.-E. Wolf, "Compliance and pulse wave velocity assessed by mri detect early aortic impairment in young patients with mutation of the smooth muscle myosin heavy chain," *Journal of Magnetic Resonance Imaging*, vol. 28, no. 5, pp. 1180–1187, 2008.

[4] E.-S. H. Ibrahim, K. R. Johnson, A. B. Miller, J. M. Shaffer, and R. D. White, "Measuring aortic pulse wave velocity using high-field cardiovascular magnetic resonance: comparison of techniques," *Journal of Cardiovascular Magnetic Resonance*, vol. 12, no. 1, p. 26, 2010.

[5] K. Dickstein, "Clinical utilities of cardiac mri," *e-journal of the ESC Council for Cardiology Practice*, vol. 6, no. 39, 2008.

[6] M. Groenink, A. de Roos, B. J. Mulder, J. A. Spaan, and E. E. van der Wall, "Changes in aortic distensibility and pulse wave velocity assessed with magnetic resonance imaging following beta-blocker therapy in the marfan syndrome," *The American journal of cardiology*, vol. 82, no. 2, pp. 203–208, 1998.

[7] A. L. Wentland, O. Wieben, C. J. François, C. Boncyk, A. Munoz Del Rio, K. M. Johnson, T. M. Grist, and A. Frydrychowicz, "Aortic pulse wave velocity measurements with undersampled 4d flow-sensitive mri: comparison with 2d and algorithm determination," *Journal of Magnetic Resonance Imaging*, vol. 37, no. 4, pp. 853–859, 2013.

[8] I. Voges, M. Jerosch-Herold, J. Hedderich, E. Pardun, C. Hart, D. D. Gabbert, J. H. Hansen, C. Petko, H.-H. Kramer, and C. Rickers, "Normal values of aortic dimensions, distensibility, and pulse wave velocity in children and young adults: a cross-sectional study," *Journal of Cardiovascular Magnetic Resonance*, vol. 14, no. 1, p. 77, 2012.

[9] I. Bargiotas, E. Mousseaux, W.-C. Yu, B. A. Venkatesh, E. Bollache, A. De Cesare, J. A. Lima, A. Redheuil, and N. Kachenoura, "Estimation of aortic pulse wave transit time in cardiovascular magnetic resonance using complex wavelet cross-spectrum analysis," *Journal of Cardiovascular Magnetic Resonance*, vol. 17, no. 1, p. 65, 2015.

[10] A. Meloni, H. Zymeski, A. Pepe, M. Lombardi, and J. C. Wood, "Robust estimation of pulse wave transit time using group delay," *Journal of Magnetic Resonance Imaging*, vol. 39, no. 3, pp. 550–558, 2014.