Beat-to-Beat Stroke Volume Estimation Using Magnetohydrodynamic Voltages induced in intra-MRI Electrocardiograms

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Target Audience: Scientists and physicians interested in non-invasive methods for continuous assessment of aortic flow and stroke volume inside MRI.

Purpose: To develop a technique for non-invasive assessment of beat-to-beat Stroke Volume (BTB-SV) in real-time using Magnetohydrodynamic Voltages (VMHD). VMHD voltages are overlaid on Electrocardiogram (ECG) recordings obtained inside the MRI bore (intra-MRI ECGs) [1]. The major effect due to VMHD, with the heart at the magnet isocenter, is flow across the magnetic field line in the aortic arch. As are result, VMHD can potentially be used to assess the volume of blood flowing in the aortic arch at various times in the cardiac cycle. These flow volumes can be readily assessed with cine Phase Contrast (PC) MRI, but substitution of an ECG measure would allow continuous physiological monitoring, leaving the MRI free to perform other imaging tasks. When the flow volumes are time-integrated over the systolic phase, SV is obtained, leaving it possible to compute SV from VMHD. In this study, a methodology was developed to compute flow velocity and SV from ECG vector-decomposition of the VMHD signal ($\overrightarrow{VMHD(t)}$). $\overrightarrow{VMHD(t)}$ was compared to cine PC-based time dependent flow during a training session to compute coefficients of correlation. With these coefficients, the study derived a $\overrightarrow{VMHD(t)}$ measure of SV, and compared it to the PC "gold standard." The study was then validated after the patient-specific training session was completed, $\overrightarrow{VMHD(t)}$ could be used to continuously assess flow and SV, even when patient conditions changed (e.g. exercise-based stress), leaving the MRI free to perform diagnostic or interventional imaging.

Methods: Phase Contrast (PC) Cine was performed in the ascending aorta in three healthy volunteers (#1-3) at rest in a Siemens Skyra 3T MRI. PC and Real-Time PC (RTPC) was then performed in two healthy volunteers (#4-5) at rest and during exercise stress, in a Siemens Trio 3T MRI (Fig. 1), in order to obtain single cardiac-cycle flow and SV measures. 12-lead ECGs were recorded from subjects using an MRI-compatible 12-Lead ECG recording system similar to [2-3]. VMHD voltages at each electrode were extracted through the subtraction of ECGs obtained with the subjects outside and inside the MRI [2]. An inverse Dower transform was used to convert the VMHD traces into a Vectorcardiogram (VCG) frame of reference [4], where $\overrightarrow{VMHD(t)}$ is composed of three spatial (X, Y, Z) components. A multiple linear regression (MLR) model (Fig. 2) was developed individually for each subject, using subject-specific coefficients, to correlate $\overrightarrow{VMHD(t)}$ to blood flow as a function of time, which was measured by Cine PC MRI over 30 cardiac cycles (Fig. 3a). The VMHD'-derived blood flow was then integrated over the systolic phase to estimate BTB-SV, and compared to the PC MRI "gold-standard". Validation of $\overrightarrow{VMHD(t)}$ derived BTB-SV was performed using the RTPC sequence during exercise stress testing using an MRI-compatible bike in subjects #4-5. Blood flow volumes and SV were compared during elevated heart rates (HR) (subject #4: 96-118bpm, and subject #5: 80-120bpm), and after the return to baseline. Subjects #4-5 were chosen to validate the flow and SV estimation methods as they represent a **90th Percentile Male** (Weight: 127kg; Height: 185cm; Chest Circumference: 135cm; Age: 19) and a **50th Percentile Male** (Weight: 68kg; Height: 168cm; Chest Circumference: 94cm; Age: 23).

Eq. 1: $FlowVolume(t)_{PC} = A_0 + A_1 \times VMHD(t)_X + A_2 \times VMHD(t)_Y + A_3 \times VMHD(t)_Z$

Eq. 2: $SV = \int_{Systolic\ Phase} FlowVolume_{VMHD} dt$

Fig. 2: Equations for (1) PC-derived blood flow volume as a function of the directional $\overrightarrow{VMHD(t)}$ components, where A_0, A_1, A_2, & A_3 were computed using MLR. Equation 2: SV was thereafter derived from systolic time-integrated blood flow volume.

Table 1: Assessment of MLR Fit for VMHD-derived Blood Flow and Stroke Volume Estimation

Subjects	Flow Correlation	$\overrightarrow{MHD(t)}$ SV	Avg. PC SV	SV Error
#1	0.94	73.7 mL	75.7 mL	2.62 %
#2	0.95	78.5 mL	78.1 mL	0.59 %
#3	0.84	55.1 mL	53.2 mL	3.56 %
#4 (90th)	0.99	76.8 mL	77.6 mL	1.00%
#5 (50th)	0.95	79.0 mL	78.4 mL	0.76%

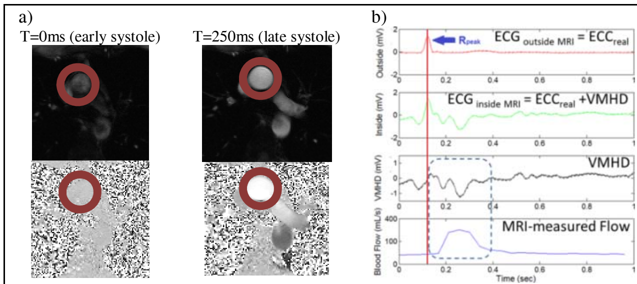

Fig. 1: (a) Assessment of aortic flow using Phase Contrast MRI. Magnitude (top) and velocity (bottom) maps. (b) Correlation of $\overrightarrow{VMHD(t)}$ to blood flow in ascending aorta.. PC parameters: VENC=150 cm/s; TR/TE/flip angle=44.08ms/3.28ms/20°.

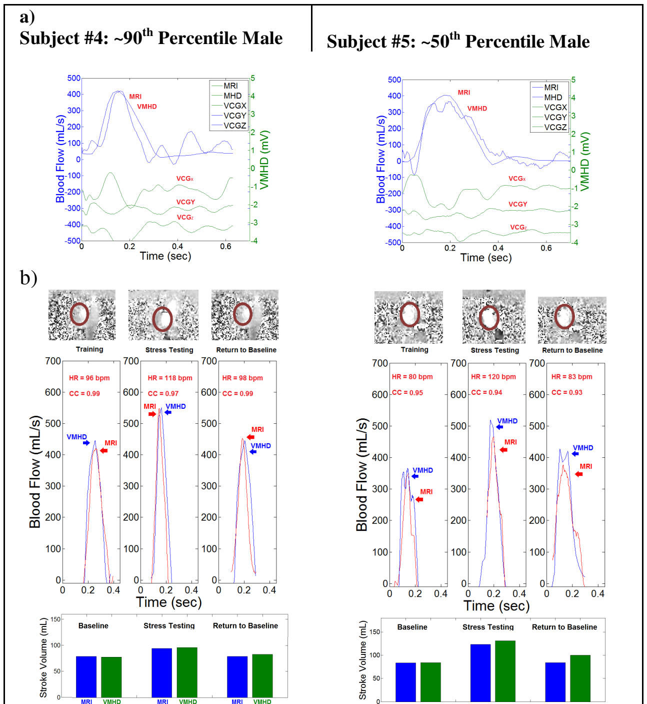

Fig. 3: SV Estimation using $\overrightarrow{MHD(t)}$, VENC PC, and RTPC in Subjects #4 and #5. (a) MRI & $\overrightarrow{VMHD(t)}$ derived blood flow (blue) compared to extracted VMHD components (green). b) Comparison of BTB $\overrightarrow{VMHD(t)}$-derived SV and Blood Flow with RTPC and cine PC results during rest & stress. RTPC parameters: VENC=150 cm/s; TR/TE/flip angle=82.24 ms/5.76ms/30°.

Results: After MLR was performed for each subject, aortic blood flow as a function of time was computed from $\overrightarrow{VMHD(t)}$ and compared to PC scans to evaluate the fit (Table 1). Correlation was determined through a Spearman's Ranked Coefficient, and found to be > 0.84. $\overrightarrow{VMHD(t)}$-based SV was determined with a < 3.6% error, relative to PC, in all five subjects after the initial subject-specific fits were generated. Fig. 3b shows the real-time BTB blood flow and SV derived from $\overrightarrow{VMHD(t)}$, as well as the associated HR and raw ECG trace (precordial Lead V6). Validation of BTB $\overrightarrow{VMHD(t)}$-derived flow and SV was performed in subjects #4-5 using RTPC, illustrating method accuracy (Fig. 3) (Table 2).

Table 2: Assessment of VMHD-derived flow and stroke volume compared to RTPC ground truth (in subjects #4 & #5)

Stress Testing			
Flow Waveform Correlation	Peak Flow Error	Difference in Ejection Period	SV Error
0.955	5.99%	30ms	4.3%
Return to Baseline			
Flow Waveform Correlation	Peak Flow Error	Difference in Ejection Period	SV Error
0.96	8.145%	50ms	11.91%

Conclusions: Utilizing a relatively short PC Cine measurement (~30 seconds) to compute patient-specific parameters, accurate BTB SV and blood flow estimates could be obtained from MHD voltages extracted from 12-lead ECG. This method provides a means for enhanced physiological monitoring, which can potentially detect an intra-MRI cardiac event.

References: [1] Gupta, IEEETransBioMedEng. 2008. [2] Tse, MRM 2013. [3] Gregory, MRM 2014. [4] Dower, JElectroCardiol, 1984.