Comparison of Pulse Wave Velocity Measurements from 2D PC Slices and Radially Undersampled 4D PC MR

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INTRODUCTION. Pulse wave velocity (PWV) is an indirect measure of vascular stiffness that is used as a biomarker of atherosclerosis and stroke risk [1]. While invasive catheter measurements are the gold standard for evaluating PWV, the invasive nature of such a procedure has prompted research on the use of phase contrast (PC) MRI for assessing PWV. The majority of work has focused on calculating PWV from a series of 2D PC images along the length of the aorta [2-3]. Such methods are highly dependent on accurate cardiac triggering and distance calculations between the imaging planes. Other investigators have explored the use of 4D PC MRI [4], but such lengthy volumetric exams usually require compromises in temporal resolution, which is vital to PWV calculations. The purpose of this study was to i) introduce a MATLAB-based tool for the computation of PWV from both 2D and 4D PC MR data sets and to ii) assess the feasibility of computing PWV from a radially undersampled 4D PC MR (PC VIPR) technique [5] that provides large volumetric coverage, three-directional flow encoding, and greater temporal resolution than previous reports using 4D velocity mapping.

MATERIALS & METHODS. Five healthy volunteers (1 male; 4 females; average age = 35.8 ± 16.7 years, range = 22 - 59 years) were included in this HIPAA-compliant study, which was approved by our local IRB. Written informed consent was obtained prior to participation. Inclusion criteria were BMI<30 and no history of smoking or cardiovascular disease.

MR Imaging. 4D PC VIPR data were acquired on a 3T MR scanner (MR750, GE Healthcare, Waukesha, WI) using a 32-channel body coil (NeoCoil, Pewaukee, WI). Typical scan parameters were: VENC=150 cm/s, TR/TE/flip=6.4-6.7ms/2.2ms/20-22º, hertz/pixel=976.6, imaging volume = 32x32x22cm^3, readout=256, resulting in 1.25 mm^3 isotropic spatial resolution. A dual-echo, 5-point flow encoded PC VIPR [5] technique was acquired with retrospective ECG gating and a temporal resolution of 32-33.5ms using temporal filtering in the RR cycle [6]—similar to high spatial frequency view-sharing in Cartesian acquisitions. Depending on heart rate, 26-34 time frames/cardiac cycle were acquired. Adaptive respiratory gating (50% eff.) was used, resulting in a scan time of ~11.5min.

A product 2D PC sequence with prospective ECG gating and optimized for temporal resolution (63 ± 13 time frames) was used for flow imaging in the ascending aorta, aortic arch, and in the proximal and supra-diaphragmatic descending aorta (spatial resolution = 1.6x1.6mm^2, slice thickness=7mm). An MR angiogram with 0.03mmol/kg gadofosveset trisodium (Ablavar, Lantheus, Billerica, MA) injected at 0.6mL/s followed by a 30mL saline chaser was performed to guide placement of the 2D planes.

Data evaluation. An in-house developed MATLAB-based tool (v7.9, The MathWorks, Cambridge, MA) was used for evaluating data and computing PWV (Figure 1). For obtaining the flow waveform from *2D PC slices* ROIs were placed in the aortic lumen. The distance between slices was measured on a spline-interpolated centerline along the length of the aorta on the basis of a 'candy cane' view of the aorta (angiogram). For *4D PC-VIPR data*, two approaches were pursued: ***A) "4D-approach":*** 7-8 planes were placed along the length of the aorta using a surface-shaded 3D display of the aorta (Figure 1). Each plane was used to extract the flow waveform from the corresponding phase difference information. The centroid of each plane was used to compute a cubic spline interpolant that approximated an aortic centerline. The distance of each plane from the first plane was computed from the centerline. ***B) "2D→4D-approach":*** Location and orientation of the ROI from each 2D slice was mapped to the 4D data and used to extract flow waveforms from only those slices (otherwise the same processing steps as the 4D-approach).

PWV computation: Four methods were tested, including time-to-peak (TTP), time-to-foot (TTF), and cross-correlation (XCorr) as previously reported [4]. For time-to-upstroke (TTU), the second derivative of the flow waveform was computed and used to define the zero point corresponding to the maximum rate of change along the upstroke of the flow waveform. The corresponding time of this zero crossing was recorded. The distances between planes were plotted against the time shifts as identified with each of the four methods. The PWV for each method was computed as the inverse slope of a line fitted to these data [4]. PWV measurements from the five volunteers were tabulated and plotted.

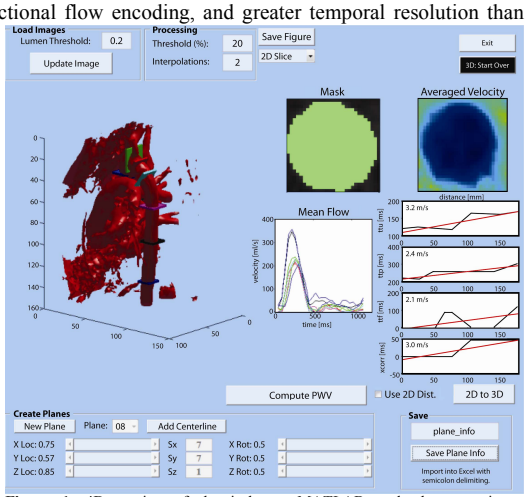

Figure 1. 4D portion of the in-house MATLAB tool, demonstrating a representative case in which 8 planes were defined along the aorta. From the 8 planes, flow waveforms were obtained and used to derive PWV measurements.

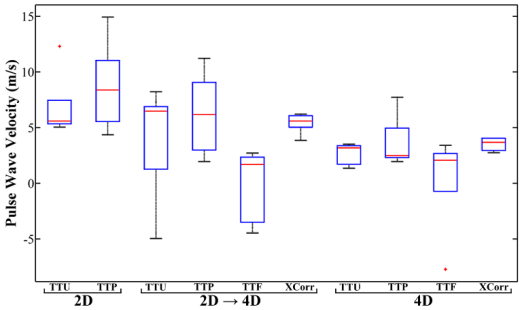

Figure 2. Box plots of PWV measurements for five volunteers as calculated from 2D PC slices, with the 2D slices mapped to the 4D PC VIPR data set, and with the 4D data independently. PWV was computed with time-to-upstroke (TTU), time-to-peak (TTP), time-to-foot (TTF), and cross-correlation (XCorr).

RESULTS & DISCUSSION. PWV results from the five volunteers are shown in Figure 2 and Table 1. Best agreement with data typically described in the literature [4] was found for 4D TTU, TTP, and XCorr and 2D→4D XCorr and TTU measurements. For the 4D data, the XCorr method was the least variable, whereas the TTU method was the least variable for the 2D data set. 4D independent measurements were less variable than measurements acquired from the 2D→4D approach. 2D TTF, 2D XCorr, and 4D TTF revealed non-physiological results that were flawed by non-robust measurements. This was of special note since 2D scans are widely used for PWV calculation and can be considered a reference standard. The erroneous TTF and XCorr results are likely due to the lack of measurements at the beginning of the cardiac cycle. Time frames from our prospectively gated 2D PC acquisition often began during the upstroke of the flow waveform, especially in the ascending aorta. As a result, a foot could not be accurately defined; since parts of the characteristic waveform were missing for planes in the ascending aorta, and more completely defined for planes downstream, cross-correlation was often erroneous. For the 4D acquisition, the use of retrospective gating allows for measurements throughout the complete RR cycle. For future 2D PC MR measurements, triggering with shorter delay times or an implementation with retrospective ECG gating would be highly desirable yet very challenging to implement as a time-efficient Cartesian acquisition.

Table 1. PWV measurements for five volunteers as calculated from 2D PC slices, with the 2D slices mapped to the 4D PC VIPR data set, and with the 4D data independently. PWV was computed with 4 different methods: time-to-upstroke (TTU), time-to-peak (TTP), time-to-foot (TTF), and cross-correlation (XCorr).

	PWV (m/s)		
	2D	2D → 4D	4D
TTU	6.86 ± 3.06	3.92 ± 5.24	2.66 ± 0.98
TTP	8.68 ± 4.06	6.22 ± 3.74	3.74 ± 2.35
TTF	300.2 ± 172.4	-0.18 ± 3.35	0.38 ± 4.56
XCorr	659.0 ± 1525	5.44 ± 0.92	3.54 ± 0.61

CONCLUSIONS. We successfully demonstrated the feasability of computing PWV from a 4D PC VIPR acquisition using a MATLAB-based tool specifically designed for analyzing 2D and 4D data sets. Our PWV measurements in healthy volunteers were similar to previously reported PWV measurements [3-4]. The radial sampling scheme employed in our 4D acquisition allows for high temporal and spatial resolution while maintaining a clinically feasible scan time. Additionally, the PC VIPR acquisition provided PWV measurements that were less variable than measurements obtained from the four 2D PC slices. Not all methods of computing PWV were compatible with our data sets—producing particularly erroneous results with TTF and XCorr methods. In future work we will investigate a retrospectively gated 2D acquisition that is not limited by such trigger delays. Additionally, we are actively recruiting more subjects to increase the statistical power of our results.

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