Longitudinal Optical Imaging Study for Locomotor Recovery After Stroke

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Background and Purpose—We sought to investigate cerebral mechanisms underlying locomotor recovery after stroke.

Methods—We measured cortical activities during hemiparetic gait on the treadmill before and after 2 months of inpatient rehabilitation in 8 patients with initial stroke (5 men, 3 women; 4 with right and 4 with left hemiparesis; aged 57 years; 3 months after stroke on average), using an optical imaging system.

Results—On the initial evaluation, hemiparetic gait was associated with increased oxygenated hemoglobin levels in the medial primary sensorimotor cortex (SMC) that were greater in the unaffected hemisphere than in the affected hemisphere as well as in the premotor cortex (PMC) and supplementary motor area. On the second examination, the asymmetry in SMC activation significantly improved, and there was enhanced PMC activation in the affected hemisphere. Improvement of the asymmetrical SMC activation significantly correlated with improvement of gait parameters.

Conclusions—Locomotor recovery after stroke may be associated with improvement of asymmetry in SMC activation and enhanced PMC activation in the affected hemisphere. (Stroke. 2003;34:2866-2870.)

Key Words: cerebral cortex ■ gait ■ optics ■ rehabilitation ■ spectroscopy, near-infrared ■ stroke

As a result of recent advances in functional neuroimaging such as positron emission tomography and functional MRI, there is growing evidence that functional recovery of paretic hand after stroke depends on cortical reorganization, including the peri-infarct area in the primary sensorimotor cortex (SMC), other motor-related areas such as the premotor cortex (PMC) and supplementary motor area (SMA) in the affected hemisphere, and some combination of these areas in the unaffected hemisphere.1–10 Little is known about the mechanisms underlying locomotor recovery, one of the essential determinants of rehabilitation outcome in stroke, mainly because of technical limitations in assessing cerebral activation during dynamic movements. An optical imaging technique using near-infrared spectroscopy (NIRS)11–14 has enabled visualization of cortical activation during human gait that centered in the medial SMC and SMA.15 In patients with stroke, hemiparetic gait was associated with asymmetrical SMC activation and recruitment of PMC and pre-supplementary motor area (pre-SMA).16,17 In this longitudinal study we sought to clarify how cortical activation changed in the course of locomotor recovery after stroke.

Subjects and Methods

We evaluated cortical activation during hemiparetic gait on the treadmill in 8 patients with initial stroke (Table). All were right-handed. All were transferred to our hospital for inpatient multidisciplinary rehabilitation based on neurodevelopmental technique.18,19 The patients did not reach an independent level in ambulation and activities of daily living after medical treatment and less intensive physical therapy for 2 to 3 months in acute hospitals. Each patient underwent NIRS recording before and after 2 months of inpatient rehabilitation. This study was approved by the local ethical committee. Written informed consent was obtained from each patient.

For NIRS recording, patients walked on the treadmill at a speed of 0.2 km/h. Each 30 seconds of task period for walking was alternated by 30 seconds of rest period for 4 times. Experienced therapists, standing by the patients on the paretic side, assisted them mechanically to ensure safe gait performance by holding them on the foot or thigh of the paretic leg if necessary. Four patients (cases 1, 5, 6, and 7) with severe hemiplegia needed 20% of partial body weight support using the overhead harness with a pelvic belt and thigh strips20,21 to perform the walking task. Task conditions were identical in the 2 measurements before and after inpatient rehabilitation in each individual.

Details of the optical imaging system (Shimadzu) were previously described.15,17 In brief, it consisted of 12 light source fibers and 12 detector fibers, resulting in a 36-channel recording of cortical changes in oxygenated hemoglobin (oxyHb), deoxygenated hemoglobin (deoxyHb), and total hemoglobin. The spatial resolution was a few centimeters beyond the interoptode distance set at 3.0 cm, and the temporal resolution was 380 ms. The optodes were placed tightly on the skull with the use of a holder cap fabricated from custom-made thermoplastic resin. Cz was the marker for ensuring replicable placement of the optodes. An anatomic MRI scan22 revealed that the optodes were located over an area of 13×13 cm in the bilateral...
frontoparietal regions (Figure 1). The medial SMC was covered by the medial parts of the posterior channels (channels 16 and 17 in the left hemisphere and channels 22 and 23 in the right), SMA by the medial parts of the middle channels (channels 14 and 15 in the left hemisphere and channels 20 and 21 in the right), and PMC by the lateral parts of the middle channels (channels 2, 3, 8, 9 in the left hemisphere and channels 26, 27, 32, 33 in the right). Pre-SMA was located in regions rostral to the SMA and above the anterior commissure line23 (channel 13 in the left hemisphere and channel 19 in the right). The prefrontal cortex was partially covered by channels 1 and 7 in the left hemisphere and channels 25 and 31 in the right. We used oxyHb value as the marker for cortical activity because there was a task-related increase of oxyHb levels without apparent changes in deoxyHb levels in the medial SMC, and the cortical maps based on changes in oxyHb levels were similar to those from functional MRI during foot movements and gait imagery.15 Experimental data have also shown that oxyHb is the most sensitive marker of activity-dependent changes in regional cerebral blood flow.24–26 We obtained images depicting average changes in oxyHb during the task periods and the middle 20 seconds of the 30-second rest periods were used because there was approximately a 3- to 5-second delay in the response of hemoglobin oxygenation related to the tasks.15 To compare the amount of regional activation between the serial measurements on different occasions before and after inpatient rehabilitation, we defined regional activation as Average ΔoxyHb in Channels Covering Each Region/Total ΔoxyHb of All Channels. To evaluate interhemispheric asymmetry of regional activation, we calculated the laterality index6,10,17 (LI), defined as (ΔoxyHb in Affected Hemisphere–ΔoxyHb in Unaffected Hemisphere)/ΔoxyHb in Affected Hemisphere+ΔoxyHb in Unaffected Hemisphere, in each region.

For objective measurement of gait performance, we videotaped each walking task and evaluated cadence (steps per minute) and swing-phase LI, which was similarly defined as (Time for Swing Phase of Sound Leg−Time for Swing Phase of Paretic Leg)/(Time for Swing Phase of Sound Leg+Time for Swing Phase of Paretic Leg). Motor impairment was assessed with the Fugl-Meyer Scale.27 We also monitored blood pressure, heart rate, and arterial oxygen saturation measured using pulse oximetry at the baseline and after performance of the task.

To compare regional activation and LI before and after inpatient rehabilitation, we performed a 2-way repeated-measures ANOVA with time (before and after rehabilitation) as a within-subject factor and side of region (SMC, SMA, PMC, and pre-SMA) as a between-subject factor. Gait and physiological parameters were compared with 1-way repeated-measures ANOVA. The Fisher least significant difference test was used as a post hoc test. Correlation between changes of regional activation and gait parameters was analyzed with linear regression. Statistical significance was set at \( P<0.05 \).

Results

Cortical Mapping of Gait in Patients With Stroke

Cortical activation maps during hemiparetic gait in individual cases are shown in Figure 2. In the first evaluation, activities were observed in the medial SMC that were fewer in the affected hemisphere than in the unaffected hemisphere, SMA, and PMC. Activation in the pre-SMA and prefrontal cortex varied but tended to be seen in patients with large cortical lesions and severe hemiplegia (Figure 2C and 2D), but there was no activation in the damaged cortical areas, as expected in these patients. In the second study, the asymmetry in SMC improved, and there was enhanced PMC activation, particularly in the affected hemisphere. Prominent pre-SMA or prefrontal activation was observed in patients with large areas of cortical damage (Figure 2C and 2D).

Regional Activation During Hemiparetic Gait

To confirm the findings from individual cortical maps, we performed group analyses. For regional activation, ANOVA

**Figure 1.** Location of optodes. The NIRS system consists of 12 light source (white) and 12 detector (gray) fibers, resulting in 36 channels of source-detector pairs. The light source fiber next to the posterior one in the center column was located in the Cz portion. See text for the corresponding channel for each cortical region. CS indicates central sulcus.

**Table 1.** Demographic Data of Patients

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<th>Lesion</th>
<th>Side</th>
<th>MMSE</th>
<th>Days1</th>
<th>Days2</th>
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Mean (SD) 57 (12) 27.4 (2.6) 81 (30) 159 (29) 7.1 (2.2) 16.1 (7.2) 8.5 (5.0) 21.9 (7.6)
revealed that there was no significant main effect of time or site. There was a significant interaction between time and site ($F_{1,56}=2.329, P=0.0370$). These findings indicated that time had distinct effects on regional activation. The effect of time on regional activation was significant only in the PMC in the affected hemisphere ($F_{1,17}=5.686, P=0.0486$), suggesting that enhanced activation in this area may be associated with locomotor recovery (Figure 3). For LI, there was no main effect of time or site. There was a significant interaction between time and site ($F_{1,16}=3.156, P=0.0403$), indicating that time had distinct effects on regional LI. The effect of time on regional LI was significant only in the SMC ($F_{1,15}=10.016, P=0.0158$), suggesting that asymmetrical SMC activation significantly improved after inpatient rehabilitation (Figure 4).

Gait Performance
After inpatient rehabilitation, motor impairment as measured by the Fugl-Meyer scale and gait performance significantly improved ($P<0.05$; Table). Cadence was significantly greater ($P<0.005$) on the second evaluation ($55.3\pm18.6$ steps per minute; mean $\pm$SD) than on the first evaluation ($49.5\pm17.6$). Swing-phase LI was significantly greater ($P<0.05$) after rehabilitation ($-0.113\pm0.095$) than before rehabilitation ($-0.199\pm0.108$). Importantly, changes of swing-phase LI significantly correlated with changes of LI in SMC ($r=0.723, P<0.0427$) but not with changes of LI in PMC, SMA, or pre-SMA (Figure 5). Physiological parameters were comparable between the first and second NIRS measurements. There were no significant differences in baseline blood pressure (measurement 1 versus 2: $120\pm8/85\pm12$ versus $123\pm9/86\pm10$ mm Hg), heart rate ($84\pm12$ versus $80\pm10$ beats per minute), and arterial oxygen saturation ($96\pm1\%$ versus $96\pm1\%$). After the tasks were performed, blood pressure (measurement 1 versus 2: $127\pm10/92\pm8$ versus $128\pm8/91\pm8$ mm Hg) and heart rate ($93\pm8$ versus $89\pm7$ beats per minute) significantly increased from baseline levels ($P<0.01$), but the changes were comparable. There were no significant changes in arterial oxygen saturation after the task was performed in either the first or second evaluation ($97\pm1\%$ versus $97\pm1\%$).

Discussion
There are 2 major differences in cortical activation patterns during gait between healthy subjects and patients with...
activation in these areas may possibly be related to improved
metry in SMC significantly improved after inpatient rehabilitation.

Figure 4. Changes of interhemispheric asymmetry of regional
activation during hemiparetic gait as measured by LI. Positive LI
indicates more activation in affected hemisphere than in unaf-
fected hemisphere, and negative LI indicates the reverse. Asy-
metry in SMC significantly improved after inpatient rehabilitation
(\(P < 0.05\)). Lower, middle, and upper horizontal lines of boxes
represent 25th, 50th, and 75th percentiles, respectively. Vertical
lines extend from 10th to 90th percentiles.

Figure 3. Changes of regional activation during hemiparetic gait.
Solid line (Pre) represents quantified regional activation in SMC,
PMC, SMA, and pre-SMA (pSMA) during hemiparetic gait before
inpatient rehabilitation. Dotted line (Post) represents regional
activation after inpatient rehabilitation. There was a significant
difference (\(P < 0.05\)) in PMC activation in the affected hemi-
sphere (AH). Data are mean \pm SE. UH indicates unaffected
hemisphere.

stroke. The first is the asymmetry of activation. Importantly,
control of gait performance. Second, enhanced PMC activa-
tion may reflect the need for stabilizing proximal limbs and
trunk during gait since it participates in control of the
cortical motor networks. Similarly, hand recovery
after stroke has been associated with bilateral activation in
SMC, PMC,33 SMA, and cerebellum. Finally, altered activation patterns may result from reorgani-
zation of cortical motor networks. Notably, poststroke
advantages were seen in pre-SMA and prefrontal
cortex. Pre-SMA activation is associated with performance
of complex sequential motor tasks, selection of response in a
simple choice reaction time task, and the initial stages of skill
acquisition.36,37 Prefrontal lesions diminished attention to
novel events.38 Thus, these activations are possibly associated
with learning of gait, especially in severely affected patients,
since patients showed enhanced prefrontal activation in the
second evaluation; further studies are needed, however.

It is possible that some of our findings may depend on
changes in basic cerebral blood flow rather than changes in
brain function since cerebral blood flow and diachisis evolve
over time after stroke. Further studies are also needed to
investigate how gait speed, cadence, and body weight support
affect cortical activation patterns. NIRS imaging is a highly
noninvasive technique, and patients with stroke tolerated the
repeated measurements well. If we can elucidate cerebral
activation patterns associated with improved real-world out-
come, we might develop a brain-based as well as evidence-
based rehabilitation technique that would induce the preferred
cerebral activation.

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stroke.

References
The functional anatomy of motor recovery after stroke in humans: a study


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