Influence of command on tongue elevation during swallowing: examination of tongue pressure and ultrasound imaging

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Abstract

Aim and objectives: The purpose of this study was to investigate the difference between swallowing with command and without command.

Design: Subjects were eight healthy male young adults with ordinary mastication and/or swallowing functions. Subjects were asked to swallow 3mL of water in the following manner: Trial 1: Swallowing with Command (C) and Trial 2: Swallowing in his usual way (No Command = NC). Tongue pressure distribution was measured and synchronized with midline ultrasound sagittal sections of tongue movement images for further analysis.

Results: All subjects exhibited tipper-type swallow in ultrasound images. The second point of peak in tongue pressure corresponded with the point at which the hyoid was in its most elevated position. The duration of palatolingual contact was clearly shorter in the C than in the trial NC (C, 1.26 s; NC, 1.67 s, P < 0.01). The pressure integrals were markedly smaller in the trial C than in the trial NC (P < 0.05).

Conclusions: These results indicate that the duration of swallowing is shorter in swallow onset with, than without command. The tongue movement in swallowing with command may be more effective than in swallowing without command.

Key words: Tongue pressure, ultrasonography, swallow-to-command techniques, deglutition, tongue pressure distribution

Introduction

Impairment in swallowing function interferes with a healthy life; therefore diagnostic assessment and rehabilitation of swallowing function, oral cleaning, and other forms of oral health care are important key factors for improving the quality of life (QOL) of patients with dysphagia (Ueda et al., 2004; Nakamura et al., 2005). Dysphagia is a symptom that affects 15% of hospital inpatients, older people, people with neurological disease, cancers of the head and neck and people with severe reflux. This symptom affects a person’s ability to remain well nourished and hydrated and increases the risks of ill health (Nazarko, 2008). Moreover, dehydration was found to be common among orally fed patients with dysphagia (Leibovitz et al., 2007). Improvement of water ingestion is an important agenda for patients requiring special care with dysphagia, because the flow of water is faster than that of solid food.

Generally, swallow-to-command techniques are used in both diagnostic assessment and rehabilitation of patients with dysphagia. Spontaneous or reflexive swallowing occurs between meals without awareness and during sleep in humans. Significant impairments of this type of swallowing are observed in the elderly and patients with neurogenic dysphagia (Lang, 2009). Although the phases of swallowing are controlled by the brain stem and peripheral reflexes (Lang, 2009), the effect of command on the processes of swallowing is not well known. A recent study using videofluorography recordings has showed that the processes of bolus transport, bolus aggregation, and swallow initiation might be altered when the subject was commanded to begin swallowing (Palmer et al., 2007).

On swallowing a bolus of liquid, the bolus is usually held in the oral cavity until the time of swallow onset. The swallow is initiated as the bolus reaches the fauces. Once the oral stage is initiated, the pharyngeal stage follows in rapid sequence (Dodds et al., 1990). The sequence of events is quite different when a healthy young subject eats solid food. A portion of the food is propelled through the fauces to the oropharynx (stage II transport) during mastication (Palmer et al., 1992; Dua et al., 1997; Palmer, 1998). Previous studies with brain imaging techniques have shown that different but overlapping areas of the cerebrum are
activated in volitional and automatic swallowing of saliva or water (Martin et al., 2001; Kern et al., 2001).

Nonaka et al. (2009) suggested involvement of the supplementary motor area, suggesting that the processing of the cue to swallow water activates wider areas in the brain than swallowing water without command. There are few studies which have examined the effect of command on swallowing of water using surface electromyography (Sekikawa et al., 2009; O’Kane et al., 2010); furthermore, these studies investigated whether swallowing with command was more effective than spontaneous swallowing. However, the differences in tongue movement between swallowing water with command and swallowing water without command remain unclear. The tongue is one of important organs for mastication, swallowing and speech articulation. The tongue helps to maintain and control the bolus in the oral cavity and to transport it to the pharynx during swallowing.

Tongue movement upon swallowing was studied using various techniques, such as dynamic palatography (Harley, 1972; Imai and Michi, 1992), measurement of tongue pressure (Kawashima, 1993; Ono et al., 2004; Hori et al., 2006; Sugita et al., 2006; Kieser et al., 2008; Youmans et al., 2009; Lenius et al., 2009; Tamine et al., 2010), ultrasonography (US) (Keller, 1987; Imai et al., 1995; Sonies et al., 1996; Akgul et al., 1999; Casas et al., 2002) and videofluoroscopy (VF) (Adnerhill et al., 1989; Bisch et al., 1994).

Tongue pressure is an effective measurement for evaluating tongue movements. It has been studied by several groups using the Iowa Oral Performance Instrument (Youmans et al., 2009), a simple tool that does not allow the jaws to close. Previous studies have evaluated tongue pressure using an experimental palatal plate installed with miniature pressure sensors (Sugita et al., 2006; Kieser et al., 2008; Lenius et al., 2009). Ono et al. (2004) presented a method to measure the timing and pressure of the tongue-hard palate using seven miniature pressure sensors installed in predetermined positions of a palatal plate. They showed that the order, magnitude, and duration of tongue pressure patterns against each part of the palate were coordinated. Kawashima (Kawashima, 1993) simultaneously detected palatolingual contact on ultrasonography (US) and measured miniature pressure sensors using a synchronised observation system to observe tongue movement.

This study expanded these methodologies to associate tongue pressure with real-time US sagittal sections of tongue movement during swallowing. Moreover, temporal alternations in tongue pressure were depicted using dynamic tongue pressure distribution, and US images of tongue movement were used in a synchronised observation system to examine the effect of swallowing with command.

The purpose of this study was to investigate the difference between swallowing with command and swallowing without command, and to apply the results in clinical assessment and functional training.

**Subjects and methods**

**Subjects**

This study included eight healthy male young adults (mean age = 22.62 ± 2.82 years) who had no impairments in mastication, swallowing, and/or occlusion. The experiments were carried out after obtaining informed consent from each subject. This study was approved by the Showa University Research Ethics Committee (No. 2010-01).

**Fabrication of experimental palatal plate**

An impression of the upper jaw of each subject was taken using alginate impression material (Algiace Z; DENTSPLY-Sankin, Tochigi, Japan), and a cast was constructed using dental plaster (New Plastone; GC, Tokyo, Japan). A 1mm thick palatal plate was constructed from a 1.5mm thick acrylic disk (Yamahachi Dental, Aichi, Japan) by the use of a heating vacuum press.

Two identically shaped palatal plates were fabricated for each subject; one had to be worn for seven days before the experiment for adaptation (Ono et al., 2004), and the other was to be equipped with pressure sensors to obtain experimental data. The region of palatal plates covering the occlusal portions of the teeth was carved out to bring the teeth into occlusion.

Seven miniature pressure sensors (PS-2KC; 6 mm in diameter, 0.6 mm in thickness; Kyowa Electronic Instruments, Tokyo, Japan) were installed into the experimental palatal plate. Figure 1(a) shows the location of the sensors in relation to oral structures and the constructed plate.

The positions at which pressure sensors were installed in our experimental palatal plate were based on the dental arch and the anatomical landmarks of the incisive papilla and hamular notch (Ono et al., 2004). Three sensors (Ch.1–3) were placed along the median line of the hard palate: Ch.1 was set 5 mm posterior to the incisive papillae, Ch.2 was set one-third anterior, and Ch.3 was set at one third posterior between the incisive papillae and posterior edge of the hard palate.

Toward the edges of the plate, Ch.4 was set at the left one-third anterior and Ch.5 at left one-third posterior between the incisive papillae and left hamular notch, with Ch.6 and Ch.7 set in corresponding contralateral positions. In the experimental palatal plate, each sensor was fixed by paraffin wax (All climate paraffin wax; GC, Tokyo, Japan) (Kieser et al., 2008). Cables from each sensor exited from the angle of mouth via the oral vestibule. Subjects were asked to wear the experimental palatal plate during trials.
Positioning and tongue pressure equipment
The subjects were ordered to sit upright in a fan-backed chair with a fixed headrest. They were asked to sit upright on the chair, with 90° hip flexion and 90° knee flexion, while contacting the ground with their soles. Their heads were kept steady by the headrest so that the Frankfort Plane was parallel to the floor (Kawashima, 1993). Tongue pressure was recorded using dynamic data acquisition software (DCS-100A; Kyowa Electronic Instruments, Tokyo, Japan) through sensor interfaces (PCD300A; Kyowa Electronic Instruments) with a frequency of 100 Hz.

Diagnostic ultrasound system
All scanning was performed using a B-mode diagnostic ultrasound system (Power vision 6000; Toshiba Medical Systems, Tochigi, Japan). The 6.0 MHz convex-array probe (PVM375AT; Toshiba Medical Systems, Tochigi, Japan) was positioned at the median sagittal plane. In our pilot study involving five healthy young adults, we identified the most appropriate angle of the probe that can be used to identify median sensors (Ch.2, Ch.3). The results of previous experiments suggested that the sagittal angle of the probe should be 200 posteriorly and the coronal angle should be zero degrees. The probe was fixed using a spring probe-holder, which can be used to adjust the angle (Keller, 1987). An ultrasound gel pad (SONAGEL; Takiron, Tokyo, Japan) was set on the probe to allow better visualisation of superficial structures and to avoid obstruction of the laryngeal elevation.

The shadows of pressure sensors (Ch.2 and Ch.3) were scanned and identified by using US; these shadows could be pointed out by each subject using his tongue before measurement.

Measurement of tongue pressure and recording of US
The US image was visualized on a PC monitor through converting software (Power producer 5; CyberLink, Taipei, Taiwan). The US images and tongue pressure data were synchronised onto the same PC monitor and were recorded by screen recording software (Camtasia Studio; TechSmith, Michigan, USA) with a frequency of 30Hz for later analysis. The frequency was chosen to conform to a fundamental study that used US and tongue pressure for observation of tongue movements (Kawashima, 1993). Figure 1(b) shows setup of the experimental palatal plate and US, and Figure 2 shows a diagram of the recording system.

Figure 1. Location of pressure sensors (a), and (b) Setup of an experimental plate and US image.
A spoon was used to feed 3mL of water from a spoon to each subject, in conformity with a previous study (Furuya et al., 2008). Boluses were at 37°C to minimize sensor variability. All subjects were told to swallow 3ml of water in the following two ways:

**Trial 1, With command (C)** — Each subject was instructed to (a) hold the water in the mouth; and (b) swallow on command of the investigator. The command was given immediately after the tongue pressure became stable.

**Trial 2, No command (NC)** — Each subject was asked to swallow in their usual manner. Each trial was recorded seven times; moreover, five of the seven recordings were chosen as stable data for further analysis.

**Parameters**
For tongue pressure, the following parameters were recorded: time of pressure onset (Ton), the point of maximum pressure (Tmax), the second point of peak in tongue pressure (T2nd), and time of pressure offset (Toff). In addition, maximum magnitude of tongue pressure (MP), pressure integral, and duration of palatolingual contact (TD) were compared between the trial C and NC. Figure 3 shows the method of tongue pressure analysis. Ton at Ch.1 was set to 0. The relationships of US images and tongue pressure waveforms with the time at which the hyoid reached the most elevated position were measured using analysis software (NI DIAdem ver. 11.0; National Instruments, Texas, USA). Ton at Ch.1 was set to the onset of US analysis. Temporal alternations of tongue pressure were depicted as dynamic tongue pressure distributions by using the same analysis software.

**Statistical analysis**
The tongue pressure parameters (Ton, Tmax, T2nd, Toff, MP, TD, and pressure integral) were determined using a paired sample t-test in order to examine the difference between the trial C and NC. Statistical differences between the seven sensors were determined using repeated-measures analysis of variance (ANOVA), and comparison testing was performed using Tukey’s HSD significant difference test.

The relationship between tongue pressure waveform and the time at which the hyoid reached the most elevated position were compared using the Pearson product-moment correlation coefficient. P-values less than 0.05 were considered significant in all cases.

**Results**

**Tongue pressure waveform and US images**
Tipper-type swallowing was observed in all subjects based on US images recordings. Figure 4 shows an example of tongue pressure synchronisation (tongue pressure waveform and dynamic pressure distributions expressed by colour alteration) and US images. In tipper-type swallowing, small negative pressure (mean value of minimum magnitude of tongue pressure: C, -3.0 ± 0.22kPa; NC, -4.1 ± 0.29kPa) was initially exhibited, followed by positive pressure that increased rapidly and reached a maximum magnitude of tongue pressure at each channel. The onset of positive pressure at Ch.2 and Ch.3 corresponded with...
Figure 3. Tongue pressure analysis parameters. Time of pressure onset (Ton), the point of maximum pressure (Tmax), the second point of peak in tongue pressure (T2nd), time of pressure offset (Toff), maximum magnitude of tongue pressure (MP) and pressure integral, and duration of palatolingual contact (TD)

the tongue contact with Ch.2 and Ch.3 according to US images. The contact continued until tongue pressure returned to baseline. After the onset of positive pressure, the tongue moved from the anterior to the posterior in a wavelike movement and transported the bolus into the pharynx.

After the maximum magnitude of tongue pressure was reached (Figure 4A), the hyoid was rapidly elevated. The time of second peak of tongue pressure (Figure 4B) corresponded with the time at which the hyoid reached the most elevated position. The hyoid started to shift downward when the tongue pressure began to decrease. The second point of peak in tongue pressure corresponded to the point at which the hyoid was in its most elevated position. Moreover, the time of second peak of tongue pressure significantly correlated with the time of the hyoid bone reaching in its most elevated position (P < 0.01) both in the trial C and NC.

Statistical analysis

Data collected from eight subjects were used for statistical analysis. Figure 5(a) shows the time of pressure onset at each sensor (Ton). Significant differences were not observed between the trial C and NC. Mean values of Ton at Ch.1 were significantly lower than those of Ch.3 in both the trial C and NC (P < 0.05).

Figure 5(b) shows the mean value of the point of maximum pressure (Tmax) at each sensor. At all channels, mean values of Tmax were significantly shorter for the trial C than for the trial NC (Ch.6, P < 0.01; Ch.1, Ch.2, Ch.3, Ch.4, Ch.5, and Ch.7, P < 0.05). No significant differences were observed among the seven sensors used in the trial.

The intervals between Tmax and T2nd were not significantly different between the trial C and NC. No significant difference was observed among the values of the seven sensors used in the trial. Time intervals between T2nd and Toff were significantly shorter for the trial C than for the trial NC (P < 0.05). No significant differences were observed among the values of the seven sensors used in the trial.

Figure 5(c) shows the mean value of maximum magnitude of tongue pressure (MP) at each sensor. Significant differences were not observed between the trial C and NC. Figure 5(d) shows pressure integrals at each sensor. The pressure integral was significantly lower for trial C than for trial NC (Ch.3 and Ch.7, P < 0.01; Ch.1, Ch.2, Ch.4, Ch.5, and Ch.6, P < 0.05). The pressure integral at Ch.1 was significantly greater than that at Ch.3 in the trial NC (P < 0.05).

Figure 6 shows the mean duration of palatolingual contact production. The duration of palatolingual contact was significantly shorter for the trial C than for the trial NC (P < 0.01).
Figure 4. Examples of synchronised tongue pressure (tongue pressure waveform (a) and dynamic pressure distributions that were expressed by colour alteration (b), and US images (c). baseline; A, the point of maximum pressure; B, the point of second peak of tongue pressure

Figure 5. Mean values of the time of pressure onset (Ton) (a), mean values of maximum tongue pressure (Tmax) (b), mean values of magnitude of tongue pressure (MP) (c), and mean values of pressure integral (d) at each sensor. M: Midline, L: Light, R: Right
Discussion

Traditionally, the act of swallowing, or deglutition, is described as a highly coordinated process involving four stages: oral preparatory stage, oral stage, pharyngeal stage, and oesophageal stage (Gleeson, 1999). These stages were observed in swallowing with command. Bolus formation and deglutition of liquids involves a rapid sequence of events: a volume of fluid is propelled from the oral cavity, which crosses the fauces, passes down and across the pharyngeal surface of the tongue, and enters the hypopharynx and then the oesophagus. In contrast, triturated food is accumulated on the pharyngeal surface of the tongue after passage through the fauces, with a variable period in which additional aliquots of food are moved in a posterior direction. After a variable period of elapsed time, the bolus in the pharynx is transported to the oesophagus. Stage II transport (movement of material through the fauces) is considered to be a more accurate descriptor of the process because it describes the movement of material from the oral cavity to the oropharynx with no connotation as to the timing of subsequent events (Hiiemae et al., 1999).

Most studies regarding Stage II transport investigated deglutition with mastication (Hori et al., 2006; Palmer et al., 2007). The tongue pressure has been thought to be an index of swallowing function.

Few studies have investigated the process of swallowing liquid (Nonaka et al., 2009; Sekikawa et al., 2009); however, the changes in the oral phase, including tongue movement, pressure, and tongue elevation, have not been surveyed using objective methods. Thus, in this study, dynamic tongue pressure distribution and US images of tongue movement were used with a synchronised observation system, and the differences between swallowing with command and without command were investigated.

Synchronisation of US and tongue pressure
To confirm tongue movement and organ motions around the pharynx associated with swallowing, tongue pressure and US images were synchronised. In a previous study, the difference in the length of time measured with US and the strain-gauge pressure transducer was on the order of less than 1 frame (0.033 s) (Kawashima, 1993). Therefore, the reproducibility was considered appropriate for comparing values obtained for the duration of tongue movement with US images to a strain-gauge pressure transducer.

Previous research suggested that there are defined individual patterns of pressure change during liquid swallowing (Kennedy et al., 2010). Tongue pressure measurement and US images allowed us to determine the correlation among tongue pressure, tongue movement, and elevation of the hyoid bone during swallowing. Moreover, these data reveal information regarding the relationship between tongue movement and patterns of tongue pressure change during water swallowing.

Preparing for the measurement with palatal plate
Nagano et al. (2002) prepared four occlusal vertical dimension conditions: intercuspal position and vertical dimension of occlusion by approximately 4, 8, and 12 mm. Their data indicated that the maximum pressure decreased significantly as the vertical dimension increased in young adults during swallowing of 2 mL of water. Accordingly, in this study, the region of palatal plates covering the occlusal portion of the teeth was carved out to bring their teeth into occlusion to eliminate the effect caused by the vertical dimension.

Ono et al. (2004) evaluated tongue pressure by using palatal plates used adaptation periods of 7 days. Furuya et al. (2008) suggested that the influence of the palate covering on swallowing 3 mL of water function is relieved after 7 days. In this study, subjects were instructed to wear
a palatal plate for 7 days before the experiment for adaptation; hence, we believe that the 7-day adaptation eliminated the effect caused by plate covering.

Comparison among each sensor
In this study, 3mL of water was used to determine the effect of a command on swallowing (Furuya et al., 2008). Significant differences were observed between the anteriomedian point (Ch.1) and the posteriomedian point (Ch.3) in time of onset of tongue pressure in both the trial C and NC, and in pressure integrals in the trial NC. Furuya et al. (2008) reported that the onset of tongue pressure with the posterior point was significantly longer than with the anterior point on the midline. This finding is consistent with our results comparing the posterior and anterior points on the midline. This result indicated that distinguished differences were not observed between the anterior and posterior points on the midline in other parameters. The midline of the tongue may play a role in and pushing a bolus backward, resulting in relatively constant tongue pressure. However, tongue pressure may increase to facilitate the transport of a bolus when the volume of water is increased. A previous study using 15mL of water in swallow manoeuvres suggested that magnitude and duration of tongue pressure were significantly larger in the anteriomedian part compared to the other parts measured, and were significantly smaller in the posteriomedian part (Ono et al., 2004). Therefore, 3mL of water was chosen in this study so that significant differences could be clearly observed from point to point with increased amounts of water. This suggests future studies are required using similar amounts.

Comparison between swallowing with command and without command
Most studies regarding Stage II transport investigated deglutition with mastication (Hori et al., 2006; Palmer et al., 2007). A previous study (Hori et al., 2006) suggested normal patterns of tongue contact against the hard palate, control of tongue activity, and coordination with jaw movement during mastication; furthermore, the authors described that the magnitude and duration were significantly larger in late stages of chewing.

A recent study showed that the processes of bolus transport, bolus aggregation, and swallowing initiation might be altered by volitional swallowing or command swallowing, suggesting differences in cognitive functions during volitional and command swallowing in humans (Palmer et al., 2007). Nonaka et al. indicated that the supplementary motor area activates wider areas in the brain for swallowing with command than for swallowing without command (Nonaka et al., 2009). Moreover, few previous studies compared the differences in tongue pressure on swallowing of liquids with command and without command.

In this study, the point of maximum pressure and the duration of palatolingual contact were significantly shorter in trial C than in trial NC, and the pressure integral was significantly smaller in trial C than in trial NC. However, the maximum magnitude of tongue pressure at each channel did not show significant differences between trials C and NC. The pressure integral indicated that the magnitude of tongue pressure from the onset to the offset of tongue pressure was markedly smaller in trial C, than in trial NC; these findings suggest that the point of maximum pressure and the duration of palatolingual contact were responsible for the significantly smaller pressure integral in trial C, than in trial NC.

Electromyographic activity of the suprahypoid muscle on swallowing with command was significantly lower than that on swallowing without command (Sekikawa et al., 2009). Additionally, electromyographic activity of the suprahypoid muscle was strongly correlated with tongue pressure (Lenius et al., 2009). Therefore, the duration of swallowing was shorter in swallowing with command than in swallowing without command. This result may be related to hyoid elevation, which is coordinated with tongue movement.

The oral and pharyngeal stages of swallowing were identified using this method. Forward and upward phases of tongue blade movement are initially prevalent in the oral stage of the normal swallow (Stone and Shawker, 1986) and are highly synchronous with the movement of the hyoid bone, which serves as a supporting structure for the larynx and/or platform for the tongue (Gleeson, 1999). The oral stage of swallowing is initiated by the onset of a leading complex of four closely related events (Cook et al., 1989): (a) the onset of tongue tip movement; (b) tongue base movement; (c) vertical hyoid movement, and (d) submental electromyographic activity. The oral and pharyngeal stages of swallowing are closely coupled in normal swallowing (Gleeson, 1999).

Tipper-type swallow is known to account for nearly 80% of total swallowing (Dodds et al., 1989); furthermore, tipper-type swallow was observed in all subjects in this study. This swallowing pattern involves the initiation of swallowing from the tip of the tongue against the incisors and pharyngeal stages of swallowing, and (d) submental electromyographic activity. The oral and pharyngeal stages of swallowing are closely coupled in normal swallowing (Gleeson, 1999).

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the point of maximum pressure and the point of second peak of tongue pressure. Furthermore, research regarding the relationship of tongue elevation and hyoid movement may require further experiments to measure not only the maximum tongue pressure but also the second peak of tongue pressure.

Conclusions

- The duration of swallowing was shorter in swallowing with command than in swallowing without command. This result suggests that tongue movements in swallowing with command may be more effective than in swallowing without command.
- The time of the second peak of tongue pressure corresponded to the time of the hyoid reaching its most elevated position.

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