High Resolution ASL and BOLD Imaging in Skeletal Muscle using Spiral Sequences

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Introduction: Interest has recently renewed in functional magnetic resonance imaging (fMRI) in skeletal muscle. Similarly to fMRI in brain imaging, the blood oxygenation level-dependent (BOLD) effect [1], which can provide quantitative measures of T2* changes, has been used to study peripheral artery disease (PAD) [2]. Since BOLD is dependent on many factors such as blood flow, vascular volume and perfusion, it is advantageous to measure as many of these parameters as possible [3]. In this study, we developed a new spiral sequence with four gradient echoes to estimate T2* maps for both healthy volunteers and patients with PAD. This sequence is combined with our Flow-Sensitive Alternating Inversion Recovery (FAIR) pulsed arterial spin labeling (ASL) sequence [4] to measure perfusion and T2* near simultaneously.

Method: In contrast to the BOLD effect in brain imaging, T2* changes are usually significantly more obvious in skeletal muscle. The region of interest is predictable since we can visualize which muscles are used in exercise. Also, we can trade time resolution for spatial resolution, because the response to exercise is relatively slow. In order to get high resolution BOLD images in skeletal muscles, we developed a multi-slice, multi-echo spiral sequence as in Fig. 1. The sequence consists of six interleaves with four spiral gradient echoes in each interleaf. The first and third echoes have the same gradient waveform while an inverted waveform is used to generate the second and fourth echoes. The k-space trajectory is rewound to the origin between each pair of echoes. T2* maps are estimated using a monoexponential fit of the reconstructed images at different echo times. The real k-space trajectories are measured using a sphere water phantom to reduce the eddy current effects [5].

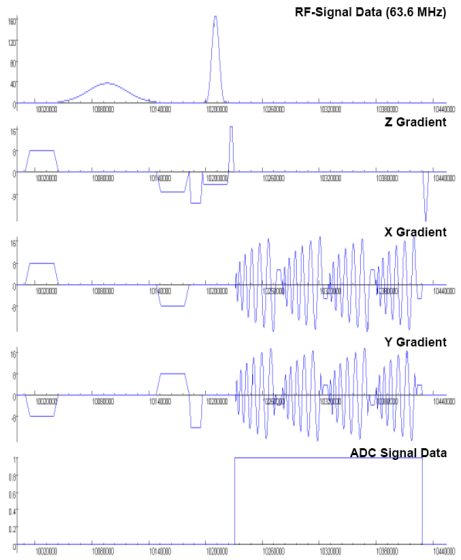

Fig. 1. Multiple gradient echo spiral sequence

The sequence was tested on a 1.5T Siemens Avanto scanner with the subjects supine on the table. Plantar flexion exercise was performed to exhaustion using a pedal ergometer. BOLD data was collected using the multi-echo sequence pre-exercise and post-exercise. The TE was 2 ms for the first echo and the echo spacing was 18.56 ms. The TR was 100 ms. Immediately after the multi-echo BOLD sequence, ASL data was acquired using a time-resolved high-resolution spiral ASL pulse sequence with hyperbolic secant inversion pulses for both tag and control FAIR labeling. This sequence used six variable-density spiral interleaves with a spatial resolution of 1.0-1.5 mm.

Results and Discussion: We collected data on two healthy volunteers and a patient with mild PAD. The BOLD effects are readily seen in all cases. Fig. 2 shows ASL images and T2* maps estimated from pre/post exercise data from a normal subject. ASL demonstrated an increase in flow from 66±7 to 149±18 ml/min/100g with exercise in the anterior tibialis. Quantitative analysis demonstrates that T2* increased from 29.7 ms pre-exercise to 36.2 ms post-exercise, an increase of 21%. This exercise effect is greater than the 13% increase seen by Ledermann et al [2] with occlusion/hyperemia. In the PAD subject of Fig. 3, ASL demonstrated an increase in flow from 55±7 to 92±9 ml/min/100g with exercise. T2* increased from 31.6 ms to 37.4 ms, an increase of 18%, less than the 21% increase in the normal subject. Thus, we are able to obtain simultaneous ASL measures of perfusion and BOLD measures of oxygenation in normal volunteers and PAD patients at peak exercise.

Conclusion: We developed a multi-echo spiral sequence to measure T2* maps of healthy volunteers and PAD patients. Perfusion rate is measured using a FAIR ASL spiral sequence following the BOLD sequence. Both T2* and perfusion rate increased substantially from pre-exercise to post-exercise. More subjects will be needed to evaluate the ability of these tests to discriminate between normal subjects and PAD patients at peak exercise. Future work will include evaluating these techniques at 3T. Overall, combined ASL and BOLD measurements before and after exercise show substantial promise in the evaluation of peripheral arterial disease.

References: 1. Ogawa S et al. MRM. 14:68–78 (1990); 2. Ledermann et al Circulation. 113: 2929-2935 (2006); 3. Duteil S et al. 55:450–454 (2006); 4. Woldeysus H et al. ISMRM. 15:2691 (2007); 5. Jeff H. Duyn et al. JMR 132: 150-153 (1998)

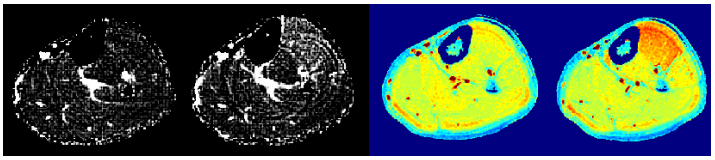

Fig. 2. FAIR ASL spatial perfusion distribution from a healthy volunteer (left) and post-exercise (2nd from left). Perfusion increases the most in the anterior tibialis. Simultaneous T2* images of healthy volunteers pre- (left) and post-exercise. T2* increases in the anterior tibialis region.

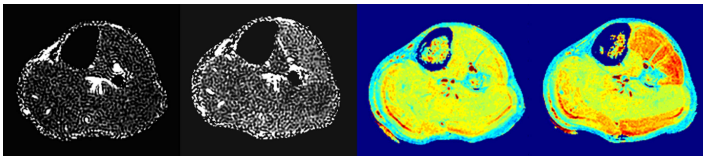

Fig. 3. FAIR ASL spatial perfusion distribution from a patient with PAD (left) and post-exercise (2nd from left). Perfusion increases diffusely with the greatest increase in the anterior tibialis. Simultaneous T2* images from the same patient pre- (2nd from right) and post-exercise (right). T2* increases primarily in the anterior tibialis and gastrocnemius.