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Original

Biomechanics of human tongue movement during bolus compression and swallowing

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Abstract: We evaluated the effects of gel consistency and bolus volume on ingestion in humans. Eight healthy men were asked to ingest liquids, and sample foods of different gel consistencies and volumes, as usual. Tongue pressure against the hard palate was recorded at five points, and bolus flow was recorded using videoendoscopic images. The number of squeezes increased as gel consistency and volume increased. The integrated magnitude of tongue pressure during squeezing increased with increasing gel consistency. Bolus propulsion into the pharynx was affected by bolus characteristics, and location of the bolus head at the onset of pharyngeal swallowing was not related to squeezing behavior. The trigger point at which pharyngeal swallowing began was subject-dependent. During swallowing, the magnitude of tongue pressure moderately increased with increasing gel consistency, as compared with squeezing. Tongue pressure was not related to bolus volume. The current results suggest that patterns of tongue pressure during squeezing and swallowing are differentially affected by bolus conditions. However, healthy subjects differed in the techniques used for squeezing and swallowing.
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Keywords: swallowing; squeezing; tongue pressure; dysphagia.

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Introduction

The tongue is a critical structure in systematic orofacial movements such as chewing, swallowing, respiration, and speech. During chewing and swallowing, the tongue contributes to the formation, placement maintenance, and propulsion of a bolus, with saliva, into the oropharynx (1,2). Furthermore, propulsion of a bolus into the oropharynx by the tongue during the final stage of chewing is essential to normal initiation of a naturally evoked swallowing reflex (3). Once the swallowing reflex is initiated, retraction of the tongue muscles can also help in moving the bolus into the esophagus through the upper esophageal sphincter (4,5). To fully understand the role of the tongue in chewing and swallowing in humans, we recently developed a novel sensor sheet that measures tongue pressure in a simple, mobile procedure, thus allowing evaluation of dynamic tongue movements during swallowing (6). Miniaturized pressure sensors allow a subject to freely move the tongue in the oral cavity. This device has been widely used for clinical assessment of lingual movements and their involvement in swallowing in patients with stroke-induced dysphagia (7) and postoperative head and neck cancers (unpublished observation), and in elderly adults (8).

Gelatinous foods such as jelly are prepared for elderly people or dysphagic patients because these foods do not require powerful jaw movements during reduction and swallowing (9). Although these gelatinous foods may be more easily ingested, thus increasing compliance, it remains unclear how they are manipulated, propelled from the mouth to the oropharynx, and swallowed. We

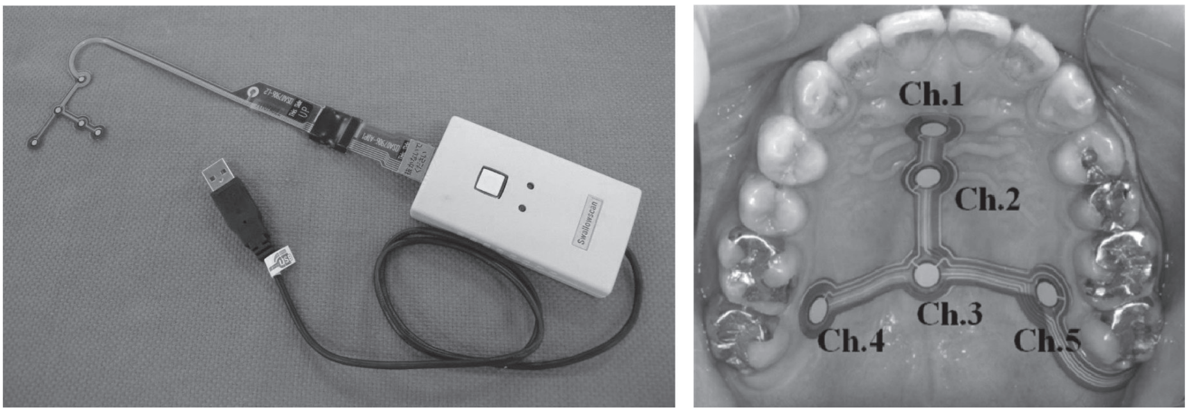

Fig. 1 Photograph of the Swallow scan system (left) and locations of palate sensors (right).

evaluated the effects of the texture and volume of gelatinous foods on ingestive behavior, specifically squeezing and swallowing movements between the tongue and palate, by measuring tongue pressure against the palate. We hypothesized that (1) when the hardness of a bolus increases, the effort required for squeezing and swallowing also increases in relation to the magnitude of the tongue pressure produced and (2) increasing bolus volume does not increase swallow-related tongue pressure but does increase squeeze-related tongue pressure, because increased volume leads to a compensatory increase in the number of swallows in one trial.

Materials and Methods

Participants

Eight healthy men participated in the study. Subject age ranged from 24-42 yrs (average ± SD, 28 ± 3 yrs). Informed consent was obtained from all participants. No subject had any history of pulmonary disease, neurological disease, structural disorders, speech disorders, or voice problems. They also had no abnormalities in the number or position of teeth, no history of orthodontic treatment or temporomandibular disorders, and no abnormalities in occlusion. The experiments were approved by the Ethics Committee of the Niigata University Faculty of Dentistry (21-R4-09-03, 2009).

Test foods and liquid

Jelly samples made of a mixture of gellan gum and psyllium seed gum (San Support G-1014; San-Ei Gen F.F.I., Inc., Osaka, Japan) at concentrations of 1% (soft), 1.8% (medium), and 2.8% (hard) were prepared, as were samples of distilled water (liquid). The samples comprised 1-, 3-, 5-, and 10-mL boluses and were colored green (0.01% of artificial colorant); thus, 16 distinct materials were prepared.

For the soft, medium, and hard jellies, the hardness values were 1,618, 5,738, and 12,317 N/m^2, respectively, and the adhesion values were 44, 112, and 192 J/m^3, respectively. Cohesion values were 0.32, 0.32, and 0.38 for soft, medium, and hard jellies, respectively. All jelly samples were maintained at 4℃ in a styrene foam box before the recordings, to minimize sensory thermal effects on swallowing function.

Data recordings

A tactile sensor system was used to measure pressure distribution by means of a 0.1-mm-thick sensor sheet (Swallow scan; Nitta, Osaka, Japan) (Fig. 1) that recorded positive tongue pressure at five points (channels 1-5) between the tongue surface and hard palate (6). The sensor for the anteromedial region (channel 1) was set at a point 5 mm posterior to the incisive papilla, that of the posteromedial region (channel 3) at a point one-third posterior between the incisive papillae and posterior edge of the hard palate, and that of the midmedial region (channel 2) at a point between channels 1 and 3. Two other sensors (channels 4 and 5) were positioned in the posterolateral regions of the hard palate. The signals from these sensors exited the oral cavity posterior to the most posterior molar tooth on the left side.

Simultaneously, to identify the swallowing event, videoendoscopic (VE) images were collected throughout the recordings. The endoscope was inserted through the nose by the usual method and set as steady as possible in a position that allowed observation of the base of the tongue and pharyngeal region as well as the bolus head over the pillars of the fauces (Fig. 2).

Data collection and analysis

Subjects were asked to sit on a chair with their head free but, as much as possible, vertical to the Frankfort plane. After the food or liquid was inserted into the mouth by the researcher, the subject was asked to retain it on the floor

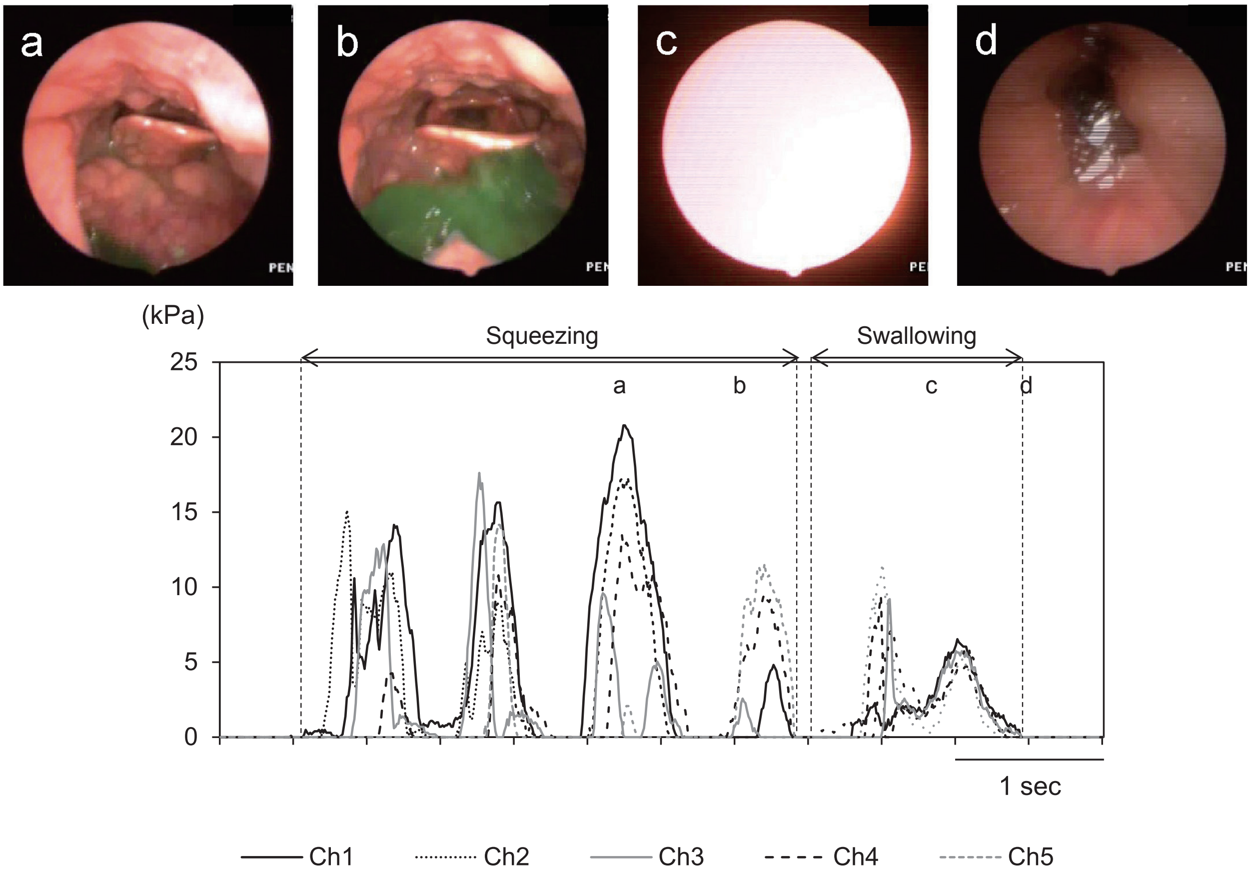

Fig. 2 Example of matched recordings of tongue pressure waveforms and videoendoscopic (VE) images.
Waveforms show tongue pressures recorded during the ingestion of 10 mL of hard jelly. Lower case letters represent events detected by VE recordings shown at the top: a, start of pharyngeal propulsion; b, arrival at epiglottic vallecula; c, onset of whiteout; d, end of whiteout.

of his mouth and then swallow it on cue. The subject was instructed to squeeze and swallow the jelly foods with the tongue against the palate, without biting, between the upper and lower teeth. Two data sets were collected for each material so that the total number of trials was 32 for each subject. The order of trials was randomized. Tongue pressure signals were converted by an AD convertor (Swallow scan; Nitta) at a 100-Hz sampling rate and stored and analyzed on a personal computer.

VE images were passed through an interface board (PowerLab; ADInstruments, Colorado Springs, CO, USA) at a 30-Hz sampling rate and stored on another personal computer. Data analyses of tongue pressure waveforms and VE images were then performed using the PowerLab software package (Chart 5 for Windows; ADInstruments).

First, the total number of swallows in one trial was counted from VE recordings. Data analysis was then performed using tongue pressure data from the start of ingestion (squeezing) to the end of the first swallow. One squeezing action was defined as a concurrent single-peaked wave in all channels, and swallowing was defined as the period of whiteout on VE images (Fig. 2). The number of squeezing actions until the first swallow was counted, and the integrated magnitude (area) of tongue pressure during squeezing and swallowing was measured separately.

Finally, we used the recordings of tongue pressure and VE images to determine the location of the bolus head at the beginning of pharyngeal swallow, i.e., the start of whiteout in VE images. The location was classified as the oral cavity, the mid-pharynx (until the level of the epiglottic vallecula), or the hypo-pharynx (at the level of the pyriform sinus) (Fig. 2).

Statistical analysis

The differences in 1) the number of swallows during an entire sequence, 2) the number of squeezing actions until the first swallow, and 3) the area of tongue pressure during both squeezing and swallowing among the different gel consistencies and volumes were examined using two-way ANOVA and the Tukey post-hoc test.

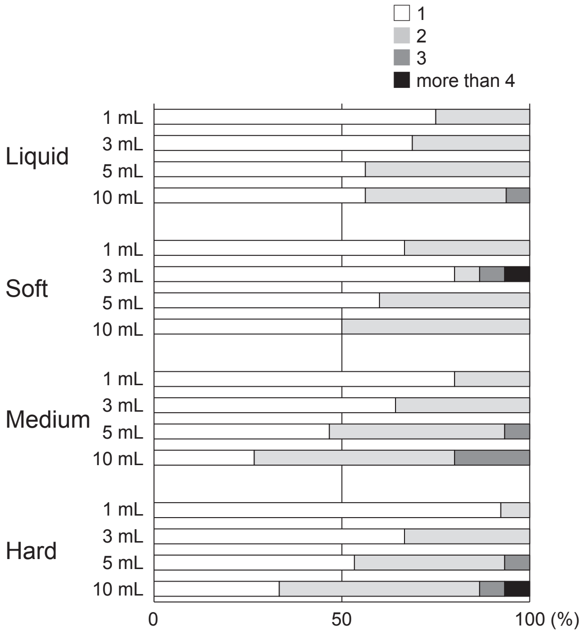

Fig. 3 Number of swallows in one trial.
The data are shown as proportions. The number of swallows for 5-mL samples was significantly larger than that for 1-mL samples, and the number of swallows for 10-mL samples was significantly larger than that for 1- and 3-mL samples ($P < 0.05$, annotations not shown).

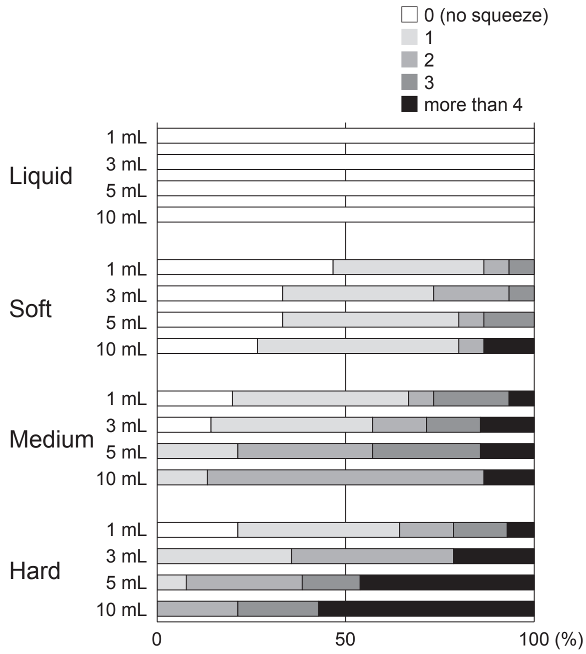

Fig. 4 Number of squeezing actions in one trial.
The data are shown as proportions. There was a significant difference in the number of squeezing actions for liquid vs jelly, soft vs medium jelly, and soft vs hard jelly ($P < 0.05$, not annotated on the chart). The number of compressions required for 1-mL samples was significantly less than that required for 5- and 10-mL samples ($P < 0.05$, annotations not shown).

Differences in the location of the bolus head at the onset of pharyngeal swallowing among the different gel consistencies and volumes were examined in the same manner. In this statistical procedure, the oral cavity, mid-pharynx, and hypo-pharynx were scored as 0, 1, and 2, respectively. Because squeezing could affect bolus propulsion into the pharynx, the relationship between bolus location at the beginning of pharyngeal swallowing and the number of squeezing motions was examined using regression analysis. In the present study, tongue pressures were not compared between channels. The statistical software SPSS 16.0J for Windows (SPSS Japan, Tokyo, Japan) was used for the statistical analysis. Statistical significance was defined as a P value of <0.05.

Results

General characteristics of squeezing and swallowing

Figure 3 shows the number of swallows in all conditions. The mean (± SD) number of swallows for liquid was 1.25 ± 0.45, 1.31 ± 0.48, 1.56 ± 0.63, and 1.50 ± 0.63 for 1-, 3-, 5- and 10-mL boluses, respectively. The mean (± SD) number of swallows was 1.33 ± 0.49, 1.40 ± 0.91, 1.40 ± 0.51, and 1.50 ± 0.52 for soft jelly, 1.20 ± 0.41, 1.36 ± 0.50, 1.60 ± 0.63, and 1.93 ± 0.70 for medium jelly, and 1.14 ± 0.36, 1.33 ± 0.49, 1.53 ± 0.64, and 1.79 ± 0.80 for hard jelly, respectively ($n = 16$). As expected, the number increased with increasing bolus volume ($P < 0.05$): the number of swallows for 5-mL samples was significantly larger than that for 1-mL samples, and the number of swallows for 10-mL samples was significantly larger than that for 1- and 3-mL samples. In contrast, gel consistency was not significantly associated with total number of swallows.

Each squeeze-related waveform was clearly identified and was independent of other squeezing actions (Fig. 2). Compared with the tongue pressure waveforms for swallowing, those for squeezing ranged widely in amplitude and duration among the actions and channels, and changed irregularly during the process. Although there was also wide variation among subjects (see the following section), intrasubject reproducibility, in terms of number, was high. The number of squeezes was 0 for all volumes of liquid. Swallowing without squeezing was observed in all cases of liquid swallowing and in some cases of jelly swallowing. In this case, tongue pressures occurred by contact with the anteromedial and midmedial regions (channels 1 and 2), then the posterolateral regions (channels 4 and 5), and finally the posteromedial region (channel 3) as previously described (6). The number of squeezes was 0.73 ± 0.88, 1.00 ± 0.93, 1.00 ± 1.00, and

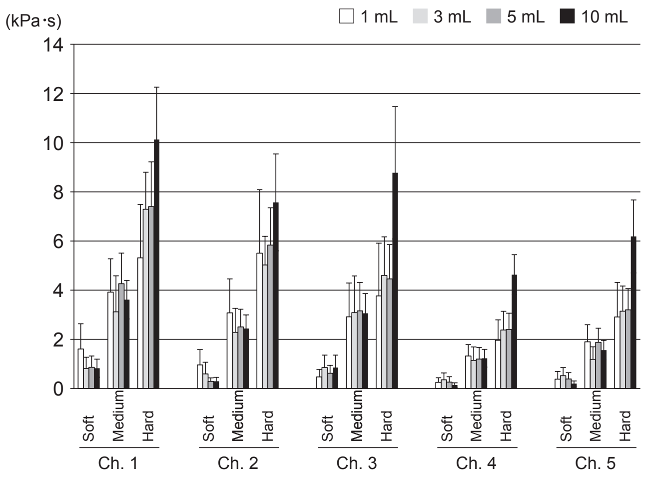

Fig. 5 Mean amplitudes and SDs of areas of tongue pressure during squeezing and swallowing.
The area of tongue pressure during squeezing significantly increased with increasing gel consistency for the same bolus volume at all channels ($P < 0.05$, not annotated). During squeezing of hard jelly, the area significantly increased with increasing volume ($P < 0.05$, not annotated) but was unaffected by other differences in volume.

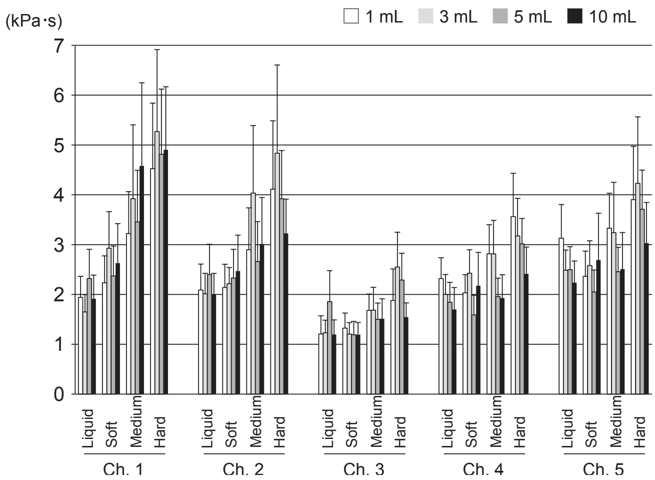

Fig. 6 Mean amplitudes and SDs of areas of tongue pressure during swallowing.
The area significantly increased with increasing gel consistency ($P < 0.05$, not annotated) and with increasing volume at channels 1 and 2 ($P < 0.05$, not annotated). All other differences were not significant.

1.29 ± 1.27 for 1-, 3-, 5-, and 10-mL boluses of soft jelly, 1.47 ± 1.25, 1.93 ± 1.77, 2.60 ± 1.55, and 2.27 ± 1.16 for medium jelly, and 1.50 ± 1.40, 2.33 ± 1.45, 3.64 ± 1.95, and 4.00 ± 2.60 for hard jelly, respectively (mean ± SD, $n = 16$). Number of squeezes was significantly associated with bolus characteristics (Fig. 4). Squeezing was more frequent with harder, more adhesive, and larger boluses. In addition, the number of squeezing actions in one trial increased with increasing volume.

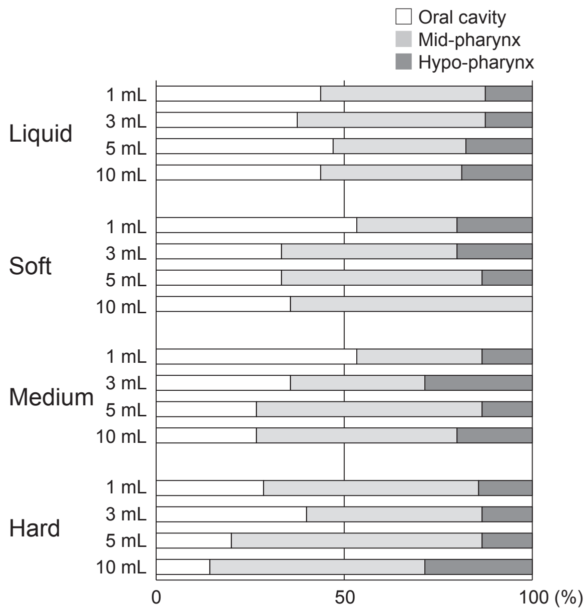

Fig. 7 Location of the leading edge of bolus at onset of pharyngeal swallowing.
There was no significant difference in location in relation to bolus conditions, consistency, or volume.

Tongue pressure during squeezing and swallowing

The area of tongue pressure during squeezing generally increased with increasing gel consistency (Fig. 5). The area increased with increasing volume during squeezing of hard jelly but was unaffected by increasing volume during squeezing of soft and medium jelly. Variation in the area of tongue pressure in relation to bolus conditions and subjects was smaller during swallowing than during squeezing (Fig. 6). The area increased with increasing gel consistency but was not affected by volume, in contrast to our findings regarding squeezing.

Findings from VE recordings

The location of the tip of the bolus at the onset of pharyngeal swallow was first evaluated using VE recordings (Fig. 7). Although there was wide variation among subjects in location at the onset of pharyngeal swallowing, it was not significantly affected by bolus characteristics or volume. Because no significant differences in location were noted in relation to volume, the data for all volumes in each sample were combined for each subject and compared with respect to bolus type and subject (Fig. 8). The location of the bolus head varied widely among subjects. In three subjects (subjects A, B, and G), pharyngeal swallow was evoked when the bolus was located in the oral cavity, regardless of bolus type; otherwise, they were located in the mid- or hypo-pharynx. The relationship between bolus location at onset of pharyngeal swallowing and squeezing motions was evaluated. The data showed that

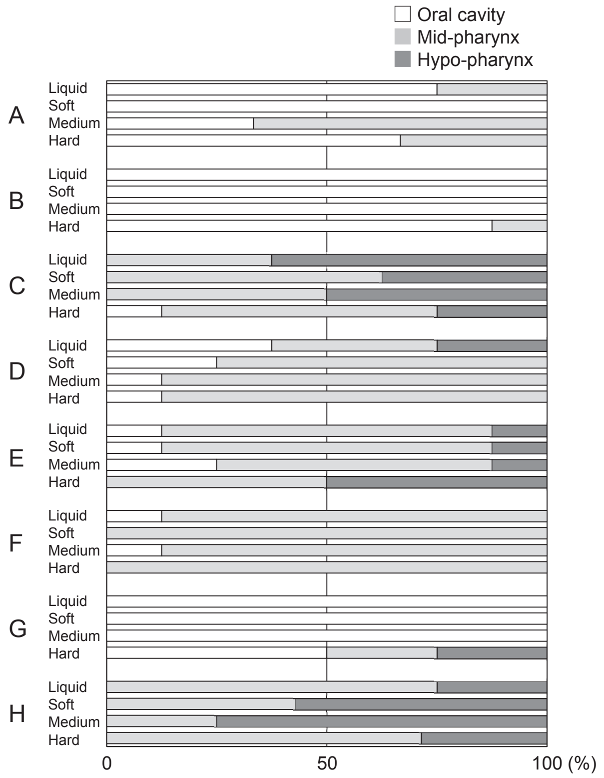

Fig. 8 Location of leading edge of bolus at onset of pharyngeal swallowing in each subject.
There was considerable subject-dependent variation in bolus head location.

it was unlikely that squeezing directly caused the flow of the bolus tip into the pharynx, because there was no significant relationship between the number of squeezing motions and location of the bolus head at the onset of pharyngeal swallowing: the regression line was $y = 0.12x + 0.59$ ($r^2 = 0.10$).

Discussion

All subjects exhibited squeezing actions in certain situations, and the rate increased when gel consistency or volume increased. Squeezing behavior occurred not only to propel the bolus, but also to adjust the physical characteristics of the bolus to prepare it for swallowing, as previously reported (10). This can also be explained by our finding that the number of squeezing actions was not significantly related to propulsion of the bolus into the pharynx. Data from VE recordings suggest that propulsion of the bolus into the pharynx was not significantly related to squeezing movements performed by the tongue. Quantitative analysis of these data was performed, and functional explanations were investigated.

Feeding behavior before first swallow

A previous study found that most food is swallowed in the first swallow of the masticatory sequence and that any residual food is aggregated by the tongue into a bolus and then swallowed in the last swallow. Therefore, the process of bolus formation before the first swallow is likely to be critical. Okada et al. demonstrated that when ingesting food freely humans need at least two swallows, even with one bite of food, although most of the food is swallowed in the first swallow (11). This was confirmed in our previous study (12). In sum, these findings suggest that food processing before the first swallow is essential in completing bolus formation in preparation for swallowing.

Effects of bolus conditions on squeezing behaviors

The number of squeezing actions increased with increasing gel consistency and bolus volume, although values varied widely between subjects. In addition, squeezing did not directly cause flow of the bolus tip into the pharynx. These results suggest that the subjects attempted not only just to swallow but also to reduce the food texture, as described during chewing. It has been extensively reported that reduction of food to facilitate swallowing is affected by bolus characteristics, e.g., food consistency/texture and water content or lubrication (12-15). These studies confirmed the presence of a swallowing threshold, as bolus textures at the time of swallowing were comparable among subjects. This concept may be relevant to the present study, in that people strive to obtain optimal bolus characteristics before swallowing.

The area of tongue pressure increased with increasing gel consistency (in all conditions) and increasing bolus volume (in the case of squeezing of hard jelly). Food consistency strongly affects jaw-closing muscle activity per chewing cycle during food reduction (16,17), and increased food hardness, toughness, or resistance to trituration increases the number of chewing cycles before swallowing (18,19). The bolus volume in one bite was found to have similar effects on chewing behaviors, as most parameters—including the jaw-closing muscle activity (20,21) and duration (19)—increased with bolus volume. Blissett et al. reported that changes in the physical properties of boluses, rather than changes in the bolus volume during chewing, had significant effects on tongue movement (22). Bolus characteristics had similar effects on muscle behaviors responsible for food reduction during both chewing and squeezing, although it is not known if neuronal mechanisms for adaptation of tongue muscle activity are involved in tongue pressure or whether cyclic tongue movements are regulated by the same central pattern generator (CPG) as the chewing

CPG, the output of which is modified by sensory inputs from the oral and pharyngeal cavities (16,23).

Tongue pressure did not significantly increase with increasing bolus volume, particularly during squeezing of soft and medium jelly, possibly because differences in bolus consistency and volume were not large enough to change tongue activity under these conditions, although we lack direct evidence of this. The squeeze-related motor action involved in tongue and hyoid movement may be unaffected by sensory inputs within a certain range.

Effects of bolus characteristics on tongue pressure during swallowing

Our results clearly show that bolus characteristics (e.g., gel consistency) affected tongue pressure. Studies have confirmed that hard foods prolong oral transit time (24,25) and decrease the velocity of lingual and pharyngeal peristalses (24) during swallowing. It was also reported that oral pressure produced by the tongue against the palate was greater at heavier consistencies (26-28), which was consistent with our findings regarding the effect of bolus characteristics on tongue pressure during swallowing.

Why is the area of tongue pressure unaffected by bolus volume? Previous studies of the effects of bolus volume on tongue pressure during swallowing also emphasized that bolus volume affected neither peak amplitude nor duration of tongue pressure (29,30), perhaps because the total number of swallows increased with increasing volume and with the number of squeezes until first swallow.

In this regard, we found no relationship between number of swallows and area of tongue pressure in any individual (data not shown). Honma et al. measured hyoid movement during natural mastication in humans and identified two types of swallows: interposed and terminal (31). In the present study, although we noted differences in the size of the bolus passing through the pharyngoesophageal junction, there was no difference between the two swallows in hyoid movement on the vertical or horizontal plane. This suggests that the swallow-related motor action involved in tongue and hyoid movement is centrally programmed and is unaffected by bolus volume under the current conditions or by squeeze-related characteristics. In addition, each subject may have his own optimal volume of swallowing and thus divides boluses into several smaller pieces for swallowing, so as to avoid excessive tongue pressure in an attempt to swallow the whole bolus.

We investigated patterns of tongue pressure against the palate during ingestion of liquid and jelly in healthy humans. Depending on bolus conditions, squeezing behaviors were observed in some cases of jelly ingestion. The number of squeezes generally increased with increasing gel consistency and volume. The integrated magnitude of tongue pressure during squeezing increased with increasing gel consistency. Bolus propulsion into the pharynx was affected by bolus characteristics, but location of the bolus head at the onset of pharyngeal swallowing was not related to squeezing behavior. During swallowing, the magnitude of tongue pressure moderately increased with increasing gel consistency, as compared with squeezing, and was not associated with bolus volume. Like chewing, squeezing aids in swallowing the bolus during ingestion and reducing food texture. The current results suggest that patterns of tongue pressure during squeezing and swallowing are differentially affected by bolus conditions. However, healthy subjects differ in the techniques used for squeezing and swallowing.

Acknowledgments

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