Identification of Systematic Differences Between Different Methods for Extracting Pulse Wave Velocity with 4D Flow MRI

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TARGET AUDIENCE: People with an interest in vascular stiffness and pulse wave velocity estimation.

PURPOSE: Several methods for the estimation travel-time have been described in the literature and it has been shown that the choice of method may impact the PWV estimate[1-6]. The purpose of the present study was to evaluate different methods for extracting pulse wave velocity (PWV) from 4D MR velocity data.

METHODS: Aortic 4D flow MRI velocity data were acquired with a spatial resolution of 2.3-2.8 mm isotropic and a temporal resolution of 39-43 ms in 8 young (age: 23 ± 2 years) and 8 older (age: 58 ± 2 years) normotensive male volunteers.

Calculation of PWV require estimation of the time (travel-time) it takes for the pulse wave to travel a specific vascular distance (travel-distance). Six different methods to the estimation of the travel-time were compared (**see Table 1**)[1-6]. The TTU, TTF, and TTF2 methods operate on the upslope of the flow waveform and will be referred to as the "*upslope group*". The FA, XC, and COM methods, on the other hand, use information about larger parts of the waveform and will be referred to as the "*waveform group*". Flow waveforms in a large number of analysis planes were generated throughout the aorta. Travel-time was calculated between each plane and a reference location. Travel-distance was obtained from an aortic centerline. The PWV in the descending aorta (top of arch to renal arteries) was obtained by linear fitting of travel-time vs. travel-distance.

Table 1. Methods for the evaluation of PWV evaluated in the present study

	Method	Description
Waveform group	Fourier analysis (FA)	Estimates travel-time based on the phase-shift between waveforms.
	Cross-correlation (XC)	Estimates travel-time as the time-shift that results the maximum cross correlation between two waveforms.
	Center-of-mass (COM)*	Tracks the center-of-mass of the main lobe of the flow waveform.
Upslope group	Time to peak upslope (TTU)	Tracks the point of peak derivative at the upslope of the waveform.
	Time to foot (TTF)	Tracks the point at which a line fitted to the upslope of the flow curve crosses the base of the flow waveform.
	Time to foot #2 (TTF2)	Tracks the point at 20% of the flow rate at the point of the maximum derivative of the upslope of the waveform.

* To our knowledge, this method has not been previously published

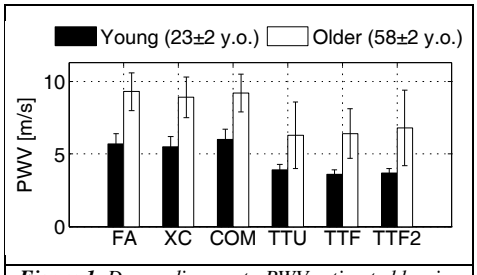

Figure 1. *Descending aorta PWV estimated by six different methods in young and old normal volunteers.*

RESULTS: The PWV for the different methods and age-groups are shown in **Figure 1**. All methods estimated higher PWV in the older compared to young volunteers (t-test, $p < 0.05$). One-way ANOVA revealed a significant difference in PWV among the six different methods for extracting PWV ($p < 0.05$). Post-hoc tests showed that methods in the *waveform group* generated higher PWV compared to methods in the *upslope group*. Moreover, there were no significant differences within the *waveform* or *upslope* groups, respectively, for any of the two age groups.

Detailed analysis of the XC and TTF methods with linear regression and Bland-Altman analysis indicated strong correlation but a systematic difference of more than 2 m/s. A comparison between the TTF method, XC method and previously reported values of PWV in the descending aorta is shown in **Table 2**.

Table 2. *Age-related descending aortic PWV obtained with 4D flow MRI (present study) and with higher temporal resolution (8,14).*

Study	Method	Temporal resolution [ms]	Age [years]	PWV in desc ao [m/s]
Present study, TTF	4D flow MRI	39-43	23 ± 2	3.6 ± 0.4
Present study, XC	4D flow MRI	39-43	23 ± 2	5.5 ± 0.7
Grotenhuis et al.[7]	2D through-plane PC-MRI	6-10	29 ± 8	4.3 ± 0.6
Taviani et al.[8]	1D FVE MRI	3.5	~30*	4.2 ± 0.7
Taviani et al.[8]	1D FVE MRI	3.5	~50*	5.9 ± 0.9
Present study, TTF	4D flow MRI	39-43	58 ± 2	6.4 ± 1.7
Present study, XC	4D flow MRI	39-43	58 ± 2	8.9 ± 1.4
Taviani et al. (14)	1D FVE MRI	3.5	~70*	8.0 ± 1.3

* Approximate mean age extracted from Taviani et al.[7].

DISCUSSION:

Our findings show that PWV-estimation methods that operate on large parts of the waveform (FA, XC, COM) overestimate PWV compared to methods that operate on the upslope portion of the waveform (TTU, TTF and TTF2). Similar trends can be observed in previously reported 4D flow data[5,6]. The difference between the two groups of methods is likely due to the fact that the methods in the *waveform group* are more sensitive to the effects of reflected waves[2].

An additional finding was that the age-related descending aorta PWV 4D flow MRI TTF results compares excellently against methods with much higher temporal resolution. This may be due to the high "spatial resolution" (i.e. availability of large/arbitrary number of planes to extract *complete* flow waveforms from) of 4D flow PWV estimation.

CONCLUSION: Methods that operate on large parts of the waveform (FA, XC, COM) overestimate PWV compared to methods that operate on the upslope portion of the waveform (TTU, TTF and TTF2). Care must be taken when interpreting PWV estimates obtained by different types of methods.

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