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In vivo Time-resolved DOT measurement and image reconstruction of human forearm under exercises*

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Abstract— ***In vivo* measurement of time-resolved diffuse optical tomography (TR-DOT) were performed for human forearms under the exercises. The DOT images of oxygenation state were reconstructed, and the activities of the inner muscles were assessed.**

I. Introduction

During the forearm exercise, it is generally understood that the inner muscles work for the task, and the outer muscles work to fix the joints for efficient work of the inner muscles. For evaluation of the exercise, quantitative measurement of muscle activities is necessary, and electromyograph (EMG) and optical mapping have been used for that purpose. Both EMG and optical mapping are modalities of safe, portable and noninvasive measurements of muscle activities. EMG can measure the myoelectrical changes under the muscle exercise while optical mapping can make qualitative images of the changes in the oxygenation state of the muscle under the exercise. However, both EMG and optical mapping can provide information only in the vicinity of the skin surface. Therefore, other modalities of noninvasive imaging of inner muscle activities are required.

Time-resolved diffuse optical tomography (TR-DOT) can provide cross-sectional images of the change in the oxygenation state inside human forearms[1,2,3]. Previous studies employed TR-DOT systems to obtain DOT images of human forearms under handgrip exercise only. This study tries to obtain the DOT images of the forearm under not only handgrip exercises but also other exercises with various conditions.

In this study, *in vivo* measurements using a TR-DOT system were performed for human forearms under the dorsal and palmar flexion and handgrip exercises with the different postures and fixation of the forearm during the excises. The tomographic images of the oxygenation state were reconstructed using the algorithm based on the modified generalized pulsed spectrum technique(mGPST)[4]. The difference of the inner muscle activities are discussed by comparing the DOT images with the MR image of the forearm. The activities of the inner muscles are quantitatively assessed to some extent.

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II. Image reconstruction

The time-dependent photon diffusion equation was used for the photon migration model. For image reconstruction of TR-DOT, a 2-D mGPST algorithm was employed. It is a Newton-Raphson method based technique, which minimizes, in the least-square sense, the error between the featured measurement data and the forward solution of the Laplace-transformed photon diffusion equation with the absorption coefficient, μ_a, being updated iteratively. The finite element method was employed to solve the photon diffusion equation[4].

From the previous study on the forearm measurement, the changes in the reduced scattering coefficient, $\Delta\mu_s$', from the reference to task states were found to be negligibly small[1,2,3]. Therefore, only the changes in the absorption coefficient, $\Delta\mu_a$, which is the difference in μ_a between the task and reference states, at two wavelengths were reconstructed from the measurement data. The reconstructed images were the 2-D distributions of $\Delta\mu_a$ in the plane of interest. The spatial resolution is highly dependent on the broadening of light propagation path, and ranges from a few millimeter near the skin to more than 5 mm at the center of the forearm.

The reconstructed $\Delta\mu_a$ images were converted to the changes in the oxy-, deoxy- and total-hemoglobin and myoglobin concentrations (ΔoxyHb&Mb, ΔdeoxyHb&Mb, and ΔtotalHb&Mb) by use of the spectra of their molar extinction coefficients. The change in the oxygen saturation can be calculated from ΔoxyHb&Mb and ΔtotalHb&Mb together with the initial value of the oxygen saturation. Because our algorithm does not provide the initial value of the oxygen saturation the change in the oxygen saturation cannot be calculated. The absorption of myoglobin is very similar to those of hemoglobin. So it is difficult to separate them, and the combined hemoglobin and myoglobin concentrations were calculated although the contribution of myoglobin was estimated to be very small because the loads of the task were small enough for myoglobin to keep its oxygenation state.

III. Experiment

A 16-channel TR-DOT measurement system[5] shown in Fig. 1 was used for this experiment. It consisted of a time-correlated single photon counting system and two pulsed laser diodes emitting ultra-short light pulses with a pulse width of about 100 ps at the wavelengths of 759 nm and 834 nm, respectively. The optical fiber bundles had a coaxial structure with the inner core as a source and outer annulus as a detector. 16 fiber bundles were attached on the surface on the forearm radially with the spacing of 22.5 degree through a fiber holder.

The measurements were performed on two healthy adult subjects, A and B. The diameters of both of the forearms were about 70 mm. One fiber probe working as a source illuminated the forearm with pulsed light, and the other fiber probes detected light transmitted through the forearm. Repeating the measurements by changing the source probe one by one, a dataset for reconstruction was acquired. Data acquisition time for one of the 16 source positions was 5sec, and the total measurement time of data acquisition for one DOT image was about 150 sec.

Figure 2 shows the measurement protocol. Reference data of the rest state were firstly acquired before exercise. Soon after the reference measurement of the rest state, the subject started the exercise. The blood flow in the forearm is believed to change dynamically soon after the start of the excise. Since DOT measurement cannot respond to the fast dynamic changes in the blood flow, DOT measurement started 30 sec after the start of the exercise when the change in the blood flow seemed to have reached a steady state. DOT measurement under the excise lasted for 120 seconds with the measurement conditions same as those of the measurement under the rest state.

Two types of postures and fixation of the forearm were employed during the exercises as shown in Fig. 3. For the first posture, the forearm was placed horizontally with the wrist and elbow fixed on arm holders. as shown in Fig. 3(a). For the second posture shown in Fig. 3(b), the subject laid prone on a bed and the forearm was hung down vertically with the shoulder fixed at the end of the bed. There was a possibility that the outer muscles of the forearm were activated to fix the joints for the horizontal posture. It was supposed that the outer muscles were activated much less for the vertical posture than the horizontal posture, and it was anticipated that the difference in these postures would make differences in the DOT images.

The tasks employed in this study were the dorsal flexion, palmar flexion and handgrip exercises. The angles of the dorsal and palmar flexion exercises were kept at 45 degrees which were controlled by adjustment plates as shown in Fig. 4. No weight was loaded for dorsal and palmar flexion exercises, while the load of the handgrip exercise was 6 kg weight.

After the DOT measurement, MR images of the forearms were obtained by a 1T MRI system (Siemens, MAGNETOM Impact). The positions of the forearms measured by MR were the same as that measured by TR-DOT. The various muscles in the forearms were identified by the facia recognized in the MR image as shown in Fig. 5. There were flexor muscles on the upper region and extensor muscles on the lower region. The inner muscles were observed near the center of the image.

IV. Results

Figure 6 shows the reconstructed DOT images of $\Delta\mu_a$ under the dorsal flexion exercise at the wavelengths of 759 nm and 834 nm when the forearm of subject A was placed horizontally. These images are the differential images between the task and reference states, and the directional positions of the DOT images are the same as that of the MR image. The areas with large positive or negative changes appearing in the vicinity of the skin surface are considered to be artifacts caused by the changes in the contact condition between the surface of the forearm and fiber bundles during

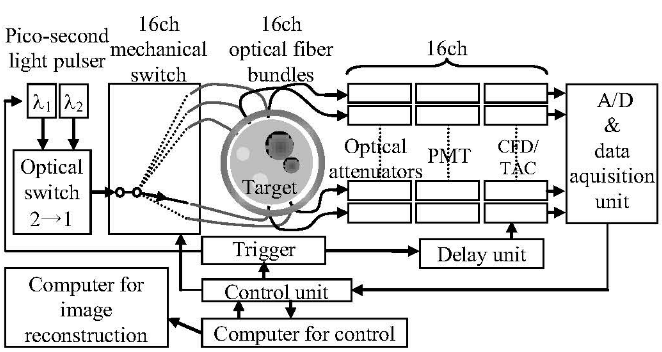

Fig. 1 Schematic illustration of TR-DOT

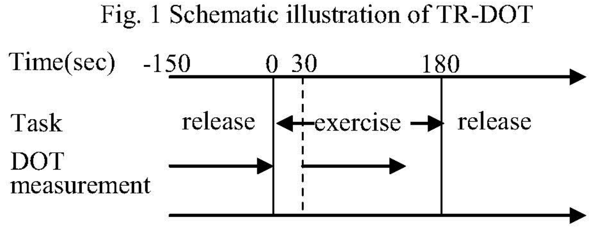

Fig. 2 Measurement protocol

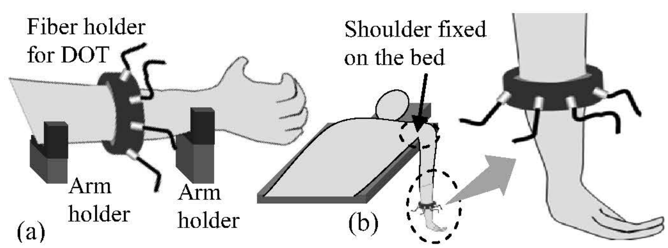

Fig. 3 The postures and fixation of the forearm
(a) Holizontal posture with the forearm placed horizontally
(b) Vertical posture with the forearm hung down vertically

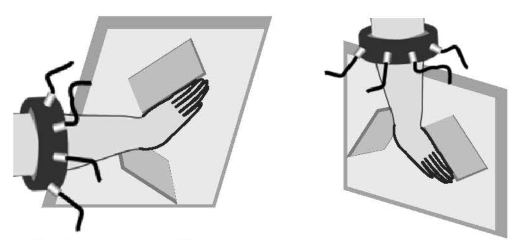
Fig. 4 The angle adjustment plate for flexion exercises

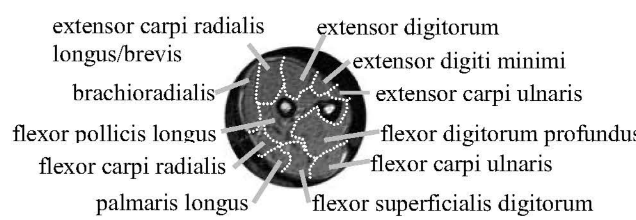

Fig. 5 MR image of the forearm with the dotted curves showing the facia.

measurements, and they should be ignored.

At the wavelength of 759 nm, a weaker absorption area is observed in the upper region and a stronger absorption area is observed in the lower region. At the wavelength of 834nm, stronger absorption area is observed in the upper and lower region. Comparing Fig. 6 with Fig. 5, flexor muscles exist in the upper region and extensor muscles in the lower region. The absorption changes in the inner muscles were smaller than those in the outer muscles. In this case of the horizontal posture, the activities of the outer muscles might be higher than those of the inner muscles.

Figure 7 shows the reconstructed $\Delta\mu_a$ images under the dorsal flexion exercise when the forearm of subject A was hung down vertically. An increase in μ_a is observed near the center of the forearm at both wavelengths. In this case of the vertical posture, the activities of the inner muscles might be higher than those of the outer muscles. From Figs. 5 and 6, it can be said that the areas larger $\Delta\mu_a$ differ by different postures and fixation of the forearm.

Figure 8 shows the reconstructed DOT images of ΔoxyHb&Mb, ΔdeoxyHb&Mb and ΔtotalHb&Mb (in μM) converted from Fig. 6 for the dorsal flexion exercise with the horizontal posture for subject A. Again the areas with large changes appearing in the vicinity of the skin surface are the artifacts to be ignored.

Because the extensor muscles are supposed to be used mainly by the dorsal flexion exercise, large changes were expected to appear in the upper region of the reconstructed images. Actually the reconstructed images show positive changes of about 10 μM in the upper region, while the regions near the center show smaller changes. The Positive changes are also observed in the lower region. The flexor muscles in the lower region of the forearm are supposed to have activated for supporting the weight of the hand. It can be said that the outer muscles were activated more than the inner muscles for this exercise with the horizontal posture.

Fig. 9 shows the reconstructed DOT images of ΔoxyHb&Mb, ΔdeoxyHb&Mb and ΔtotalHb&Mb for the palmar flexion exercise when the forearm of subject A was placed horizontally. By the palmar flexion exercise, the flexor muscles are supposed to be used mainly, and large changes are expected to appear in the lower region of the reconstructed images. As expected the reconstructed images show large changes in the lower regions. Under the palmar flexion exercise with the horizontal posture, it can be said that the flexor muscles were activated mainly.

Figure 10 shows the reconstructed DOT images of ΔoxyHb&Mb, Δdeoxy-Hb&Mb and ΔtotalHb&Mb for the handgrip exercise with the horizontal posture for subject A. By the handgrip exercise, most of the inner muscles are supposed to be used to compress the handgrip, and large changes are expected to large inner areas of the reconstructed images. Actually large areas in the reconstructed images are occupied by large change. The area was larger than those of the palmer exercise.

Figures 11, 12 and 13 show the reconstructed DOT images of ΔoxyHb&Mb, Δdeoxy-Hb&Mb and ΔtotalHb&Mb for the dorsal flexion, palmar flexion and handgrip exercises with the veritcal posture for subject A. The areas of large changes appearing inside the forearm are smaller than those in Figs. 8, 9 and 10. Also the artifacts near the skin surface are much less than those for the horizontal posture. The difference in the posture of the forearm may have caused the difference in the activated muscles for the exercises. Comparing Figs. 11, 12 and 13, the differences in the areas showing large Hb&Mb changes are small and less dependent on the type of the exercise although the activated area for the dorsal flexion exercise is a little bit larger than those for palmar flexion and handgrip exercises.

Figures 14, 15, and 16 show the the reconstructed DOT images of ΔoxyHb&Mb, Δdeoxy-Hb&Mb and ΔtotalHb&Mb for the dorsal flexion, palmar flexion and handgrip exercises

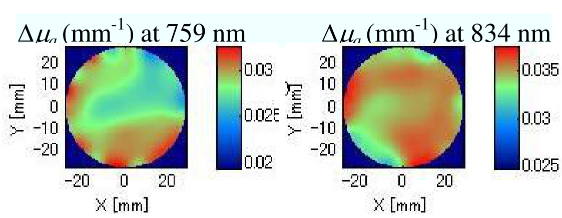

Fig. 6 Reconstructed images of $\Delta\mu_a$ for the dorsal flexion exercise with the horizontal posture.

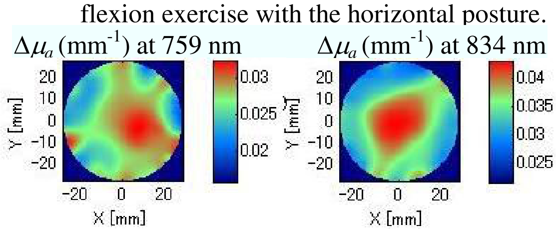

Fig. 7 Reconstructed images of $\Delta\mu_a$ for the dorsal flexion exercise with the vertical posture.

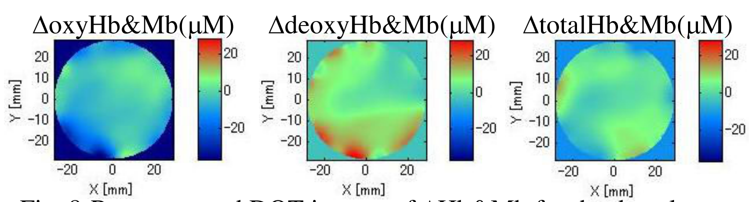

Fig. 8 Reconstructed DOT images of ΔHb&Mb for the dorsal flexion exercise with horizontal posture.

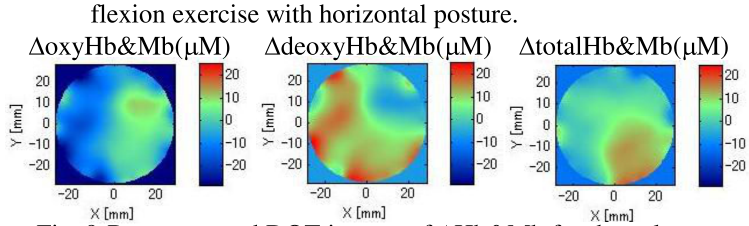

Fig. 9 Reconstructed DOT images of ΔHb&Mb for the palmar flexion exercise with the horizontal posture.

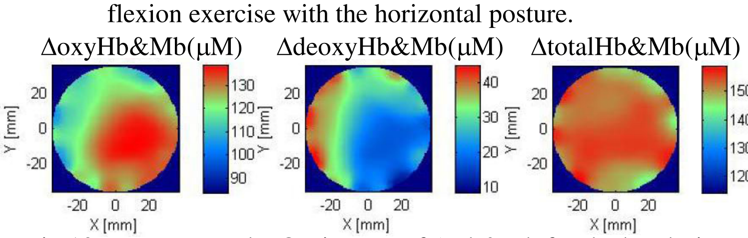

Fig.10 Reconstructed DOT images of ΔHb&Mb for the handgrip exercise with the horizontal posture.

with the veritcal posture for subject B. These images are similar to those for subject A, and the same explanations and discussions as the above are applicable.

V. Discussion and Conclusions

TR-DOT experiments on the human forearm under the dorsal flexion, palmar flexion and handgrip exercises were carried out with the horizontal and vertical postures of the forearm. DOT images of the oxygenation changes of Hb&Mb were reconstructed to evaluate the activities of the inner and outer muscles, and the followings are discussed and concluded.

The inner muscles are supposed to be activated mainly by the exercises of forearm. Actually the DOT images have shown that the activities of the inner muscles were dominant for the vertical posture. In case of the horizontal posture, the activities of the outer muscles were also observed, and it was estimated that the outer muscles were also activated to fix the joints for efficient work of the inner muscles. In particular, under the dorsal flexion exercise with the horizontal posture, the activities of the outer muscles were observed stronger than those of the inner muscles. In case of the dorsal flexion exercise with the vertical posture, the activities of the outer muscles were weak while the activities of the inner muscles were dominant.

Under the palmar flexion exercise with the horizontal posture, both the inner and outer flexor muscles were activated. On the other hand for the vertical posture, the activities of the outer muscles were weak, and the inner flexor muscles were mainly activated with the activities of the inner extensor muscles.

Under the handgrip exercise with the horizontal posture, all the inner muscles and the outer flexor muscles were activated while, for the vertical posture, the inner flexor muscles and a part of the inner extensor muscles were mainly activated with the weak activation of the outer muscles.

It has been found that the activated muscles were different with the different exercises and with the different postures and fixation of the forearm during the excises.

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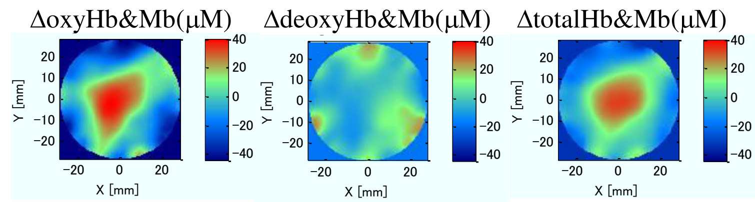

Fig. 11 Reconstructed DOT images of ΔHb&Mb for the dorsal flexion exercise with the vertical posture of subject A.

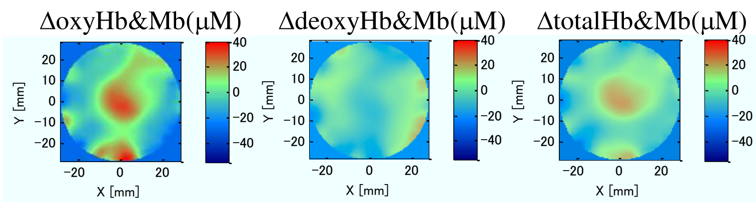

Fig. 12 Reconstructed DOT images of ΔHb&Mb for the palmar flexion exercise with the vertical posture of subject A.

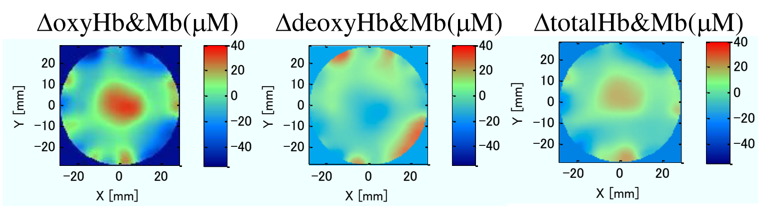

Fig. 13 Reconstructed DOT images of ΔHb&Mb for the handgrip exercise with the vertical posture of subject A.

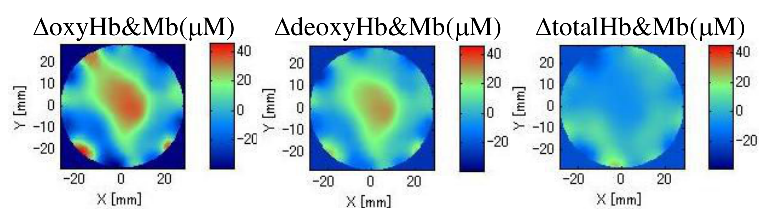

Fig. 14 Reconstructed DOT images of ΔHb&Mb for the dorsal flexion exercise with the vertical posture of subject B.

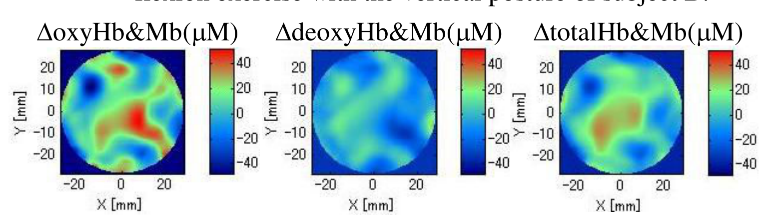

Fig. 15 Reconstructed DOT images of ΔHb&Mb for the palmar flexion exercise with the vertical postureof subject B.

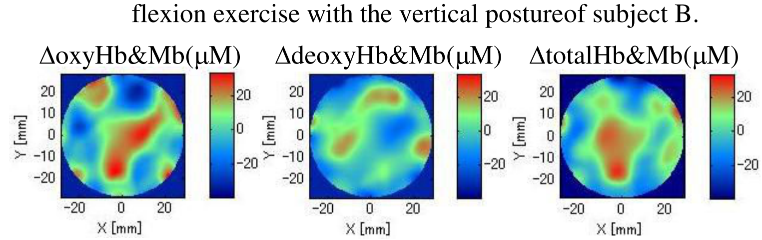

Fig. 16 Reconstructed DOT images of ΔHb&Mb for the handgrip exercise with the vertical posture of subject B.