Stroke volume and cardiac output measured on a beat-to-beat basis

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Introduction: Cardiac output (CO) measurement is valuable as a means of assessing and monitoring the severity of cardiac dysfunction in patients with cardiovascular disease, however, there is currently no non-invasive gold-standard [1,2]. This abstract introduces a method for real-time measurement of stroke volume (SV), and hence beat-to-beat CO, using slice-selective phase-contrast MRI with variable-density spiral readouts. Operator interaction simply involves drawing a polygon around the aorta in a color flow display. This is performed only once, and based on this polygon the system automatically prescribes a time-varying region-of-interest (ROI) that follows the aorta during the cardiac-cycle and free-breathing. Phase-offsets due to eddy currents [3] are corrected automatically. No cardiac or respiratory triggering is required. The method was applied *in vivo* at 3T, and beat-to-beat SV/CO changes during Valsalva's maneuver, breath-holding, and free-breathing are illustrated.

Methods:

Pulse sequence: Consists of a slice selective excitation, a through-plane bipolar flow-encoding gradient, a variable-density spiral readout, and a gradient spoiler, with scan plane prescribed perpendicular to the ascending aorta. Scan parameters are listed below.

flip angle	Venc	FOV	resolution	interleaves	readout	TR	Temporal resolution	frames/sec
10^o	200 cm/s	25~6 cm	3 mm	4	4 ms	7 ms	56 ms	18 fps

Operator interaction: Using a single color overlay image that highlights voxels where flow velocity exceeds a threshold (e.g. 25 cm/s) during the acquisition period, the operator draws a convex polygon around the ascending aorta (Fig 1).

ROI-following: The prescribed polygon is used to generate a time-varying region-of-interest (ROI). The ROI in each time frame contains all pixels where flow velocity exceeds a threshold within a temporal window (e.g. ±1 s). The time-varying estimate of cross-sectional area is the size of the ROI in each time frame (Fig. 2b).

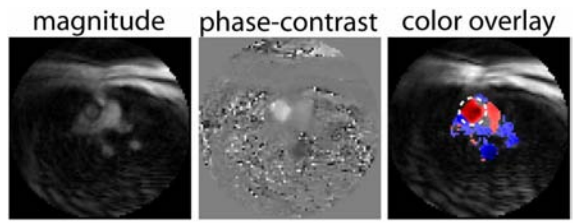

Fig. 1: ROI prescription. The operator draws a convex polygon around voxels where high velocities were detected (dashed circle). This is performed only once.

Phase-offset correction: The mode of the time-velocity distribution is calculated and subtracted. The expected mode is zero, as no flow is expected during diastole.

SV/CO calculation: From the time-velocity distribution (Fig. 2a) and the cross-sectional area (Fig. 2b), a volume flow waveform is obtained (Fig. 2c). The beat-to-beat intervals are estimated from these data (red dots), and the SV for each heartbeat is calculated (Fig. 2d). The beat-to-beat cardiac output is computed as stroke volume divided by the beat-to-beat interval.

Experiments: Studies were performed on a GE Signa 3T EXCITE HD system, with gradients capable of 40 mT/m amplitude and 150 T/m/s slew rate. Healthy volunteers were imaged at rest (free-breathing), while performing a Valsalva's maneuver, and during breath-hold.

Results: Fig. 3 illustrates changes in SV due to breath-holding and Valsalva's maneuver. SV fluctuations of 35% and 10% were observed during free-breathing and breath-holding, respectively. A 50% drop in SV was observed during Valsalva's maneuver.

Discussion: Without ROI-following, real-time methods are sensitive to in-plane motion due to breathing. ROI-following improves fidelity, but through plane motion and motion-induced changes in phase-offset may still affect the measurement. The precision of beat-to-beat interval estimation can be improved by using ECG signals or by increasing the frame rate to 140 fps with view-sharing. The precision of the cross-sectional area estimation may be improved by image interpolation, or by improving spatial resolution using parallel imaging.

Conclusions: Real-time measurement of stroke volume and cardiac output can be performed using phase-contrast MRI with variable-density spirals at 3T. Operator interaction is minimal, and the method is robust to in-plane motion and phase-offsets due to eddy currents. Expected dynamic changes in stroke volume during free-breathing, breath-holding and Valsalva's maneuver were detected. A comparison with invasive catheter-based measurement is needed to validate this technique.

References: [1] Park JB, et al. MRM 56:432, 2006. [2] Shankaranarayanan A, et al. ISMRM 13:600, 2005. [3] Pelc NJ, et al. MRQ 10:125, 1994.

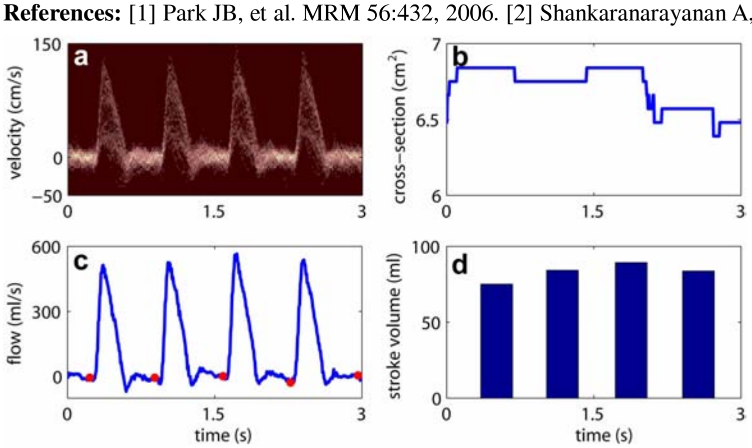

Fig. 2: Stroke volume calculation: (a) time-velocity distribution within ROI; (b) cross-sectional area; (c) volume flow waveform; (d) stroke volume.

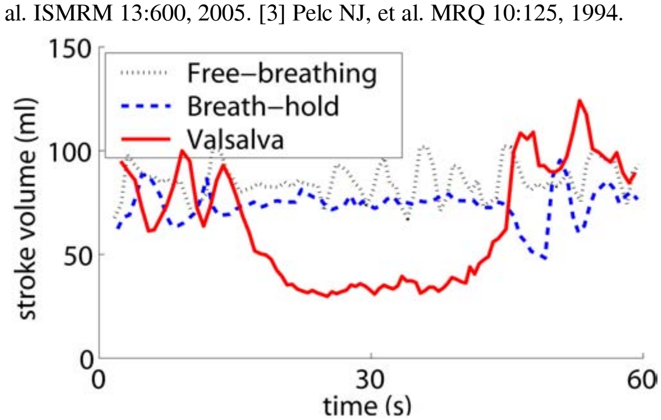

Fig. 3: Real-time SV measurement. A 50% drop is observed during Valsalva's maneuver (red). Fluctuations of 35% and 10% were observed during free-breathing (black) and breath-holding (blue).