Velocity-Selective Inversion Prepared Arterial Spin Labeling for 3D Whole-Brain Perfusion Measurment

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TARGET AUDIENCE: MRI physicists interested in velocity-selective arterial spin labeling (VSASL) and 3D whole-brain CBF mapping.

PURPOSE: Velocity-selective ASL (VSASL)[1] is a labeling technique based on the velocity of arterial blood instead of spatial location. This significantly reduces the arterial transit time and thus holds great promise for perfusion measurements in many clinical applications, e.g. stroke. The simple "jump-return" VS preparation module in previous implementations[1,2] can produce only a velocity-dependent cosine function. Thus a velocity-selective inversion (VSI) pulse is desired for higher SNR. VSI pulse trains using a *k*-space formalism[3,4] with incorporated refocusing pulses for removing off-resonance effects[5] offer a potential solution for this pursuit. Here we report an extended VSI pulse train designed with more robust insensitivity to B0/B1 field inhomogeneity and eddy currents. We demonstrate its utility in a 3D whole-brain high-resolution VSASL protocol for cerebral blood flow (CBF) measurement on a human 3T scanner.

METHODS: Extending from the recent introduction of a single composite refocusing pulse between two unipolar gradients for each *k*-segment to combat B0 off-resonance effect[5], we propose to embed a pair of tanh/tan adiabatic refocusing pulses among four groups of three consecutive gradient lobes corresponding to the three orthogonal velocity directions respectively (Fig. 1). A total of 8 *k*-segments are repeated to allow velocity encoding for Δv = 4 cm/s within a field of speed (FOS) of 32 cm/s and a targeted inversion band within ±4 cm/s. This VSI pulse train is dubbed Double Refocused Inversion with Velocity Encoding (DRIVE). With the limit of maximum B1 amplitude of 13.5 µT and gradient strength of 40 mT/m, the duration of the DRIVE pulse shown in Fig. 1 is 105.6 ms.

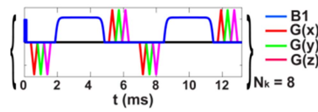

Fig.1: One of the eight k-segments of the DRIVE pulse train.

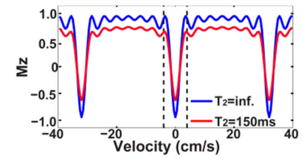

Fig.2: The simulated Mz-Velocity response of the DRIVE pulse train (105.6 ms) with and without T_2 effect.

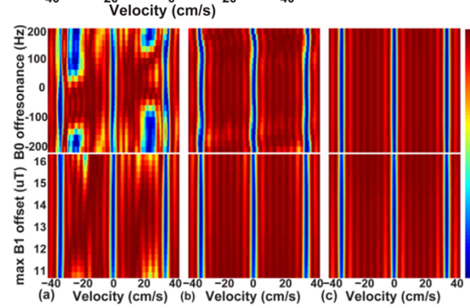

Fig.3: The simulated Mz-Velocity responses at different B0/B1 conditions after applying VSI pulses with inserted refocusing pulses: (a) one composite pulse; DRIVE: a pair of (b) composite (c) adiabatic pulses.

Experiments were conducted on a 3T Philips scanner using a 32-channel head receive-coil. Six healthy subjects (25-54 yrs) were enrolled with informed consent. The labeling for the VSASL sequence used the proposed DRIVE pulse train, with the gradient lobes turned off for the control counterpart. Background suppression (BS): a slab-selective saturation pulse (2 s pre-labeling), a slab-selective inversion (1 s pre-labeling), and three nonselective inversion pulses (0.49 s, 1 s, 1.37 s post-labeling) during a 1.5 s post-labeling delay (PLD). Note that the DRIVE pulse also serves as a partial inversion for static spins and is taken into account in the timing calculation of the BS pulses. Motion-sensitized gradients (Venc=4 cm/s) were applied during the acquisition to suppress large-vessel signals. A 3D GRASE acquisition scheme was employed with FOV of 220x220x120 mm^3 and acquisition resolution=3x3x4 mm^3 (echo train duration: 130 ms). With a TR=5 s, each dataset (control and label) takes about 1.7min. Total measurement time with 4 averages was about 7 min. With the same resolution and acquisition scheme, the following extra scans were also performed: PCASL (labeling duration τ: 1.8 s, PLD: 1.8 s); M0 map (TR=10 s); A double inversion recovery (DIR) image to visualize gray matter only; noise image (RF pulse turned off) for assessing the systematic SNR levels.

RESULTS: The simulated Mz response of the DRIVE pulse train to various velocities is displayed in Fig. 2. When the T_2 of arterial blood (~150 ms) is accounted for, the inversion efficiency reduces to 0.7 (red). For a range of B0 off-resonance and B1 offset incurred in the brain area at 3T, the simulations were compared by applying the VSI pulses train with inserted refocusing pulses using: (a) one composite pulse; (b) a pair of composite pulses; (c) a pair of tanh/tan adiabatic pulses. The DRIVE pulse train with composite or adiabatic pulses showed much improved robustness to B0/B1 field inhomogeneity with the superior performance by the adiabatic pulse pair (Fig.3).

No obvious artifacts from eddy currents are observed in the images of the VSASL employing DRIVE pulse train. Standard equations were used for CBF quantification for both VSASL and PCASL scans. CBF maps obtained from VSASL and PCASL produce similar results. Fig.4 displays representative CBF maps for both the VSASL (DRIVE) and PCASL scans at three orthogonal cross-sections, referenced to the gray matter images from the DIR scan. For each subject, five ROIs in the gray matter (frontal lobe, temporal lobe, parietal lobe, occipital lobe, and cerebellum) were manually drawn bilaterally from the DIR images. Averaged CBF values from these ROIs of all six subjects are compared between VSASL (DRIVE) and PCASL. Fig. 5 shows reasonable correlation (a, linear regression) and agreement (b, Bland–Altman plot) between the two methods. When averaged from different ROIs of the six subjects, the measured CBF for VSASL (DRIVE) and PCASL were 49±12 mL/100g/min and 49±13 mL/100g/min, respectively; the calculated systematic SNRs were 9±3 and 10±4 respectively.

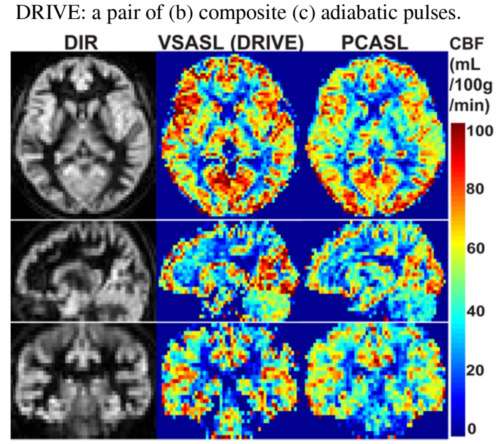

Fig.4: Data from subject 1 with whole-brain coverage: DIR images (left) and CBF maps using VSASL employing DRIVE pulse (middle) and PCASL (right).

DISCUSSION: The proposed DRIVE pulse train, by using a pair of adiabatic pulses for refocusing each *k*-segment, can greatly mitigate artifacts from B0/B1 field inhomogeneity and eddy currents. For the employed 16 tanh/tan adiabatic refocusing pulses, the VSASL protocol costs 6% more SAR than the applied PCASL sequence. The differences between the label and control in VSASL are the gradient lobes turned on or off, so no MT effects are expected to affect the data. The b value of the employed DRIVE pulse train is less than 1 sec/mm^2, therefore diffusion weighting can be ignored. Although the VSASL is a type of pulsed labeling technique, the similar SNR levels with PCASL observed in this study are probably due to the much shorter arterial transit time compared to PCASL and much longer bolus duration compared to conventional pulsed ASL.

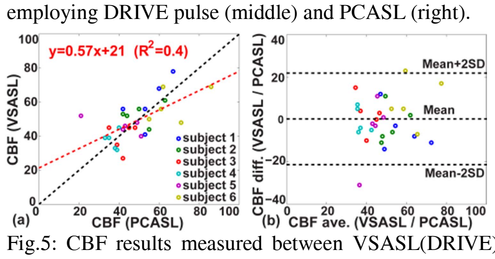

Fig.5: CBF results measured between VSASL(DRIVE) and PCASL: (a) correlation and (b) agreement.

CONCLUSION: We have developed a novel velocity-selective inversion pulse train based on the *k*-space formalism that is robust to B0/B1 field inhomogeneity and eddy current effects. The utility of this technique is demonstrated in a 3D high-resolution whole-brain VSASL study, which shows a reasonable agreement in both CBF quantification and SNR level with the standard PCASL method. Further optimization of the reported technique is under way. The advantage of the VSASL technique will be tested in various clinical applications.

REFERENCE: (1) Wong EC, et al. *MRM* 2006;55(6):1334-134; (2) Duhamel G, et al. *MRM* 2003;50(1):145-153; (3) de Rochefort L, et al. *MRM* 2006;55(1):171-176. (4) Shin T, et al. *MRM* 2013;69(5):1268-1275; (5) Shin T, et al. *MRM* 2013;70(5):spcone.