Improved IVIM Image Quantitation of Exercised Lower Back Muscles by Local Principle Component Analysis

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Target audience Researchers in MR physics and muscle physiology

Purpose Contributions of perfusion to the diffusion-weighted (DW) MR signal in the micro-vascular system are described by the intra-voxel incoherent motion model (IVIM), which considers an additional component in the signal equation [1]. Recently, the model has been applied to MR studies of abdominal organs and skeletal muscles [2-4]. Due to the inherently low SNR in DW MRI, denoising techniques, such as LPCA (local principle component analysis) decomposition, have recently been proposed for improving image quality [5]. In this study, IVIM imaging and LPCA denoising was used to evaluate muscle fatigue by quantifying the load-induced perfusion changes in exercised lower back muscles.

Methods The study included 14 healthy volunteers (male, 20-30 years old). All MR images were acquired in transverse orientation at the height of the intervertebral disk L3-L4 using a clinical 3 T whole-body MR scanner and a spine coil array (TIM Trio, Siemens Healthcare, Erlangen, Germany). A series of DW images with 16 incrementally increasing b-values which were applied in three orthogonal directions (SE-EPI sequence, 3 slices, NEX = 6; FOV = 330 × 276 mm²; 3.0 × 3.0 mm²; d = 9 mm; TR = 2.5 s; TE = 68ms; TA = 9 min, b = 0, 5, 10, 15 ,20, 25, 30, 35, 40, 45, 50, 75, 100, 150, 200, 400 s/mm²) was acquired pre- and post-exercise (2 min after end of loading). Two transverse saturation pulses were applied in caudal and cranial direction to avoid signal contamination from vascular flow in large blood vessels. Exercises were performed outside the scanner for 10 min and arranged as a modified Sørensen test [6] using a dedicated ergometer device with an adjustable counterweight to support the subjects with 50 % of their upper body weight. Pre- and post-load DWI data were co-aligned by using a non-linear image registration method (www.picsl.upenn.edu/ANTS). All post-processing routines, including LPCA, mono-exponential fitting and ROI analyses, were written in MATLAB. The LPCA removes noise effects in the DW series by decomposing the signal decay over 16 applied b-values and using only the first component on a local kernel of 3 × 3 × 3 voxels to reconstruct filtered intensities [5]. Denoised b_0 and $b_{100\text{-}400}$ images were used for a pixel-wise fitting of the function $S_i/S_0 = e^{-bi*D} - f$ to the signal decay (as simplification of the bi-exponential IVIM signal equation, whereby commonly used mono-exponential function was extended by the term *f* describing the perfusion-related signal loss for b-values < 50 s/mm²; demonstrated in Fig. 1). Additionally, ROIs were bi-laterally drawn in the inner (*M. multifidus*, MF) and outer (*M. erector spinae*, ES) regions of the lower back muscles on the b_0 images to determine the median *D* and *f* values. Differences between median pre- and post-load values were tested with a two-sided sign test.

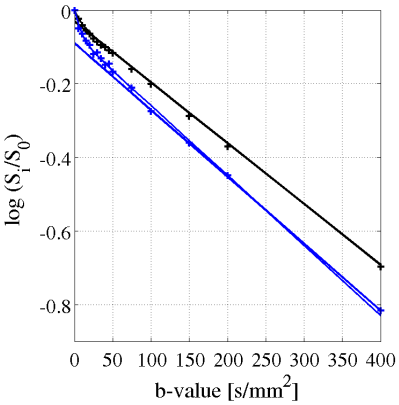

Fig. 1 *Bi-exponential signal decay in a series of DW images, which were acquired in lower back muscle pre- (black) and post- exercise (blue). Mono-exponential decay was calculated based on $b_{100\text{-}400}$ images.*

Results Fig. 2 shows *D* and *f* maps, which indicate inhomogeneous spatial intensity distributions in the lower back muscles. However, compared to pre-exercise maps an increase of *D* and *f* is clearly visible in the post-load maps. Comparison between maps calculated from raw and denoised data indicates the beneficial effect of noise reduction and image smoothing on the IVIM parameter mapping. Mean *D* and *f* values determined by ROI-based analyses of denoised data are listed in Tab. 1 and Tab. 2, respectively. All *D* and *f* values show load-induced increases, whereby only the left ES and MF reached significance ($p < 0.1$) between the pre- and post-load data. The *p*-values obtained with denoised data were one order of magnitude smaller than the *p*-values with raw data.

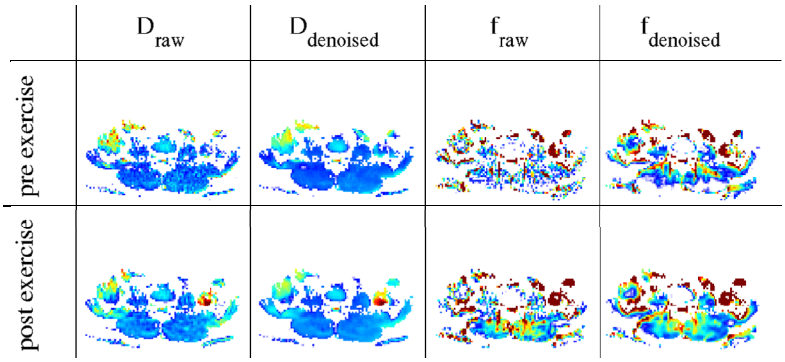

Fig. 2 *Transverse slice of mapped IVIM parameters D and f, which were calculated pixel-by-pixel based on raw (D_{raw}, f_{raw}) and denoised data ($D_{denoised}$, $f_{denoised}$) acquired pre (1st row) and post isometric load (2nd row).*

Tab. 1 *Mean diffusion coefficients D (mean ± SD in 10^{-3} mm²/s) pre and post exercise (2 min after end of exercise) for 14 subjects.*

ROI	mean D ± SD pre-exercise	mean D ± SD post-exercise	*p*-value
left ES	1.69 ± 0.05	1.74 ± 0.06	0.002
left MF	1.70 ± 0.05	1.75 ± 0.05	0.057
right MF	1.70 ± 0.05	1.72 ± 0.05	0.791
right ES	1.69 ± 0.07	1.73 ± 0.07	0.180

Tab. 2 *Mean f values (mean ± SD in %) for 14 subjects.*

ROI	mean f ± SD pre-exercise	mean f ± SD post-exercise	*p*-value
left ES	5.29 ± 2.66	8.16 ± 2.46	0.057
left MF	7.96 ± 3.76	10.64 ± 3.11	0.057
right MF	8.53 ± 3.99	10.08 ± 3.68	0.424
right ES	5.87 ± 3.34	7.39 ± 3.24	0.791

Discussion and Conclusion This study demonstrates the feasibility of combined functional IVIM image quantitation and LPCA-based denoising method in lower back muscles. Mean *D* and *f* values revealed spatially varying increases post exercise. The spatially resolved perfusion contribution may be used as physiological marker of muscle activity and fatigue during exercise. Future studies may help to assess additional information on the disease progress of non-specific chronic low back pain patients.

References **1.** Le Bihan D. Radiology. 1986;161(2):401-7. **2.** Yanagisawa O *et al.* Magn Reson Imaging. 2009;27(1):69-78. **3.** Sigmund EE *et al.* Proc ISMRM 20 (2012), #3252. **4.** Hiepe P *et al.* Proc ISMRM 19 (2011), #2013. **5.** Manjon JV *et al.* Proc ISMRM 20 (2012), #3580. **6.** Biering-Sørensen F. Spine. 1984;9(2):106-19.