Real-Time Volume Flow Measurements with Complex Difference MRI

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Synopsis: Complex difference processing of differentially flow encoded image data (phase contrast MRI) greatly simplifies image content by subtracting out signal from stationary tissue. We demonstrate that a single projection can be used to measure quantitative volume flow rates in large vessels (several mm) with a real-time temporal window of two acquisition lengths (TRs). We address the suppression of unwanted background signals and calibration of the projected complex difference signal (ml/s). Validation is provided by comparison with conventional gated-segmented phase contrast MRI in a flow phantom and in vivo in the popliteal artery and aorta in a normal volunteer.

Introduction: Quantitative measurement of blood volume flow rates in large vessels using gated-segmented phase-contrast (PC) MRI is an established technique whereby through-plane velocities are measured in an imaging plane oriented perpendicular to the direction of flow (1). Conventional segmented cardiac-gated PC-MRI is not appropriate for imaging flow that is transient in nature or if breathing or other non-cardiac motion is present due to the assumption of reproducible motion for all cardiac cycles imaged. We present a real-time velocity imaging method that allows quantitative volume flow measurements with as few as two differentially flow encoded projections (2) by using complex difference processing to eliminate signal from stationary tissue and to remove partial volume effects (3,4). Conventional PC-MRI is used to validate the flow rates measured with the projection complex difference technique in a flow phantom and in vivo in the popliteal artery and aorta in a normal volunteer.

Methods: Like conventional PC-MRI, the complex difference projection method encodes through-plane motion with bipolar gradients applied in the slice-selection direction. The differentially flow-encoded projections are subtracted to generate a “complex difference projection”. Standard read encoding is used to spatially resolve a single direction perpendicular to the slice, and the final orthogonal direction is the projection direction. The projected complex difference signal is integrated across the vessel profile to calculate the total flow rate. In order to effectively eliminate the background signal and obtain quantitative flow information the following experimental parameters/techniques were used:

1) Long TR (≥35 ms) and thin slice (1.5 – 3.0 mm) to allow for maximal arterial spin replenishment every TR.
2) Saturation of venous flow with a thick slab saturation pulse applied every TR.
3) Large V_{max} for a linear relationship between velocity, v, and the complex difference signal (2\*V_{max} ≥ 5\*v_{max} ⇒ sin(\gamma M1 v) ~ γM1v with a 6.45% error at v_{max}).
4) Optimized flow encoding gradients to minimize eddy current differences between flow encoding steps.
5) A spin-density image is collected in order to calibrate the complex difference signal intensity to true volume flow rates (ml/s).
6) Other sequence parameters: 192 readout points, BW = ± 28 kHz, flip = 30 degrees (rf spoiling), FOV = 192 mm (knee) and 320 mm (aorta).

Continuous imaging allowed an instantaneous flow rate to be calculated every 2*TR (70 ms). The two interleaved series of differential flow encoded projections were interpolated to allow a complex difference flow rate estimate every TR (35 ms). MR imaging was performed on a Siemens 1.5 T Sonata scanner (Siemens Medical Systems, Erlangen, Germany) using a flexible surface coil or the head coil.

Results: Flow rates measured in a tube phantom with conventional phase contrast correlate well (r^2 > 0.99) with the complex difference projection results over a range of 6 to 50 ml/s. The complex difference method underestimates flow by 5%. Figure 1 displays a spin-density image acquired at the level of the knee along with a sample illustrative complex difference projection, averaged over two heartbeats. Figure 2a displays the integrated complex difference flow rate in the same artery over four heartbeats. In fig. 2b these four cycles of flow are separated and overlayed with the flow measured with a gated-segmented phase-contrast experiment, showing excellent agreement. Figure 3 displays the flow rate in the abdominal aorta during a Valsalva maneuver measured with the real-time complex difference method.

Discussion: Blood flow rates measured with the real-time complex difference projection technique correlate well with conventional gated segmented phase-contrast results. The use of sufficiently long TRs and thin slices in combination with optimized flow encoding gradients resulted in excellent suppression of unwanted signal from stationary spins and allowed quantitative flow rates to be measured using a single projection direction with a 2*TR temporal window. Measurement of flow rates with real-time methods eliminate the need for breath-holding, cardiac-gating, and allow transient flow events to be imaged.