Change of MR diffusion property during Active Muscle Contraction in the Calf

Y. Okamoto[1], A. Kunimatsu[2], and M. Minami[3]

[1]University of Tsukuba hospital, Tsukuba, Ibaraki, Japan, [2]Radiology, University of Tokyo hospital, Japan, [3]University of Tsukuba hospital, Japan

Introduction

Studies demonstrating the differences in the diffusion properties between non-injured and injured (1), or fatigued (2), or between muscles of young and old subjects (3) have been widely reported in the territory of the diffusion tensor imaging (DTI) of the skeletal muscle. In these studies, the subjects were examined for changes in diffusion properties by observing the alterations resulting from passive or active muscle contraction and the elongation of the gastrocnemius medialis and anterior tibialis (4-6). According to these reports, the diffusion properties were also dynamically changed by the muscle contraction. In this study, we observed the diffusion property changes due to the active muscle contraction, and compared our data with the previously reported "passive" contraction data obtained by Hatakenaka (4) and Heemskerk (6), and the preliminary "active" muscle contraction data reported by Deux et al (5).

Materials and Methods

Healthy volunteers including 4 males aged 25-51 year-old and 6 females aged 26-41 year-old were recruited as subjects in this study. DTI of bilateral calves were obtained using a 1.5 T clinical MR machine (Achieva, Nova dual, Philips, Best, The Netherlands) at the proximal portion of bilateral calves with feet first supine position. The 4 channels of SENSE body coil for parallel imaging was convolved around the anterior and posterior aspects of their bilateral calves. DTI parameters were based on previously published literature describing DTI scans of muscle. A single-shot spin-echo EPI sequence was used for DTI with following parameters, b=500 s/mm², FOV 400 (cm) RFOV 75%, matrix size 128×128, slice thickness 6mm, number of slice 12, TR=2500ms, TE=59ms, SENSE factor 2, number of MPG directions 6, number of excitations 10. Total scan time was 5 minutes 30 sec. At the resting state, T1-weighted fast-field echo (T1-FFE) image were acquired as anatomical mapping with the following parameters; matrix size 256×192, slice thickness 6 mm, number of slices 12, TR=13 ms, TE=2.3 ms, SENSE factor 1.4, and total scan time 3 minutes, 4 sec. First, bilateral calves were scanned simultaneously in the resting state. Next, plantar flexion of the right ankle inducing contraction of the dorsal side of the right calf muscles was obtained by pressing on a custom-made foot brake-like device placed under the right plantar (Figure 1).The same imaging parameters were used in the resting state and active contraction. FA, eigenvalues, and ADC were measured in the gastrocnemius medialis (GCM) and anterior tibialis (AT) muscles of bilateral calves by seeding three box shaped (15 pixels each) regions of interest (ROI) to each muscle at its thickest part. Referring to the T1-FFE anatomy images, each opposite muscle was also seeded at the same site and level with three ROIs of the same shape and size. The right to left ratio was calculated from FA, λ_1, λ_2, λ_3 values and ADC of each muscle. Differences in the ratios of resting and contraction were assessed by Paired t-test.

Results

The change of diffusion property ratios (right/left) of 10 volunteers and p-values for paired t-test on GCM (contraction) and on AT (passive elongation) are shown in Figure 2a and 2b. GCM showed elevated FA ratio after contraction. The FA ratios at resting state and after contraction were 1.05 and 1.17, respectively. The λ_1 and λ_2 ratios also increased, with both ratios 0.99 of at resting state and 1.06 (λ_1) and 1.07 (λ_2) at the contraction state. The ADC ratio was also increased with 0.99 at rest and 1.03 at contraction. Statistically significant differences were observed in FA ($P<0.05$), λ_1, λ_2, and ADC ($P<0.01$). As for λ_3, its ratio was 0.98 at resting state and 0.94 at contraction state. This difference was not statistically significant. On the contrary in AT, a decrease of λ_1, λ_2 and ADC ratio were observed. The ratios were 0.99 (λ_1), 1.01 (λ_2), and 1.00 (ADC) in resting state, and 0.96 (λ_1), 0.94 (λ_2) and 0.96 (ADC) at elongation. Statistically significant differences were observed in λ_1, λ_2 ($P<0.05$) and ADC ($P<0.01$) in AT. The ratio of λ_3 was 0.99 at resting state, and 0.98 at elongation. This difference was not statistically significant. Although there were some differences in the physical body size between genders, there were no statistically significant differences in the change of the diffusion property ratio including FA, λ_1, λ_2, λ_3 and ADC between 4 males and 6 females (P=NA) in both GCM and AT.

Discussion

The trends of our results were apparently different from those reported by Hatakenaka (4) and Heemskerk (6), but resembled those obtained by Deux (5). Similar to Deux's study, we also obtained elevated levels of λ_1 and λ_2 due to contraction. However, contrary to our results they reported lower FA and higher λ_3 values. We assume that the diffusion properties of muscles vary with the extent and kind of contraction (passive or active) involved. In our study model, the active contraction observed GCM is characterized by slight thickening and shortening of muscle length due to plantar flexion of the ankle, and by an increase in λ_1 and λ_2 values. According to the study of Hatakenaka (4), and Galbán et al (3, 7), eigenvalues changed in conjunction with the change in intracellular space of the muscle fibers. In our study model, theoretically, the contracted muscle is expected to show a decrease in λ_1 and an increase in λ_3 due to the shortening of the sarcomere length and thickening of muscle fiber radius. However, these changes were not accompanied with any substantial change in the muscle fiber diameter of GCM. Therefore, we think other parameters except for the change of diffusion restricting factor must strongly affect to the results in this study. There are some other determinants that may affect diffusive parameters. As Hatakenaka et al. suggested, focal temperature and perfusion could also influence focal water diffusion (4). In our study model, perfusion could affect on the diffusion property of both AT and GCM. However, as GCM was actively contracted and AT was passively elongated, GCM was thought to be more easily affected by the change of focal temperature than AT. Therefore, AT might be mainly affected by the change of perfusion, and GCM might be affected by the mixture change of perfusion and temperature in our study. Substantially, λ_1 and λ_2 were slightly decreased during elongation in AT. This result may be explained that the focal blood flow decrease the diffusion property depending on the direction of the blood flow from vessels and branches corresponding to λ_1 and λ_2. In GCM, λ_1, λ_2 and ADC were apparently increased during contraction. These increases may mainly be induced by the elevation of focal temperature in addition to the effect of perfusion change.

Conclusion

FA and λ_1, λ_2 values of muscles were higher at contraction than at rest. We suppose they reflect complicated changes including microscopic morphological changes of the diffusion restricting factor, focal temperature, and perfusion. Especially, AT could be influenced by the change of perfusion, and GCM could be influenced by both the change of focal perfusion and temperature in this study.

References

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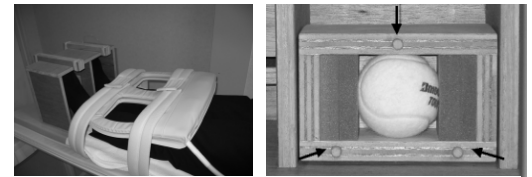
Figure 1 custom-made foot-break like device

Volunteers put their bilateral foot into these peddles with supine position at MRI scanning. SENSE body coil was convolved after setting the pedal around the foot (left). Behind the brake pedals, a hard tennis ball was set and fixed (right). Three stoppers around the tennis ball was pointed to avoid the over pressing to a ball (black arrows in right).
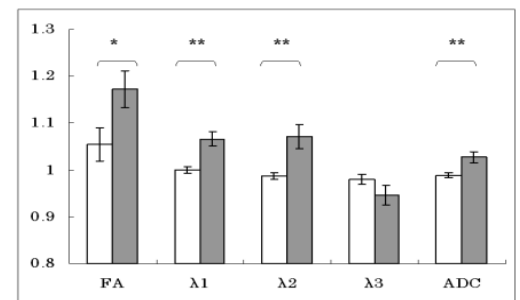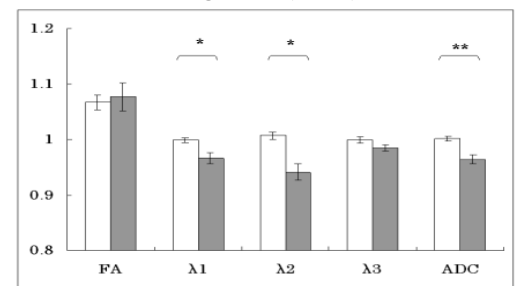

Figure 2a (GCM)

Figure2b (AT)

These are the graphs of the diffusion property change due to planter flexion of the right ankle joint. White bars are the right to left ratio of diffusion properties including FA, λ_1, λ_2, λ_3, and ADC at resting state. Gray bars are those at the contraction in GCM (a), and passive elongation in AT (b). In GCM, statistically significant elevations are seen in FA (P<0.05 *), λ_1 (P<0.01 **), λ_2 (P<0.01 **), and ADC (P<0.01 **). In AT (b), statistically significant descents are seen in λ_1 (P<0.05 *), λ_2 (P<0.05 *), and ADC (P<0.01 **).