The correlation between pennation angle and the image quality of skeletal muscle fiber tractography using the deterministic diffusion tensor imaging

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Introduction

Deterministic diffusion tensor imaging (DTI) is one of the most popular data acquisition methods available to generate the skeletal muscle tractography. We have previously reported that gender differences exist in the fiber tractography images generated by deterministic DTI (1). In this report, fiber tractography by deterministic DTI of the calf was of higher quality in female than in male normal volunteers when scanned with identical parameters and reconstruction algorithms. The difference was most pronounced in the visualization of the soleus (SOL) muscle.We hypothesized that the observed differences may have correlated with variations in the pennation angle. The purpose of this prospective study was to ascertain whether a correlation existed between the muscle pennation angle and angle variation and the ability to successfully perform calf muscle fiber tractography by deterministic DTI in normal volunteers.

Materials & Methods

Fourteen volunteers between the ages of 20 and 39 (seven males and seven females) participated in this study. All volunteers were initially scanned with MRI. We scanned DTIs of calves using a 1.5 T clinical MR machine (Nova Dual release 2.6, Philips, Best, the Netherlands). The 4-channel SENSE body coil (sized 45×30 cm for parallel imaging) was convolved around the anterior and posterior aspects of the bilateral calves. The deterministic diffusion tensor imaging (DTI) was scanned. From the acquired DTI data, six fiber tractographic images from unilateral calf were generated (Figure 1) from each volunteer. These six tract graphs included three ventral muscles (anterior tibialis (AT), extensor digitorm longus (EDL), and peroneal muscle (PM)) and three dorsal muscles (gastrocnemius medialis (GCM), gastrocnemius lateralis (GCL), and soleus (SOL)). At generation of the fiber tractography, ROIs were placed at both the most cranial and caudal slices of the DTIs on the operator console. "Fiber density" was defined by the equation: Fiber density = the number of tracts / physiological cross sectional area (PCSA, voxel). Calculations were performed in each muscle, and eighty-four fiber densities were obtained from all fourteen volunteers for each of the six muscles. In addition, fractional anisotropy (FA) was also measured in the DTI at one point for each muscle on the operator console.

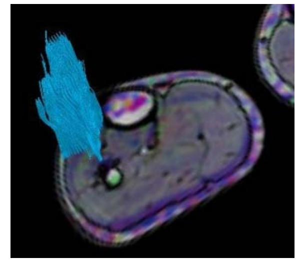

Figure 1
The fiber tractography of the anterior tibialis (AT) generated in a 28-year-old female volunteer.

DTIs were acquired using a single-shot spin-echo planer imaging (EPI) sequence with the following parameters: b-values of 0 and 500 seconds/mm^2, field of view (FOV) 350 (mm), rectangular FOV 51.79%, matrix size 224×224, slice thickness 6 mm without gap, internal number of slices 12 (7.2 cm of the length of scan range), TR = 4000 ms, TE = 60 ms, SENSE factor 2.2, number of motion probing gradient (MPG) directions 6, number of excitations 6, and total scan time 5 minutes 20 sec.

Ultrasonography (US) was performed to measure the pennation angle of each muscle. The scan range was 7.2 centimeter (cm) long in the cranio-caudal direction in the panoramic image mode. The center of the scan range was defined using the skin marking at the MRI described above. 7.2 cm distance corresponded to the range of tractography. Tractography was generated in the 7.2 cm range because the slice thickness was 6 mm without a gap, and the number of slices was 12.

A 4-11MHz linear probe (Aplio XG, TOSHIBA, Japan) was used for scanning. In six muscles for each volunteer, measurements of the average pennation angle and the angle variation were taken. Measurements were taken at three points each at the cranial and caudal sides of the image, and six pennation angle values were averaged (AVPA). The standard deviation (SD) was defined as the SDPA (SD of the pennation angle).

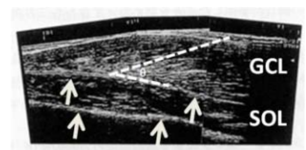

Figure 2
A panoramic image of the dorsal side of the calf. Arrows indicate the aponeurosis.
The pennation angle is the angle formed by the aponeurosis with the muscle fiber (dotted lines) arising from each aponeurosis (θ).

Statistically, AVPA, SDPA, fiber density, and FA were not normally distributed by the Kolmogorov-Sminov test. Therefore, we analyzed these data by nonparametric methods only. For each of the parameters including AVPA, SDPA, fiber density, and FA, each correlation was statistically analyzed by the Spearman's rank-correlation coefficient in all eighty-four muscles. In addition, the same analysis was performed in fourteen muscles in each six muscle.

Results & Discussion

The actual diffusion property value, its standard deviation, and comparisons of each muscle for FA, three eigenvalues, and ADC between A and B, and between Rt andActual values for all parameters including AVPA, SDPA, fiber density, and FA are shown in Table 1. The correlation table of these parameters in all eighty four muscles is shown in Table 2. AVPA and SDPA showed a strong statistically significant correlation (R=0.57 P<0.01). FA showed no statistically significant correlation. AVPA and fiber density showed a strong correlation (R=0.72, P<0.01). SDPA and fiber density also showed a strong correlation (-0.47, P<0.01). With respect to comparisons within each muscle, AVPA and fiber density showed a strong correlation (-0.57) in GCL (not shown).

Our results demonstrate that the size of the pennation angle (AVPA) and its standard deviation (SDPA) strongly affect resolution of the skeletal muscle tractography generated by deterministic DTI.

The principle of deterministic DTI is to track highly anisotropic structures consecutively at the micrometer level. Tracking stops when directionality differs between adjacent structures. In our results, AVPA and SDPA also showed a high correlation, indicating that a muscle with a large pennation angle also had a variable pennation angle. Muscles having a variable pennation angle may have had variability in the fiber orientation at a micrometer level, which increased the possibility of erroneous tracking.

The SOL has the highest percentage of slow-twitch muscle fibers in the calf (2), which may have contributed to our findings as we performed our imaging using a medium-b value (b=500mm/sec) DTI. The medium-b value DTI reflects intracellular water diffusion in skeletal muscle (3,4). Slow-twitch fibers combust fatty acids and contain numerous mitochondria. Mitochondria are one of the main restricting factors of water diffusion in the cell. Therefore, it is also possible that the SOL erroneous tracking may be the result of restricted water diffusion by the mitochondria.

	AVPA	SDPA	FA	fiber density
AT	8.03	2.01	0.43	1.73
EDL	5.13	1.06	0.41	3.11
PM	8.52	1.66	0.41	2.07
GCL	16.61	1.79	0.39	0.93
GCM	21.01	2.18	0.37	0.41
SOL	20.63	5.13	0.29	0.12
ALL	13.33	2.31	0.38	1.39

Table 1
The actual values of each US and MRI parameter in six muscles and averaged across all muscles

	AVPA All	SDPA all	FA all	fiber density all
AVPA All	/	0.57 **	0.23	-0.72 **
SDPA all	0.57 **	/	0.11	-0.47 **
FA all	0.23	0.11	/	0.21
fiber density all	-0.72**	-0.47 **	0.21	/

Table 2 The correlation coefficient table among AVPA, SDPA, FA and fiber density Analysis was performed by Spearman's rank-correlation coefficient
** statistically significant difference (P<0.01)

Conclusion

Our data suggest that a larger, more variable pennation angle resulted in worse skeletal muscle tractography using deterministic DTI.

References 1) Magn Reson Med Sci. 2010;9:111-118 2) HistochemicalJournal 1975; 7: 259-266 3) J Magn Reson Imaging. 2008;27:932-937 4) J Gerontol A Biol Sci Med Sci. 2007;62:453-458