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The clinical characteristics of motor function in chronic hemiparetic stroke patients with complete corticospinal tract injury

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Abstract. Clarification of the clinical characteristics of motor function in stroke patients with complete corticospinal tract (CST) injury would be of importance in stroke rehabilitation. However, this topic has not been clearly elucidated. We conducted an investigation of the clinical characteristics of motor function in chronic hemiparetic stroke patients with complete CST injury, as confirmed by transcranial magnetic stimulation and diffusion tensor imaging. Forty-one consecutive chronic hemiparetic stroke patients who showed an absence of motor evoked potential in muscles of the upper and lower extremities upon transcranial magnetic stimulation and in whom the integrity of the CST discontinued around stroke lesion on diffusion tensor imaging tractography were recruited. Mean Medical Research Council scores for distal musculature were lower than those for proximal musculature ($P < 0.001$). Mean Medical Research Council scores for upper extremity muscles were lower than those for lower extremity muscles ($P < 0.001$). The mean Motricity Index score for muscles of the upper extremities was lower than that for muscles of the lower extremities ($P < 0.001$). None of the patients had a functional hand; in contrast, 56% of patients were able to walk independently. We found that motor weaknesses of distal joint musculature and upper extremities were more severe than those of proximal joint musculature and lower extremities following complete injury of the CST in stroke, respectively. As a result, despite the absence of a functional hand in all patients, more than half were able to walk independently.

Keywords: Corticospinal tract, motor function, stroke, diffusion tensor tractography

1. Introduction

The corticospinal tract (CST) is the primary neural tract in mediation of voluntary skilled movement, particularly for distal musculature [5,8,11,28,31]. CST injury in stroke patients is known to accompany severe motor deficit. Some clinical studies have reported on this topic; however, the clinical characteristics of stroke patients with complete CST injury have not been well elucidated [1,18]. Detailed knowledge of clinical characteristics following complete injury of the CST in patients with stroke can aid clinicians in prediction of prognosis and in establishment of strategies for rehabilitative management. Therefore, clarification on this topic would be of importance in stroke rehabilitation.

Transcranial magnetic stimulation (TMS), functional neuroimaging, and diffusion tensor imaging (DTI) have been used in evaluation of the state of the CST [1, 16,18,29]. TMS is a sensitive electrophysiological tool for use in detection of the presence of the CST, and has been used for several decades in evaluation of the electrophysiological integrity of the CST [16,29]. By contrast, DTI is a recently developed technique, which, by virtue of its ability to visualize water diffusion char-

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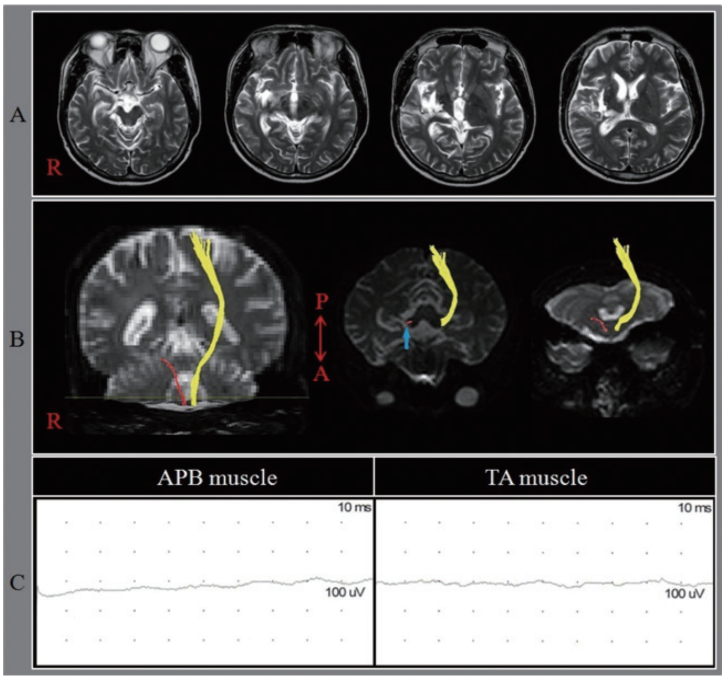

Fig. 1. Results of diffusion tensor imaging tractography and transcranial magnetic stimulation of a patient (52-year-old male). (A) T2-weighted brain MRIs show a leukomalactic lesion in the right basal ganglia; (B) The integrity of the corticospinal tract was discontinued below the lesion (arrow) on diffusion tensor imaging tractography; (C) Transcranial magnetic stimulation findings show absence of motor evoked potentials in the affected abductor pollicis brevis and tibialis anterior muscles. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/NRE-2012-0790)

acteristics, allows for evaluation of the anatomical integrity of the CST [2,26]. Therefore, combined use of TMS and DTI allows for evaluation of complete injury of the CST in stroke patients [17,20].

In the current study, we investigated the clinical characteristics of motor function in chronic hemiparetic stroke patients with complete CST injury, as confirmed by TMS and DTI.

2. Subjects and method

2.1. Subjects

Among 126 chronic stroke patients admitted to the rehabilitation department of a university hospital for rehabilitation, 41 consecutive patients (28 men, 13 women; mean age, 54.97 ± 10.13 years; range, 40–78 years) were recruited, according to the following inclusion criteria: (1) first-ever stroke due to intracranial hemorrhage or cerebral infarct; (2) a duration from onset to the time of evaluation of more than 6 months; (3) age 20–79 years; (4) brain MRI evidence of injury along the CST pathway, as confirmed by a neuroradiologist [13,14,19]; (5) absence of motor evoked potentials (MEPs) in the affected abductor pollicis brevis muscle (APB) and tibialis anterior muscle (TA); and (6) the integrity of the CST was discontinued around a stroke lesion on DTI tractography (Fig. 1). Characteristics of stroke patients were as follows: (1) lesion side; right-23, left-18. (2) type of stroke; putaminal hemorrhage 19 (46.3%), middle cerebral artery territory infarct 15 (36.5%), thalamic hemorrhage 6 (14.6%), and pontine infarct 1 (2.4%).

2.2. Clinical evaluation

Motor function was evaluated at the time of DTI scanning. The Medical Research Council score (MRC), the Motricity Index (MI), the modified Brunnstrom Classification (MBC), and the Functional Ambulation Categories (FAC) were used for determination of motor function [4,9,12,24]. The MRC score is as follows: 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 [24]. The MI score is a modification of the MRC system, with a maximum score of 100 [9]. The MI score, except for prehension, is as follows: 0; no movement, 28; palpable contraction, but no movement, 42; movement, but not full range or against gravity, 56; movement, full range against gravity, not against resistance, 74; movement against resistance, weaker than the contralateral side, 100; normal strength. The MI score for prehension is as follows: 0; no movement, 33; beginning of prehension, 56; grips cube, without gravity, 65; holds cube, against gravity, 77; grips against pull, but weaker than the other side, 100; normal. The upper MI score is the average of the MI scores for shoulder flexor, elbow flexor, and prehension, and the lower MI score is the average of the MI scores for the hip flexor, knee extensor, and ankle dorsiflexor. The total MI score is the average of the upper and lower MI score. The MBC score is as follows: 1; unable to move fingers voluntarily, 2; able to move fingers voluntarily, 3; able to close hand voluntarily, unable to open hand, 4; able to grasp a card between the thumb and medial side of the index finger, able to extend fingers slightly, 5; able to pick up and hold a glass, able to extend fingers, 6; able to catch and throw a ball in a near-normal fashion, able to button and unbutton a shirt [4]. Walking ability was assessed using the FAC, which were designed for characterization of levels of assistance required during a 15 m walk. The six categories include the following: 0; non-ambulatory, 1; a need for continuous support from one person, 2; a need for intermittent support from one person, 3; a requirement for verbal supervision only, 4; help required on stairs and uneven surfaces, and 5; ability to walk independently anywhere [12]. The reliability and validity of MRC, MI, MBC, and FAC are well established [4,7, 9,10]. Evaluators of clinical data were blinded to TMS and DTI data, as well as each other.

2.3. Transcranial magnetic stimulation

TMS was performed at the time of DTI scanning, with the patient seated comfortably in a 60 degree reclined chair. A magnetic stimulator (Magstim Novametrix 200, Novametrix Inc., Wallingford, CT, USA) and circular coil (diameter 90 mm) were used. Cortical stimulation was performed at the vertex with the coil held tangentially. The left hemisphere was stimulated by a counterclockwise current, and the right hemisphere was stimulated by a clockwise current. MEPs were recorded from the abductor pollicis brevis muscle (APB) and tibialis anterior muscle (TA), while the patient was in a relaxed state. Stimulation intensity was set at 100% of the stimulator output. One hemisphere was stimulated 4 times with a minimum interval of 10 seconds.

2.4. Diffusion tensor imaging

DTI data were acquired at an average of 726 days (range; 181–2836 days) after stroke onset using a 1.5 T Philips Gyroscan Intera (Philips Ltd, Best, The Netherlands) equipped with a 6-channel head coil with a single-shot spin echo planar imaging sequence. For each of the 32 non-collinear diffusion sensitizing gradients, we acquired 60 contiguous slices parallel to the anterior commissure–posterior commissure line. The following imaging parameters were used: matrix $=$ 96×96, reconstructed to matrix $= 128 \times 128$, field of view $= 221 \times 221$ mm^2, echo time (TE) $=$ 76 ms, repetition time (TR) $=$ 10,726 ms, parallel imaging reduction factor (SENSE factor) $=$ 2, echo planar imaging factor $=$ 49, b $=$ 600 s/mm^2, NEX $=$ 1, and a slice thickness $=$ 2.3 mm (acquired isotropic voxel size $2.3 \times 2.3 \times 2.3$ mm^3). Oxford Centre for Functional Magnetic Resonance Imaging of Brain (FMRIB) Software (FSL; www.fmrib.ox.ac.uk/fsl) was used in preprocessing of DTI datasets. Affine multi-scale two-dimensional registration was used for removal of Eddy current-induced image distortions and motion artifacts. DTI-Studio software (CMRM, Johns Hopkins Medical Institute, USA) was used for evaluation of the CST; fiber tracking was performed using the fiber assignment continuous tracking (FACT) algorithm, a brute-force (BF) reconstruction approach, and a multiple regions of interest (ROIs) approach. The seed ROI was drawn in the CST portion of the mid-pontine basis on a number of 2-D fractional anisotropy (FA) color maps. The target ROI was drawn in the CST portion of the lower pontine basis. Fiber tracts passing through both ROIs were designated as the final tracts of interest. Termination criteria used for fiber tracking were FA < 0.2 and an angle change > 60 [21].

2.5. Data analysis

Muscles were classified into two musculatures. Shoulder abductor, elbow extensor, hip flexor, and knee extensor were assigned to the proximal musculature, and wrist extensor, finger flexor, finger extensor, ankle dorsiflexor, toe flexor, and toe extensor were assigned to distal musculature. SPSS 17.0 software (SPSS Inc, Chicago, USA) was used for performance of statistical

Table 2
Comparison of Medical Research Council and Motricity Index scores

	Mean	SD	P-value
Proximal musculature	2.00	1.10	0.000**
Distal musculature	0.50	0.74	
Upper extremity muscles	0.86	0.89	0.000**
Lower extremity muscles	1.34	1.34	
Finger extensor	0.12	0.33	0.018*
Toe extensor	0.43	0.77	
Upper MI	22.42	9.80	0.000**
Lower MI	39.30	11.54	

SD: standard deviation; MI: Motricity Index.
$^{*}p < 0.05$, $^{**}P < 0.001$.

analysis. An independent t-test was used for determination of differences between the mean MRC score for proximal and distal musculatures, and the mean MRC score and MI score for upper and lower musculatures, and the mean MRC score for finger extensor and toe extensor. The level of significance was set as $p < 0.05$.

3. Results

Patients' clinical data are summarized in Tables 1, 2, and Fig. 2. The mean MRC score for knee extensor (2.85) was the highest, followed by hip flexor (2.32), elbow flexor (1.44), shoulder abductor (1.39), finger flexor (0.88), ankle dorsiflexor (0.71), wrist extensor (0.49), toe extensor (0.43), toe flexor (0.39), and finger extensor (0.12). Maximum MRC scores were 3 for shoulder abductor, elbow flexor, and toe extensor, 4 for hip flexor and knee extensor, and 1 for finger extensor. The mean MRC score for proximal musculature (2.00) was higher than that for distal musculature (0.50) ($P < 0.001$). The mean MRC score for lower extremity muscles (1.34) was also significantly higher than that for upper extremity muscles (0.86) ($P < 0.001$). The mean MI score for upper extremities (22.42) was lower than that for lower extremities (39.30) ($P < 0.001$). In addition, the mean MRC score for finger extensor (0.12) was lower than that for toe extensor (0.43) ($P < 0.05$).

Distribution of the MBC and FAC is shown in Table 3. All patients showed less than MBC 3; in contrast, 56% patients showed more than FAC 3, which indicates independent walking. Six (14.6%) of 41 patients could walk as FAC = 4.

4. Discussion

In the current study, we investigated the clinical characteristics of motor function in chronic stroke patients with complete CST injury. We found that the clinical characteristics of the patients, in terms of motor weakness and functional level, can be summarized as follows: 1) Motor weakness: motor weaknesses of distal joint musculatures (wrist, finger, ankle, and toe) were more severe than those of proximal joint musculatures (shoulder, elbow, hip, and knee). These findings coincide with results of previous studies showing that neural innervations for motor function differ according to the location of the muscles: the distal musculature for fine movement is controlled mainly by the lateral CST; in contrast, the axial and proximal muscles are controlled by extrapyramidal motor pathways, such as the corticoreticulospinal tract or the anterior CST [1,5,8, 15,16,23,25,31]. On the other hand, motor weaknesses of upper extremity musculature were more severe than those of lower extremity musculature. In addition, weakness of finger extensor was more severe than that of toe extensor. These results suggest greater involvement of the lateral CST in motor function of upper extremities than in lower extremities, and are compatible with findings from the study by Rinske et al., showing that voluntary finger extension may reflect the function of the lateral CST [27]. 2) Functional level: none of the patients had a functional hand (MBC: 5–6); in contrast, 56% of patients were able to walk independently (FAC: 3–5). After complete injury of the lateral CST, stroke patients are unable to perform fine motor activities of the hands; in contrast, recent studies have demonstrated that stroke patients were able to walk even after complete injury of the lateral CST, suggesting that walking is not as strongly associated with the lateral CST as hand function [1,8,15,16,18,31]. Therefore, in humans, the lateral CST does not play an essential role in walking; instead, it is essential for control of skilled walking [1,3,6,18,31]. In addition, compared with hand function, walking requires a smaller degree of motor function [15]. In detail, stroke patients can walk when the motor function of the proximal joint musculatures (hip and knee) is recovered at least to the degree of being against gravity; however, hand function requires a larger degree of recovery to distal joints. Consequently, in cases of complete injury of the lateral CST, stroke patients appear to have a greater potential to walk than to gain hand function.

Several previous studies have reported on clinical manifestation of motor function following complete CST injury in the monkey and human brain [1,18,22, 30]. In 1940, Tower SS reported that monkeys were able to locomote over ground after a brief recovery period following pyramidotomy [30]. However, their

Table 1
Patients' clinical data

		Mean	SD	Minimum	Maximum
MRC	Shoulder Abductor	1.39	0.74	0	3
	Elbow flexor	1.44	0.98	0	3
	Wrist extensor	0.49	0.67	0	2
	Finger flexor	0.88	0.87	0	3
	Finger extensor	0.12	0.33	0	1
	Hip flexor	2.32	0.93	0	4
	Knee extensor	2.85	1.06	0	4
	Ankle dorsiflexor	0.71	0.81	0	3
	Toe flexor	0.39	0.66	0	2
	Toe extensor	0.43	0.77	0	3
MI	Upper extremity	22.42	9.80	0	42
	Lower extremity	39.30	11.54	9.3	63.3
	Total	30.93	9.76	4.6	50.3
FAC		2.42	1.12	0	4
MBC		1.76	0.79	1	3

SD: standard deviation; MRC: Medical Research Council; MI: Motricity Index; FAC: Functional Ambulation Category; MBC: Modified Brunnstrom Classification.

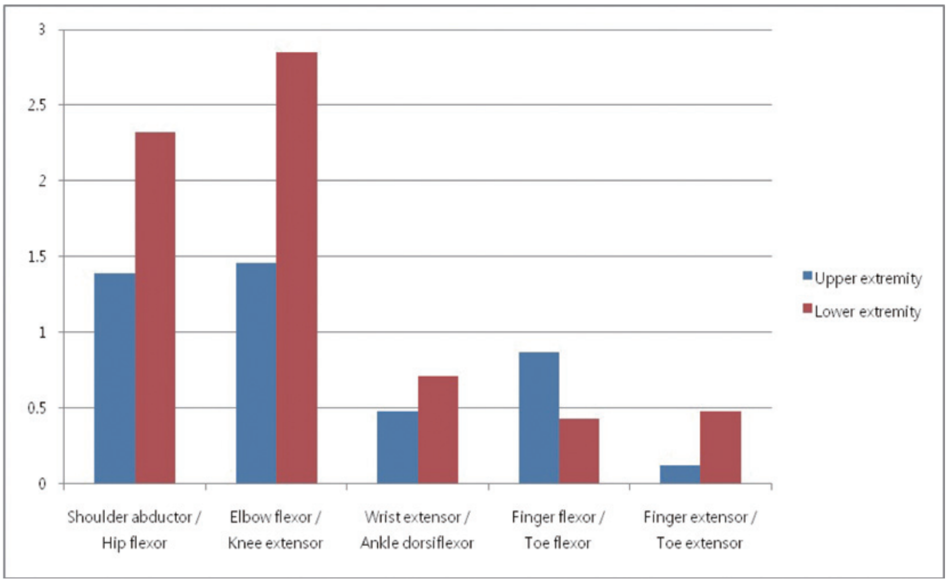

Fig. 2. Mean Medical Research Council scores. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/NRE-2012-0790)

performance of more skilled tasks, such as beam walking, was impaired. Lawrence and Kuypers [22] reported that 41 rhesus monkeys were able to run and climb the bars of the cage after bilateral pyramidotomy in a manner that made them indistinguishable from their un-operated littermates. However, the capacity for individual finger movement was not recovered [22]. As for humans, Jang et al. [18] reported on a patient with intracerebral hemorrhage whose motor function of the affected hip and knee had recovered to the extent that she was able to overcome gravity; however, her affected upper extremity showed no significant motor recovery. Complete CST injury of the affected hemisphere was demonstrated by DTI [18]. Subsequently, Ahn et al. [1] reported on the clinical characteristics of 10 hemiparetic stroke patients with complete lateral CST injury [1]. In this preliminary study, we recruited only patients who were able to walk independently and complete injury of the lateral CST was demonstrated only by DTI without TMS evidence. In addition, there were no detailed data for motor function, including distal joints. However, the general clinical characteristics of motor function coincided with those of the current study.

In conclusion, we investigated the clinical character-

Table 3
Distribution of Functional Ambulation Category and Modified Brunnstrom Classification scores

FAC	Patient No.	Percentage (%)	MBC	Patient No.	Percentage (%)
0	2	4.8	1	19	46.3
1	8	19.5	2	13	31.7
2	8	19.5	3	9	21.9
3	17	41.4	4	0	0
4	6	14.6	5	0	0
5	0	0	6	0	0

FAC: Functional Ambulation Category; MBC: Modified Brunnstrom Classification.

istics of motor function in stroke patients with complete CST injury. We found that motor weaknesses of distal joint musculature and upper extremities were more severe than those of proximal joint musculature and lower extremities, respectively. Therefore, despite the absence of a functional hand for all patients, more than half were able to walk independently. To the best of our knowledge, this is the first study to describe clinical characteristics following complete CST injury in a consecutive large number of stroke patients. We believe that the results of this study would be helpful in research on motor control and stroke rehabilitation. The major limitation of this study is that we were not able to identify non-CST injury, which might be attributed to motor deficit of these patients. We think that at least some of the motor deficit of our patients could be ascribed to non-CSTs injury. However, identification of non-CSTs has been impossible so far; therefore, further studies for non-CST identification would be necessary in order to clarify this limitation.

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