Optimized Estimation of Global and Regional Aortic Pulse Wave Velocity

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Introduction: Pulse wave velocity (PWV) as a measure of aortic stiffness is an important clinical marker for the presence of atherosclerosis [1,2]. For PWV estimation using Phase contrast (PC) MRI transit-time (TT) methods have been employed which estimate temporal differences in flow waveforms between two locations in the vessel with known distance [3]. However, precision was limited by the accuracy of estimating the differences in flow and the distance. Methodological improvements include continuous evaluation along a vessel center line, which, however, relied on 2D PC data exactly transecting the thoracic aorta [4, 5]. Recently, more comprehensive 3D CINE techniques in combination with 3-directionally encoded velocities (flow sensitive 4D MRI) have provided information on multidirectional blood flow with full volumetric coverage of the aorta [6]. The aim of this study was to develop a more stable PWV estimation based on multiple flow waveforms distributed homogenously along the entire thoracic aorta. In contrast to previous studies [3, 7], the complete coverage offers, for the first time, the possibility to analyze regional PWV in the ascending aorta (AAo), aortic arch, and descending aorta (DAo). PWV was evaluated in a study with 12 healthy volunteers and 9 patients with atherosclerotic disease. In patients, maximum aortic plaque thickness was used as a measure of severity of atherosclerosis.
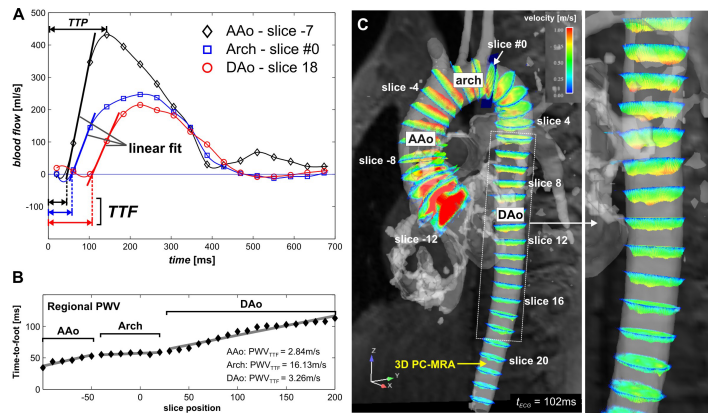
Methods: All healthy volunteers (n=12, mean age = 24.5 +/- 3.2y) and patients (n=9, mean age = 61.4 +/- 8.3y, max. plaque thickness = 4.6 +/- 0.7mm) were examined on a 3T system (TRIO, Siemens, Germany). ECG gated and respiration controlled flow sensitive 4D MRI was performed using a sagittal oblique 3D volume covering the entire thoracic aorta (TE/TR = 2.6-3.5ms/5.1-6.1ms, α=7-15°, temporal resolution = 40.8-48.8ms, spatial resolution = 1.7x2.0x2.2mm³) [6].
A 3D phase contrast (PC) MR angiography derived from the 4D data [6] was used to position a series of 2D planes along the thoracic aorta (figure 1C, EnSight, CEI, USA). For inter-subject comparability an initial plane #0 was positioned distal to the left subclavian artery. All other analysis planes were subsequently positioned upstream and downstream with an inter-plane distance of 10mm (figure 1C). PWV was derived from the blood flow curves for each plane by identifying the time-to-peak (TTP) and time-to-foot (TTF) of the flow waveform as shown in figure 1A. TTF was extracted by fitting a line to the upslope portion of the waveform (between 20% and 50% of the peak flow). Global PWV was determined by the slope of a linear fit to the data of all slices. Regional PWV (figure 1B) was calculated by three independent fitting procedures to data associated with the AAo (slices < -3), aortic arch and proximal DAo (slice -3 to 2), and DAo (slices > 2). Results were compared to standard methods by estimating PWV based on TTP and TTF in 2 analysis planes in the AAo and DAo, separated by a distance of 20cm.

Results: Up to 38 aortic slices (mean = 32.1 +/- 3.4, min = 24) were analyzed. 3D vector graph visualization illustrated the travelling pulse wave (figure 1C, fully developed profiles in the proximal DAo and continuously lower profiles further downstream). PWV estimation in all 12 volunteers (figure 2A) based on TTF and 4D data demonstrated lowest data variability (small inter-quartile and overall data range). The increased data range using TTP or standard methods indicates less reliable assessment of temporal differences in flow waveforms and thus PWV. PWV estimated by TTF and 4D data was in agreement previous studies [3-5]. Patients (figure 2B) demonstrated significantly (p<0.001) increased and more widely varying PWV. Noticeably, a tendency for enhanced global PWV with increased maximum plaque thickness was found (figure 3) indicating a correlation of PWV with the severity of atherosclerotic disease. Analysis of regional PWV revealed significant (p<0.05) regional differences in aortic stiffness in healthy volunteers with markedly increased PWV, i.e. decreased compliance, in the aortic arch. In patients a similar PWV distribution was observed while values in the AAo and DAo were higher compared to normal controls.

Discussion: The results of this study demonstrate the value of flow sensitive 4D MRI for optimized estimation of normal and pathologically increased PWV. By using regularly spaced analysis planes with fixed inter-slice distance even complex aortic shapes can be analyzed. Errors in inter-plane distance are expected to be less severe since PWV was estimated by fitting data points from a large number of slices. Compared to standard techniques (2 slices in AAo and DAo) considerably reduced inter-subject variability and more reliable PWV calculation could be achieved. In general, TTP provided the least consistent results, most likely due to reflected pressure waves as reported previously [3]. PWV in volunteers was significantly increased in the aortic arch which has not been described before. We hypothesize that this is predominantly due to the usually lower diameter of the arch compared to the ascending aorta leading to a local acceleration of flow. Subsequent reduction of PWV in the DAo may be related to pressure loss by partial out-flow off blood into the supra-aortic branching arteries. More studies are needed to test the value of the proposed method for the assessment of aortic atherosclerosis and the prediction of future cerebro-vascular ischemic events.

Fig. 1: PWV estimation based on flow-sensitive 4D MRI data. Equidistant analysis planes positioned along the aorta (**C**) were used to evaluate temporal changes in the flow waveforms (**A**) and global and regional PWV (**B**).
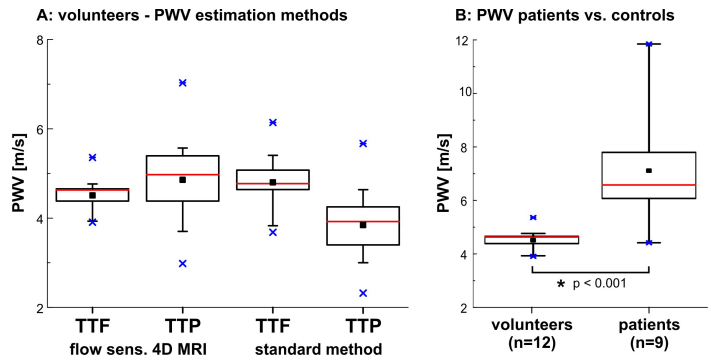
Fig. 2: Box-plot of the PWV of normal volunteers calculated with different methods (**A**) and for volunteers compared to patients (**B**). Filled box = mean, red line = median; large box = lower and upper quartile; error bars = range of values within [5,95]% of the data, blue x = min/max values within [1,99]% of the data.
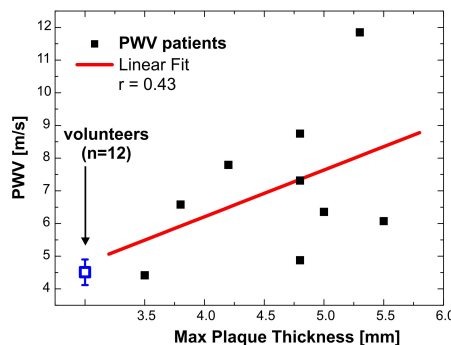
Fig. 3: Mean pulse wave velocity for volunteers (box with error bar, left) and PWV for patients as a function of maximum plaque thickness in the aorta. In addition to a clear PWV increase for patients compared to volunteers, a systematic PWV increase with increasing plaque thickness is evident.

Fig. 4: Comparison of mean regional PWV in normal volunteers and patients. (* = p<0.05).
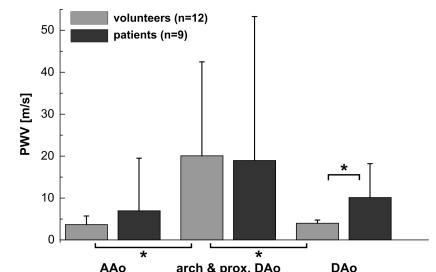
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