The More the Merrier? Finding the "Right" Temporal Resolution for Blood Velocity Measurements: a Multimodal Study

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Target audience. Physicians working in cardiovascular imaging, MR Technicians and Physicists

Purpose. Quantitative flow imaging with phase contrast (PC) MRI has become an important diagnostic tool for cardiovascular diseases, and has been subject of great technological improvements and clinical validation in the last few years. Surprisingly, however, there is limited information about the signal characteristics of the physiological velocity waveform that would be useful to establish quantitative requirements for a proper choice of temporal resolution. To this end, the spectral content of the velocity signal is hereby analyzed in healthy volunteers in various anatomical locations with PC-MRI and compared to Doppler ultrasound. The possibility of optimizing the temporal resolution to adapt it to the frequency content of the signal is also investigated.

Methods. Four healthy volunteers were scanned on a 3T whole-body scanner at 3 different anatomical locations: Common Carotid Artery (CCA, right and left), Aorta (Ao, ascending and descending), Femoral Artery (FA, right and left). A 2D PC-MRI sequence, retrospectively gated to the index fingertip photoplethysmogram, was set up with the parameters shown in Table 1. In addition, all volunteers underwent Doppler ultrasound imaging of the carotid arteries and of the femoral arteries for external validation of the measures. After acquisition, regions-of-interest (ROIs) were identified on the vessels of interest and the corresponding power spectrum P(f) of the velocity waveform v(t) was calculated according to $P(f) = \left| FFT\left(v(t)\right) \right|^2$. A cutoff frequency f_{max} was defined, containing 99% of the energy, and assumed to reflect the maximum frequency content of the signal. The waveform from the CCA was subsequently downsampled and interpolated (by upsampling and low-pass filtering) to investigate whether a sampling frequency above the measured Nyquist rate ($2\times f_{max}$) is sufficient to fully retain the signal characteristics.

Location	Resolution (mm³)	Actual temporal resolution (ms)	TR/TE (ms)	Reconstructed cardiac phases
CCA	1x1x4	10	5/2.9	100
Ao	2.7x2.7x6	20	5/2.5	100
FA	1.25x1.25x4	10	5/2.9	100

Table 1: PC-MRI sequence parameters. Venc was set to 150cm/s.

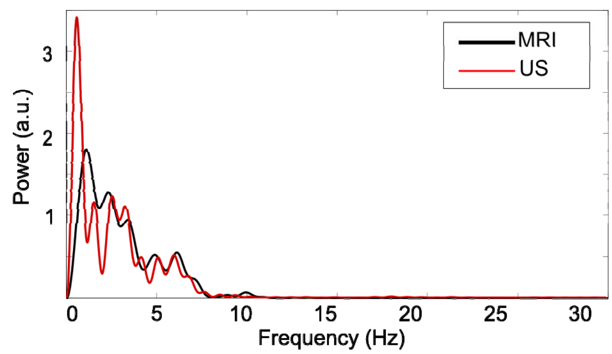

Fig. 1: Power spectrum of the velocity waveform in the common carotid artery, measured by MR (black) and Doppler Ultrasound (red)

Results. MR and Ultrasound produced similar power spectra (fig. 1). In the CCA, MRI gave a cutoff frequency f_{max} of 11.6±2.4 Hz, whereas Doppler revealed 12.9±3.0 Hz (p-value not significant). For the FA, a f_{max} of 13.0±3.7 Hz was observed with MRI and a f_{max} of 11.0±2.9 with Doppler (p-value not significant). In the ascending and descending Aorta f_{max} was 7.2±0.4 Hz and 8.9±0.6 Hz, respectively (p=0.03). As shown in Fig. 2, the temporal signal in the CCA retained its important characteristics (slope and peak) up to a sampling rate of 25Hz, in accordance with theoretical expectations.

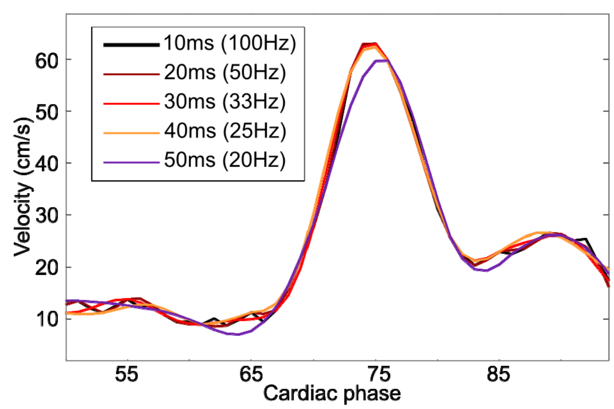

Fig. 2: Systolic phase of a velocity waveform in the carotid as measured by MRI, sampled at decreasing frequencies and interpolated.

Discussion. Despite their differences in resolution of the low-frequency peaks, Doppler and MRI spectra were very similar, yielding similar results for the frequency contents of the signal. Interestingly, all distal locations had significantly higher frequency content with respect to the ascending aorta. This is somewhat surprising due to the Windkessel effect, but it is explainable by the nonlinear nature of the cardiovascular system giving rise to higher harmonics in the waveforms. Doppler validation was only performed on the CCA and FA because of the availability of an acoustic window.

Conclusion. Our analysis of the frequency content of the velocity waveform indicates that, regardless of the implementation details of the acquisition method, a true temporal resolution of at least 30 to 40ms is necessary to correctly retain the signal characteristics of the peripheral vessels. In the Aorta, this can probably be reduced to 50ms. Interpolation of the signal, using upsampling & low-pass filtering (or B-spline interpolation), however, is important to restore the full dynamics of the signal.