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Measurement of pulmonary arterial pulse wave reflection from single-slice phase-contrast and steady-state free precession MRI

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Summary
Pulmonary arterial hypertension (PAH) is associated with elevated pulmonary vascular resistance, resulting in increased reflection of pressure and flow waves from distal vessels[1]. The gold standard for assessing PAH is right heart catheterization, an invasive procedure that carries a 5% risk of major complications[2]. We validate a noninvasive method for quantifying pulmonary arterial reflection using phase-contrast (PC) and steady-state free precession (SSFP) sequences acquired in a single slice.

Background
An arterial segment approximates a hydraulic transmission line terminated distally by a reflection site that partially reflects forward-traveling pressure and flow (q) waves back toward the heart[3]. Due to finite pulse wave velocity (PWV), backward-traveling waves are minimal in early systole (Figure 1); since arterial cross-sectional area (a) increases roughly linearly with pressure, $PWV = \partial q(t)/\partial a(t)$. Combining this with the water hammer equation yields an expression for the backward flow wave[4]:

<center>$q_b(t) = [q_{meas}(t) - PWV \times a(t)]/2$,</center>from which arterial reflection magnitude (R) can be computed in the frequency domain:

<center>$R(\omega) = Q_b(\omega)/Q_f(\omega)$.</center>

Methods
The right pulmonary artery in three healthy adult volunteers was imaged on a 1.5 T MR system (Siemens, Germany) using retrospectively ECG-gated cine PC and SSFP sequences to quantify blood velocity and vessel cross-section, respectively. PC and SSFP images were co-registered in MATLAB (The MathWorks, USA). The arterial lumen was outlined semi-automatically using Segment (Medviso, Sweden), yielding flow and area time series that were resolved into forward and backward flow waves in MATLAB. The frequency-domain ratios of backward to forward flow waves yielded estimates of R which were then averaged over the fundamental heart frequency and the next two harmonics[3] and compared to literature values using a two-tailed Student's t-test.

Results
The single-slice MRI method reliably resolved forward and backward flows *in vivo* (Figure 2), enabling noninvasive measurement of normal right pulmonary arterial reflection magnitudes, R (SD) = 0.34 (0.05), statistically equivalent (p = 0.74) to invasively measured literature values[5] of R (SD) = 0.33 (0.13).

Conclusions
The feasibility of single-slice MRI measurement of pulmonary arterial reflection in healthy adults motivates follow-up studies in adult and pediatric patient populations and lays the groundwork for noninvasive assessment of pulmonary hypertension.

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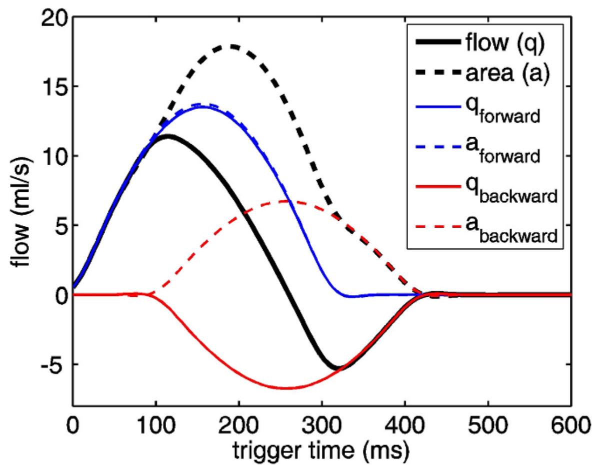

Figure 1 Illustration of single-slice wave separation. Before the onset of backward waves, flow and area are related by the constant factor *PWV*. Backward-traveling flow and area waves are equal in form but opposite in sign, and are proportional to the difference between *PWV* × area and flow.

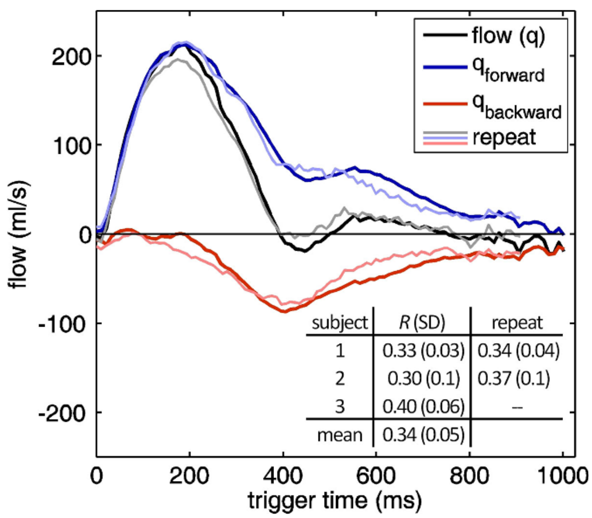

Figure 2 Flow wave separation in the right pulmonary artery of Subject 1 calculated from an initial MR study and a repeat scan 36 days later. Reflection magnitudes and standard deviations are tabulated for all subjects. Scan parameters were TR/TE = 9.8/2.2 ms, 192 × 192 matrix, 28 × 28 cm^2 FOV, 2 averages, flip angle = 10° (PC) and 45° (SSFP). The root-mean-variances of the forward, measured and backward flow waves between scans were 11, 16 and 8 ml/s, respectively.

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