MR Doppler of High-Speed Jets

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Introduction: Approximately 10% of patients with heart disease in the United States have valvular heart disease. It is important in assessment of these patients to quantify the intracardiac flow velocities. Doppler ultrasound is a noninvasive approach that provides this capability, but can be limited by the accessible geometry and by a poor acoustic window. MR Doppler [1-3] is an MRI-based approach analogous to Doppler ultrasound that provides real-time spatial and temporal resolution of velocity distribution along an interrogation cylinder. MR Doppler has the benefit of not being limited by acoustic windows or restrictive geometries, as well as the potential of being part of an integrated comprehensive MRI examination of heart disease. However, MR Doppler imaging of high-speed jets is prone to significant image degradation. We present here a novel interleaved, echo-shifted readout for MR Doppler that is less sensitive to jets and is designed to minimize ghosting artifacts.

Methods: An assumption made in MR Doppler is that the velocity of flowing spins remains constant throughout the acquisition (typically 10-25 ms). However, this assumption is invalid for a high-speed stenotic jet that may accelerate from 1 to 4 m/s over 1 cm. Accordingly, we developed an interleaved readout scheme that reduces the acquisition period at the cost of requiring multiple interleaves.

Figure 1a shows the overlay of a two-interleaf "bowtie" [1] that form a partial acquisition of k_v-k_z (velocity-position) space. Figures 1b-c show two overlays of possible gradient interleaf waveforms $G_z(t)$ that both trace out the trajectory of Fig. 1a. The pre-encoding waveform prefacing the train of bipolar lobes is calculated for each interleaf to provide the equal spacing in k_v as shown. Figure 1c shows the echo-shifted variation where a deliberate delay is introduced following the pre-encoding lobe. The smoother temporal sampling of k_v reduces ghosting artifacts due to off-resonance and T_2^* decay, similar to echo-shifting in interleaved echo planar imaging [4].

Results: The MR Doppler sequence was implemented as part of a real-time system interfaced to a GE 1.5-T Signa scanner (40 mT/m, 150 T/m/s). Images were reconstructed in real-time (up to 70 frames/s) from the partial k-space data by incorporating homodyne weighting into the sample densities used by a gridding reconstruction. Figure 2 illustrates that high-velocity jets (4 m/s) in a flow phantom at the nozzle of an area reducer are better resolved with the echo-shifted interleaved acquisition compared to a single acquisition with the same total readout duration at the expense of poorer temporal sampling of the waveform. Note the absence of N/2 ghosts in the interleaved acquisition, even during periods of rapid flow acceleration. There is also good correlation with a continuous-wave Doppler ultrasound image. Figure 3 illustrates an *in vivo* application of a 3-interleaf acquisition obtaining high spatial and velocity resolution velocity spectrum images at the aortic valve of a normal volunteer.

Conclusions: The echo-shifted interleaved acquisition for MR Doppler provides greater immunity to artifacts from flow acceleration near jets, and has accurately imaged flow up to 4 m/s as validated by continuous-wave Doppler ultrasound. The reduced temporal sampling rate does not present any obvious difficulty in identifying the peak velocity.

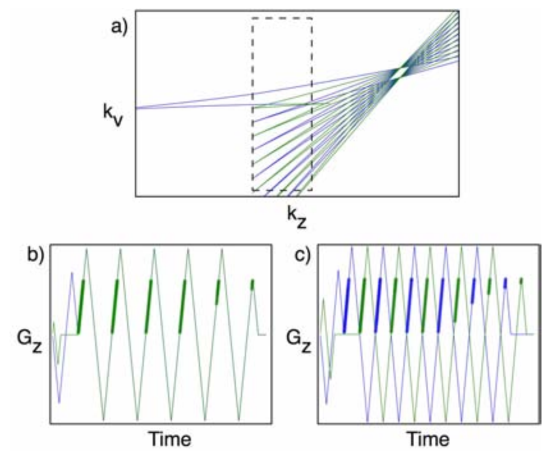

Figure 1: a) Closeup of central k_v-k_z space as sampled by a two-interleaf trajectory. The dashed box represents the data used for reconstruction. b,c) Gradient waveforms for non- and echo-shifted interleaves overlaid on each other. The thick lines show the readout period that is used for reconstruction.

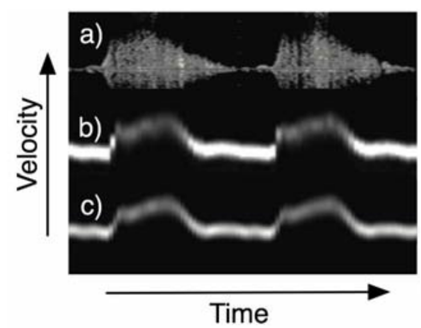

Figure 2: Velocity-spectrum images from 4 m/s flow at the nozzle of a 3/8-inch to 1/8-inch diameter reducer using: (a) continuous wave Doppler ultrasound, (b) a single 12-ms acquisition and (c) a two-interleaf echo-shifted acquisition with a 6-ms readout. Sequence TRs were 19 and 15 ms respectively.

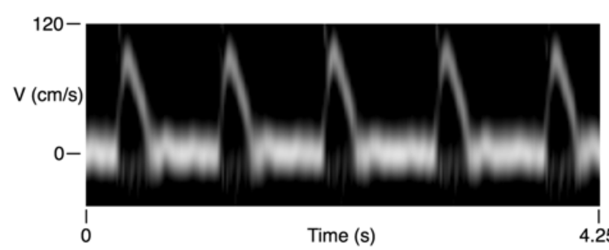

Figure 3: *In vivo* aortic-valve velocity-spectrum image acquired of normal volunteer with three 8-ms echo-shifted interleaves. The velocity resolution was 19 cm/s with +/- 120-cm/s FOV. The spatial resolution was 0.4 cm with a 30-cm FOV. The sequence TR was 17 ms.

References: [1] P. Irarrazabal *et al. Magn. Reson. Med.*, 30:207–212, 1993. [2] C.K. MacGowan *et al. J. Magn. Reson. Imag.,* 21(3):297-304, 2005. [3] J. C. DiCarlo *et al. Magn. Reson. Med.*, 54(3):645–55, 2005. [4] K. Butts *et al. Magn. Reson. Med.*, 31(1):67–72, 1994.