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RAPID REPORT

CEREBRAL ACTIVATION RELATED TO THE CONTROL OF MASTICATION DURING CHANGES IN FOOD HARDNESS

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Abstract—To investigate the neural network involved in the control of mastication during changes in food hardness, we employed functional magnetic resonance imaging while 15 healthy subjects chewed gum whose hardness was changed by chewing. By comparing the areas activated when the hardness of the bolus varied widely with those seen when the hardness of the bolus had stabilized, we identified selective activations of the supplementary motor area, the dorsolateral prefrontal cortex, the superior temporal gyrus of the left hemisphere, and the premotor area and inferior parietal lobule of the right hemisphere. These findings indicate that these areas are probably related to processes linking sensory input and motor output involved in the change of hardness food during mastication.

Key words: functional magnetic resonance imaging, supplementary motor area, dorsolateral prefrontal cortex, superior temporal gyrus, premotor area, inferior parietal lobule.

Mastication consists of the integrated activity of the jaw muscles, which generate the biting force as well as jaw movements, and the muscles of the tongue and face, which bring the food between the upper and lower dental arch to be cut or crushed and then bring the food bolus to the pharynx to be swallowed. The CNS continuously modulates the motor commands controlling the biting force and pattern of masticatory movement according to a precise feedback control, because the physical properties of foods change substantially throughout the masticatory sequence (Plesh et al., 1986; Hiiemae et al., 1996).

Functional magnetic resonance imaging (fMRI) is a useful technique to investigate brain activity during mastication because it provides information on functional brain activity in association with motor and cognitive tasks. With the development of physiology of masticatory movements, a number of fMRI studies recently reported on brain activity during chewing (Onozuka et al., 2002, 2003; Tamura et al., 2003). They have addressed chewing gum on the condition that physical properties should be invariable. The masticatory movements are strongly related to the physical properties of foods. However, little is known about the relationship between the neural network and the mastication during changes in food texture. In the present study, we attempt to identify the cerebral areas involved in the control of mastication during changes in food hardness.

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Abbreviations: DLPFC, dorsolateral prefrontal cortex; EMG, electromyogram; fMRI, functional magnetic resonance imaging; IPL, inferior parietal lobule; MNI, Montreal Neurological Institute; PFC, prefrontal cortex; PM, premotor area; SMA, supplementary motor area; STG, superior temporal gyrus.

EXPERIMENTAL PROCEDURES

Subjects

Experiments were performed on 15 right-handed young adults (8 males, 7 females; mean age, 27.3 years; age range, 22–31 years) without any history of neurological or psychiatric disorders. All subjects had all teeth without malocclusion. The study was approved by the Committee of Medical Ethics, Graduate School of Medicine, Hokkaido University and they gave informed consent according to institutional guidelines.

Test of chewing gum hardness

The test food used was chewing gum (the value of hardness: 9.18 kgf) without odor and taste components, provided by the General Laboratory of Lotte Co. Ltd. (Saitama, Japan). Tests of chewing gum hardness were performed with the Universal Materials Testing Machines (Instron Corporation, Norwood, MA, USA). Chewing gum hardness was defined as the maximum load value, which was recorded when a 3.0 mm penetration in the bolus of the test food was made with a 30 mm diameter probe having a flat base at a speed of 3.0 mm/min, because these parameters had been sensitive to the test of chewing gum hardness.

Experimental task

In the present experiment, the task was chewing gum. Prior to the experiment, the subjects practiced chewing gum at a rate of about 80 times/min while listening to a metronome. During the fMRI scanning they performed the task in the supine position without metronome. After the experiment, subjects performed the task in the supine position outside the scanner to measure the cumulative number of the chewing by means of recording the electromyograms (EMGs) from the masseter muscles. We defined a masticatory movement as the period from the onset of one masseter EMG burst to the onset of the next. The statistical significance of the cumulative number of masticatory movement among sessions was assessed using one-way analysis of variance. The significance level was set at $P=0.05$.

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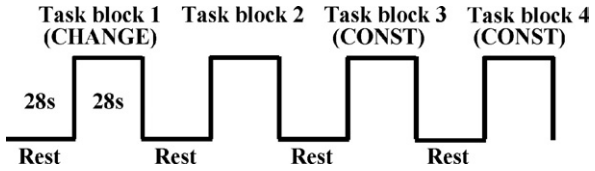

Fig. 1. A graphic representation of the experimental design used in the present experiment.

The sessions were designed in a block manner (four rest and four task blocks each lasting for 28 s) and it took 224 s for a single task session. Each subject participated in four sessions (Fig. 1). In each session, the test food used was new chewing gum. The trial began with the rest block, followed by the task block at a given auditory signal. During the experiment, the room lights were dimmed and subjects' eyes were closed.

fMRI scanning and data analysis

Brain imaging data were acquired a GE Signa 1.5 T whole-body MRI scanner using a head coil. For functional imaging covering the entire cerebrum, we used a gradient-echo echo-planar imaging sequence (GRE-EPI) with the following parameters: field of view 24×24 cm; matrix 64×64; slice thickness 5 mm; slice gap 2.5 mm; TR 4 s; TE 40 ms; flip angle 90°. The spatial resolution was 3.75×3.75×5 mm. Sixteen slices were obtained from a single session. Sessions that showed brain motion exceeding 0.75 mm were repeated to avoid functional activation due to pixel misalignment. After image construction, fMRI time series data consisting of consecutive EPI images were analyzed using SPM2 software (Welcome Department of Cognitive Neurology, London, UK). T1-weighted anatomical images were coregistered to the mean images of the functional scans and spatially normalized. The calculated nonlinear transformation was applied to all functional images for spatial normalization. Finally, the functional images were smoothed with an 8 mm full-width-at-half-maximum Gaussian kernel. Contrasts were calculated by fixed-SOA from the protocol as epochs and by convolving them with the hemodynamic response function to specify the appropriate design matrix. Condition and subject effects were estimated according to the general linear model at each voxel in brain space. To minimize effects of physiological noise, a high-pass filter of 80 s was applied within the design matrix. Moreover, a low-pass filter of the Gaussian type (4 s) was also used. Specific effects were tested by applying appropriate linear contrasts to the parameter estimates for each condition, resulting in a statistic for each and every voxel, while group data were analyzed using a random effects model. The resulting correlates were transformed into a *z* score map. Only clusters >10 activated voxels were reported. Activated brain structures were identified the Montreal Neurological Institute (MNI) coordinate.

RESULTS

There was no significant difference in the cumulative number of masticatory movement among four task blocks (Table 1). As Fig. 2 shows, after the cumulative number of masticatory movement was over about 60, the hardness value of chewing gum was regarded as a constant. In task block 2 the condition of the chewing gum hardness differed from one subject to another. Put another way, the chewing gum hardness could be thought to be changing in task block 1 (CHANG), and constant in task blocks 3 and 4 (CONST). Accordingly, to determine which areas were generally activated by the change of chewing gum hardness, we calculated the fields of activation in the CHANG and CONST conditions. The peaks in activation fields are summarized in Tables 2 and 3. Activation of the bilateral sensorimotor areas was found in both the CHANG and CONST conditions ($P<0.05$ corrected multiple comparison). Then, aiming to identify the cerebral areas involved in the change of the chewing gum hardness during mastication, we subtracted the activation during CONST from that during CHANG. In condition CHANG minus condition CONST at $P<0.05$ corrected for multiple comparison, there was no significant difference in cerebral areas. However, at the lower threshold ($P<0.0001$, uncorrected), significant differences were found in the supplementary motor area (SMA), dorsolateral prefrontal cortex (DLPFC), superior temporal gyrus (STG) of the left hemisphere, and the premotor area (PM) and inferior parietal lobule (IPL) of the right hemisphere. The results of condition CHANG minus condition CONST are shown in Table 4 and Fig. 3.

Table 1. The mean±SD cumulative number of masticatory movement in each task block

Task block 1	Task block 2	Task block 3	Task block 4
32.4±3.63	32.5±3.16	32.6±2.72	33.0±3.54

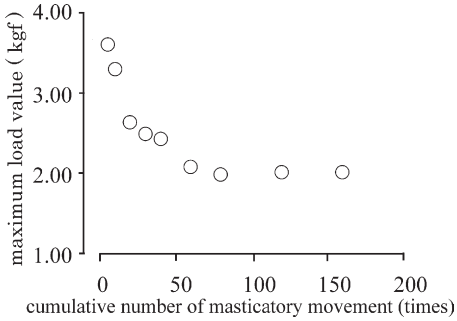

Fig. 2. Hardness values of chewing gum in association with the progress of the masticatory sequence. Abscissa, the cumulative number of masticatory movement. Ordinate, the hardness values of chewing gum.

DISCUSSION

In the present study, the main finding was that, when the hardness of chewing gum varied widely in oral cavity during mastication, there were selective activations of the SMA, DLPFC and STG of the left hemisphere, and the PM and IPL of the right hemisphere in dentate young adults

Table 2. Regions of brain activation in condition CHANG

Region of activation	*x*	*y*	*z*	Z value
Right hemisphere				
Sensorimotor area	52	−8	38	5.75
Left hemisphere				
Sensorimotor area	−50	−10	32	6.13

Z scores and localizations (MNI coordinates) for all significantly activated voxels ($P<0.05$, corrected for multiple comparisons) located within a cluster larger than 10 voxels.

Table 3. Regions of brain activation in condition CONST

Region of activation	*x*	*y*	*z*	Z value
Right hemisphere				
Sensorimotor area	50	−10	38	5.67
Left hemisphere				
Sensorimotor area	−52	−10	24	5.88

Z scores and localizations (MNI coordinates) for all significantly activated voxels ($P<0.05$, corrected for multiple comparisons) located within a cluster larger than 10 voxels.

without malocclusion. Thus, we demonstrated that there was a cortical neural network involved in the control of mastication during changes in food hardness.

Masticatory movement is commonly accompanied by bilateral activation of the rolandic sensorimotor cortex lining the central sulcus. In previous PET and fMRI studies, it has been reported that gum-chewing significantly activates the oral region of the sensorimotor area (Momose et al., 1997; Onozuka et al., 2002, 2003; Tamura et al., 2003). Our results are in line with these reports. It is known that the face region of the primary motor area has strong effects on the trigeminal motor system. This area plays an important role in the coordination of the tongue, jaw and facial muscles necessary for normal efficient mastication (Larson et al., 1980) and in controlling the strength of muscular contraction (Hoffman and Luschei, 1980). A study using bilateral reversible inactivation of the face primary somatosensory cortex by cooling in monkeys suggested that this area might be important in the fine control of jaw movement (Lin et al., 1993). Moreover, Hiraba et al. (1997) have shown the presence of mastication-related neurons in the orofacial primary somatosensory cortex. Thus, these reports indicated that these areas were indispensable throughout the masticatory sequence. We observed increasing brain activation in the bilateral sensorimotor areas during mastication, that is, the conditions CHANG and CONST. However, no activations in the bilateral sensorimotor areas were seen in the subtraction image of the condition CHANG minus the condition CONST. Because the subtraction method has analytical limitations, the subtraction image might cause the reduction of the activation areas by signal-to-noise reduction (Parrish et al., 2000).

The SMA and PM are generally responsible for planning of motor tasks. It was suggested that the SMA received inputs from the somatosensory system and the voluntary movements modulated the somesthetic excitability of SMA in human (Mima et al., 1999a). However, the exact reason for the involvement of the SMA in mastication is not understood. Human brain imaging studies have shown that the PM is involved in tactile perception (Mima et al., 1999b). Moreover, Kawashima et al. (2002) suggested that this area might comprise the cortical network implicated in tactile macrogeometric information processing. Hence, a possible explanation for these results is that the activation of PM is related to planning of masticatory movements in response to the tactile bolus information changed by chewing in the oral cavity.

It is known that brain lesions of the parietal cortex disturb object perception and recognition associated with tactile apraxia (Binkofski et al., 2001). It was reported that focal lesions in the IPL produced a selective deficit in shape perception and representation with preserved lower somatosensory functions and tactile exploration behavior (Reed et al., 1996). Furthermore, activity of the IPL associated with manipulating and identifying an object's shape (Deibert et al., 1999) might also play an important role in the integration of moving tactile stimuli independently provided on multiple fingers (Kitada et al., 2003). During mastication, the texture of chewing gum provides tactile and kinesthetic information. Thus, combining the findings in the present study and these observations, it could be thought that the IPL is involved in the tactile and kinesthetic information during mastication to control the biting force and pattern of masticatory movements according to a precise feedback control.

The prefrontal cortex (PFC), a neocortical area in the frontal lobe, is involved in integrating various stimuli and planning appropriate behaviors. After studying rabbits with PFC lesions, McLaughlin and Powell (2001) suggested that this area was involved in retrieval of information that determined performance of the jaw movement response. The PFC, especially DLPFC in primates, is implicated in the working memory that is used for temporary storage and manipulation of information (Funahashi, 2006). The working memory system contains the following two components: short-term storage on the order of seconds and an executive process that operates on the contents of storage. Chewing gum in the present study could maintain bolus hardness throughout condition CONST, but there were changes of bolus hardness throughout condition CHANG. In condition CHANG of our study, significant activation was observed in the DLPFC of the left hemisphere. We can reasonably assume that the working memory might hold information needed to continuously modulate the motor command controlling the biting force and pattern of masticatory movements according to a precise feedback control.

The STG has recently been regarded as a polymodal integration area (Karnath, 2001). It was reported that the STG was part of the brain activation pattern in somatosensory discrimination tasks with recognition of shape proper-

Table 4. Regions of brain activation in subtraction images of condition CHANG minus condition CONST

Region of activation	*x*	*y*	*z*	Z value
Right hemisphere				
IPL	64	−26	28	4.72
PM	50	10	54	4.30
Left hemisphere				
STG	−62	−42	8	4.12
SMA	0	−8	56	4.07
DLPFC	−46	40	0	3.99

Z scores and localizations (MNI coordinates) for all significantly activated voxels ($P<0.0001$, uncorrected) located within a cluster larger than 10 voxels.

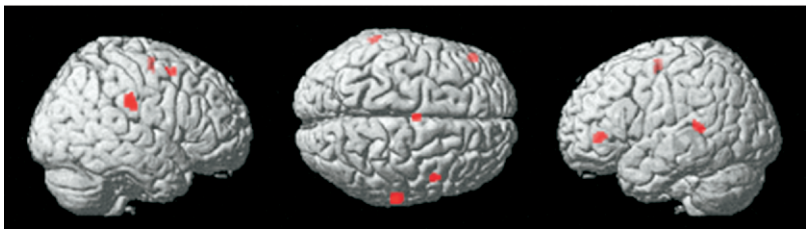

Fig. 3. Surface-projection color-coded statistical parametric maps superimposed onto MNI standard brain. Left and right sides represent the left and right hemispheres, respectively. The center represents an overhead view. The threshold is set at $P<0.0001$, uncorrected. For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.

ties (O'Sullivan et al., 1994). Therefore, the STG also would play an important role in integrating somatosensory feedback of sequential masticatory movement.

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