Comparison of phase-contrast MRI and arterial tonometry pulse wave velocity quantification in young and old healthy subjects

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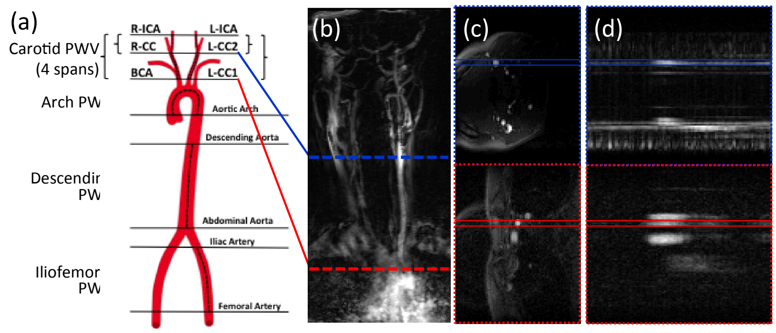
PURPOSE: This study aims to develop and evaluate a full-body segmental pulse-wave velocity (PWV) MRI protocol and to compare the MRI-derived results to the standard PWV measurement method, arterial applanation tonometry, in both young and old healthy subjects. PWV is defined as the propagation velocity of the systolic pressure wave along a segment of the arterial tree. By measuring the transit time (Δt) and the path length (Δd) of the systolic wave front from one arterial segment to another one can determine PWV in m/s as: PWV= $\Delta d/\Delta t$ [1]. In tonometry, the arterial waveform is measured with respect to the EKG R-wave separately at the carotid and lilac arteries, with the distance between these two segments estimated by superficial measurement. Thus, tonometry provides an average of the PWV along the central artery, and across many heartbeats. With MRI velocity-encoded projections, it is possible to measure the arterial velocity simultaneously at two distinct slice locations along the vessel, allowing for quantification of PWV along specific segments of the central artery [2,3]. Previous studies have shown that age-related changes in PWV may differ between the aortic arch, descending aorta, and iliofemoral arterial segments [2], thus, segmental measurement may provide added information about local vascular function. Using previously developed techniques to measure aortic arch PWV [3], descending aorta and iliac artery PWV [2] and carotid artery PWV [4], PWV can be quantified from the carotid to the femoral artery. In this study, segmental PWV MRI was measured in the carotid arteries, aortic arch, descending aorta, and iliac arteries, and compared to carotid-to-femoral PWV measured by tonometry.

METHODS: ***Segmental MRI Pulse-Wave Velocity Sequences –*** PWV measurement is based on the principle of velocity-encoded projections [3]. By removing phase encoding from a traditional 2D PC-MRI pulse sequence and choosing a suitable readout direction to avoid vessel overlap in the 1D projection image, velocity can be measured with temporal resolution equal to the TR (3.7 - 6 ms, depending on segment). For the aortic arch, the ascending aorta and descending aorta can be captured in a single slice, whereas the descending aorta, iliofemoral, and carotid artery segments require signal acquisition at two separate locations (**Fig 1a**). In these segments, dual slice excitation is achieved using a cosine-modulated sinc pulse, and signal from the upper and lower slice are separated based on local coil sensitivity. For example, the use of body and spine array and carotid surface coils allows for separation of signal from the lower common carotid (body and spine coils) and upper-most extent of the common carotid artery (carotid coils) (**Fig 1 b-c**). The complex difference between positive and negative flow-encoded projections is averaged in a region corresponding to the vessel, yielding a waveform that is proportional to velocity (**Fig 1 d-e**). The onset of the systolic wave at each location is determined based on intersecting tangents, and the temporal offset is determined based on the foot-to-foot method [5]. Segmental path length is determined from a set of axial scouts.



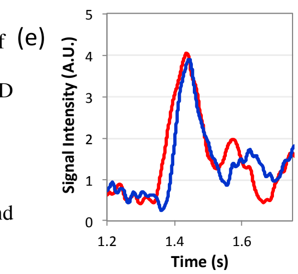


Figure 1: (a) Schematic indicating relative locations of various MRI pulse wave measures; (b) slice locations for LCC PWV determination with corresponding (c) 2D magnitude and (d) 1D time resolved velocity images. Complex difference processing yields a time-resolved signal with magnitude proportional to velocity. The signal in (d) in a region corresponding to the vessel of interest in the lower and upper slices is averaged (e) and used to determine Δt via the foot-to-foot method.

Tonometry – After placement of EKG leads, a pressure tonometer is placed at the most superficial portion of the left carotid and left femoral artery and pressure waveforms are measured relative to the EKG R-wave to determine Δt. The distance, Δd, is obtained with a measuring tape, subtracting the distance from the carotid prominence to the sternal notch from the distance from sternal notch to the femoral pulse.

In Vivo Study – 9 young (<30 years) and 9 old (>65 years) healthy subjects underwent tonometry followed by a MRI session involving segmental PWV of the carotid arteries, aortic arch, descending aorta, and iliac arteries.

RESULTS: Table 1 lists the results of tonometry and MRI-measured PWV in the carotid, aorta, and iliac arteries. The correlation between tonometry and the average aortic PWV measured with MRI (**Fig 2a**), and between the average aortic and carotid PWV both measured with MRI (**Fig 2b**) are shown.

Table 1: Average (standard deviation) PWV reported in m/s measured in each arterial segment with MRI and tonometry. P-values are generated from Student's t-tests.

	MRI-measured carotid PWV				*MRI-measured central PWV*			*Tonometry*
	RBC-RCC	*RBC-RIC*	*LCC1-LCC2*	*LCC1-LIC*	*Arch*	*Descending*	*Iliac*	*Carotid-Iliac*
Young	5.9 (0.9)	5.9 (0.9)	5.3 (0.8)	5.0 (1.2)	6.3 (0.7)	4.4 (0.8)	7.2 (1.4)	5.6 (1.0)
Old	7.8 (1.4)	8.4 (2.0)	9.1 (3.4)	9.2 (3.6)	9.0 (2.7)	8.4 (2.5)	10.7 (2.6)	9.5 (2.5)
p-value	*0.0040*	*0.0007*	*0.0044*	*0.0052*	*0.0101*	*0.0003*	*0.0031*	0.0005

DISCUSSION: Increased PWV is a known consequence of age-related arterial stiffening due to loss of elastic fibers and increased central pressures [6]. Results in **Table 1** indicate that all seven MRI based measures were sensitive to these changes ($p<0.05$), with some arterial segments showing an equal level of significance as tonometry. The correlation between aortic PWV from both methods (**Fig 2a**) was no better than the correlation between MRI-based carotid and aortic PWV (**Fig 2b**), suggesting that the MRI measures may be more sensitive to subject specific variations in PWV. This could be explained by the fact that the path length (Δd) is measured directly in MRI, whereas tonometry must rely on estimation based on a superficial measurement, the error of which will increase in older individuals as vessels become more tortuous. Although not explored here, another potential advantage of MRI PWV is the ability to assess beat-by-beat variation in PWV, which is possible since the MRI measurement is in real-time. Because tonometry measures Δt independently at each site with respect to the R-wave, it is not possible to investigate beat-by-beat variation in PWV. Finally, even though the subjects in this study were free of symptomatic cardiovascular disease, older subjects may have varied in their vascular health, as the standard deviation of PWV measured with both methods is larger than in young subjects. Segmental MRI PWV may have the potential advantage of being sensitive to focal pathology such as atherosclerosis. The relative sensitivity of segmental MRI PWV compared to tonometry to detect disease related changes in PWV merits further investigation. **Conclusion:** PWV from the carotid to femoral artery can be measured with a segmental velocity-encoded projection MRI protocol, results from which are sensitive to changes in vessel compliance due to aging.

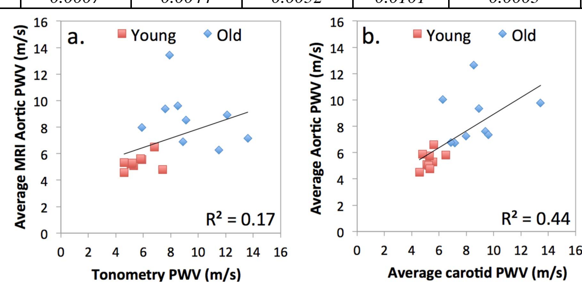


Figure 2: Correlation between tonometry and average PWV measured in the aorta (a), or between MRI-measured carotid and aortic PWV (b). Δt increases with lower PWV, so improved precision is expected for both methods at lower PWV.

REFERENCES: [1] McDonald, JAP **24** (1968); [2] Langham et al., *JCMR* **13** (2011); [3] Langham et al., *MRM* **64** (2010); [4] Rodgers et al., *Proc. ISMRM,* p. 1237 (2012); [5] Cockcroft et al., *Eur Heart J* **27** (2006); [6] Rogers et al., *JACC* **38** (2001). **ACKNOWLEDGEMENTS:** Supported by an award from the AHA, and NIH R01HL10954 5, R01HL075649, 5T32EB009384, and T32EB000814.