Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing

Hiroshige Taniguchi,1 Tetsu Tsukada,1 Sachiko Ootaki,2 Yoshiaki Yamada,3 and Makoto Inoue1

Divisions of 1Dysphagia Rehabilitation and 3Oral Physiology, Niigata University Graduate School of Medical and Dental Sciences, and 2Unit of Dysphagia Rehabilitation, Niigata University Medical and Dental Hospital, Niigata, Japan

Submitted 3 April 2008; accepted in final form 9 June 2008

Taniguchi H, Tsukada T, Ootaki S, Yamada Y, Inoue M. Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing. J Appl Physiol 105: 791–799, 2008. First published June 12, 2008; doi:10.1152/japplphysiol.90485.2008.—This study aimed to evaluate the effects of food texture and viscosity on the swallowing function by measuring tongue pressure and performing a videofluorographic (VF) examination. Eleven normal adults were recruited for this study. Test foods with different consistencies and liquid contents, i.e., a half-solid nutrient made of 0.8 and 1.5% agar powder, syrup, and a liquid containing 40 wt/vol% barium sulfate, were swallowed, and the anterior (AT) and posterior tongue pressures (PT) and electromyographic (EMG) activity of the suprahyoid muscles were recorded, together with VF images. The timing of each event obtained from EMG, tongue pressure, and VF recordings was measured and then compared. We found that the AT and PT activity patterns were similar and showed a single peak. The peak, area, and time duration of all of the variables for AT and PT and EMG burst increased with increasing hardness of the bolus. The onset of the EMG burst always preceded those of the AT and PT activities, while there were no significant differences in peak and offset times among EMG burst, AT, and PT. Total swallowing time and oral ejection time were significantly longer during the swallowing of 1.5% agar than any other boluses, while pharyngeal transit time and clearance time were significantly longer during the swallowing of syrup, which was as hard as the liquid, but showed a higher viscosity than the liquid. The results suggested that the major effects of food hardness were to delay oral ejection time, which strongly delays total swallowing time. In addition, pharyngeal bolus transit is not dependent on the hardness of food but on its viscosity.

food hardness; food viscosity; videofluorography

THE SWALLOWING REFLEX IS ONE of the most complicated mechanisms in which the systematic actions of several structures, including the jaw, teeth, tongue, pharynx, and larynx, are all recruited within 1 s. Furthermore, the basic patterns of swallowing are fine-tuned in response to both peripheral feedback and centralafferent inputs associated with variations in bolus volume, consistency, and taste (13, 23). Numerous kinesiological and electromyographic (EMG) studies have focused on the effects of bolus consistency on the coordinated variables of swallowing (8, 17, 31, 33, 36) and suggested that the major effects of a high bolus viscosity were to delay the oral and pharyngeal bolus transit times, increase the duration of pharyngeal peristalsis-like waves, and prolong and increase the upper esophageal sphincter (UES) opening. Dantas et al. (8) recorded EMG activity in the submental and infrahyoid muscles, performed manometry and videofluorography (VF) during swallowing, and found that a paste bolus yielded a greater duration and amplitude of muscle activities than those for a liquid, and the onset of the infrahyoid EMG activity was earlier when swallowing a liquid than a paste bolus. On the other hand, bolus volume affected the timing of each swallowing event; i.e., an increase in bolus volume led to an earlier onset of tongue, palatal, laryngeal, and UES movements. All of these results demonstrated that both the bolus volume and consistency affected the oropharyngeal swallowing function but in different ways. Reimers-Neils et al. (31) investigated the effects of food consistency on EMG activity in the supra- and infrahyoid muscles during swallowing of thick and thin pastes and liquid and found that liquid and thin pastes failed to significantly affect any EMG measurements, although the total duration and amplitude of EMG activity increased from liquid and thin paste to thick paste. Butler et al. (3) also reported that neither changes in bolus consistency nor changes in taste affected swallowing apnea duration. It seems that these conflicting results may be caused by the different experimental conditions used.

The human tongue participates in several orolingual motor functions, including chewing, sucking, swallowing, respiration, and speech. During swallowing, the tongue plays a critical role in collecting and transporting the food bolus from the oral cavity into the pharynx (28, 29, 38). The structural characteristics of the tongue allow it to perform a wide range of movements to seal the bolus content anteriorly and laterally and generate pressure for the posterior propulsion of the bolus (5, 14, 24, 26). Previous studies have assessed tongue pressure during swallowing in humans, but the assessments were somewhat subjective in nature, although they were performed under conditions where the experts, such as speech pathologists, were involved in the judgment of the results (9, 20, 32). Recently, some devices have been introduced to measure tongue function objectively during swallowing (6, 15, 16, 27, 36, 41). However, some of these methods have limitations for quantitatively measuring tongue-palate contact function. For example, dynamic palatography can effectively show temporary changes in tongue contact position but cannot measure the amplitude of tongue pressure (6). It also seems unsuitable to use a pressure sensor consisting of an air-filled bulb attached to a pressure

Address for reprint requests and other correspondence: Makoto. Inoue, Div. of Dysphagia Rehabilitation, Niigata Univ. Graduate School of Medical and Dental Sciences, 2-5274 Gakkokocho-dori, Chuo-ku, Niigata 951-8514, Japan (e-mail: inoue@dent.niigata-u.ac.jp).

http://www.jap.org 8750-7587/08 $8.00 Copyright © 2008 the American Physiological Society
transducer during bolus swallowing (16, 41). Recently, a new technique that allows the accurate measurement of tongue pressure during swallowing using an introral appliance with multichannel pressure sensors has been reported (15, 27). However, details of the movement of the tongue surface during swallowing of foods with different consistencies and demonstrated that bolus consistency affected the tongue pressure of the anterior and posterior portions against the hard palate in different ways. The authors showed that there were significant differences and wide variations in the peak amplitude and area of the posterior tongue pressure (PT) that were larger for a thick paste compared with liquids and thin and medium pastes. It took a significantly longer anterior tongue pressure (AT) to swallow a thick paste compared with a liquid or a thin paste, while there was no difference in peak amplitude and area among these different foods.

It seems better to record the generation and modulation of the pattern of the tongue pressure than recording EMG activity to observe the direct bolus transport in the oral cavity during swallowing. So far, there has been no report of the simultaneous recording of tongue pressure and VF images to evaluate whether the time for the passage of the bolus, which was determined by VF recordings, essentially coincided with the EMG activity of the suprahyoid muscles as well as VFs during voluntary swallowing. The data collected were also used to evaluate whether the time for the passage of the bolus, which was determined by VF recordings, essentially coincided with those of any variables obtained from EMGs and/or tongue pressures.

**MATERIALS AND METHODS**

**Participants.** Eleven normal adults (5 men and 6 women) participated in the study. Subject age ranged from 21 to 40 yr (average ± SD, 30 ± 2 yr). Informed consent was obtained from all participants, and no subject had a history of pulmonary disease, neurological disease, structural disorders, speech disorders, voice problems, and masticating and swallowing problems. The experiments were approved by the Ethics Committee of the Niigata University Faculty of Dentistry.

**Test foods.** Test foods with different texture, viscosity, and liquid contents were prepared. They consisted of 5-ml boluses of a half-solid nutrient, which was made of agar powder (low-gel strength agar, Ina Food Industry, Nagano, Japan) at different concentrations using 0.8% (thin paste) and 1.5% (thick paste), a syrup (Blueberry syrup, Knott’s), and 5-ml water (liquid). These materials were all mixed with barium sulfate (40 wt/vol% solution).

The hardness, adhesiveness, and cohesiveness of the foods were measured as physical properties using a creep meter (RE2-3305, Yamaden, Tokyo, Japan) (Table 1). The specimens, on the table, were elevated toward a polyacetal plunger (diameter, 20 mm; height, 15 mm) at a speed of 10 mm/s, and the plunger was connected to a loading cell. Stress values were obtained through the loading cell, and data analysis was performed using an analysis software package (Creep analysis version 2.0, Yamaden, Tokyo, Japan). Yield stresses were 22, 28, 181, and 894 Pa, and adhesions were 1.9, 6.0, 28, and 95 J/m³ for the liquid, syrup, and thin and thick pastes, respectively. The order of these two values was thick paste > thin paste > syrup > liquid. Cohesions were 0.7, 0.2, 0.4, and 0.4 for the liquid, syrup, and thin and thick pastes, respectively. The viscosities of the syrup and liquid were measured using a viscometer (TV-22, Toki Industry) (Table 1). The specimens were set on the table, and the loading cell rotated at a speed of 50 rpm. They were 3 and 828 mPa/s for the liquid and syrup, respectively.

The test foods were placed in a 10-ml syringe, which had its tip cut off, and were maintained at 13–15°C in a styrene foam box before recordings to minimize sensory thermal effects on the swallowing function.

**Data collection.** Subjects were asked to sit on a chair with their head vertical to the Frankfort plane. After the food was inserted into the mouth by the experimenter, the subject kept it on the floor of the mouth, and then swallowed it with a cue in a single swallow [dipper-type swallow (7)]. Because each subject was asked to perform eight repetitions of swallowing foods of different consistencies, i.e., swallow- ing of the liquid and syrup, 0.8% and 1.5% agar, as instructed during the recording period, two data sets were collected from the same material in one subject. However, for the analysis of the recordings of EMG and tongue pressure, one of the two data sets was used, which was randomly selected. Before the recordings, the subject was trained to complete the tasks. The order of task completion was randomized within one participant.

The procedures to measure the tongue pressure against the hard palate have been reported in a previous study (36). In brief, two pressures at both the AT and PT portions were measured by a midline disk-shaped pressure sensor (Flexi Force Sensor model A101-1, Tekscan) (Fig. 1). The position of the sensors was determined according to previous studies (27, 36), because our previous study showed that the peak amplitude and the area of PT were larger for thick paste compared with those for liquid and thin and medium pastes, and the time duration of the AT was significantly longer during swallowing a thick paste compared with those for a liquid and thin paste. One sensor was set 10 mm posterior to the incisive papilla for AT, and the other one was set at one-third of the distance between the incisive papilla and the posterior edge of the hard palate for PT, which were fixed using ethyl cyanoacrylate (super glue). These sensors had long cables covered by a vinyl tube, which exited the oral cavity via the oral vestibule at the incisor portion. Since the vinyl tube was thin and long, no subject reported that the sensor unit interfered with their jaw, tongue, or lip movements during swallowing.

Pairs of surface electrodes with a diameter of 8 mm (NT-211u or NT-212u, Nihon Kohden) were used for EMG recordings of the left and right anterior and posterior portions of the tongue. To detect the laryngeal movements during swallowing, a pulse transducer (MLT1010, ADInstruments, Colorado Springs, CO) was employed, which was placed between the cricoid and thyroid cartilages at the midline. A reference electrode was affixed to the earlobe. To detect the laryngeal movements during swallowing, a pulse transducer (MLT1010, ADInstruments, Colorado Springs, CO) was employed, which was placed between the cricoid and thyroid cartilages at the midline. A reference electrode was affixed to the earlobe.

<table>
<thead>
<tr>
<th>Table 1. Texture characteristics of test food</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress, Pa</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Liquid</td>
</tr>
<tr>
<td>Syrup</td>
</tr>
<tr>
<td>0.5% Agar</td>
</tr>
<tr>
<td>1.0% Agar</td>
</tr>
</tbody>
</table>

The signals from the EMG electrodes and tongue sensors were amplified (Dual Bio Amp, ADInstruments for EMGs, and a laboratory-made amplifier for pressure sensors), and stored on a personal computer. The sampling rate was 10 kHz, and the signals were passed through an interface board (PowerLab, ADInstruments). Data analysis was performed using the PowerLab software package (Chart 5 for windows, ADInstruments).
The oral and pharyngeal organs of the subjects and bolus transport were observed using VF equipment (MULTISKOP, Siemens, Munich, Germany) installed at the Niigata University Medical and Dental Hospital. VF images were obtained in the sagittal plane at a speed of 25 frames/s. The total exposure to radiation per session was estimated to be 89.77 mGy and was limited to a maximum of 2 min per subject. The data were then converted and stored on a computer through a video recorder (Handy cam, Sony, Tokyo, Japan).

**Data analysis.** The EMG bursts were full-wave rectified and smoothed (time constant, 20 ms). In a single burst, the times of onset, peak, and offset, as well as the burst time duration, peak amplitude, and burst area of the filtered EMGs, were obtained. The same variables were also obtained for AT and PT activities. In the present study, the onset time was referred to as the time of onset in the EMG burst, according to previous reports that investigated the effects of food condition on EMG activity related to the swallowing event, and in which the start of the swallowing event was defined as the appearance of the suprahyoid muscle burst (19, 31).

The video recordings were analyzed using a single-frame analysis. The times of each event were determined by directly reading the digital clock on each video frame. Using this method, the times of each event were determined by directly reading the video recorder (Handy cam, Sony, Tokyo, Japan).

The video recordings were analyzed using a single-frame analysis. The times of each event were determined by directly reading the digital clock on each video frame. Using this method, the times of each event were determined by directly reading the video recorder (Handy cam, Sony, Tokyo, Japan).

The oral and pharyngeal organs of the subjects and bolus transport were observed using VF equipment (MULTISKOP, Siemens, Munich, Germany) installed at the Niigata University Medical and Dental Hospital. VF images were obtained in the sagittal plane at a speed of 25 frames/s. The total exposure to radiation per session was estimated to be 89.77 mGy and was limited to a maximum of 2 min per subject. The data were then converted and stored on a computer through a video recorder (Handy cam, Sony, Tokyo, Japan).

**Data analysis.** The EMG bursts were full-wave rectified and smoothed (time constant, 20 ms). In a single burst, the times of onset, peak, and offset, as well as the burst time duration, peak amplitude, and burst area of the filtered EMGs, were obtained. The same variables were also obtained for AT and PT activities. In the present study, the onset time was referred to as the time of onset in the EMG burst, according to previous reports that investigated the effects of food condition on EMG activity related to the swallowing event, and in which the start of the swallowing event was defined as the appearance of the suprahyoid muscle burst (19, 31).

The video recordings were analyzed using a single-frame analysis. The times of each event were determined by directly reading the digital clock on each video frame. Using this method, the times of each event were determined by directly reading the video recorder (Handy cam, Sony, Tokyo, Japan).

The oral and pharyngeal organs of the subjects and bolus transport were observed using VF equipment (MULTISKOP, Siemens, Munich, Germany) installed at the Niigata University Medical and Dental Hospital. VF images were obtained in the sagittal plane at a speed of 25 frames/s. The total exposure to radiation per session was estimated to be 89.77 mGy and was limited to a maximum of 2 min per subject. The data were then converted and stored on a computer through a video recorder (Handy cam, Sony, Tokyo, Japan).

**Fig. 1. Sensor positions.** Although the subject could not close her jaw completely because the sensors for measuring tongue pressure exited the oral cavity via the oral vestibule at the incisor portion, the strip with the sensor was so light and thin that it did not interfere with the jaw, lip, and tongue movements and swallowing.

**Fig. 2.** Swallowing sequence and bolus transport determined by videofluorography. Although the onset time of swallowing was set at zero when the electromyographic (EMG) burst of the suprahyoid muscles started, the tip of the tongue touched the palate at a different time from the onset of swallowing (A), which is followed by the bolus movement. The bolus head reaches the fauces (B). The bolus head reaches the upper esophageal sphincter (UES) (C), and the bolus tail passes the fauces (D). At last, the bolus tail passes the UES (E). Total swallowing time (a), oral ejection time (b), pharyngeal transit time (c), clearance time (d), fauces transit time (e), and UES transit time (f) are also indicated.
RESULTS

Basic patterns of the EMG burst and tongue pressure. In the present study, we examined the effects of food consistency on swallowing function, EMG activity in the suprahypoid muscles, tongue pressure against the hard palate (AT and PT), and bolus transport from the oral cavity into the esophagus through the pharyngeal cavity in healthy, adult humans. As shown in Fig. 3, recorded voluntary swallowing was characterized by an EMG burst and peristaltic waves during AT and PT activities. The small and static EMG burst at the beginning of swallowing increased in amplitude and then reached a peak. The AT and PT activity patterns were similar: they showed a single peak, and the AT burst tended to precede the PT one (Table 2). A small movement of the larynx occurred coinciding with swallowing.

Amplitudes of the EMG burst and tongue pressure. Because the individual peak amplitude and area and durations of the EMG burst and AT and PT activities showed a wide variation among subjects, they were initially normalized to the one during liquid swallowing, as mentioned in MATERIALS AND METHODS. There were no significant differences between men and women for all variables (Mann-Whitney rank sum test, \( P = 0.7-0.9 \)). Based on this, data from men and women were pooled for the subsequent statistical analysis and compared for the different foods (Fig. 4). All variables tended to increase from liquid to syrup and thin and thick pastes, suggesting that the hardness of foods affected the activity patterns of the suprahypoid and tongue muscles. The peak amplitudes of the EMG burst were 98 ± 5, 115 ± 45, and 165 ± 54% for syrup and thin and thick pastes, respectively. Those of AT activity were 134 ± 70, 189 ± 107, and 454 ± 642%; and those of PT were 178 ± 50, 160 ± 145, and 366 ± 391% for syrup and thin and thick pastes, respectively. Remarkable differences in the peak amplitude were noted in all of the channels, mainly between liquid and thick paste. The areas of the EMG burst were 99 ± 11, 164 ± 54, and 222 ± 178% for syrup and thin and thick pastes, respectively. Those of AT were 141 ± 64, 568 ± 1,001, and 961 ± 1,430%, and those of PT were 157 ± 89, 467 ± 967, and 1,008 ± 890% for syrup and thin and thick pastes, respectively. The areas also exhibited similar changing patterns, but only the AT pattern showed significant differences between liquid and thick paste. The durations of the EMG burst were 99 ± 20, 153 ± 34, and 208 ± 176% for syrup and thin and thick pastes, respectively. Those of AT activity were 146 ± 62, 300 ± 387, and 324 ± 388%; and those of PT activity were 99 ± 33, 224 ± 351, and 449 ± 544% for syrup and thin and thick pastes, respectively. The harder the food texture, the longer the durations of AT and PT activities. Some parameters of AT and PT activities showed significant differences but not for the EMG burst. When the coefficient of variation (CV) was compared among the parameters, the CV of the AT or PT activities was always larger than that of the EMG burst, and those during the swallowing of thin and thick pastes were much larger than that of syrup (Fig. 4).

Time courses and durations of the EMG burst and tongue pressure. The onset, peak, and offset times of each activity relative to the onset time of the EMG burst were measured (Table 2 and Fig. 5). The order of appearance in one swallowing sequence was first compared. The onset times of the AT and PT activities were significantly delayed compared with that of the EMG burst (not shown in Table 2). However, the AT and PT activity patterns were similar, but there was a significant difference in the onset time between the AT and PT activities during the swallowing of thin and thick pastes. On the other hand, no differences in peak and offset time were noted among the different boluses.

When the same parameters were compared for different foods, the timing of occurrence tended to be delayed with increasing hardness of food. Particularly, there were significant differences in the peak time of PT activity and offset times of the EMG burst and AT and PT activities between the liquid and thick paste.

VF recordings. The results obtained by VF recordings indicated that the timing of bolus transport from the oral cavity to the esophagus through the pharyngeal cavity should be considered in reference to food consistency (Fig. 6). Total swallowing times were 1.12 ± 0.22, 1.19 ± 0.41, 1.72 ± 0.50, and 2.44 ± 1.02 s for the liquid, syrup, and thin and thick pastes,
Time course of swallow-related activity

<table>
<thead>
<tr>
<th></th>
<th>EMG</th>
<th>AT</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>Peak: 0.69±0.32, Offset: 1.37±0.40</td>
<td>Onset: 0.60±0.62, Peak: 0.95±0.77, Offset: 1.37±0.84</td>
<td>Onset: 1.03±0.51, Peak: 1.18±0.53, Offset: 1.45±0.65</td>
</tr>
<tr>
<td>Syrup</td>
<td>Peak: 0.65±0.40, Offset: 1.32±0.35</td>
<td>Onset: 0.80±0.72, Peak: 1.17±0.64, Offset: 1.76±0.67</td>
<td>Onset: 1.27±0.62, Peak: 1.56±0.66, Offset: 1.83±0.75</td>
</tr>
<tr>
<td>Thin paste</td>
<td>Peak: 1.28±0.60, Offset: 2.07±0.59</td>
<td>Onset: 1.14±0.97, Peak: 1.62±0.94, Offset: 2.24±1.08</td>
<td>Onset: 1.76±0.94, Peak: 2.05±0.91, Offset: 2.59±1.15</td>
</tr>
<tr>
<td>Thick paste</td>
<td>Peak: 1.05±1.01, Offset: 2.50±1.25</td>
<td>Onset: 1.10±0.91, Peak: 2.32±1.75, Offset: 3.03±1.84</td>
<td>Onset: 2.24±1.42, Peak: 2.72±1.53, Offset: 3.17±1.75</td>
</tr>
</tbody>
</table>

Values are means ± SD in seconds. EMG, electromyography; AT, anterior tongue pressure; PT, posterior tongue pressure. Reference time was determined at zero when the EMG burst started. Among the time events: significant difference vs. AT onset, AT peak, AT offset, PT onset, PT peak, PT offset: P < 0.05. *Significant difference among the boluses, P < 0.05.

regression analyses were first performed to determine whether there was a significant linear relationship in time between the variables. Interestingly, the distribution of the values was quite different between the data during swallowing thick paste and other foods (Fig. 7). A significant linear relationship was noted between the offset of the EMG burst and passage of the bolus tail at the UES. The correlation coefficient was much larger, and the slope was near 1.0 in a case without thick paste (r² = 0.77, slope = 0.97) than with thick paste (r² = 0.72, slope = 0.60). This was also the case between the AT peak and passage of the bolus tail at the fauces, and PT peak and passage of the bolus tail at the fauces, which showed small but significant linear relationships. The correlation coefficient and the slope of the relationship between the AT peak and passage of the bolus tail at the fauces for r² = 0.58, slope = 0.74 without thick paste, and r² = 0.65, slope = 0.68 with thick paste. Those between the PT peak and passage of the bolus tail at the fauces were r² = 0.63, slope = 0.79 without thick paste, and r² = 0.64, slope = 0.67 with thick paste. There was no significant correlation between the onset of the EMG burst and tongue tip touching the palate.

The mean time was 2.87 s for the AT peak vs. 2.69 s for the passage of the bolus tail at the fauces (P = 0.27), 3.46 s for the PT peak vs. 2.69 s for the passage of the bolus tail at the fauces (P < 0.001), 1.85 s for the onset of the EMG burst vs. 1.62 s for tongue tip touching the palate (P = 0.72), and 3.74 s for the

respectively. Oral ejection times were 0.80 ± 0.21, 0.77 ± 0.39, 1.44 ± 0.52, and 2.16 ± 1.08 s for the liquid, syrup, and thin and thick pastes, respectively. Swallowing thick paste (or hard food) led to a longer swallowing time, resulting from a longer oral ejection time than with any other boluses. Unique results were also noted for the pharyngeal transit time and clearance time; they were significantly longer when swallowing syrup than any other boluses. Pharyngeal transit times were 0.26 ± 0.10, 0.39 ± 0.11, 0.27 ± 0.09, and 0.27 ± 0.08 s for the liquid, syrup, and thin and thick pastes, respectively. Clearance times were 0.55 ± 0.11, 0.85 ± 0.14, 0.53 ± 0.09, and 0.55 ± 0.22 s for the liquid, syrup, and thin and thick pastes, respectively. There were no significant differences in the fauces transit time and UES transit time among the boluses, although they tended to be longer for the syrup compared with the liquid and thin and thick pastes.

Correlation between physiological and biomechanical events. Previous reports suggested that some passage times of the different types of boluses virtually coincided with the upstroke onsets of biomechanical events (7, 37). In the present study, the timings of the AT peak and passage of the bolus tail at the fauces, peak of PT and passage of the bolus tail at the fauces, and offset of the EMG burst and passage of the bolus tail at the UES were compared with each other, as well as those of the onset of the EMG burst and tongue tip touching the palate (start of voluntary swallowing) (Fig. 7).
offset of the EMG burst vs. 3.13 s for the bolus tail at the UES ($P < 0.001$). Unexpectedly, the $P$ value did not remarkably change after removing all of the values for the thick paste. The mean values were 2.65 s for the AT peak vs. 2.51 s for the passage of the bolus tail at the fauces ($P = 0.27$), 3.13 s for the PT peak vs. 2.51 s for the passage of the bolus tail at the fauces ($P < 0.001$), 1.69 s for the onset of the EMG burst vs. 1.63 s for the tongue tip touching the palate ($P = 0.646$), and 3.25 s for the offset of the EMG burst vs. 2.90 s for the bolus tail at the UES ($P < 0.001$).

**DISCUSSION**

*Effects of food consistency on tongue pressure.* It has been reported that hard foods lead to an elongation of the oral ejection time (1, 8, 17, 31) and a decrease in velocity of lingual and pharyngeal peristalses (2, 8). It was also reported that oral pressure produced by the tongue against the palate increased with heavier consistencies (34, 36). These reports led us to believe that tongue pressure is strongly affected by food consistency, and the activation of tongue pressure required to propel a hard food bolus through the pharynx to the esophagus is of long duration.

In the present study, it was noted that the CV of all values increased with increasing hardness of food. Our results highlighted some differences, suggesting that they resulted from individuals squeezing the bolus between the tongue and palate and transporting it to the pharyngeal region in various ways during swallowing hard foods. When comparing the tongue movements between the tongue blade and body, the latter action seemed to be more dynamic than the former using a VF study (2, 10) and could cause a wide variation in pressure magnitude. Thus swallowing hard foods may require a large amplitude and cause large variations in tongue activity.

However, our present results differ somewhat from some of our previous ones, in that the peak amplitude was dependent on food consistency only for the PT, while the duration was longer during the swallowing of thin paste than for thick paste only for the AT (36). Although the differences were quite small between our two studies, the ease of swallowing would change by both decreasing and increasing the bolus volume compared to hard food.
with the optimal volume of swallowing for each material (25). If the optimal volume is not the same among the subjects, the activity pattern of the muscles can also be modulated under the same experimental conditions.

**Effects of food consistency on suprahyoid muscle activity.** In the present study, there was a significant difference only in the peak amplitude of the EMG burst among the different foods, although all parameters tended to increase with increasing hardness of food. Suprahyoid muscle activity is involved in the entire swallowing sequence; it forms a platform and provides support for tongue movements (7, 35). Previous reports have demonstrated that the swallowing of thick foods causes an increase in the duration of the EMG burst of the swallowing-related muscles (34, 35). Reimers-Neils et al. (31) reported that there were significant differences in the peak and mean EMG activity of the suprahyoid muscles during swallowing between thick pastes and liquids, and between thick and thin pastes. Furthermore, the magnitude of the hyoid movements would be expected to be greater for a hard bolus than other boluses because of the greater activity of the EMG burst, as previously suggested (12). In fact, the amplitude of the upward displacement of the hyoid is dependent on the bolus condition, while that of the forward displacement that follows the upward movement does not differ among conditions. Although we did not trace the trajectories of the hyoid in the present study, differences in food consistency have been large enough to lead to significant differences in the peak amplitude of the EMG burst but not in duration among foods.

Another possible reason for the minor differences may be that suprahyoid EMGs are not a precise measure of the contraction of the floor of the mouth, because the measured amplitude could reflect lingual contribution, as suggested by Leow et al. (19). With previous findings (11) showing that the generation of increased lingual pressure with an increase of duration in the EMG burst during effortful swallowing, it seems likely that surface EMG amplitude could strongly reflect an increased tongue effort during the swallowing of thick boluses. In this regard, Palmer et al. (30) recorded surface EMGs of suprahyoid muscles, as well as five individual muscles, i.e., mylohyoid, anterior belly of the diagastric, geniohyoid, genioglossus, and platysma, during swallowing to investigate the contributions of individual muscles to the surface EMGs. The authors concluded that the contributions of the genioglossus muscle to the electrode were minimal.

**Effects of food consistency on bolus transport.** The VF recordings in the present study revealed interesting findings. The major effect of thick foods was to increase total swallowing time and oral ejection time. On the other hand, viscous foods increase pharyngeal transit time and clearance time. As mentioned above, the former may be because of the decreased velocity of lingual peristalsis to transport the bolus into the pharynx (1, 8, 17). Furthermore, in the present study, the authors realized that some subjects had difficulty keeping a bolus of thick paste in the oral cavity and swallowed it at once, causing difficulty for the initiation of voluntary swallowing. When one starts swallowing a bolus, sensory feedback from

---

Fig. 7. Scatterplots of the time of events obtained by EMG of the suprahyoid muscles (EMG) and pressure of AT and PT, and those determined by videofluorographic recordings. The graphs show the relationship between the AT peak and passage of the bolus tail at the fauces, PT peak and the passage of the bolus tail at the fauces, onset of the EMG burst and the tongue tip touching the palate, and offset of the EMG burst and the passage of the bolus tail at the UES. The time was set at zero when the larynx was hit.
the oral region may be vital enough to modulate the initiation and assistance of a voluntarily evoked oral phase of swallowing.

The delayed transit of a viscous bolus may be associated with increased duration of peristaltic waves of the tongue and pharyngeal muscles, duration of UES opening, and duration of the hyoid movement compared with a thin bolus. These mechanisms may be dependent on one another, because slowing transit would be expected to prolong the duration of peristaltic waves. Although the bolus length was not measured in the present study, that with thick paste may not be long, while that with a viscous bolus may be longer, at least in the pharyngeal cavity. This difference was possibly caused by a viscous bolus (syrup) having less fluidity for flow and so would remain in the pharyngeal cavity longer compared with other foods. As for the agar paste, which showed a shorter pharyngeal transit time compared with that of the syrup, the pharynx distended more with thin and thick pastes than with the syrup; therefore, the bolus length would not be long, although it would be hard to propel the thick bolus in the oral cavity.

Association between physiological events and bolus movements. Previous studies of bolus transport during swallowing have used different measurement methods (18, 39). For example, to examine bolus movement, VF, videodensitographic, manometric, and ultrasound examinations were performed. Recordings of the hyoid or tongue movements on VF images were also used in combination with recordings of EMG activity from related muscles. Some previous methods have used mixed measurement criteria, which were also employed in the present study. For a meaningful assessment of the swallowing function, the most effective and feasible noninvasive method of measurement should be selected.

The results obtained from EMG, tongue pressure (AT and PT activities), and VF recordings in the present study suggested that, under certain conditions, some physiological variables can be good markers to track a bolus during the oropharyngeal phases of swallowing. A significant linear regression was noted between the offset of the EMG burst and the passage of the bolus at the UES. However, this was not the case during the swallowing of thick foods, such as 1.5% agar, suggesting that, when the sensory inputs are over a physiological range, the coordination between the swallowing-related muscle activity and bolus flow cannot be maintained (Table 2). It is also noteworthy that mean values were different between the above groups. Because the basic patterns of tongue pressure and suprskyoid muscle activity were maintained centrally, regardless of the differences in food consistency, it could be speculated that the delay between the offset of the EMG burst and the passage of the bolus at the UES was constant. On the other hand, it was found that the coordination between tongue pressure and the passage of the bolus at the faucies was weak. Indeed, it did not exist between the onset of the EMG burst and the tongue touching the palate. Muscle activity and movements of related organs in the preparatory and oral stages of swallowing are highly variable and involve the various muscles that control the face and mandible and have many receptors (4). Furthermore, at the initiation of swallowing, these muscles may be subject to inputs from higher centers (21, 22, 40). The effects of subjective factors, such as cognition, should also be considered to better understand the underlying neuromechanisms controlling the swallowing function.

ACKNOWLEDGMENTS

The authors thank Hidetoshi Hirano and Dr. Shin-ichiro Sugino for technical assistance.

GRANTS

This study was supported by a Grant-in-Aid for Scientific Research (no. 18209056 to Y. Yamada) from the Ministry of Education, Culture and Science, Japan.

REFERENCES


