With recent developments in neuroimaging, functional mapping, and anesthesia, the cortical functions in patients with brain tumors have been identified more safely and precisely than ever before.\textsuperscript{9,21,30} In turn, more lesions, including tumors within eloquent cortices, have become resectable, thus allowing significant recovery of neurological deficits.\textsuperscript{10}

For better operative results in patients with brain lesions, the locations of subcortical fibers have been estimated using either fiber-tracking techniques based on DT imaging data\textsuperscript{8,13,23} or intraoperative electrical stimulation.\textsuperscript{11,15} Fiber-tracking images and electrical stimulation reflect different physiological phenomena (that is, anatomical and functional connectivity) that may compensate for each other in brain mapping, but the validity of using these techniques simultaneously in neurosurgery remains unconfirmed. To determine the value of using fiber-tracking images and subcortical electrical stimulation to predict the location of the pyramidal tract near a brain tumor, we have compared the results of these two techniques.

**Clinical Material and Methods**

**Patient Population**

We examined 22 patients, with ages ranging from 15 to 61 years, in whom the lesion margins were less than 2 cm from the preoperative fiber-tracking pyramidal tracts (Table 1). Mild or moderate motor weakness was preoperatively observed in seven patients, and motor aphasia in two.

**Fiber Tracking**

Detailed methods for fiber tracking have been described elsewhere by one of the authors (T.O.).\textsuperscript{24,25} Preoperative DT MR imaging was performed using a whole-body 3-tesla MR unit (Trio; Siemens). Source images from DT imaging data sets were visually inspected by a single author (T.O.), and those images with potential artifacts were discarded. Both tensor calculations and fiber tractography reconstructions were determined using the fiber assignment by continuous tracking method and DtiStudio software (version...
Fibers that did not contribute to the pyramidal tract, we confirmed the points of stimulation in separate from the pyramidal tracts by using a two-ROI method. The Digital Imaging and Communications in Medicine navigation error. All data sets were automatically registered, and the six independent scalp point markers for anatomical registration. All data sets were automatically registered, and the anatomic landmark registrations were verified to minimize the navigation error.

Intraoperative Electrical Stimulation

The bilateral adductor pollicis brevis, biceps, brachialis, deltoid, gastrocnemius, quadriceps femoris, and tibialis anterior muscles were examined using electromyography recording. Muscle relaxants were administered during intubation but were not present during the surgery. After the craniotomy, cortical motor regions defined by somatosensory evoked potentials were stimulated to induce MEPs as well as to determine the adequate current density required to stimulate subcortical fibers. During removal of the lesions, MEPs corresponding to subcortical electrical stimulation were examined repetitively. Detailed methods for intraoperative electrical stimulation have been described elsewhere. We confirmed the points of stimulation indicated by the navigation system. Distances between the points of stimuli and the pyramidal tract determined by fiber tracking were measured with postoperative tractography in all patients.

Surgical Procedure

To evaluate intraoperative language, sensory, and motor functions, 16 patients underwent awake surgery. All procedures were approved by the ethics committee of Kyoto University Graduate School of Medicine (No. 542), and written informed consent was obtained from all patients. Resection of the lesions was stopped when a subcortical MEP response was elicited or when clinical deficits, such as aphasia and motor dysfunction, appeared.

Results

In all patients, one or more of the following were suc-
cessfully defined via intraoperative cortical stimulation and were later preserved: motor, sensory, or language function. According to the fiber-tracking images (Fig. 1) in 11 patients, the MEP was elicited on the white matter at the bottom of the lesions when less than 12 mm separated the lesion margin from the pyramidal tracts. The motor responses elicited by electrical stimulation were predominantly clonic and distal contralateral movements and were differentiated from responses induced by electrical stimulation of the supplementary motor area. The MEP was always produced when the separating distance was less than 6 mm. In the nine patients in whom the distance was between 8 and 12 mm, stimuli at the level of the corona radiata always elicited upper extremity MEPs (five of five patients; Cases 1, 2, 4, 6, and 8), whereas stimuli at the level of the brainstem or internal capsule never elicited MEP responses (zero of four patients; Cases 7, 15, 16, and 20).

During the final step of surgical manipulation (removal of the tumor at its base in the white matter) in the patients in Cases 1 and 2, in whom the first MEP had been elicited, both patients suffered from mild motor weakness of the contralateral upper extremities (Fig. 2). The weakness continued for approximately 5 minutes but resolved completely during the operation. In all seven patients the MEP was elicited at the level of the corona radiata (including these two patients), and preoperative anisotropy maps showed anteroposteriorly projecting fiber bundles around the tumor (Fig. 3). These fiber bundles were penetrated by short corticocortical connection fibers, which were visualized by fiber tracking from the precentral gyrus in the lower convexity.

![Fig. 2. Preoperative (upper) and postoperative (center) T2-weighted MR images with pyramidal tract fiber tracking (red areas) in three patients. In the patients in Cases 1 and 2 (Pt. 1 and Pt. 2), the MEP (shown as a waveform from the right abductor pollicis brevis muscle in the patient in Case 2 lower) was elicited by electrical stimulation at the bottom of the tumor (intersection of the yellow lines in an intraoperative navigation image), where transient and mild motor weakness of the upper extremities occurred during surgical manipulation. No MEP response or motor weakness was elicited in the tumor cavity in the patient in Case 15 (Pt. 15).](image-url)
Discussion

In the present study fiber-tracking images were obtained preoperatively by using a neuronavigation system, thus allowing us to directly evaluate the spatial relationship between the electrically stimulated subcortical site and the pyramidal tract as estimated on fiber tracking. In the 13 patients in whom the distance between the fiber-tracking pyramidal tracts and the stimulated site at the deepest portion of the lesions was close (< 7 mm) or far apart (> 13 mm), the MEP responses were consistent. Although the distance appeared to be approximately the same between 8 and 12 mm, the MEP responses differed in the nine patients with such distances. Among the five patients with positive MEPs at the level of the corona radiata, we observed transient and mild upper-extremity motor weakness in two. In contrast, no deficits were observed in the four patients with no MEPs at the level of the brainstem or internal capsule. These observations suggest that MEP testing is more sensitive than the fiber-tracking images in predicting pyramidal tracts, and thus can provide important information before certain surgeries for brain lesions.

To address this issue, it is important to understand the physiological characteristics inherent to electrical stimulation and fiber-tracking images. Electrical stimulation of the primary motor cortex and its descending subcortical pathways (pyramidal tracts) elicits an MEP via either cervical epidural electrodes or electromyography. The MEP is a useful intraoperative index for mapping and monitoring motor function associated with the pyramidal tracts, although there are some limitations in estimating the tract location. Electric current spreads to adjacent brain matter during stimulation and elicits an MEP from areas as far as 2 to 3 mm away. Pathological factors affect electric conductivity and resistance, which in turn affect the MEP response.

With the advent of MR imaging, it has become possible to visualize white matter fibers of the brain on DT imaging. Using this technique, anisotropy and the orientation of water molecule diffusion properties in the brain can be recorded, and the obtained information is useful in delineating the white matter tracts. Although DT imaging–based tractography is considered a promising technique for neurosurgery, it has many limitations. The errors in fiber-tracking trajectories are due to the signal-to-noise ratio, the selection of the seed ROIs, the thresholding of fractional anisotropy, and the selected algorithm. In addition, the effects of crossing fibers and the multiple principal directions of the eigenvector should be considered. The descending white matter pathways from the upper-extremity motor cortex curve inferiorly and medially. These fibers intersect or pass very close to the SLF, which tracks anteroposteriorly through the corona radiata and the centrum semiovale, causing complicated fiber tracking of the upper-extremity motor pathways.

Fig. 3. Upper: Preoperative relative anisotropy maps for patients in Cases 1 and 2 (Pt. 1 and Pt. 2). Each of the anisotropy maps indicates the principal eigenvector (green, anteroposterior; red, right–left; and blue, inferosuperior). Lower: Coronal slices showing the fibers corresponding to the SLF (green lines) and the pyramidal tracts (red lines) around the tumor. The SLF tracks anteroposteriorly through the corona radiata and the centrum semiovale, causing complicated fiber tracking of the upper-extremity motor pathways near the tumors.
tensors, eigenvectors, and non–model fitting methods such as diffusion spectrum imaging may improve the reproducibility of fiber tracking and solve the fiber-crossing problem. In addition to the aforementioned technical aspects, factors such as preoperative motor weakness and tumor-related edema could also affect the results of fiber tracking and MEP recording.

Taking into consideration all the advantages and disadvantages of MEP recording and the fiber-tracking technique, we speculate that our difficulty in estimating the fiber-tracking pyramidal tracts in the patients in Cases 1, 2, 4, 6, and 8 were most likely due to the crossing effect by the SLF surrounding the tumors. Preoperative evaluation of the SLF, which could include motor fibers from the upper-extremity motor cortex, would be necessary for lesions located near the corona radiata through the centrum semiovale. According to the spatial relationship of the resecting area and the fiber-tracking tracts detected using neuronavigation, subcortical stimulation should be applied relatively early to determine whether motor fibers are in the area.

Conclusions

In 22 patients with brain tumors near the pyramidal tract, the MEP on the white matter was consistently positive at distances less than 7 mm and consistently negative when more than 13 mm from the fiber tracking of the pyramidal tracts. In the remaining nine patients in whom the distances were between 8 and 12 mm, an MEP was elicited when stimulation was applied at the level of the corona radiata. Given that the anteroposteriorly running SLF could cause complications in the fiber tracking of motor pathways at the level of the corona radiata, subcortical electrical stimulation should be applied at some margin from the pyramidal tract as estimated by fiber tracking during resection of tumors located near the corona radiata.

References

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