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Influence of Human Jaw Movement on Cerebral Blood Flow

ABSTRACT

Temporal changes in cerebral blood flow induced by jaw movement have yet to be investigated. To assess the influence of pattern and intensity of muscle contraction during jaw movement on task-induced change in cerebral blood flow, we performed bilateral transcranial Doppler ultrasound examination during clenching, gum chewing, and tooth tapping in healthy volunteers. A random-effects model analysis revealed a significant increase in middle cerebral artery blood flow velocity during clenching (high muscle activity) and gum chewing (moderate muscle activity), compared with the preceding rest period; however, such an increase was not detected during tooth tapping (low muscle activity). Cerebral blood flow was greater on the working side during the intensive isometric contraction of the masseter muscle in clenching. These results suggest that task-induced change in cerebral blood flow during jaw movement is influenced by the change in peripheral circulation evoked by muscle contraction.

KEY WORDS: jaw clenching, tooth tapping, chewing, cerebral blood flow, transcranial Doppler ultrasound (TCD), muscle.

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INTRODUCTION

Recent brain-mapping studies have revealed activation in the pre-frontal cortex associated with memory during chewing (Onozuka *et al.*, 2003), as well as activation in sensory and/or motor areas during chewing, tooth tapping, and clenching (Momose *et al.*, 1997; Onozuka *et al.*, 2002; Tamura *et al.*, 2002, 2003; Kubota *et al.*, 2003; Shinagawa *et al.*, 2004). These findings support earlier evidence that neural activity is closely connected to local changes in regional cerebral blood flow (Woolsey and Rovainen, 1991)—changes that can be detected by imaging techniques such as positron emission tomography and functional magnetic resonance imaging. Although brain mapping has high spatial resolution, its low temporal resolution and requirement for a special recording environment make it very difficult for task-induced temporal change in cerebral blood flow to be evaluated during jaw movement.

Transcranial Doppler ultrasound (Aaslid *et al.*, 1982) is an easy-to-use non-invasive monitoring method of cerebral blood flow that has the advantage of continuous, real-time recording. This method measures the velocity of blood flow in the middle cerebral artery, which supplies blood to about 80% of the cerebral hemisphere, including the frontal, parietal, and temporal lobes and the basal ganglia (Keith and Aaslid, 1992). Changes in middle cerebral artery blood flow velocity measured by a transcranial Doppler device are reported to reflect accurately the activated areas observed during Xe-enhanced computed tomography (Friedman *et al.*, 1991), positron emission tomography (Sitzer *et al.*, 1994), and single-photon-emission computed tomography (Dahl *et al.*, 1992, 1994; Borbely *et al.*, 2003). To date, however, few transcranial Doppler ultrasound studies have investigated the characteristics of task-induced change in cerebral blood flow during jaw movement, with the exception of a few studies on chewing (Sugiyama *et al.*, 1999; Lin *et al.*, 2002).

Task-induced change in cerebral blood flow during exercise is multifactorial and can be influenced by the cardiovascular response and the change in peripheral circulation due to muscle activity, as well as by task-specific neural activity. Transcranial Doppler ultrasound revealed that middle cerebral artery blood flow velocity contralateral to the performing side increased during hemispheric-specific tasks, such as hand exercise (Jørgensen *et al.*, 1993; Pott *et al.*, 1997; Ide *et al.*, 1999), indicating that it has sufficient sensitivity to detect task-specific neural activity. In the case of jaw movement, however, the influence of muscle contraction intensity on changes in cerebral blood flow might differ, because of the adjacency of the jaw muscles to the brain. In the present study, to test our hypothesis that the pattern and intensity of muscle contraction during jaw movement influence task-induced change in cerebral blood flow, we performed simultaneous recording—during clenching, gum chewing, and tooth tapping—of the following parameters: bilateral middle cerebral artery blood flow velocities, heart rate, bilateral electromyography of the masseter muscles, and transcutaneous partial pressure of arterial carbon dioxide. The working side was limited to the right side. Task-induced change in each parameter was analyzed statistically by means of the random-effects model.

METHODS

Volunteers

For the study, we recruited 12 volunteers (seven males and five females; mean age, 26.6 ± 3.5 yrs) with no history of craniomandibular disorder, brain disease, or tooth loss except for third molars. Written informed consent was obtained from each person after explanation of the aim and methodology of the study. Before it began, the study protocol received approval from the ethics committee of Osaka University Graduate School of Dentistry.

Data Recordings

Right and left middle cerebral artery blood flow velocities were continuously and simultaneously monitored by means of the Multi Dop-T system (DWL Elektronische System GmbH, Sipplingen, Germany). We initiated transcranial Doppler ultrasound from the localized cranial window, to ensure that the ultrasonic beam could penetrate without being excessively damped. Probes were fixed on the temporal bone above the zygomatic arch with a probe holder (Marc 600, Spencer Technologies, Seattle, WA, USA) (Fig. 1). Then, to identify the middle cerebral artery, we selected a depth of the ultrasonic beam to expose the transverse portion of the middle cerebral artery distal to the carotid bifurcation, and to maximize signal intensity (48-60 mm) (Aaslid, 1987). Sample volumes were fixed at 10 mm in diameter. Data were captured at each change in heart rate and recorded on a personal computer.

Evaluation of cerebral blood flow based on changes in middle cerebral artery blood flow velocity follows the assumption that the middle cerebral artery diameter remains constant during the task. Because partial pressure of arterial carbon dioxide affects vessel diameter (Markwalder *et al.*, 1984; Moraine *et al.*, 1993), middle cerebral artery blood flow velocity should be corrected when it fluctuates widely during the task (Giller *et al.*, 2000). Therefore, we recorded transcutaneous partial pressure of arterial carbon dioxide using a transcutaneous blood gas monitor (Surface Monitor 9900MK, Kohken Medical, Tokyo, Japan), to ensure the accuracy of middle cerebral artery blood flow velocity measurement as an index of cerebral blood flow. Transcutaneous partial pressure of arterial carbon dioxide and heart rate data were captured every second by the transcutaneous blood gas monitor and recorded on a personal computer.

We performed bilateral electromyography (EMG) of the masseter muscles using an evaluation system of mandibular movement (K6-I, Myo-Tronics, Taren Point, Australia) and surface electrodes (Duo-trode; interelectrode distance, 19.5 mm; Myo-Tronics) placed parallel to the masseter muscle fibers. EMG data were recorded at a sampling rate of 240 Hz and were amplified at a time constant of 0.06 sec. Analogue data from K6-I were converted by means of an A/D converter (AD12-8, Contec, Osaka, Japan), then full-wave-rectified and integrated for evaluation on a personal computer. The ratio of integrated EMG activity during each task to that during clenching with maximum effort for 2 sec (%MVC) was calculated for each volunteer as an index of muscle activity.

Tasks

Volunteers were seated in an upright position, with their heads stabilized by the chair headrest to maintain the Frankfort plane parallel to the floor, and their eyes masked. They were instructed to rest their arms on the chair armrest and keep their eyes closed. Each person performed the following 3 tasks, in which the working side was limited to the right side. A metronome was used for task frequency.

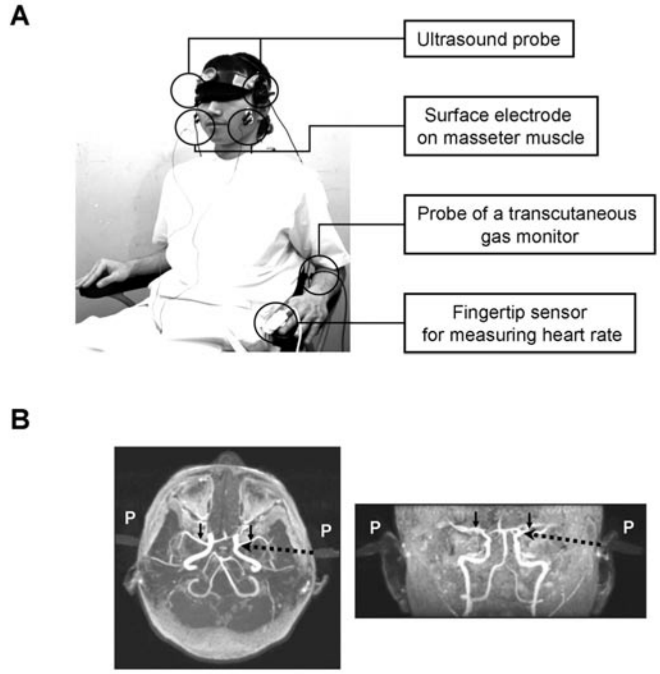

Figure 1. Simultaneous recording system of bilateral middle cerebral artery blood flow velocities, heart rate, transcutaneous partial pressure of arterial carbon dioxide, and bilateral electromyography of the masseter muscles **(A)**. Magnetic resonance angiographic images in the coronal section (left) and frontal section (right) show the three-dimensional relationship between the probes (P) and the middle cerebral blood artery (arrows) **(B)**.

Clenching: Volunteers performed clenching for 45 sec with a bite plane that covered the maxillary dentition of the working side, so as to avoid interjaw contact on the non-working side during the task.

Gum chewing: Volunteers chewed 2 pieces of chewing gum (Free Zone, Lotte, Tokyo, Japan) for 5 min on the working side at a rhythm of 1.0 Hz.

Tooth tapping: Volunteers performed tooth tapping for 3 min at a rhythm of 1.0 Hz with a bite plane on the maxillary dentition of the working side.

The data series recorded for each volunteer for each of the consecutive tasks consisted of 3 min of preceding rest (pre-task), the task (on-task), and subsequent rest with the same duration as the task (post-task). Each volunteer participated in recording of the 3 tasks once a day at the same time over 3 consecutive days. Each task was randomized in a Latin-square design. All measurements were performed in a quiet, dimly lit room at constant ambient temperature (25°C).

Data Analysis

To compare the pre-task, on-task, and post-task periods, we averaged data on the tracing at five-second intervals for the following parameters: area under effect curve (AUEC), maximum value (E_{max}), and time of maximum value (T_{max}) (Fig. 2). The means and 95% confidence intervals (CIs) of the AUEC and E_{max} for the on-task and post-task periods were then determined by the random-effects model with replication data. For T_{max}, the median and CIs were calculated. Statistical significance was set at $P < 0.05$.

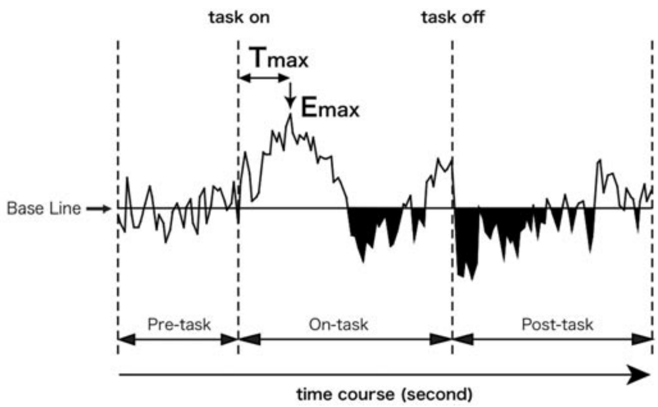

Figure 2. Analysis of area under effect curve (AUEC), maximum values (E_{max}), and time of maximum values (T_{max}) for pre-task, on-task, and post-task periods. The area surrounding the wave of the experimental and baseline data (set by the median in the pre-task period) was calculated as AUEC in the on-task and post-task periods. In this Fig., AUEC in the post-task period was calculated as the difference in area between data above and below the baseline.

RESULTS

Task-induced changes in each middle cerebral artery blood flow velocity, heart rate, EMG activity, and transcutaneous partial pressure of arterial carbon dioxide through the total sequence of clenching, gum chewing, and tapping are shown in Fig. 3 and the Table. Transcutaneous partial pressure of arterial carbon dioxide did not differ significantly in the pre-task, on-task, and post-task periods among the 3 tasks.

Clenching

Bilateral middle cerebral artery blood flow velocities and heart rate peaked 20 sec after the task began. Bilateral middle cerebral artery blood flow velocities in the on-task period were significantly higher than in the pre-task (left and right sides, $P < 0.0001$) and post-task periods (left side, $P = 0.0049$; right side, $P < 0.0001$), and were higher on the working (right) side ($P = 0.0139$). Heart rate in the on-task period was significantly higher than in the pre-task and post-task periods ($P < 0.0001$). There was no difference in heart rate between the pre-task and post-task periods. Masseter muscle activity peaked immediately (2 sec) after the task began (right side, 82.6% MVC; left side, 71.4% MVC), then decreased over the time-course, showing higher values on the working (right) side ($P < 0.0001$).

Gum Chewing

Bilateral middle cerebral artery blood flow velocities and heart rate peaked 145 sec and 125 sec, respectively, after the task began. On-task bilateral middle cerebral artery blood flow velocities were significantly higher than in the pre-task and post-task periods (left and right sides, $P < 0.0001$), with no side-to-side difference. Heart rate in the on-task and post-task periods was significantly higher than in the pre-task period ($P < 0.0001$). Masseter muscle activity peaked immediately after the task began (right side, 44.1% MVC; left side, 40.2% MVC), then decreased over the time-course, showing higher values on the working (right) side ($P = 0.0173$).

Tooth Tapping

Bilateral middle cerebral artery blood flow velocities and heart rate peaked 82-100 sec and 92 sec, respectively, after the task began. While there was no difference in bilateral middle cerebral artery blood flow velocities between the pre-task and on-task periods, heart rate in the on-task and post-task periods was significantly higher than in the pre-task period ($P < 0.0001$). Masseter muscle activity showed a constant low level (right side, 10.1% MVC; left side, 9.8% MVC; no significant side-to-side difference).

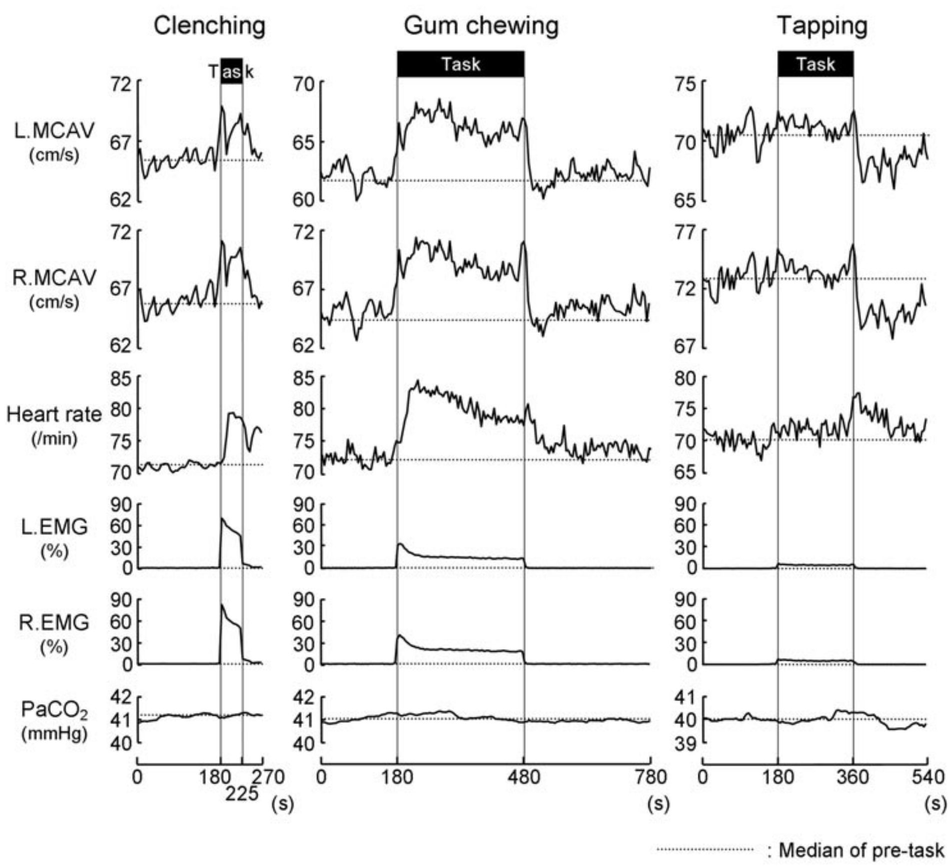

Figure 3. A representative recording of left and right middle cerebral artery blood flow velocities (MCAVs), heart rates, left and right EMG activities (EMGs), and transcutaneous partial pressures of arterial carbon dioxide ($PaCO_2$) in which baseline (median in pre-task period) data are shown as a dashed line.

DISCUSSION

Transcutaneous partial pressure of arterial carbon dioxide showed no significant change during any of the 3 tasks and was within the normal range (37-45 mm Hg; Aaslid *et al.*, 1989) in all volunteers, suggesting that middle cerebral artery diameter remained constant during tasks, and that middle cerebral artery blood flow velocity measured in this experiment was an accurate index of cerebral blood flow.

Activation in cerebral blood flow was demonstrated quantitatively by a significant increase in middle cerebral artery blood flow velocity during both clenching (high muscle activity) and gum chewing (moderate muscle activity); however, no such increase was observed for tapping (low muscle activity). These results suggest that pattern and intensity of muscle contraction during jaw movement influence activation in cerebral blood flow. In addition, functional magnetic resonance imaging (f-MRI) has revealed larger numbers of activated pixels during clenching than during tapping or gum chewing (Tamura *et al.*, 2003). Taken together, these findings suggest that activation of the entire cortical area that contributes to programming and execution of jaw movement influences task-evoked change in cerebral blood flow. In contrast, task-induced change in general circulation appeared to have less influence on cerebral blood flow than other factors, because heart rate increased significantly in the on-task and post-task periods of each jaw movement.

It was noteworthy that cerebral circulation was activated by gum chewing, a relatively weak exercise, and that it was semi-automatically controlled by the pattern generator. Increased sensory input during chewing might influence the neural activity controlling the chewing system. In this regard, Onozuka *et al.* (2002) reported that regional increase in brain neural activity caused by gum chewing was related to the hardness of the gum. Hence, many problems remain to be clarified in the relationship between cerebral blood flow and factors affecting chewing.

Continuous recording of bilateral middle cerebral artery blood flow velocity revealed a remarkable difference in (a) the time to reach peak velocity and (b) laterality of cerebral blood flow between clenching and gum chewing. To the best of our knowledge, these are the first findings on jaw-movement-induced changes in cerebral blood flow. Clenching is a jaw exercise characterized by intensive isometric contraction of the masseter muscle, while gum chewing is one that involves repeated masseter contraction and relaxation. Middle cerebral artery blood flow velocity and blood pressure are reported to rise immediately after the start of exercises involving intensive isometric contraction during weight-lifting (Dickerman *et al.*, 2000) and static exercise (Panerai *et al.*, 2001). The significant difference between clenching and gum chewing with respect to the time until peak middle cerebral artery blood flow velocity and heart rate might be caused by the pattern and intensity of muscle contraction.

Table. Median in the Pre-task Period, Mean of Maximum Values (E_{max}) in the On-task period, and Mean in On-task and Post-task Periods, and Mean Difference between On-task and Post-task Periods in Left and Right Middle Cerebral Artery Blood Flow Velocities (MCAVs), Heart Rate, Left and Right EMG Activities (EMGs), and Transcutaneous Partial Pressure of Arterial Carbon Dioxide ($PaCO_2$)

			Pre-task	On-task E-max	On-task	Post-task	Difference, On-task & Post-task
Clenching	MCAV [cm/sec]	Left	65.8	76.4	69.9*	68.1†	1.5‡
		Right	66.1	77.0	71.7*	69.0	2.7‡
	Heart rate [beats/min]		71.0	82.9	78.1*	76.8†	1.8
	EMG [%]	Left	1.3	71.4	53.9		
		Right	1.3	82.6	62.6		
	$PaCO_2$ [mm Hg]		40.5	41.3	40.6	40.6	0.02
Gum chewing	MCAV [cm/sec]	Left	61.9	74.0	66.0*	61.9	4.0‡
		Right	64.8	77.5	68.6*	64.9	3.7‡
	Heart rate [beats/min]		71.8	86.6	81.3*	75.4†	6.0‡
	EMG [%]	Left	3.2	40.2	17.3		
		Right	3.0	44.1	21.9		
	$PaCO_2$ [mm Hg]		41.0	41.7	41.5	41.3	0.2
Tapping	MCAV [cm/sec]	Left	70.1	78.9	71.1	68.3††	2.8‡
		Right	72.1	82.4	73.1	69.5††	3.5‡
	Heart rate [beats/min]		69.7	81.9	73.1*	73.5†	-0.3
	EMG [%]	Left	1.1	9.8	5.5		
		Right	1.6	10.1	5.9		
	$PaCO_2$ [mm Hg]		40.0	40.4	40.0	40.0	-0.05

MCAV: Middle cerebral artery blood flow velocity. (mean)
EMG: The ratio of integrated activity of masseter muscle.
$PaCO_2$: Transcutaneous partial pressure of arterial carbon dioxide.
* MCAV or heart rate in on-task period is higher than that in pre-task period.
† MCAV or heart rate in post-task period is higher than that in pre-task period.
†† MCAV in post-task period is lower than that in pre-task period.
‡ MCAV or heart rate in on-task period is higher than that in post-task period.

In our experimental setting, we insulated afferent information from the periodontal ligament on the non-working (left) side by placing a bite plane on the working side. This condition might allow for activation of neurons on the non-working side, based on the assumption that processing of afferent information in the sensory areas was due to reverse hemispheric dominance. In addition, EMG activity of the masseter muscle during clenching and gum chewing was greater on the working side than on the non-working side. Our evaluation using transcranial Doppler ultrasound, however, revealed a bilateral increase in middle cerebral artery blood flow velocity during both clenching and gum chewing. Furthermore, middle cerebral artery blood flow velocity on the working side exceeded that on the non-working side during clenching. These observations suggest that side-to-side differences in cerebral blood flow during jaw movement could not be fully accounted for by hemispheric dominance of the sensory and motor control system, as is the case for hand exercises (Jørgensen *et al.*, 1993; Pott *et al.*, 1997; Ide *et al.*, 1999).

In summary, the results of the present study confirmed that pattern and intensity of muscle contraction during jaw movements influenced the task-induced change and side-to-side difference in cerebral blood flow when the working side was limited to one side of the jaw. Our experimental set-up and methodology for analyzing task-induced change in cerebral blood flow during jaw movement could also prove advantageous to future researchers examining hemispheric dominance of cerebral blood flow by comparing the middle cerebral artery blood flow velocity on the same side during a task with different working sides.

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