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Original Article

Relationship between trunk function and corticoreticular pathway in stroke hemiplegic patients: analysis using probabilistic tractography

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ABSTRACT

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Objective: The purpose of this study was to visualize the corticoreticular pathway (CRP) of stroke hemiplegic patients by using probabilistic tractography and to clarify the relationship between the degree of CRP damage and the trunk function.

Methods: The CRP of 17 convalescent patients with stroke hemiplegia was visualized using probabilistic tractography, and the results of the Trunk Control Test (TCT) and Functional Assessment for Control of the Trunk (FACT) of the non-injured and injured groups were compared.

Results: There were no significant differences in all TCT and FACT scores between the CRP non-injured and injured groups.

Conclusion: If the corticospinal tract in the cerebral hemisphere is not injured, TCT and FACT might not reflect the qualitative aspects of trunk function associated with CRP injury, such as reduced motor efficiency and antigravity extension activity.

Key words: probabilistic tractography, corticoreticular pathway, trunk function, stroke hemiplegic patients, convalescent

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Introduction

In general, many patients with hemiplegic stroke are known to have impaired trunk function [1]. As trunk function is known to be related to walking ability and activities of daily living (ADLs), in addition to anticipatory postural adjustments and balance ability [2], the importance of trunk function evaluation has been recognized in recent years. Currently, the Trunk Control Test (TCT) [3] and the Functional Assessment for Control of the Trunk (FACT) [4] are the most frequently used tests for evaluating trunk function in clinical settings, and the TCT score at admission of stroke hemiplegic patients is related to the Functional Independence Measure exercise item scores and gait levels at discharge [5, 6]. It has been reported that individuals with ADL independence have significantly higher FACT scores than those who need assistance [7]. The primary white matter fibers that govern the trunk muscles are the anterior corticospinal tract (CST) and the corticoreticular pathway (CRP) [8]; however, the anterior CST is a small nerve bundle that accounts for 5–10% of the entire CST, and many trunk muscles are believed to be controlled by the CRP. In recent years, diffusion tensor tractography (DTT) of the CRP using magnetic resonance imaging (MRI) [9, 10] has revealed that the degree of CRP injury in stroke hemiplegic patients is related to weakness of the proximal muscles of the upper and lower limbs [11]. In addition, it has been reported that patients with injury in both the CST and CRP have low values of the motricity index, modified Brunnstrom classification, and Functional Ambulation Categories [12]. However, the relationship between the degree of CRP injury and the trunk function is not known.

The purpose of this study was to visualize the CRP of stroke hemiplegic patients by using DTT and to clarify the relationship between the degree of CRP injury and the TCT and FACT scores.

Methods

1. Subjects

The subjects were 17 patients with first-stroke hemiplegia who were admitted to our convalescent rehabilitation ward and did not have contraindications to MRI (age 59.8±16.2 years; 12 men, 5 women). All subjects were right handed. Those with a history of cerebrovascular disorders, significant higher brain dysfunction, cognitive dysfunction, cardiovascular disease, or bone and joint disease were excluded.

In addition, to verify the reliability of the examiner's muscle thickness measurements using an ultrasound imaging system, 12 healthy men (age 25.5±3.6 years) who did not have musculoskeletal disease and had no low back pain during the measurements were analyzed.

This study was conducted with the approval of our ethics committee (2016112801) and the university ethics committee (16-Ifh-075).

2. Evaluation of basic attributes and trunk function

The basic attributes of the subjects, including age, sex, number of days from onset to hospitalization, and days from onset to MRI, were collected from the medical records (Table 1). To evaluate trunk function, TCT and FACT were performed at the time of admission. Furthermore, the thicknesses of the external abdominis oblique (EO), internal abdominis oblique (IO), and transverse abdominis (TrA) on both sides were measured using B-mode short-axis scanning with an ultrasound imaging system (Hitachi Medical, Mylab25, linear probe 3 MHz). The muscle thickness was measured in the supine position, and an abdominal ultrasound scan taken at the end of a resting breath was recorded as a still image (Figure 1). The measurement site was the intersection of the armpit line and the umbilical height [13]. One examiner measured each muscle three times, calculated the average value, and calculated the ratio of muscle thickness on the paralyzed side to that on the non-paralyzed side.

3. Imaging conditions for brain MRI

MRI was performed using Brivo MR355 1.5 T (GE Healthcare Japan), and diffusion tensor imaging (DTI) was performed during hospitalization. The DTI conditions were as follows: single-shot echo planar imaging, 96×96 matrix, field of view 280×280 mm^2, repetition time 14,285.0 ms, echo time 65.7 ms, flip angle 90°, ASSET 2.00 Ph, number of additions 1, slice thickness 3.0 mm, number of slices 60, b-value 1000 s/mm^2, and number of diffusion-encoding directions 32.

Table 1. Characteristics of the subjects.

	Age (years)	Sex	Time from onset to hospitalization (days)	Time from onset to MRI (days)	Type of stroke	Damaged area	Paralyzed side	B.R.S.	Presence of sensory impairment	Means of movement in ADL
No.1	34	M	24	28	Hemorrhage	Putamen	Left	II−II−II	Yes	Wheelchair
No.2	51	M	17	20	Infarction	Medulla oblongata	Left	III−II−III	Yes	Wheelchair
No.3	69	M	13	15	Infarction	Posterior limb of the internal capsule	Right	VI−VI−VI	None	Gait
No.4	40	F	21	22	Hemorrhage	Putamen	Left	II−II−II	Yes	Wheelchair
No.5	69	F	14	17	Hemorrhage	Temporal lobe - parietal lobe	Left	VI−VI−VI	Yes	Gait
No.6	75	F	18	19	Infarction	Corona radiata	Right	V−V−VI	Yes	Gait
No.7	62	F	30	43	Hemorrhage	Thalamus	Left	II−II−II	Yes	Wheelchair
No.8	37	F	27	30	Hemorrhage	Putamen	Left	V−V−V	Yes	Gait
No.9	61	F	30	49	Infarction	MCA	Right	VI−V−VI	None	Gait
No.10	85	F	21	35	Infarction	MCA	Right	V−V−V	Yes	Gait
No.11	36	F	25	29	Hemorrhage	Putamen	Left	VI−VI−VI	None	Gait
No.12	55	F	25	31	Hemorrhage	Putamen	Left	II−II−III	Yes	Wheelchair
No.13	44	F	30	37	Hemorrhage	Putamen	Right	III−II−IV	None	Wheelchair
No.14	67	M	34	38	Infarction	Posterior limb of the internal capsule - corona radiata	Left	V−V−V	None	Wheelchair
No.15	50	F	14	20	Hemorrhage	Thalamus	Left	VI−VI−VI	Yes	Gait
No.16	82	F	11	17	Infarction	MCA	Right	VI−V−VI	None	Wheelchair
No.17	80	M	13	15	Hemorrhage	Frontal lobe - parietal lobe	Left	VI−V−VI	Yes	Gait

F, female; M, male; MRI, magnetic resonance imaging; MCA, middle cerebral artery; ADL, activities of daily living.
B.R.S., Brunnstrom recovery stage (upper limb−fingers−lower limb).

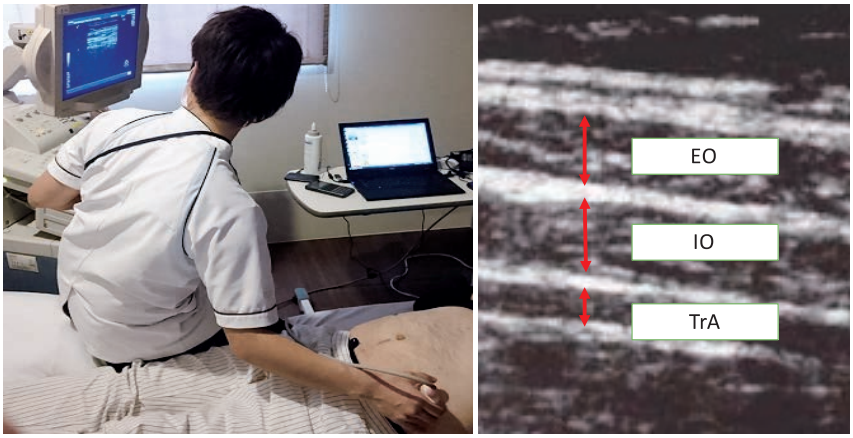

Figure 1. (Left) Measurement of muscle thickness using an ultrasonic diagnostic imaging apparatus and (right) cross-sectional image of the trunk muscles.
EO: external abdominis oblique
IO: internal abdominis oblique
TrA: transverse abdominis

4. Image analysis of the CRP and CST

The Functional MRI of the Brain Software Library [14] was used for image analysis, and the CRP and CST of both hemispheres were visualized using probabilistic tractography. First, after correcting the eddy current of the captured image, the diffusion parameter distribution was calculated for each voxel using the Markov chain Monte Carlo method (diffusion parameter image). Thereafter, the regions of interest (ROIs) of the CRP and CST were set freehand and ROI images were created. The ROI of the CRP was the reticular formation of the medulla, midbrain tegmentum, and premotor area of the cerebral cortex [10], and the ROI of the CST was the ventral medulla oblongata, midbrain cerebral peduncle, and primary motor cortex [15]. Finally, the diffusion parameter image and the ROI image were synthesized, and CRP and CST probabilistic tractography was performed. Subsequently, the connectivity between the CRP and CST in the damaged hemisphere depicted using probabilistic tractography was visually evaluated, and unnecessary trajectories deviating from the ROI were deleted at an arbitrary threshold. On the basis of the presence or absence of damage, the CRT and CST were defined as "non-injured" if the cortex was visualized and "injured" if the cortex was not depicted. Accordingly, the subjects were classified into the following four groups: CRP non-injured/CST non-injured, CRP non-injured/CST injured, CRP injured/CST non-injured, and CRP injured/CST injured. The connectivity was evaluated by two examiners with more than 3 years of experience in brain image analysis.

5. Statistical analysis

The statistical software SPSS version 14 was used for statistical analysis. In the CRP non-injured and CRP injured groups, age, days from onset to hospitalization, days from onset to MRI, total TCT score, total FACT score, EO muscle thickness ratio, IO muscle thickness ratio, and TrA muscle thickness ratio were compared using the Mann-Whitney U-test, and sex was compared using Fisher's exact probability test. The score of each item of TCT and the score of each item of FACT were compared using the Kruskal-Wallis test. The reliability of the measurements of trunk muscle thickness ratios was determined from the intraclass correlation coefficient (ICC) (1, 3) of the intra-rater reliability of EO muscle thickness ratio, IO muscle thickness ratio, and TrA muscle thickness ratio. The significance level was set at 5%.

Results

There were no significant differences in subject characteristics among all items (Table 2).

Through probabilistic tractography, the CRP and CST of the unaffected side were visualized in all subjects. With respect to the injured hemisphere, there were seven subjects (41.2%) in the CRP non-injured/CST non-injured group, none (0.0%) in the CRP non-injured/CST injured group, nine (52.9%) in the CRP injured/CST non-injured group, and one (5.9%) in the CRP injured/CST injured group (Table 3, Figure 2). Among them, the CRP non-injured/CST non-injured group and the CRP injured/CST non-injured group were extracted. The total TCT score and each TCT item score, as well as the total FACT total score and each FACT item score, were compared between the two groups. The comparison showed no significant differences in all scores (Tables 4 and 5). The intra-rater reliability of the muscle thickness ratio measurements was ICC=0.99 (95% confidence interval 0.98–0.99) for the EO muscle thickness ratio,

ICC=0.62 (95% confidence interval 0.25–0.88) for the IO muscle thickness ratio, and ICC=0.80 (95% confidence interval 0.47–0.94) for the TrA muscle thickness ratio. There were no significant differences in the EO muscle thickness ratio, IO muscle thickness ratio, or TrA muscle thickness ratio between the CRP non-injured/CST non-injured group and CRP injured/CST non-injured group (Table 6).

Discussion

The CRP originates from the premotor area of the cerebral cortex; passes through the corona radiata, the front part of the posterior limb of the internal capsule, and the midbrain tegmentum cover; leads to the reticular body of the pons and medulla; and governs the reticulospinal tract and bilaterally controls the trunk muscles [16]. Therefore, it is considered that the trunk function is reduced by CRP damage. In addition, trunk muscles are known to contribute to anticipatory postural adjustments and anti-gravity extension activities that occur before the main movement [17]. Therefore, compensatory abnormalities in the upper and lower limbs on the paralyzed and non-paralyzed sides occur as a result of the decline in trunk function. It has been reported that this leads to decreases in

Table 2. Comparison of the subjects' characteristics.

	Non-injured group (*n*=7)	Injured group (*n*=9)	*p*-Value	
Age (years)	66.0±18.7	55.0±14.2	0.204	n.s.
Sex				
F	3 (42.9%)	8 (88.9%)	0.106	n.s.
M	4 (57.1%)	1 (11.1%)		
Time from onset to hospitalization (days)	18.4±6.9	24.1±7.2	0.790	n.s.
Time from onset to MRI (days)	25.6±12.7	29.3±9.2	0.265	n.s.

Non-injured group, corticoreticular pathway non-injured/corticospinal tract non-injured group; Injured group, corticoreticular pathway injured/corticospinal tract non-injured group; F, female; M, male; MRI, magnetic resonance imaging Mean ± standard deviation, n.s.: not significant.

Table 3. Classification of the corticoreticular pathway and corticospinal tract in the affected side of the subjects.

	CRP	CST	Damage classification
No.1	Non-injured	Non-injured	A
No.2	Non-injured	Non-injured	A
No.3	Non-injured	Non-injured	A
No.4	Injured	Injured	C
No.5	Injured	Non-injured	B
No.6	Injured	Non-injured	B
No.7	Injured	Non-injured	B
No.8	Injured	Non-injured	B
No.9	Non-injured	Non-injured	A
No.10	Non-injured	Non-injured	A
No.11	Injured	Non-injured	B
No.12	Injured	Non-injured	B
No.13	Injured	Non-injured	B
No.14	Injured	Non-injured	B
No.15	Injured	Non-injured	B
No.16	Non-injured	Non-injured	A
No.17	Non-injured	Non-injured	A

CRP, corticoreticular pathway; CST, corticospinal tract.
A: CRP non-injured/CST non-injured group.
B: CRP injured/CST non-injured group.
C: CRP injured/CST injured group.

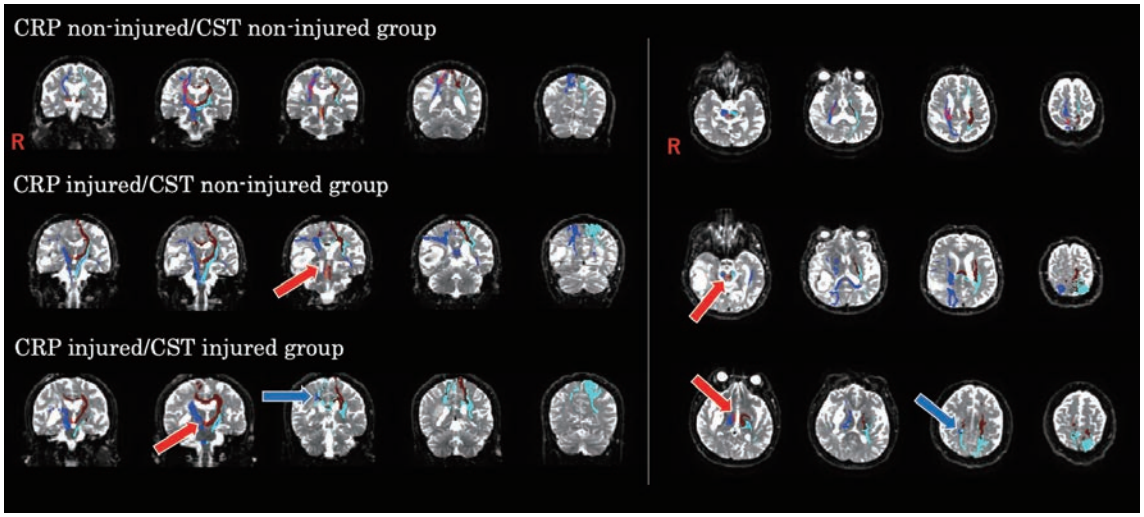

Figure 2. Representative images based on the classification of corticoreticular pathway (CRP) and corticospinal tract (CST) according to the degree of damage (coronal plane/sagittal plane).
By using probabilistic tractography, the CRP on the affected side (red), CST on the affected side (blue), CRP on the unaffected side (red brown), and CST on the unaffected side (light blue) are depicted (red arrow: disruption of cortical reticulum fibers on the affected side, blue arrow: disruption of corticospinal fibers on the affected side).
CRP non-injured/CST non-injured group: both the CRP and CST are depicted down to the cortex.
CRP injured/CST non-injured group: the CRP is not drawn to the subcortical area, but the CST is drawn to the subcortical area.
CRP injured/CST injured group: both the CRP and CST are not depicted to the subcortical level.

Table 4. Comparison of the total Trunk Control Test score and the score for each item.

		Non-injured group (n = 7)	Injured group (n = 9)	p-Value	
Rolling to weak side	(Score)	21.3±6.3	16.7±12.5	0.560	n.s.
Rolling to strong side	(Score)	21.3±6.3	20.0±6.5	0.844	n.s.
Sitting up from lying down	(Score)	19.4±6.9	16.7±12.5	0.854	n.s.
Balance in sitting position	(Score)	23.1±4.9	20.7±6.5	0.398	n.s.
Total score	(Score)	85.1±21.8	74.7±38.0	0.855	n.s.

Non-injured group: corticoreticular pathway non-injured/corticospinal tract non-injured group.
Injured group: corticoreticular pathway injured/corticospinal tract non-injured group.
Mean ± standard deviation, n.s.: not significant.

muscle tone and exercise efficiency. However, in patients with no CST injury in this study, there was no significant difference between the TCT and FACT scores between the CRP non-injured group and the CRP injured group.

Jang et al. [18] analyzed the CRP of chronic stroke patients using deterministic tractography and suggested that the volume of the CRP in the unaffected side may affect the walking ability. Thus, in this study, the functional compensation of the CRP in the unaffected side during the recovery process may have influenced the TCT and FACT scores. However, deterministic tractography is difficult to perform at sites where nerve fibers are adjacent, crossed, or branched. As the CRP is a fiber that is adjacent to or intersects with the nerve fiber near the superior longitudinal fasciculus or the inner capsule, Jang et al. reported that it may not be able to depict a part of the CRP. Therefore, in this study, CRP was drawn using probabilistic tractography, which is a better option for tracking nerve fibers than deterministic tractography. Probabilistic tractography can estimate and track the nerve fiber tracts even at sites where nerve fibers are adjacent, crossed, or branched. Therefore, the CRP, the nerves of which are considered difficult to track with deterministic tractography, can also be drawn.

Table 5. Comparison of the total Functional Assessment for Control of the Trunk score and the score for each item.

		Non-injured group (*n*=7)	Injured group (*n*=9)	*p*-Value	
Use of upper-limb support	(Score)	1.0±0.0	1.0±0.0	1.000	n.s.
Upper-limb support disuse	(Score)	1.0±0.0	0.7±0.5	0.101	n.s.
Moving the center of gravity downwards/reaching, small rotations of the trunk, and concomitant trunk activity due to gravity and against gravity	(Score)	0.9±0.4	0.7±0.5	0.398	n.s.
Moving the center of gravity forward, concomitant righting of the legs and trunk, and further moving the center of gravity to the right and left while making selective small movements of the pelvis and trunk	(Score)	1.7±0.8	1.3±1.0	0.398	n.s.
Moving the center of gravity laterally over a wide area, and concomitant righting	(Score)	1.2±0.8	1.3±1.0	0.723	n.s.
Moving the center of gravity slightly backwards and to the side, concomitant righting, and the ability to hold the trunk on the same side and at the same time as lifting one leg	(Score)	1.9±0.4	1.3±1.0	0.295	n.s.
Moving the center of gravity backwards over a wide area, concomitant righting, and the ability to hold the trunk on both sides while raising both legs	(Score)	1.4±1.0	1.3±1.0	0.844	n.s.
Moving the center of gravity laterally over a wide area, and further selective rotation of thepelvis/trunk	(Score)	1.3±1.6	2.0±1.5	0.356	n.s.
Rotation while the trunk is extended	(Score)	1.7±1.6	2.0±1.5	0.705	n.s.
Maximum spine extension	(Score)	2.6±1.1	2.3±1.3	0.696	n.s.
Total score	(Score)	14.7±5.9	14.0±9.0	0.861	n.s.

Non-injured group: corticoreticular pathway non-injured/corticospinal tract non-injured group.
Injured group: corticoreticular pathway injured/corticospinal tract non-injured group.
Mean ± standard deviation, n.s.: not significant.

Table 6. Comparison of trunk muscle thickness ratios.

	Non-injured group (*n*=7)	Injured group (*n*=9)	*p*-Value	
EO ratio	0.87±0.17	0.93±0.10	0.337	n.s.
IO ratio	0.93±0.19	1.01±0.21	0.427	n.s.
TrA ratio	0.87±0.17	0.98±0.11	0.119	n.s.

Non-injured group: corticoreticular pathway non-injured/corticospinal tract non-injured group.
Injured group: corticoreticular pathway injured/corticospinal tract non-injured group.
EO, external abdominis oblique; IO, internal abdominis oblique; TrA, transverse abdominis.
Mean ± SD, n.s.: not significant.

The subjects in this study were divided into two groups according to the presence or absence of damage (i.e., whether or not the CRP was drawn down to the cortex). Accordingly, it is possible that the depicted CRP does not reflect in detail the degree of damage in the early recovery period, such as degeneration of nerve fibers occurring immediately after onset and functional compensation due to rehabilitation. These facts imply that it is necessary to evaluate the extent of the CRP depicted in detail for evaluating the bilaterally controlled trunk function, as well as to examine the relationship between the CRP and the TCT and FACT scores in the affected and unaffected sides.

The TCT scores were assigned as follows: “I can’t do it myself ”=0 points, “Need to hold onto a stable object such as a bed rail, but I can do it myself ” = 12 points, and “Can be normal” = 25 points. On the other hand, the FACT scores were assigned as follows: “I can’t do it myself ” = 0 points and “Can be normal” = 2 or 3 points. In all cases, the implementation status of

multiple exercise tasks was evaluated on an ordinal scale. Therefore, TCT and FACT, which have no relation to the presence or absence of compensatory exercise, may not reflect in detail the effects of abnormal muscle tone and reduced exercise efficiency due to CRP injury.

Further, in this study, the intra-rater reliability [19] of the muscle thickness ratios of the EO, IO, and TrA was high, and the reliability of the muscle thickness ratio measurement was considered to be high. However, there was no significant difference in the muscle thickness ratios of the EO, IO, and TrA between the CRP non-injured group and the CRP injured group in this study. Trunk muscles are attached to the rectus sheath and thoracolumbar fascia, and even unilateral brain damage has been reported to affect muscle activity bilaterally. On the other hand, because the innervation of trunk muscles is bilateral, it has been pointed out that the effects of unilateral brain damage may be small [20], and there is no unified view on the relationship between brain damage and trunk muscles. However, it has been reported that the trunk muscles of stroke hemiplegic patients suffer atrophy during the transition from the acute phase to the chronic phase [21]. This suggests that muscle thickness may involve secondary factors such as inactivity after brain injury and disuse due to decreased activity. On the basis of these findings, the relationship between the CRP and the trunk muscle thickness ratio should be examined based on the number of days after brain injury and the amount of activity while longitudinally measuring the muscle thickness of the trunk bilaterally.

One limitation was that the probabilistic tractography used in this study probabilistically estimates the direction of nerve fibers based on Bayes' theorem. Because the ROI was set freehand, the depicted trajectory of the actual nerve fibers may not be completely captured. In addition, this was a cross-sectional study and it is difficult to discuss the effects of functional compensation of the CRP on the recovery of trunk function. Therefore, as image analysis technology develops, it will be necessary to increase the number of cases and longitudinally investigate the relationship between the CRP and the trunk function.

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