



# Segmentation of Phase-Contrast MR Images for Aortic Pulse Wave Velocity Measurements

Danilo Babin<sup>1</sup> , Daniel Devos<sup>2</sup> , Ljiljana Platiša<sup>1</sup> ,  
Ljubomir Jovanov<sup>1</sup> , Marija Habijan<sup>3</sup> , Hrvoje Leventić<sup>3</sup> ,  
and Wilfried Philips<sup>1</sup> 

<sup>1</sup> imec-TELIN-IPI, Ghent University, Ghent, Belgium  
danilo.babin@ugent.be

<sup>2</sup> University Hospital Ghent, Ghent University, Ghent, Belgium

<sup>3</sup> Faculty of Electrical Engineering, Computer Science and Information Technology,  
University J. J. Strossmayer Osijek, Osijek, Croatia

**Abstract.** Aortic stiffness is an important diagnostic and prognostic parameter for many diseases, and is estimated by measuring the Pulse Wave Velocity (PWV) from Cardiac Magnetic Resonance (CMR) images. However, this process requires combinations of multiple sequences, which makes the acquisition long and processing tedious. We propose a method for aorta segmentation and centerline extraction from para-sagittal Phase-Contrast (PC) CMR images. The method uses the order of appearance of the blood flow in PC images to track the aortic centerline from the seed start position to the seed end position of the aorta. The only required user interaction involves selection of 2 input seed points for the start and end position of the aorta. We validate our results against the ground truth manually extracted centerlines from para-sagittal PC images and anatomical MR images. The resulting measurement values of both centerline length and PWV show high accuracy and low variability, which allows for use in clinical setting. The main advantage of our method is that it requires only velocity encoded PC image, while being able to process images encoded only in one direction.

**Keywords:** Image segmentation · Cardiac MRI · Pulse Wave Velocity

## 1 Introduction

Cardiovascular diseases are number 1 cause of death in the world today attributing to approximately 30% of all deaths. Aortic stiffness has proven to be an important parameter in estimating the overall cardiovascular health of patients [7], as well as diagnostic and prognostic parameter in many diseases, such as hypertension [5], Marfan syndrome [13], Turner syndrome [6], Metabolic syndrome [15], Diabetes [8], etc. The speed of pulse wave propagation, Pulse Wave Velocity (PWV), is used to estimate the aortic stiffness.

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Measurement of PWV from MR images normally consists of 3 steps: (a) segmentation and centerline extraction of aorta (from anatomical MRI) for determining the aortic length and area of cross-sections, (b) computation of velocity curves from PC CMR images and (c) analysis of velocity curves for determining the pulse wave time propagation intervals between the aortic levels of interest. Segmentation and centerline extraction of aorta are usually performed on anatomical 3D MR images [2–4], while the calculation of velocity curves is done on Phase-Contrast MR images, which are velocity-encoded images taken in cross-sectional direction along the aortic centerline (and which are paired with anatomical MRI in order to perform segmentation of aortic cross-sections). Due to the combined use of different imaging modalities, measurement of MRI PWV can be tedious. Alternatively, para-sagittal MRI recording allows for an easier approach in PWV measurement, where a pair of anatomical and PC MRI images are recorded in para-sagittal orientation in a number of slice planes. In this fashion, the anatomical information is derived from the anatomical MR images and is used for masking the regions of interest in PC MRI, which simplifies the PWV calculation process. Once the region of the aorta is segmented from the anatomical images, velocity curves can be calculated by examining the average velocity over an aortic cross-section. One way of calculating time intervals between aortic levels is to use the maximum velocity change, as described in [10]. Approach of [9] uses cross-correlation to determine the time interval between flow waves at different locations along the aorta. A flow-sensitive 4D MRI PWV calculation method was proposed in [14]. Only few methods can perform the segmentation or centerline extraction directly from PC MR images. The method of [11] is graph-based with main emphasis on bifurcation detection, [1] performs tensor-based tracking of the aorta, [16] proposes semi-automatic level set PC MRI segmentation approach and [12] uses vector flow information to perform segmentation. However, none of these methods have been validated for PWV measurements.

In order to further simplify the PWV calculation workflow, we devise an aortic segmentation and centerline extraction method that works directly on PC MR images with velocity encoding in transversal direction. The method we present in this paper is semi-automatic, requiring only 2 user selected seed points that determine the start and the end position of the aorta. The benefit of our approach is that the anatomical MRI image is not needed in order to determine the aortic centerline and PWV measurement, which shortens execution times and simplifies user interaction. Also, it can be applied to a wider range of input images compared to the existing methods.

## 2 Method

We explain in this section our novel method for segmentation of para-sagittal PC MR images and the use of the segmentation result in centerline analysis and PWV calculation. The advantage of our approach is direct calculation on PC images without the need for accompanying anatomical images (i.e. only a single PC sequence is required to perform the processing), which leads to

shorter processing times and lower memory usage. The method is composed of the following steps:

1. Extract a magnitude image from a PC image
2. Create a pulse wave propagation image
3. Segment aorta and extract its centerline
4. Measure PWV

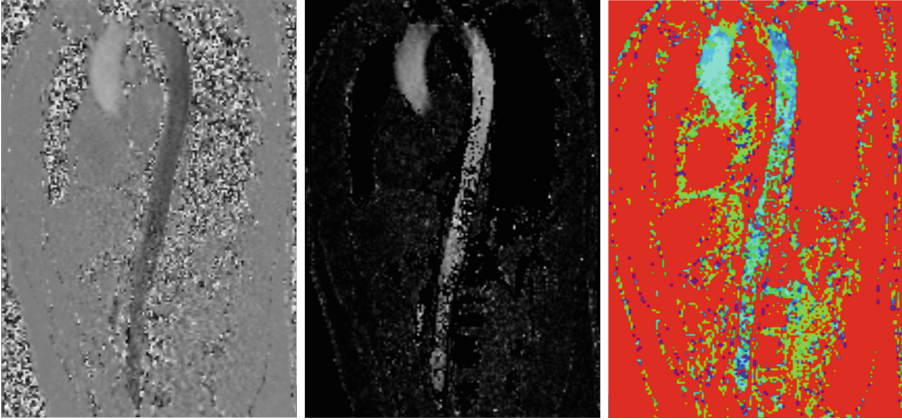
The first step performs extraction of the magnitude of blood flow information from the PC image, which will be used as a mask for the region of the aorta (it will contain high pixel values where prominent blood flow is detected). The magnitude image will be used to produce the pulse wave propagation image which will contain the propagation information of the blood flow over time in a single image slice. The pulse wave propagation image is used to extract the aortic centerline by “tracking” the values (indexes) of segmented regions in ascending order from ascending level to the abdominal level of the aorta. Finally, the centerline and the original PC velocity values are used to measure the PWV using the cross-correlation method for determining the time lapse between different positions along the aortic centerline. The detailed explanation of each of the steps follows.

## 2.1 Extraction of a Magnitude Image from a PC Image

Velocity encoding in PC images is governed by Velocity Encoding (VENC) value measured in cm/s, which is chosen to encompass the highest velocities that need to be recorded. In our data sets VENC value is set to 150 cm/s (spanning over 12 bits of gray pixel value), which means that the lowest possible pixel intensity represents the velocity of  $-150$  cm/s and the highest pixel intensity represents the velocity of 150 cm/s. Hence, the mid-range between the maximum and the minimum possible gray pixel value corresponds to velocity value 0 cm/s. Let  $\mathbf{p} = \{x, y, z\}$  be the 3D coordinates of a voxel in an image. In order to extract the magnitude of blood velocity  $m(\mathbf{p}, i)$  at pixel  $\mathbf{p}$  and time index  $i$ , we take the absolute value of subtraction of the original pixel gray value  $g(\mathbf{p}, i)$  with the gray value corresponding to velocity 0 cm/s denoted as  $g_0$ :

$$m(\mathbf{p}, i) = |g(\mathbf{p}, i) - g_0| \quad (1)$$

The resulting magnitude image is shown in Fig. 1. Apart from the useful velocity magnitude information, the image also contains noisy pixels. These pixels are often isolated (resembling “salt and pepper” noise) and can be removed by morphological operations. The size of the structuring element (SE) is determined from the pixel spacing of the images and the expected size of the aorta. In order to avoid removing the useful signal, we perform first the dilation with circular SE of a predefined size, then the erosion with the SE of double the previous size, and finally another dilation with the original SE size. This sequence of morphological operators will remove much of the noise while still preserving the flow information regions.



**Fig. 1.** Left: original PC image slice (time index 17 out of 40). Velocity encoding is done along the transversal axis,  $VENC = 150$  cm/s. Center: extracted velocity magnitude image contrasts regions of high blood velocity. The absence of high velocity values in the aortic arch happens due to velocity encoding along the transversal axis. Right: pulse wave propagation image (color-coded grayscale image ranging from red to blue color) contains voxel gray values as time index of appearance of velocity above the preset value. (Color figure online)

## 2.2 Pulse Wave Propagation Image

In this subsection we will explain the principle behind our method for segmentation of relevant aortic regions in PC images. Since the PC images are acquired as multiple para-sagittal 2D in-time slices, we can expect that some part of the deviating aorta will be under-represented in the images (this is especially so for very tortuous aortas, where some parts are even not visible in any of the 2D slices). The under-represented parts contain some blood flow information which is often corrupted with noise, where in some cases the noise prevails over the useful signal. Hence, it is of high importance to be able to determine the regions with valid blood flow information and to discard the regions containing only noise. Therefore the goal is to create a 3D image (corresponding to the magnitude image) with voxel values indicating the earliest time of appearance of the pulse wave.

To achieve this, we refine the magnitude image by thresholding the velocity values. In order to remove the noisy and artifact pixels, we set the gray value threshold parameter  $g_t$  to promote only high velocities (velocities above a desired threshold velocity  $v_t$ ). The actual threshold value is calculated from the VENC value of the PC MRI (in our case 150 cm/s) and the highest possible pixel intensity  $m_{max}$  (in our case  $m_{max}$  was  $2^{11} - 1$ , since the data was recorded in 12 bits):

$$g_t = m_{max} v_t / v_{enc} \quad (2)$$

Let  $I$  be the set of all time index values  $i$  for which a voxel with coordinates  $\mathbf{p}$  in the magnitude image has a value larger than the given threshold value  $g_t$ :

$$I(\mathbf{p}) = \{i \in Z \mid m(\mathbf{p}, i) > g_t\}. \quad (3)$$

The pulse wave propagation image contains the time index values of arrival of the pulse wave with blood velocity above the specified threshold velocity:

$$f(\mathbf{p}) = \begin{cases} \min(I(\mathbf{p})), & I(\mathbf{p}) \neq \emptyset \\ 0, & I(\mathbf{p}) = \emptyset \end{cases}. \quad (4)$$

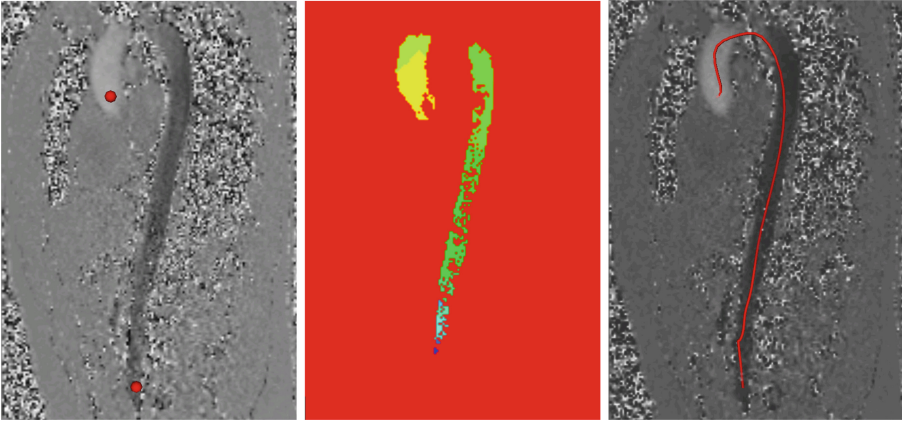
It should be noted that the original PC image and velocity magnitude image are 3D in time images (they can be considered as 4D images), while the pulse wave arrival image  $f(\mathbf{p})$  is a 3D image where the time index information  $i$  is stored as voxel gray value (see Fig. 1).

### 2.3 Segmentation and Centerline Extraction

In order to create the segmentation and the centerline from the pulse wave propagation image, we perform morphological dilation of connected components per each time index value in the ascending time index order. This means that in the first iteration (time index 1), we extract all connected components with voxel value 1 and perform dilation with circular SE of size corresponding to the radius of the maximum inscribed circle fitting in the foreground region (non-zero value voxels) in the pulse wave propagation image. In this fashion we create larger connected components labeled with the time index values. The same principle is applied to all subsequent time index values, but with taking into account not to dilate over the connected components of lower time index values. Finally, for each time index we maintain only the connected components of a certain size, while we discard all the rest. The resulting image is shown in Fig. 2. The centerline is created by connecting all the centers of mass of each connected component and performing spline interpolation (see result in Fig. 2).

### 2.4 Pulse Wave Velocity Calculation

After extracting the aortic centerline, we mark the user defined start and end positions (which correspond to ascending and abdominal levels of the aorta) as locations for velocity curve calculations and PWV measurements. Alternatively, velocity curves can be calculated at any location along the centerline using the para-sagittal PC images (the most common locations are the ascending, descending, diaphragmal and abdominal level of the aorta). For each of the seed positions we calculate the average blood velocity as average grey value of pixels belonging to the region of the aorta (defined by the segmentation, as shown in Fig. 2) in the neighborhood defined as the maximum inscribed circle (analysis is per 2D slice because we only have 3 slice planes). This results in velocity curves for each of the positions with the number of samples equal to the number of images in the CMR time sequence. We use the cross-correlation method to determine the time shift between the velocity curves. Finally, the PWV is calculated from the measured lengths and velocity curve time shifts between the aortic positions.



**Fig. 2.** Left: original Phase-Contrast image slice (time index 11 out of 40) with selected user seed points. Center: segmented regions of aorta corresponding to pulse wave propagation image that contrasts regions of high blood velocity (color-coded grayscale image ranging from red to blue color). The absence of high velocity values in the aortic arch happens due to velocity encoding along the transversal axis. Right: extracted aortic centerline. (Color figure online)

### 3 Results

The experiments were done on 10 healthy volunteers: 4 females and 6 males (age between 27 and 71 years old). Ethical committee approval was obtained for this study and all volunteers signed the written informed consent form. Images were recorded on Siemens Avanto Fit 1.5 T scanner as Phase-Contrast (PC) sequences with velocity encoding (VENC) value of 150 cm/s, and anatomical (Siemens trueFISP, i.e. Balanced-SSFP) images for ground truth centerline extraction. Para-sagittal PC sequences are recorded in 3 image planes. Each ECG triggered sequence (corresponding to one heart cycle) consists of 40 images.

Our proposed centerline extraction method for PC MR images was compared (in length) to manual centerline extraction on the same PC images and with manual centerline extraction on anatomical MR images (Siemens trueFISP, recorded either in transversal or sagittal orientation). The expert manual centerlines were drawn by placing 10 to 15 sample points along each aorta and using curve interpolation to produce the final ground truth centerlines. Results of length measurements on the whole aorta are shown in Table 1. The average mean absolute error over all cases is 12.7 mm, which is low in comparison to the length of the whole aorta, as confirmed by the average mean relative error value of 3.7%.

Taking into account that the main purpose for our proposed PC MRI segmentation and centerline extraction method is PWV calculation, we calculate the PWV to determine the applicability of our proposed method. The PWV is calculated using the same velocity curves for each PWV measurement approach

**Table 1.** Aortic lengths measured using the proposed method, manual centerline drawing on PC images and manual centerline drawing on anatomical images. Absolute error values of the proposed method were calculated against the manual measurements (as ground truth values).

Centerline length (mm)	1	2	3	4	5	6	7	8	9	10
Proposed method	429	452	412	452	441	434	471	333	445	341
Manual PC	422	470	403	502	461	432	455	358	454	365
Manual anatomical	421	462	387	476	436	422	455	333	454	326
Mean absolute error	7.5	14	17	33.3	12.5	7	16	12.5	9	19.5
Max absolute error	8	18	25	50	20	12	16	25	9	24
Mean relative error (%)	3.5	3	4.3	7.5	2.7	1.6	3.5	3.4	1.9	5.5

**Table 2.** Pulse Wave Velocity values calculated using length measurements of the examined centerline extraction methods. Absolute error values of the proposed method were calculated against the manual measurements (as ground truth values).

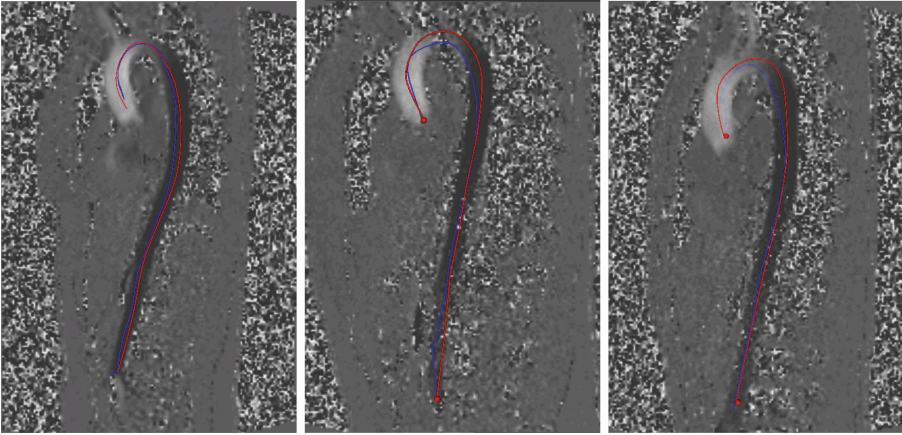
PWV (m/s)	1	2	3	4	5	6	7	8	9	10
Proposed method	6.1	7.1	4.7	9.4	4.1	4.9	4.8	4.6	4	2.9
Manual PC	6	7.5	4.6	10.7	4.3	4.9	4.6	4.9	4.1	3.1
Manual anatomical	6	7.4	4.4	10.1	4.1	4.8	4.6	4.6	4.1	2.7
Max absolute error	0.1	0.4	0.3	1.3	0.2	0.1	0.2	0.3	0.1	0.2

(in other words, the time intervals do not vary in PWV calculation for each approach, only the centerline extraction methods are different). Results of PWV measurements on the whole aorta are shown in Table 2. The average maximum absolute error amounts to 0.3 m/s, which is significantly lower than the clinically acceptable 1 m/s measurement error.

## 4 Discussion

The results of length measurements for our proposed method, the manual centerline drawing on PC image and manual centerline drawing on anatomical MRI are shown in Table 1. The results of centerline extraction for 3 cases are shown in Fig. 3, where the red line depicts the manually drawn centerline on the parasagittal PC image, while the blue centerline depicts the result of our proposed method. Visual inspection of the results shows that the centerline follows the ground truth very closely in linear segments of the aorta, but slightly shortens the curvature in the aortic arch. This is the reason for the average mean absolute error (over all cases) of 12.7 mm, although the average mean relative error is still quite low (3.7%). The method is robust to seed location selection as long as the selected seeds fall inside the region of the aorta.

The results of PWV measurements (Table 2) show that most of the calculated PWV values fall in range [2, 10] m/s (with one outlier), which is the expected



**Fig. 3.** Centerline extraction results. Manually extracted centerline is depicted in red, while the centerline extracted using our proposed method is blue. The proposed centerline extraction method follows closely the aortic centerline in the straight segments of the aorta and slightly differs in the curved segments (aortic arch). (Color figure online)

range of values in the healthy population. The calculated maximum absolute error values show that almost all values (except one) fall under 0.4 m/s, which is the error value that will not influence the diagnostic or prognostic relevance. The only case in which the error exceeds 1 m/s is the measurement on a 71 year old male volunteer. The PC image of the volunteer exhibited lower blood velocity values, so the threshold velocity  $v_t$  (and consequently gray value threshold  $g_t$ ) would need to be set to a lower value in order to correct the segmentation and centerline extraction. It has been shown that the older population exhibits stiffening of the aorta, which in turn creates higher PWV values. This is confirmed also in our test population, where the 71 year old male volunteer has the PWV value range [9.4, 10.7]. All other volunteers (all under 43 years of age) have normal range of PWV values. The para-sagittal PC MRI allows for PWV measurements on multiple places along the aorta. However, it should be noted that the PWV results per aortic segments will display higher variability (because of shorter aortic distances and pulse wave intervals).

## 5 Conclusion

We proposed in this paper a method for aortic region segmentation and centerline extraction from para-sagittal Phase-Contrast MR images with pulse wave velocity calculation as the end goal. The method works by tracking the pulse wave propagation from ascending level of the aorta down to the abdominal level of the aorta. The main advantage of our method is that it does not require any other images besides the Phase-Contrast image, which shortens the time required



for image analysis and eliminates the need for additional image modality acquisition, leading to savings in time and cost while causing less patient discomfort. The method is semi-automatic requiring only 2 user input seed points for the start and end position of the aorta. The method was validated against the manual centerline extraction in para-sagittal PC images and anatomical MR images. Both centerline length measurements and PWV measurements on the whole aorta show high enough accuracy and low variability, which allows for use in clinical setting.

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