Diffusion Tensor Imaging of the Human Calf – Distinct Changes in Fractional Anisotropy and Mean Diffusion due to Muscle Shortening and Stretching

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Introduction: Diffusion tensor imaging (DTI) is able to display diffusional anisotropy of tissue. Initially used for neuronal fiber tracking, DTI has been proven to be a powerful non-invasive tool for providing information about tissue characteristics and under physiological and pathological conditions. DTI-based tissue characterization may reflect the microarchitecture of the muscle[1]. The highly ordered molecular and cellular structure is determined by the macroscopic arrangement of the muscle fibers, forming bundles which are grouped together. Water diffuses more easily along the muscle fiber bundles rather than perpendicular to them[1,2]. It is known that the cross sectional area of the muscle fiber increases with muscle shortening and decreases with muscle lengthening. Thus, it must be assumed that water diffusivity within the muscle will change with muscle length. The aim of the present study was to validate this hypothesis by analyzing changes in diffusion characteristics due to passive flexion and extension of the ankle.

Materials and Methods: The diffusion tensor was measured in transverse slices through the lower leg of seven healthy volunteers (29±7yrs) in two different positions of the foot (40° plantarflexion and -10° dorsiflexion in the ankle). The tibialis anterior muscle (TA) and the medial head of the gastrocnemius muscle (GM) were evaluated (see ***figure 1***). Maps of the mean diffusivity (ADC, given in $10^{-3}mm^2/s$), the three eigenvalues (λ_1, λ_2, λ_3, given in $10^{-3}mm^2/s$) of the diffusion tensor and fractional anisotropy (FA) were calculated. All seven volunteers were examined in a 3 T whole-body MRI scanner (Magnetom Trio, Siemens Healthcare, Erlangen, Germany). An 8-channel transmit/receive circularly polarized extremity coil was used for all measurements. To sustain the chosen ankle position, an MRI-compatible device was used consisting of a pedal which is firmly fixed on a base plate. Diffusion images were acquired using a diffusion-weighted stimulated echo (STE) EPI sequence with following sequence parameters: TR = 5000 ms; TE = 36 ms; TM = 150 ms; slice thickness 7 mm (10 averages); receiver bandwidth 2004 Hz/Px. The image matrix was 64 x 64 and the field of view (FOV) 200 x 200 mm, leading to a voxel size of 3.1 x 3.1 x 7 mm. The chosen b-values were 0 and 700 s/mm^2.

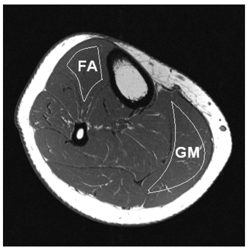

Figure 1: T1-weighted image. The muscle groups analyzed are indicated. TA: tibialis anterior muscle; GM: gastrocnemius muscle.

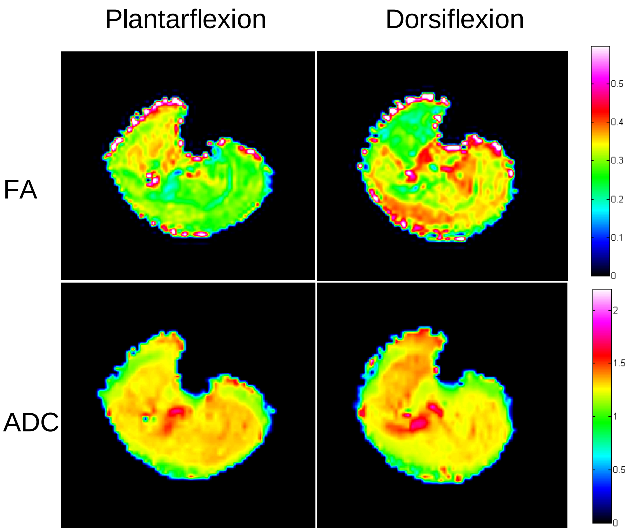

Figure 2: FA and ADC maps of one exemplary subject (female, 31 yrs). Note the behavior the antagonist muscle groups

Results: Results revealed a distinct dependency of mean diffusivity and fractional anisotropy on shortening and stretching of the antagonist muscles (see ***figure 2***). The tibialis anterior muscle showed a significant increase of 18.5% in fractional anisotropy with increasing dorsiflexion, while the fractional anisotropy of the gastrocnemius muscle significantly decreased (decrease of about 18.6 %) (for FA and ADC values see ***table 1***). Regarding the mean diffusivity of the diffusion tensor, the muscles showed an opposed response to elongation and shortening. Concerning the eigenvalues of the diffusion tensor, λ_2 and λ_3 showed significant changes in relation to muscle length. In contrast, no change in λ_1 could be found.

Discussion: Changes of muscle diffusivity are a topic of constant debate[3,4]. Recently, Hatakenaka and coworkers found significant changes in λ_1 and λ_3, but not in λ_2 in the shortened human muscle. They argued that their results reflect the shortening of the muscle fiber and myofibrils due the decreased sarcomere length which is responsible for the decrease along the fiber direction. In contrast, an increase of λ_2 and λ_3 (and therefore an elevated ADC / decreased FA) were found in our study while no changes in λ_1 were found in the shortened muscle. Thus, it must be suggested, that the fiber length of muscle cells is too large to hinder axial diffusion.

Regarding radial diffusion, not only the cell membrane but also cell organelles such as the mitochondria and the sarcoplasmatic reticulum (SR) seem to be candidates as diffusional barriers since both possess length scales of the order of that measurable by DTI[5,6]. Due to shortening of the muscle fiber the increased fiber radius allows for a facilitated diffusion of water in the radial directions.

In conclusion, the diffusional characteristics in the musculature of the human calf were shown to change for different angles of the foot. Stretching of the musculature led to increased fractional anisotropy and decreased mean diffusivity, while shortening of the muscle revealed decreased fractional anisotropy and increased mean diffusivity values.

Table 1	Plantarflexion		Dorsiflexion	
	TA	**GM**	**TA**	**GM**
FA	0.32 ± 0.02	0.28 ± 0.01	0.26 ± 0.03	0.33 ± 0.03
ADC	1.30 ± 0.05	1.37 ± 0.04	1.40 ± 0.10	1.31 ± 0.03
λ_1	1.82 ± 0.04	1.82 ± 0.03	1.85 ± 0.13	1.83 ± 0.03
λ_2	1.09 ± 0.05	1.22 ± 0.06	1.25 ± 0.14	1.13 ± 0.04
λ_3	1.00 ± 0.06	1.07 ± 0.04	1.11 ± 0.06	0.98 ± 0.04

References:
1. Van Donkelaar CC, Kretzers LJ, Bovendeerd PH, et al. J Anat 1999;194 (Pt 1):79-88.
2. Damon BM, Ding Z, Anderson AW, Freyer AS, Gore JC. Magn Reson Med 2002;48(1):97-104.
3. Hatakenaka M, Matsuo Y, Setoguchi T, et al. J Magn Reson Imaging 2008;27(4):932-937.
4. Heemskerk AM, Strijkers GJ, Drost MR, Nicolay K. ISMRM 2006.
5. Galban CJ, Maderwald S, Uffmann K, de Greiff A, Ladd ME. Eur J Appl Physiol 2004;93(3):253-262.
6. Kinsey ST, Moerland TS. J Exp Biol 2002;205(Pt 21):3377-3386.