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Cortical changes underlying balance recovery in patients with hemiplegic stroke

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ABSTRACT

Balance problems are a major sequelae of stroke and are implicated in poor recovery of activities of daily living. In a cross-sectional study, using 50-channel event-related functional near-infrared spectroscopy we previously reported a significant correlation between individual balance ability after stroke and postural perturbation-related cortical activation in the supplementary motor area (SMA) and the prefrontal cortex. However, the neural mechanisms underlying balance recovery after stroke remain unclear. Herein, we examined the cortical involvement in balance recovery after stroke by determining longitudinal regional cortical activation changes in patients with hemiplegic stroke. Twenty patients with subcortical stroke admitted to our hospital for post-acute inpatient rehabilitation participated in this study. Before and after intensive inpatient physical and occupational therapy rehabilitation, we evaluated cortical activation associated with external postural perturbations induced by combined brisk forward and backward movement on a platform. Postural perturbation-related cortical activation in the SMA of the affected and unaffected hemispheres was significantly increased after intensive rehabilitation. The increment of the postural-perturbation-related oxygenated hemoglobin signals in the SMA of the unaffected hemisphere was significantly correlated with the gain in balance function measured by the Berg Balance Scale. These findings support the conclusion that the SMA plays an important role in postural balance control, and suggest that the SMA is a crucial area for balance recovery after hemiplegic stroke.

Introduction

Maintenance of a standing posture is essential for executing activities of daily living (ADL). Human postural control is a complex motor task and is controlled by hierarchical neural systems including the spinal cord, brainstem, cerebellum, basal ganglia, and cerebral cortex. Clinical observations that supratentorial lesions often impair postural balance control clearly indicate a crucial role of the cerebral cortex in human postural control (de Haart et al., 2004; Garland et al., 2003; Verheyden et al., 2006). However, the cortical mechanisms underlying balance control and its recovery remain unknown.

To elucidate the cortical mechanisms for postural control, measurement of cortical activation during a dynamic postural task may provide important information. However, this measurement is difficult using conventional functional imaging tools such as functional magnetic resonance imaging (MRI) and positron emission tomography. Thus, imagery tasks (Jahn et al., 2004, 2008; Malouin et al., 2003; Zwergal et al., 2012) or simple ankle movement (Dobkin et al., 2004; Enzinger et al., 2009; Luft et al., 2005; Sahyoun et al., 2004) is now widely used. Among the various neuroimaging techniques, functional near-infrared spectroscopy (fNIRS) is suitable for investigating the cortical control of postural balance, as fNIRS is relatively robust with regard to subject motion (Miyai et al., 2001; Suzuki et al., 2004). For example, Mihara and colleagues applied this technique to investigate cortical activity while executing a balance task in healthy subjects (Mihara et al., 2008). Furthermore, a recent cross-sectional study in patients with stroke revealed potential roles of the prefrontal cortex and the supplementary motor area (SMA) in balance control (Mihara et al., 2012a). However, it remains unclear whether these cortical regions are associated with the recovery of postural balance. Considering that the intention to perform the balance task leads to increased SMA activation in healthy subjects (Mihara et al., 2008), and the positive correlation between the postural task-related SMA activity and individual balance ability in stroke patients (Mihara et al., 2012a), we hypothesized that the SMA may play an important role in the balance recovery after stroke, and that increased postural perturbation-related activation in the SMA may be beneficial to stroke patients. Therefore, we performed a longitudinal fNIRS study to elucidate the changes in postural perturbation task-related SMA activation after intensive inpatient rehabilitation and the relationship between regional cortical activation changes and improved balance function.

Abbreviations: ADL, activities of daily living; BBS, Berg Balance Scale; fNIRS, functional near-infrared spectroscopy; FIM, Functional Independence Measure; FMA, Fugl-Meyer Assessment scale; PET, positron emission tomography; SMA, supplementary motor area.

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Materials and methods

Subjects

Twenty patients (17 males) who suffered from subcortical stroke and who were admitted to our hospital for multidisciplinary inpatient rehabilitation participated in this study. Mean (±SD) age was 60.2 (±9.5) years and all patients were right-handed. Inclusion criteria included subcortical stroke, ability to stand without support for 5 min, no cognitive deficit, no previous history of neurologic disorders, and no sensory loss. Sensory disturbance was assessed using the sensory subscale of the stroke impairment assessment set (Chino et al., 1996). Written informed consents were obtained prior to study participation. The study protocol was approved by the ethics committee of Morinomiya Hospital, Osaka, Japan. Demographic data and clinical characteristics including age, sex, stroke subtype, location of the lesion, length from stroke onset to the participation to the study, and length from first to second evaluations are shown in Table 1.

Rehabilitative intervention

Each patient received rehabilitative intervention based on the neurodevelopmental technique 7 days per week, including daily sessions of at least 60 min of physical therapy focusing on improving muscle strength, balance, and gait control, and 60 min of occupational therapy focusing on improving coordinate limb movements and abilities for ADL (Yagura et al., 2005). The physical therapy program included general conditioning, range-of-motion exercise for trunk and limbs, muscle strengthening, static and dynamic balance exercises with standing, kneeling, and sitting, mobilizing the spine while prone and supine, walking indoors and outdoors, and climbing up and down stairs. The occupational therapy program included relaxation, training for hygiene, dressing, writing, eating, toileting, and bathing, balance exercises, reaching, coordinative tasks of the upper limbs and trunk, and dual motor tasks such as handling objects while standing and walking. An additional 60 min session of speech therapy was provided if the patient had problems with speech and/or swallowing. The maximum length of daily training session was 180 min per day.

Study protocol and assessment for clinical status

Clinical status was assessed by skilled nurses and therapists with respect to ADL using the Functional Independence Measure (FIM) (Granger et al., 1993), motor impairment using the Fugl-Meyer Assessment scale (FMA) (Fugl-Meyer et al., 1975), balance using the Berg Balance Scale (BBS) (Berg et al., 1992), and gait ability using a 10 m walk test (10MWT) (Table 2). Assessments for clinical measures and postural perturbation-related cortical activation were performed before and after intensive inpatient rehabilitation. The averaged (±SD) interval between the first and the second assessment was 41.5 (±16.1) days. A paired t-test was used to analyze the longitudinal changes of clinical measures before and after intensive rehabilitation.

fNIRS measurement

A continuous-wave fNIRS system using light of 780, 805, and 830 nm wavelength with 16 light sources and 16 detectors (OMM-3000; Shimadzu Corp., Kyoto, Japan) was used to assess task-related cortical activation through a 50-channel recording of the changes in the hemoglobin signal with sampling rate of 4 Hz, as previously described (Mihara et al., 2012a). A custom-made hard plastic cap was used to secure the fibers tightly to the scalp. We adopted an inter-optode distance of 3.0 cm to near-infrared light to ensure propagation to the gray matter beneath the optodes (Fukui et al., 2003; Mansouri et al., 2010). The light source at the center of the third row was placed at the vertex (Cz). The fNIRS channel was defined as the midpoint of the corresponding light source–detector pair. The relative changes in oxygenated and deoxygenated hemoglobin (oxyHb and deoxyHb, respectively) signals were calculated according to the modified Beer–Lambert Law for highly scattering media (Cope et al., 1988), and hemoglobin signal changes were denoted in arbitrary units (mM × mm) (Maki et al., 1995).

Postural perturbation task

The details of the task were previously reported (Mihara et al., 2012a). In brief, the subjects were instructed to stand at the center of a moveable platform with their feet shoulder-width apart. To prevent falling, the patients wore parachute jackets attached to a body weight support apparatus, without any weight support. Postural perturbation consisted of combined brisk forward and backward

Table 1
Clinical characteristics and postural stability of the subjects.

Patients	Age	Gender	Stroke subtype	Lesion	Length from onset (days)	Interval between two experiments (days)
Pt-1	56	Male	Hem.	R Put.	129	77
Pt-2	51	Male	Hem.	R Put.	52	41
Pt-3	66	Male	Isch	R CR	118	79
Pt-4	51	Male	Hem.	R Put.	200	29
Pt-5	68	Male	Hem.	L Fr.	122	63
Pt-6	76	Male	Hem.	R Th.	120	48
Pt-7	65	Male	Hem.	L Th.	74	60
Pt-8	74	Male	Hem.	R Th.	160	28
Pt-9	72	Male	Isch	L CR	115	32
Pt-10	46	Male	Isch	R CR	37	45
Pt-11	52	Male	Hem.	R Put.	135	39
Pt-12	59	Male	Hem.	R Put.	119	35
Pt-13	42	Male	Hem.	R Put.	65	39
Pt-14	67	Male	Isch	L CR	77	39
Pt-15	52	Male	Hem.	R Put.	70	28
Pt-16	68	Male	Hem.	L Th.	94	28
Pt-17	60	Female	Hem.	R Put.	138	28
Pt-18	63	Female	Hem.	R Th.	80	32
Pt-19	63	Male	Isch	L CR	96	32
Pt-20	53	Female	Hem.	L Put.	229	28
Mean ± SD	60.2 ± 9.5				111.5 ± 47.5	41.5 ± 16.1

CR, corona radiata; Fr, frontal subcortex; Hem, hemorrhagic stroke; Isch, ischemic stroke; L, left; Med, medial medulla; Pons, ventral pons; Put, putamen; R, right; Thal, thalamus.