Changes to Muscle T2 after Single-finger Exercise Measured with 0.2T MR Imaging

Masayoshi Takamori1,2, Sumikazu Akiyama1,3, Kazuya Yoshida1,3, Yoshie Imaizumi-Ohashi1, Mika Yokoi-Hayakawa1, Fumie Yamazaki1, Hiroshi Ootsuka3, Tomoyuki Haishi4, and Yoshiteru Seo1*

1Department of Regulatory Physiology, Dokkyo Medical University School of Medicine
880 Kitakobayashi, Mibu-machi, Shimotsuga-gun, Tochigi 321–0293, Japan
2Department of Physical Therapy, Aoi Medical Academy
3Department of Rehabilitation, University of Human Arts and Sciences, Faculty of Health Sciences
4MRTechnology

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We constructed an arm holder for muscle exercise from a forearm-shaped plastic shell and magnetic resonance (MR) imaging position markers and determined the echo time (39 ms) for T2-weighted spin-echo MR imaging from T2 values of the exercised (50 ms) and resting (32 ms) muscle at 0.2 tesla. The smallest detectable muscle was the extensor digiti minimi muscle (cross-sectional area 25 mm2). This combination could be useful to monitor finger exercise in patients undergoing physical therapy.

Keywords: magnetic resonance imaging (MRI), muscle, patient positioning, reproducibility, transverse relaxation time

Introduction

Electromyography (EMG) has been used to detect muscle contraction, and integrated EMG can show the linear correlation with force and velocity.1,2 The application of EMG is easy for muscles just under the skin using surface electrodes but quite difficult for muscles deep beneath the skin, and discrimination of the actual source of EMG detected by surface electrodes is difficult.3 Real-time ultrasound scanning (US) can also be applied to measure changes in thickness or the cross-sectional area of muscles.4 US is advantageous for monitoring muscles just beneath the US transducer, but its field of view (FOV) is relatively small, and it is difficult to detect synergist muscles located distant from agonist muscles in the same FOV.5

In general, magnetic resonance (MR) imaging, another noninvasive technique, has a wider FOV than US and is capable of imaging all the muscles in a single FOV in the arms and legs and even the abdomen.6 Fleckenstein and associates7 reported that the T1, T2, and water content values of skeletal muscles increased after exercise of the muscles. Several factors induced by muscle exercise, such as an increase in water content, water exchange between the intra- and extracellular spaces, blood perfusion, and temperature changes, are considered to be mechanisms involved in the increase of T2 value.3,7 Adams and colleagues8 also showed positive correlation of changes in T2 with the values obtained using integrated EMG and concluded that exercise-induced increases in T2 provide a scale for exercise intensity. Because the increased T2 values returned to original resting levels about one hour after exercise, the increase in T2 was considered completely reversible.9 Thus, MR imaging can be considered a noninvasive, safe technique for monitoring muscle activity.

Intensive studies have evaluated the use of the increase in T2 values to determine the agonist muscles,10,11 and the increase in T2 has been used to evaluate training-induced muscle inflammation.12 Therefore, MR imaging could be useful to monitor muscle exercise in patients undergoing physical therapy.3 However, commonly used clinical MR imagers are large 1.5- to 3-tesla units and usually installed in radiology departments, so their movement to rehabilitation rooms is impossible. There-
Therefore, we developed a compact MR imaging system dedicated for use during physical therapy. Using a 0.2T permanent magnet with a gap of 16 cm, the stray field of the magnet is small, which makes its installation possible within a space of 3 m². In the physical therapy of patients with stroke, rehabilitation of the muscles involved in finger function is one of the most important tasks because function of the hands is strongly related with the quality of life (QOL) of these patients.

In this study, we made arm holders for use in exercise of the forearm muscle to facilitate reproducibility of MR imaging experiments, measured the increase in T₂ value after muscle exercise to determine suitable parameters for T₂-weighted MR imaging for monitoring muscle exercise in healthy volunteers, and sought to detect muscle activity in the smallest muscle of the forearm, the extensor digiti minimi muscle.

Materials and Methods

Subjects

Ten healthy volunteers (4 men, 6 women; average age, 30.7 ± 11.1 years; average height, 169.6 ± 47.0 cm; average weight, 65.3 ± 21.7 kg [mean ± standard deviation (SD)]) participated in a study we named Protocol I, and 5 healthy male volunteers (average age, 36.4 ± 12.3 years; average height, 172.3 ± 6.9 cm; average weight, 72.3 ± 17.0 kg [mean ± SD]) participated in a study we named Protocol II. The 2 protocols will be detailed later.

The Human Research Review Board at the Dokkyo Medical University School of Medicine approved the study, and we explained the proce-
dures, purpose, and risks associated with the study to all the subjects and obtained their written consent prior to commencement of the study.

**MR imaging**

We obtained $^1$H MR images with a 0.2T compact MR imaging system (MRTechnology, Tsukuba, Japan) equipped with an oval $^1$H solenoidal radiofrequency (RF) coil (140 × 170 mm) (Fig. 1a, b). The height of the 0.2T U-shaped permanent magnet was 880 mm, the width, 490 mm, the length, 480 mm, and the weight, 520 kg. The air gap was 160 mm, and the homogeneity of the field was 30 ppm within a 120-mm sphere (X-5225, Neomax Engineering Co. Ltd., Takasaki, Japan). For each subject, the RF coil was tuned and matched at 9.0 MHz, and the RF power of 90°/180° pulses was adjusted to maximize the echo amplitude. The receiver gain was adjusted at around 50% of the range of the receiver. The amplitude gain of the Fourier transformation was also fixed. During the experiments (Protocols I and II), these parameters were fixed. A multi-slice spin-echo MR imaging sequence was employed to obtain the T$_2$-weighted MR imaging (T$_2$w-MRI). The typical parameters for transverse T$_2$w-MRI were: FOV, 20 × 20 cm; data matrix, 128 × 128; slice thickness, 9.5 mm; number of slices, 11, with 10-mm intervals; repetition time (TR), 2,000 ms; echo time (TE), 39 ms; number of accumulations (NA), one; and total image acquisition time, 4 min 16 s. The T$_2$ values were obtained using a multiple-spin-echo MR imaging sequence with FOV, 20 × 20 cm; data matrix, 128 × 128; slice thickness, 15 mm; TR, 2,000 ms, 8 TE values from 10 ms to 90 ms with a 10-ms step; NA, one; and total image acquisition time, 4 min 16 s.

Following preliminary experiments to select the suitable slice position, we set the transverse slice position at one-third of the length of the ulna from the olecranon. Three physical therapists (M.T., S.A., K.Y.), each with 2- to 3-years' experience with 0.2T MR imaging and detailed knowledge of the joints of the hand, wrist and elbow in human subjects, evaluated MR images. Muscles were determined with reference to an MR imaging atlas of the human forearm. The region of interest (ROI) of a muscle was traced on the epimysium by hand. The image intensity of the T$_2$W-MRI in each ROI was expressed as the mean and standard deviation of the mean (mean ± SD). We compared the image intensity of each ROI obtained after exercise with that obtained before exercise. An increase in image intensity was considered significant beyond the 90% confidence interval ($I_R ± 1.65$ SD) ($CL = 90\%$) and not significant (N.S.) within the 90% confidence interval, where $I_R$ was the mean of the ROI and SD was that of the ROI before the exercise. A paired $t$ test was performed for the T$_2$ values, and the significance level was set at $P < 0.01$.

We tested intraobserver agreement regarding the image intensity of the muscle studied using 2 sets of measurements conducted before and after a one-week interval. Bias, and precision (SD) values were obtained by Blant-Altman analysis.

To detect contractions of the forearm muscles with high reproducibility for positioning, we constructed a shell-type holder to fix the forearm in place. The holder consisted of a plastic shell we formed in the shape of the forearm from low density polyethylene (LDPE). Taking advantage of the elasticity of LDPE, we constructed a universal-sized shell that could provide a good fit for large, medium, and small arm sizes. The shell was fixed with a high density polyethylene (HDPE) plate (one-mm thickness) using polyethylene foam, and a pair of Velcro tapes were employed to fix the arm in place (Fig. 1c, d). We checked the position of the arm using MR imaging markers consisting of spheres of 4-mm diameter containing oil fixed in line at 5-mm intervals, varying the number of spheres in each line from one to nine (Fig. 1e, f). The position marker was placed underneath the polyethylene foam. The number of spheres in a transverse MR image showed the position of the slice (Fig. 1g). As shown in Fig. 1a, each subject was placed in a sitting position on the posterior side of the magnet and extended their forearm into the RF coil. The forearm was then fixed in place in the shell-type holder. To maintain the arm position, we affixed the base plate of the arm holder to the MR imaging table using 2 copper pins. Using this shell-type holder, we could set the slice position at the same position before each exercise session.

**Muscle exercise: Protocol I**

To confirm the reproducibility of the MR imaging experiments and select suitable parameters for T$_2$-weighted MR imaging employed to monitor muscle exercise, we measured the increase in image intensity of the T$_2$W-MRI and the increase in the T$_2$ value after the muscle exercise. We selected the extensor carpi radialis brevis (ECR-B) and flexor digitorum superficialis (FDS) muscles because the cross-sectional areas of these muscles (around 150 mm$^2$) are among the largest of all of the muscles in the forearm, and we evaluated the ECR-B as the agonist muscle and the FDS as the antagonist muscle in the exercise with dorsal flexion of the wrist joint.

Subjects performed the exercise with dorsal flex-
ion of the wrist joint with the forearm fixed in the pronated position. T_2 values and T_2W-MRI were measured before the muscle exercise. The forearm was then moved to the anterior side of the magnet, and a weighted string (25% of the maximum isometric muscle contraction) was positioned at a point proximal to the metacarpophalangeal (MP) joint. The subject did the flexing wrist joint the dorsal side against the weight, and we asked the subject to maintain that position for one second. This isotonic dorsal flexion of the wrist joint was repeated at 2-s intervals until the subject was unable to continue the dorsal flexion of the wrist. Immediately after the exercise, the arm position was restored to the original position. We measured the T_2 value 5 min after the exercise and the T_2W-MRI every 5 min for 60 min. In each slice, we set ROIs for the ECR-B muscle, FDS muscle, and subcutaneous adipose tissue using Image J software, version 1.44p (National Institutes of Health, Bethesda, MD, USA) and iPlus (MRTechnology, Tsukuba, Japan). We also calculated the cross-sectional area of each muscle from the number of pixels in the related ROIs.

**Muscle exercise: Protocol II**

To detect the activity of the smallest muscle in the forearm, the extensor digit minimi muscle (EDM), we measured extension of the MP joint of the subject’s digitus minimus on T_2W-MRI images obtained before and 5 min after the exercise. With the subject’s forearm fixed in the pronated position, a physical therapist applied manual resistance (maximum isometric muscle contraction) to extend the MP joint of digitus minimus for 5 s, and this was followed by rest for one second. The subjects did the exercise until they were unable to continue the extension of the digitus minimus. Immediately after the exercise, the arm position was restored to the original position.

**Results**

**Protocol I: Extensor carpi radialis brevis muscle and the flexor digitorum superficialis muscle**

Figure 2 shows typical examples of T_2W-MR images obtained from one subject. Figure 2a shows transverse images sliced at one-third of the length of the ulna from the olecranon. The extensor carpi radialis brevis (ECR-B) muscle (A) and the flexor digitorum superficialis (FDS) muscle (B) were traced around the muscles. (C) The extensor digitorum muscle. (D) The extensor carpi radialis longus muscle. Bold lines represent the slice positions for the longitudinal images shown in b. b. Longitudinal images sliced along the ECR-B muscle. The ECR-B muscle (A) was traced around the muscles. Bold lines represent the slice positions for the transverse images shown in a. The exercised muscles were depicted with higher signal intensity than that of the rest of the muscles.

**Fig. 2.** T_2-weighted magnetic resonance (MR) images before and 5 min after the exercise employing dorsal flexion of the wrist joint. a. Transverse images sliced at one-third of the length of the ulna from the olecranon. The extensor carpi radialis brevis (ECR-B) muscle (A) and the flexor digitorum superficialis (FDS) muscle (B) were traced around the muscles. (C) The extensor digitorum muscle. (D) The extensor carpi radialis longus muscle. Bold lines represent the slice positions for the longitudinal images shown in b. b. Longitudinal images sliced along the ECR-B muscle. The ECR-B muscle (A) was traced around the muscles. Bold lines represent the slice positions for the transverse images shown in a. The exercised muscles were depicted with higher signal intensity than that of the rest of the muscles.
muscle (A in Fig. 2a) was 170 mm² and of the FDS muscle (B in Fig. 2a), 120 mm². Image intensity in the region corresponding to the ECR-B muscle (72.7 ± 6.3) was increased after the exercise (111.4 ± 8.5; CL = 90%). Image intensities of the extensor digitorum muscle (C in Fig. 2a) and the extensor carpi radialis longus muscle (D in Fig. 2a) were also increased (CL = 90%). These muscles are synergist muscles of the ECR-B. Image intensities in the region corresponding to the FDS muscle did not differ significantly before (71.9 ± 7.7) and 5 min after (68.2 ± 8.6) the exercise (N.S.). In the longitudinal slice of the forearm (Fig. 2b), the increase in image intensity of the ECR-B muscle (A in Fig. 2b) seemed almost the same along the longitudinal axis of the muscle.

Figure 3 shows the changes in the T₂ values obtained from 10 subjects before and 5 min after the exercise employing dorsal flexion of the wrist joint. The mean and SD of the T₂ values of these ECR-B muscles before the exercise were 32.2 ± 2.5 ms. After the exercise, the T₂ values increased significantly in all subjects, and the mean and SD of the T₂ values obtained 5 min after the exercise were 50.4 ± 2.9 ms (P < 0.01). However, the T₂ values of the FDS muscle obtained before (31.8 ± 2.1 ms) and 5 min after (32.8 ± 2.4 ms) the exercise did not differ significantly. Neither did the T₂ values of the adipose tissue obtained before (99.6 ± 4.7 ms) and 5 min after (101.2 ± 3.6 ms) the exercise differ significantly.

Figure 4a shows a typical example of recovery after the exercise. The changes in the image intensity of the ECR-B muscle (agonist muscle) were plotted in Fig. 4b. The image intensity of the ECR-B muscle increased by approximately 50% and then gradually decreased to that of the FDS muscle. The differences in image intensities between the ECR-B and FDS muscles could not be discriminated by eye 35 to 40 min after the exercise (Fig. 4a). Indeed, compared with the image intensity of the ECR-B muscle before the exercise, the image intensities 30 min after the exercise were within 90% of the confidence limit (Iₚ ± 1.65SD) (Fig. 4b). The image intensities of the FDS muscle (antagonist muscle) and the subcutaneous adipose tissue were almost constant (N.S.) (Fig. 4b).

The bias of the image intensity between 2 sets of measurements done at one-week interval was 0.61. The precision of the image intensity between 2 sets
of measurements done at one-week interval was 1.75. The Bland-Altman plot showed no proportionality effect with image intensity (correlation coefficient = 0.274, n = 52; N.S.). The bias was low compared with the precision, and the precision was lower than the SD of the image intensity for the corresponding muscles.

Protocol II: Extensor digiti minimi muscle

Figure 5 shows typical examples of T2-W-MR images obtained from one of the 5 subjects. The subject did the exercise 77 times before he was unable to continue the extension of the digitus minimus. The T2-W-MR images were obtained before and 5 min after the exercise of the extension of the MP
joint of the digitus minimus. The cross-sectional area of the extensor digiti minimi (EDM) muscle (A in Fig. 5c) was 36 mm² and of the extensor digitorum muscle (B in Fig. 5c), 40 mm². The image intensities increased after exercise for both the EDM muscle (100.8 ± 15.0 to 151.7 ± 13.3; CL = 90%) and the extensor digitorum muscle (108.2 ± 14.5 to 133.8 ± 17.3; CL = 90%). No significant changes were shown in the image intensity of the subcutaneous adipose tissue obtained before (264.5 ± 17.4) and 5 min after (271.8 ± 21.6) the exercise (N.S.). Images of 4 of the 5 subjects demonstrated increased intensity of the EDM (CL = 90%), but none demonstrated increased image intensity of the subcutaneous adipose tissue (N.S.). The cross-sectional area of the EDM was 24.9 mm² ± 7.8 (n = 5). The relative image intensity of the EDM after the exercise, compared with before the exercise, was 137 ± 12 (n = 5). The relative image intensity of the adipose tissue after the exercise, compared with before the exercise, was 101 ± 2 (n = 5).

Discussion

Compared with a 1.5 to 3T MR imager, 0.2T MRI is less sensitive. Indeed, the field strength of 0.2T MRI is lower than the 0.35T MRI reported by Fleckenstein et al. Therefore, we selected parameters for T₂-W-MRI, specifying the following conditions: (1) the image intensity of the exercise muscle should be larger than 150% of that of the resting muscle, and 2) the image intensity of the resting muscle should be larger than 40% of that of the adipose tissue. The first condition is required to better discriminate the exercised and resting muscle because the values corresponding to 90% CL ranged from 15 to 25% of the image intensity of the resting muscle. The second condition is required to obtain a sufficient signal-to-noise ratio in the image of the muscle and to assign the borders of the imaged muscle according to the adipose tissue shown between the muscles. Judging by the T₂ values we obtained for resting muscle (32 ms) and exercised muscle (50 ms), the first condition was satisfied with a TE value longer than 36 ms, and judging by the T₂ values we obtained for the adipose tissue (100 ms), the second condition was satisfied with a TE value shorter than 43 ms. Thus, we selected a TE value of 39 ms, with which we could detect increase and recovery in T₂-W-MR image intensity of the ECR-B muscle after exercise using a 5-min interval (Fig. 4).

Bland-Altman analysis showed low bias and precision values for the image intensity, and no proportionality effect was detected between the 2 set of measurements conducted at different dates. Therefore, intraobserver agreement was good regarding the image intensities of muscles. The EDM muscle is the smallest muscle in the forearm; its cross-sectional area is only a sixth of that of the ECR-B. As Fig. 5 shows, we detected increases in the T₂-W-MR image intensity of the EDM muscle after the extension exercise of the MP joint of the digitus minimus. We could also discriminate between the EDM muscle and extensor digitorum muscle. Therefore, 0.2T MR imaging can be employed to detect all the muscles in the forearm of normal subjects.

The human forearm has 19 muscles, and MR imaging study of the activities of those muscles requires the stability and reproducibility of its position. Our search of the literature revealed no reports on devices for positioning the forearm. We constructed and employed a shell-type holder made from LDPE, HDPE, and polyethylene foam, plastic materials commonly used in braces and artificial limbs and in patient immobilization systems for radiotherapy and that therefore present no risks for patients. As the images in Fig. 1g show, these materials caused almost no effect on the T₂-W-MR image. We did not conduct statistical analysis of the reproducibility of the positioning of the forearm. However, Figs. 4 and 5 show representative images of an almost identical position of the forearm before and after the exercise. The increase in the image intensity of the ECR-B muscle (A in Fig. 2b) also seemed almost the same along the longitudinal axis of the muscle. Therefore, a small drift in slice position may not affect changes in image intensity. Furthermore, the accuracy of muscle exercise improved because the position of the forearm was firmly fixed so that it could not move during the exercise. Therefore, this shell-type holder should be very useful for physical therapy, for example, in patients with stroke, who suffer various movement disorders. Because we cannot predict the neuronal system that will be affected by stroke or obtain data on the seriousness of movement disorders that will result from stroke, precise information regarding the muscle activity of these patients would be most useful to plan physical therapy and obtain feedback on therapeutic efficacy. Furthermore, because MR imaging is completely noninvasive, patients more readily cooperate for follow-up studies.

In conclusion, the combination of the shell-type holder and 0.2T MR imaging is useful to monitor finger exercise of normal subjects. We are planning a study to monitor finger exercise of patients undergoing physical therapy and will also conduct lon-
gitudinal follow-ups.

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