Motor weakness is one of the most serious disabling sequelae of stroke. For successful rehabilitation, thorough estimation of the state of injured neural tracts for motor function is mandatory. After development of diffusion tensor tractography (DTT), which is derived from diffusion tensor imaging (DTI), three-dimensional reconstruction and estimation for three motor tracts, such as the corticospinal tract, the rubrospinal tract, and the corticoreticular pathway became possible (Kunimatsu et al., 2004; Puig et al., 2010; Yang et al., 2011). The corticospinal tract is known to be a major neural tract for motor function in the human brain (Binkofski et al., 1996). Many studies using DTI have reported on recovery of an injured corticospinal tract in various brain pathologies, including cerebral infarct, intracerebral hemorrhage, and traumatic diffuse axonal injury (Skoglund et al., 2008; Jang, 2011a).

Brain herniation occurs when the brain shifts across structures such as the falk cerebri or the tentorium cerebelli within the skull (Johnson et al., 2002). Brain herniation for three motor tracts, such as the corticospinal tract, the rubrospinal tract, and the corticoreticular pathway became possible (Kunimatsu et al., 2004; Puig et al., 2010; Yang et al., 2011). The corticospinal tract is known to be a major neural tract for motor function in the human brain (Binkofski et al., 1996). Many studies using DTI have reported on recovery of an injured corticospinal tract in various brain pathologies, including cerebral infarct, intracerebral hemorrhage, and traumatic diffuse axonal injury (Skoglund et al., 2008; Jang, 2011a).

Brain herniation occurs when the brain shifts across structures such as the falk cerebri or the tentorium cerebelli within the skull (Johnson et al., 2002). Brain herniation

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**Figure 1** Brain CT, T2-weighted MRI, and diffusion tensor tractography images of a 53-year-old male patient with subdural hematoma in the right fronto-parietal-temporal lobe and intracerebral hemorrhage in the right occipital lobe exhibiting mental deterioration and quadriparasis. (A) Brain CT images (onset) show a subdural hematoma in the right fronto-parietal-temporal lobe and intracerebral hemorrhage in the right occipital lobe. The midline is shifted to the left side. (B) T2-weighted images (7 months after onset) show no definite lesion. (C) Results of diffusion tensor tractography for the corticospinal tract. Both corticospinal tracts were narrowed from the cerebral cortex to the subcortical white matter (right (red color): between the cerebral cortex and the subcortical white matter just below the cerebral cortex (arrows); left (yellow color): between the cerebral cortex and the subcortical white matter at the level of the corpus callosum (arrows). However, thickenings of these narrow portions were observed on 7-month diffusion tensor tractography images.
usually accompanies severe neurological sequelae, therefore, accurate evaluation of the state of an injured neural tract in patients with brain herniation is necessary to elucidate the causes of neurological manifestations, and for establishment of scientific rehabilitative strategies, and in prediction of prognosis (Johnson et al., 2002; Yoo et al., 2008; Cho et al., 2011; Hong et al., 2012). Several studies have reported on injury of the corticospinal tract by transtentorial herniation (Yoo et al., 2008; Cho et al., 2011; Choi et al., 2012; Hong et al., 2012). In addition, some studies have demonstrated recovery of a corticospinal tract injured by transtentorial herniation (Kwon et al., 2011; Yeo and Jang, 2013). However, very little is known about injury and recovery of the corticospinal tract related to subfalcine herniation.

In the current study, we report on a patient who showed recovery of the corticospinal tract, which was injured by the effect of a subfalcine herniation, using DTI.

A 53-year-old, right-handed male presented with mental deterioration and quadriaparesis, which occurred at the onset of subdural hematoma in the right fronto-parietal-temporal lobe and intracerebral hemorrhage in the right occipital lobe (Figure 1A). Brain CT images showed midline shifting under the falx cerebri toward the left hemisphere. He underwent decompressive craniectomy and removal of a hematoma at the department of neurosurgery of a university hospital. At 6 weeks after onset, he was transferred to the rehabilitation department of the same university hospital for rehabilitation.

The Motricity Index (MI) and Medical Research Council (MRC) were used for evaluation of motor function of the affected extremities. The reliability and validity of the MI is well-established (maximum score: 100). He presented with quadriaparesis of all four extremities at onset (MI: 0/0) and at the start of rehabilitation (6 weeks after onset, [MI]: 55/55) (Table 1). From 6 to 12 weeks after onset, he received comprehensive rehabilitative management, including administration of neurotrophic drugs (ropinirole, levodopa, and amantadine), movement therapy, and neuromuscular electrical stimulation of the affected finger extensors and ankle dorsiflexors (Scheidtmann et al., 2001). Movement therapy focused on improvement of motor weakness and was performed at the physical and occupational therapy sessions five times per week. His quadriaparesis was improved from the MI score of 55/55 points at 6 weeks to 79/75 points (12 weeks) during a 6-week period of rehabilitation. After discharge, he was prescribed the same medication and performed a home exercise program, which focused on walking and upper extremity mobility. As a result, his weakness was recovered to a nearly normal state at 7 months after onset (96/96 points). The patient provided signed, informed consent and our institutional review board approved the study protocol.

DTI data were acquired twice (6 weeks and 7 months after onset) using a six-channel head coil on a 1.5 T Philips Gyroscan Intera (Philips, Ltd., Best, the Netherlands) with single-shot echo-planar imaging. For each of the 32 non-collinear diffusion sensitizing gradients, we acquired 70 contiguous slices parallel to the anterior commissure-posterior commissure line. Imaging parameters were as follows: acquisition matrix = 96 × 96, reconstructed to matrix = 192 × 192 matrix, field of view = 240 × 240 mm², repetition time = 10,398 ms, echo time = 72 ms, parallel imaging reduction factor (SENSE factor) = 2, echo planar imaging factor = 59 and b = 1,000 s/mm², number of excitations = 1, slice gap = 0, and a slice thickness of 2.5 mm. Fiber tracking was performed using the fiber assignment continuous tracking (FACT) algorithm implemented within the DTI task card software. Each of the DTI replications was intra-registered to the baseline “h₀” images to correct for residual eddy-current image distortions and head motion effect, using a diffusion registration package (Philips Medical Systems). Corticospinal tracts were determined by selection of fibers passing through two regions of interest (ROIs) at the upper and lower pons (portion of anterior blue color) (Jang, 2011b). Fiber tracking was performed with a fractional anisotropy (FA) threshold of > 0.15 and a direction threshold of < 27°.

Both corticospinal tracts originated from the cerebral cortex, including the primary motor cortex, which passed along the known corticospinal tract pathway (Figure 1C). However, both corticospinal tracts were narrowed from the cerebral cortex to the subcorical white matter (right: between the cerebral cortex and the subcortical white matter just below the cerebral cortex, left: between the cerebral cortex and the subcortical white matter at the level of the corpus callosum). However, thickenings of these narrow portions were observed on 7-month DTI.

The subfalcine herniation occurs when one hemisphere swells and shifts the cingulate gyrus beneath the falx cerebri, consequently causing injury of the cingulate gyrus (Johnson et al., 2002). In the current study, on 6-week DTI, we found that both corticospinal tracts were narrowed at the subcortical white matter in both hemispheres, suggesting injury of the corticospinal tract. Because the subfalcine herniation indicates injury of the cingulate gyrus by herniation below the falx cerebri, it appears that the right corticospinal tract was injured mainly by compression of the right subdural hematoma and the left corticospinal tract was injured by the effect of the subfalcine herniation. The quadriaparesis of the patient was compatible with the corticospinal tract findings on 6-week DTI. Thickenings of narrowed portions of both corticospinal tracts on 7-month DTI appear to indicate recovery of the injured corticospinal tracts. The good recovery of quadriaparesis in this patient appears to coincide with changes of the injured corticospinal tracts in both hemispheres.

Since the introduction of DTI, many studies using DTI have reported on injury of the corticospinal tract by transtentorial herniation in patients with brain injury (Yoo et al., 2008; Cho et al., 2011; Choi et al., 2012; Hong et al., 2012). As for recovery of the corticospinal tract injured by brain herniation, two studies have reported on recovery of a corticospinal tract injured by transtentorial herniation in patients with intracerebral hemorrhage and traumatic brain injury of < 27°.
In conclusion, we described a patient who showed recovery of the corticospinal tracts in both hemispheres, which appeared to be injured by the effect of a subfalcine herniation. This study demonstrated injury of the corticospinal tract and the process of recovery of an injured corticospinal tract related to a subfalcine herniation.

Table 1 Changes in motor function of the patient

<table>
<thead>
<tr>
<th>Duration from onset</th>
<th>Onset</th>
<th>6 weeks</th>
<th>12 weeks</th>
<th>7 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRC Shoulder abductor</td>
<td>0/0</td>
<td>3/3</td>
<td>4/4</td>
<td>5/5</td>
</tr>
<tr>
<td>(Rt/Lt) Elbow flexor</td>
<td>0/0</td>
<td>3/3</td>
<td>5/5</td>
<td>5/5</td>
</tr>
<tr>
<td>Finger flexor</td>
<td>0/0</td>
<td>3/3</td>
<td>4/4</td>
<td>5/5</td>
</tr>
<tr>
<td>Finger extensor</td>
<td>0/0</td>
<td>3/3</td>
<td>4/4</td>
<td>5/5</td>
</tr>
<tr>
<td>Hip flexor</td>
<td>0/0</td>
<td>3/3</td>
<td>4/4</td>
<td>5/5</td>
</tr>
<tr>
<td>Knee extensor</td>
<td>0/0</td>
<td>3/3</td>
<td>4/4</td>
<td>5/5</td>
</tr>
<tr>
<td>Ankle dorsiflexor</td>
<td>0/0</td>
<td>2/2</td>
<td>4/4</td>
<td>4/4</td>
</tr>
<tr>
<td>MI Upper extremity</td>
<td>0/0</td>
<td>59/59</td>
<td>84/75</td>
<td>100/100</td>
</tr>
<tr>
<td>(Rt/Lt) Lower extremity</td>
<td>0/0</td>
<td>51/51</td>
<td>74/74</td>
<td>91/91</td>
</tr>
<tr>
<td>Total</td>
<td>0/0</td>
<td>55/55</td>
<td>79/75</td>
<td>96/96</td>
</tr>
</tbody>
</table>

MRC: Medical Research Council. 0; no contraction, 1; palpable contraction, but no visible movement; 2; movement without gravity; 3; movement against gravity; 4; movement against a resistance lower than the resistance overcome by the healthy side, 5; movement against a resistance equal to the maximum resistance overcome by the healthy side. MI: Motricity Index (range: 0–100), higher scores indicate better motor function. Rt: Right; Lt: left.

injury, respectively (Kwon et al., 2011; Yeo and Jang, 2013). With regard to the subfalcine herniation, Hong et al. (2012) reported on injury of the cingulum and fornix in two patients with traumatic brain injury. As a result, to the best of our knowledge, this is the first study to demonstrate injury and recovery of the corticospinal tract related to a subfalcine herniation.

References

Copiedited by Chen ZG, Zhang J, Wang TH, Jiang BG, Li CH, Song LP, Zhao M