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Dynamic Aspects of Lingual Propulsive Activity in Swallowing

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Abstract. This investigation concerned the effect of different bolus volumes on the characteristics of lingual propulsive activity in swallowing. Young normal subjects were asked to perform dry swallows and swallows of 5, 10, and 15 ml of water. Tongue activity was recorded by tracking multiple gold pellets affixed to the tongue, utilizing the specialized research capabilities of the X-ray Microbeam facility at the University of Wisconsin. The major differences were between dry and liquid swallows, with dry swallows showing smaller range of movement, higher tongue position at the initiation of lingual propulsive activity, a slightly different direction of motion, a humped or flat rather than grooved cross-sectional contour of the tongue, lower peak velocity of motion, and slower progression of activity from tongue blade to dorsum. Within the 5–15 ml range of liquid bolus volumes, fewer consistent differences were found as a function of bolus size, and some marked individual differences in swallowing patterns were seen. Data are presented on normal within-subject variability in swallowing, with discussion of the possible contribution of sensory assessment of bolus size to the modification of oral and pharyngeal characteristics of swallowing.

Key words: Tongue – Deglutition – Bolus size

Normal swallowing has some components that are highly stereotypic, presumably brainstem functions, and other components that are quite variable and under voluntary control [1]. Sensory feedback appears to contribute to the characteristics of the oral and pharyngeal phases of swallowing [2], even to aspects considered involuntary. As a result, there is inherent variability from swallow to swallow, and modifications associated with bolus size and consistency.

Genioglossus, geniohyoid, and strap muscle activity is altered during a swallow if the bolus is of a more dense consistency [3, 4]. The velocity of the front face of the bolus as it enters the esophagus has been found to depend on bolus volume, varying from an average of 76.9 mm/s for a 5 ml bolus, to 153.8 mm/s for a 15 ml bolus, to 375 mm/s for a 30 ml bolus [5]. The bolus appeared to be decelerating as it progressed into the esophagus, since velocity calculations were lower based on sensors located slightly more distal [5]. The major forces delivering the bolus into the esophagus come from the propulsive action of the tongue and negative pressures developed in the pharyngoesophageal segment [6]. In normal subjects swallowing 5 ml boluses, an oropharyngeal bolus head velocity of 470 mm/s, and a hypopharyngeal bolus head velocity of 420 mm/s, have been measured [6].

Recent work on swallowing 1–20 ml graded increases in bolus volumes [7–11] has revealed for larger volumes a higher velocity of "oral peristalsis" [8], increases in magnitude of hyoid and laryngeal movement, lengthening of the duration of upper esophageal sphincter relaxation and opening, earlier movement of the larynx, earlier opening of the upper esophageal sphincter, and longer durations of laryngeal closure. Variables found to be independent of bolus volume were force of oral and pharyngeal peristaltic contractions and pharyngeal peristaltic velocity. Tracy and co-workers [7] also found earlier onset of laryngeal elevation with larger bolus volumes (1–20 ml), in addition to longer durations of cricopharyngeal opening

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and laryngeal closure. An interpretation suggested by Dodds [8] is that swallowing depends on a central patterned program that is modulated or reinforced by, but not dependent on, feedback from sensory input. Furthermore, feedback might occur either as an online modification during the swallowing sequence or as a preprogram modification governed by lingual proprioceptors that sense bolus size before the swallow.

Although the neuromuscular component of variations in swallowing characteristics has been considered, the effects of linked biomechanical forces have been given less attention. For example, an increase in magnitude of hyoid and laryngeal movement might be a component of a composite lingual/hyoid gesture, such that higher velocity of tongue motion creates greater hyoid and larynx movement. Such an interdependent composite gesture has been suggested by the observations of close time synchrony of oral peristalsis and hyoid motion in the normal swallow [12, 13].

Commonly used methods of studying swallowing (e.g., videofluoroscopy, manofluorography) are limited in the number of samples of swallows that can be obtained from a given subject, because of x-ray exposure considerations. Other methodologies such as ultrasonic scanning do not pose the radiation hazard, but still suffer from the need for laborious frame-by-frame analysis to obtain quantitative data. Thus observations to date are limited in interpretation, because they are influenced by within-subject variability, yet no good measure of that factor is available. Questions about modification of swallowing characteristics with changes in such factors as bolus size and consistency will need to address how particular subjects perform, for which a substantial number of swallows from a given subject will be needed.

The study reported here was designed to vary bolus volume in normal subjects and to record tongue function during swallowing on enough examples per volume that within-subject statistical analyses were possible. To accomplish this, a newly available research resource was utilized (X-ray Microbeam facility at the University of Wisconsin, Madison). The low radiation dosage and highly automated data collection and analysis capabilities at this facility permitted efficient recording and analysis of a large number of swallows from each subject. The X-ray Microbeam is designed to study tongue surface-point activity, by tracking small pellets affixed to various areas on the tongue. This instrumentation was originally designed for speech studies, but is ideally suited also for work on oral characteristics of swallowing. Previous work on swallowing using pellet tracking has been done with ultrasound [12].

It was hypothesized that subjects would show monotonic increases in several aspects of lingual swallowing behavior as a function of increasing bolus volume. Both spatial and propulsive effects were postulated:

1. The *position* of the tongue at the onset of lingual propulsive activity would differ, to accommodate the different bolus volumes.
2. The *direction* of tongue surface-point motion during lingual propulsive activity would depend on the position at the onset of that activity.
3. Maximum *grooving* of the tongue for the swallow would be greater for larger bolus volumes.

In addition to the above spatially related effects, it was assumed that the propulsive force to deliver the bolus quickly into and through the pharynx would be greater for larger bolus volumes. This assumption lead to the following specific hypotheses:

4. Peak *velocity* of tongue surface-points during lingual propulsive activity would be larger for the larger bolus volumes.
5. The *temporal progression* of activity from tongue blade to tongue dorsum in lingual propulsive activity would be more rapid for the larger bolus volumes.

Procedures

Data on dynamic tongue activity during swallowing were collected and analyzed using the X-ray Microbeam system at the University of Wisconsin, Madison [14]. This facility is a national resource laboratory developed for use by both on-site and off-site researchers.

The X-ray Microbeam instrumentation is designed to produce a narrow beam of x-rays that can track locations of small gold pellets attached to the subject. The pellets are attached to anatomical reference points on the head, and to various surface areas on oral structures such as the tongue or velum whose function is to be studied. A dental adhesive, KetacBond, is used to glue the pellets in place.

The x-ray beam was generated by an electron beam (450 KV, 3 mA) focused on a thin sheet of tungsten. The photons thus produced pass through a small pinhole, so that the x-rays directed at the subject are in a beam less than 1 mm in diameter. The x-ray beam can be directed under computer control to scan within a field approximately 20 × 20 cm, in which the subject's head is located. On the far side of the subject's head a scintillation counter reflects the strength of the received beam: this strength varies according to the nature of the tissue or material to be passed through at different locations within the measurement field. The information on received beam strength, along with the known direction of the beam scan, permits identification of the position of the radiodense gold pellets.

Just prior to data collection, the system scans to locate the pellet array. This is done by locating the centers of the pellet "shadows" (a two-dimensional x-ray count registered by a scintillation counter). Pellet location for any single scan is accurate to 0.5 mm, both for static and dynamic pellet tracking. System testing for calibration and measurement accuracy has used phantoms with known pellet interdistances on a wheel, and rotating trajectories. The dispersion about the mean perceived pellet center (standard deviation) was 150–180 μm in both the x and y dimensions.

After the pellet array is located, the scanning process is concentrated only in the predicted vicinity of the pellets. In this way radiation exposure to the subject is lessened, and the number of times per second the pellet locations can be sampled is increased. These advantages are gained at the cost of some instability in tracking of pellets. If the subject's head does not remain in a relatively stable position or if pellets are too near each other, pellets may be mistracked or "lost." If this happens, data collection is interrupted. Thus there is no interpolation of pellet positions: tracking is either proceeding accurately at the chosen sampling rate or the process is halted. These considerations must be taken into account in planning the data collection procedures. A subject with uncontrollable head movements, such as a neurologically disordered patient, can present problems in initiating tracking.

Sampling rate for the tongue pellets was 120/s. Peak entrance radiation exposure to the subjects was 97–106 mRem within a 0.5 mm^2 area, depending on the exact amount of time the experiment took for a given subject. Although the data collection session lasted an hour or more, the time of X-ray Microbeam operation to collect data on 40 swallows, including calibration and rescanning after mistracking, was actually 3.6–5.2 min. X-ray exposure to subjects was thus much less than for a single bite-wing dental x-ray (500–1000 mRem entrance exposure over 5 cm^2 area).

For this project on swallowing, 3.0 mm diameter reference pellets were used. Two of them were permanent reference pellets affixed to the bridge of the nose and the labial surface of the maxillary incisors at the gum line. These remained in place during recording. Two temporary reference pellets were also glued to the maxillary incisors and the first maxillary molar to demarcate the incisal plane during calibration. They were removed before recording so as not to interfere with tracking of tongue pellets. The subject was positioned as for a lateral view of the head. The reference pellet data were processed to correct for minor head movement during the recording. The axes of the measurement space were determined by the occlusal plane (x axis) and the vertical perpendicular to this passing through the permanent maxillary incisor pellet (y axis). Figure 4, discussed below, includes illustration of these coordinates; all positions and motions of tongue pellets were calculated in reference to this measurement plane.

In addition to the reference pellets, articulatory pellets (2.5 mm diameter) were attached to mobile structures. One was affixed to the mandibular incisors at the gum line. Four pellets were glued to the tongue (Fig. 1). Two were located in the midsagittal plane on the tongue blade (TB) and tongue dorsum (TD), and the other two were placed lateral and forward to each of them; tongue blade lateral (TBL) and tongue dorsum lateral (TDL). The purpose of the lateral pellets was to permit a measure of tongue grooving or humping by comparing the location of corresponding midsagittal and lateral pellets. To track two adjacent pellets successfully with the X-ray Microbeam system, the pellets must remain at least 1 cm apart throughout their trajectories. Thus it was not possible to have the midsagittal and lateral pellets in exactly the same coronal plane, lest they appear (in a lateral projection) to approach and cross each other during grooving and humping of the tongue during swallowing.

Another limitation in comparing positions of midsagittal and off-axis (lateral) pellets is that the error in determining

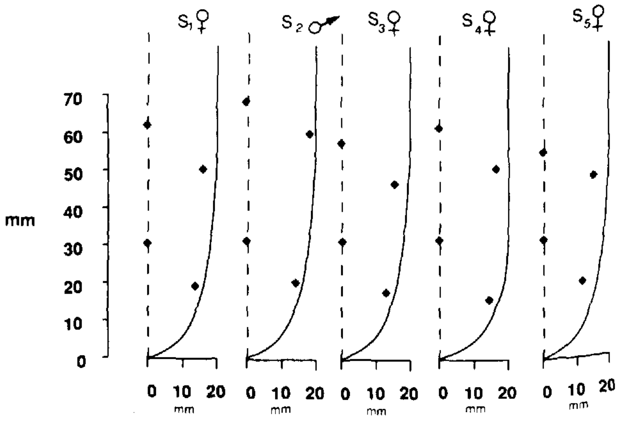

Fig. 1. Location of tongue pellets on the protruded tongue. All pellets were placed midsagittally and laterally on the left side. The midsagittal tongue blade pellet was 30 mm from the tip in all subjects, but the placement of the other pellets varied slightly depending on individual anatomy.

positional accuracy is reduced for off-axis pellets [15]. The error is more pronounced as the lateral pellet position is further away from the center of the midsagittal measurement plane. This is because the narrow x-ray beam is directed angularly at the subject from a pinhole point, and calculations of interpellet positions assume that the pellets are all located in the same plane. With all the pellets located in the midsagittal plane there is no measurable "image distortion" within that plane. Accuracy at the edges of the scanning field is the same as at the center. However, for off-axis pellets the error increases with distance from the center of the scanning field. The extent of the discrepancy between a pellet's perceived and true position due to off-axis pellet location is given by the ratio of two distances: the pinhole to midsagittal plane distance (530 mm) and the pinhole to off-axis pellet plane distance [15]. System testing using a phantom and pellets in multiple planes found the maximum error to be under 4%. This is within the 0.5 mm operating limits.

The subjects were normal young adults (four women and one man) who were undergraduate students at the University of Wisconsin. They were questioned about any history of swallowing problems and none were determined to be dysphagic. All of these subjects had teeth free of metallic dental fillings. This was a necessary selection criterion for data collection with the 450 kV X-ray Microbeam system operation, because metallic fillings could interfere with the tracking of the pellets. (A future upgrade to 600 KV operation is designed to eliminate this problem.)

After the pellets had been placed on the subject, he or she was seated in front of the X-ray Microbeam, with the head oriented lateral to the beam 530 mm from the pinhole. No head stabilization device was used. Calibration data were collected for determining the axes and scale of the measurement plane. The temporary reference pellets were then removed and a miniature accelerometer was taped to the side of the throat over the thyrohyoid membrane. The accelerometer signal recorded during swallowing [16] occurs a few hundred ms after lingual propulsive activity, and is generated by the rapid passage of the bolus through the hypopharynx and upper esophageal sphincter. This signal was used to confirm that a swallow had occurred and thus that the tongue motion analyzed was characteristic of a true swallow. Accelerometer signal data were recorded simultaneously with the X-ray Microbeam data.

The swallowing tasks involved 10 individual swallows of each different bolus volume (dry, and 5 ml, 10 ml, 15 ml of water). Information on a typical bolus size for a water swallow is scanty. Jones and Work [17] reported mean bolus volume for adult women to be 13.6 ml (SD 2.9) and for men 21.3 ml (SD 4.9). Bolus volumes for young children are in the range of 5 ml [17, 18]. Informal observations [10] estimate the physiological range of bolus volumes to be lower (2–10 ml). Our clinical impressions and pilot work indicated that boluses of greater than 20 ml may present difficulty for even some normal subjects to swallow in one gulp.

The water was delivered via a flexible tube leading from a small funnel placed approximately at the subject's eye level. The subject held the other end of the tube between the lips throughout data collection. The tubing hung below the level of the subject's mouth so that the bolus volume could accumulate in the trap thus created prior to each swallow. A measured amount of water for each swallow was delivered into the funnel via a syringe, and allowed to drain into the tubing. The subject was thus aware of the volume of water specified for the forthcoming swallow. The task for each swallow was first to hold the head still while the X-ray Microbeam system located the pellet array. Then at a tone generated by the computer system the subject sucked the water into the mouth, paused briefly, and then swallowed it "in one gulp." For the dry swallows the subject simply swallowed whatever secretions were present in the mouth at the tone. The sequence of tasks was pseudorandomized: no two dry swallows were permitted in sequence.

For data analysis the raw data files were first preprocessed by computer to reexpress pellet positions with respect to the reference axis defined by the head. Further preprocessing was done to calculate selected pellet velocities and interpellet distances through time. The preprocessed data set was then ready for detailed analysis.

Data analysis programs available to off-site users of the X-ray Microbeam facility were utilized. Multichannel time sequences of data were displayed on a graphic workstation. From such displays numerical values were extracted using mouse-aided measurement routines. The following measurements were made, all representing activity of the tongue just prior to and during lingual movement:

1. Midsagittal contour of the tongue at the initiation of lingual propulsive activity. Position of the midsagittal tongue blade (TB) and tongue dorsum (TD) pellets were noted in both the (x) and (y) dimensions (Fig. 2).
2. Midsagittal contour of the tongue just after completion of lingual propulsive activity. Positions of the midsagittal tongue blade (TB) and tongue dorsum (TD) pellets were noted in both the (x) and (y) dimensions (Fig. 2).
3. Peak velocity during lingual propulsive activity in the direction of motion for the tongue blade (TB) and tongue dorsum (TD) midsagittal pellets (Fig. 2).
4. Maximum central grooving of the tongue by comparison of midsagittal and corresponding lateral pellet positions. This measure was computed by subtracting the midsagittal from the lateral pellet position – tongue blade (TBL-TB) and tongue dorsum (TDL-TD). The maximum value just prior to or during lingual propulsive activity was used.
5. Time of occurrence for each of the above measures.

Interpellet distances were calculated as if all pellet positions were projected on a single midsagittal plane. From this information the contour of the tongue in three dimensions was inferred, based on several underlying assumptions about the shape of the tongue in the coronal plane: (1) A lateral pellet placed 1 cm anterior to the corresponding midsagittal pellet would show activity comparable to a lateral placement in the same coronal plane as the midsagittal pellet. (2) There would be no more than one inflection point in the shape of the tongue surface between lateral and midsagittal pellet flesh points (i.e., possibilities limited to flat, humped, or grooved). (3) When the lateral pellet was located superior to the corresponding midsagittal pellet, the contour of the tongue between these points was considered grooved. (4) Asymmetries in tongue shape would be minor enough that the shape could be inferred from pellets placed only on one side. This assumption is probably the weakest one, since substantial left/right asymmetries in tongue postures are known to occur, at least in speech.

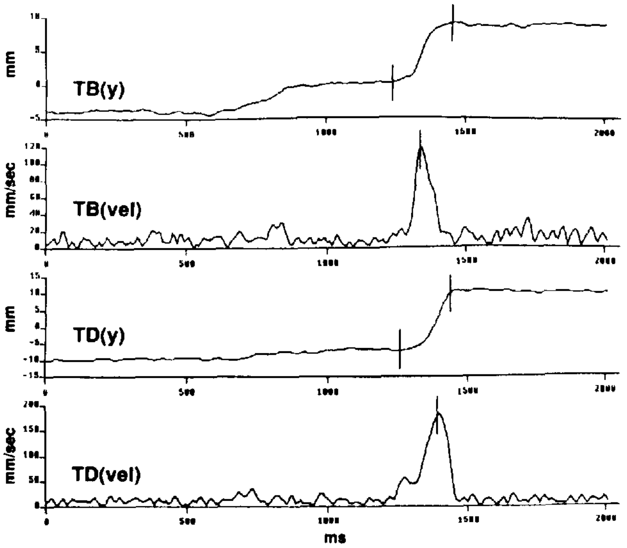

Fig. 2. Examples of tongue pellet data showing trajectories for the midsagittal pellets in the vertical (y) dimension and corresponding velocity (vel) in the direction of motion. Measurement points for tongue position are indicated at the onset and end of the rapid gesture for lingual propulsive activity, as well as the measurement points for peak velocity.

The measured data set was subjected to statistical analysis to determine representative values, in addition to differences both across and within subjects in tongue activity as a function of bolus volume. The Neuman-Keuls' multiple range test was used, with $p < 0.05$ level of significance set as the criterion.

Results

Missing Data

Some aspects of the data set were incomplete owing to a variety of factors. Recalibration was necessary a number of times when the system encountered difficulty in initially locating the pellet array, because of head movement by the subject between swallows. This occurred more frequently toward the end of the recording session when a subject was becoming fatigued. If at least eight successful data records were available for each bolus volume for that subject, the recording session was terminated when the subject showed fatigue. Some of the subjects demonstrated no measurable tongue blade movement for a dry swallow, and other subjects

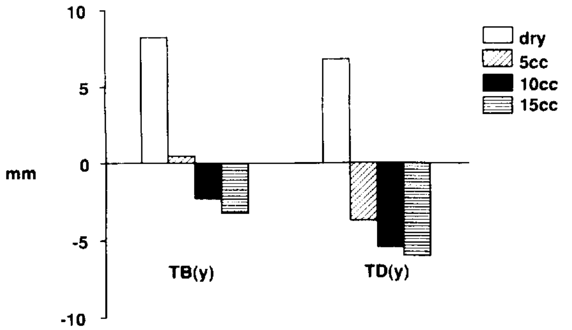

Fig. 3. Mean vertical (y) position of the midsagittal tongue pellets at the onset of lingual propulsive activity.

intermittently yielded unmeasurable movement data for dry swallows. Therefore, the data sets for both magnitude and corresponding temporal measurements of tongue blade activity for dry swallows were, in general, incomplete.

Individual Variability

In many respects the swallowing patterns for the different subjects differed qualitatively. When this was the case, it was not meaningful to group subjects for statistical analysis, and individual within-subject results are reported.

Spatial Effects

Tongue Position. Tongue posture at the onset of lingual propulsive activity was one measure for which subject results showed similar trends and thus could be combined. Figure 3 illustrates the mean vertical (y) position of the two midsagittal tongue pellets just prior to the onset of lingual propulsive activity. The posture for dry swallows was such that both midsagittal tongue points were well above the incisal plane. There was a clear pattern showing both tongue blade and dorsum pellets to be lower re the incisal plane for the larger bolus volumes, although the mean differences were not statistically significant between the 10 and 15 ml amounts.

Individual subject data can be seen in Figure 4. It should be noted that pellet positions at the completion of lingual propulsive activity tended to be more similar to each other than at the onset. This finding might be anticipated in part since the tongue conforms to the hard and soft palate at the completion of lingual propulsive activity, but the anterior-posterior (AP) point of contact could have varied. Such AP variation (1–3 mm in extent) can be seen in mean data for subjects 1, 3, and 4, and appears to be due mainly to a different pattern on dry swallows.

Direction of Motion. The direction of pellet motion during lingual propulsive activity is also shown in Figure 4. With the exception of the tongue blade pellet for subject 5, the extent of vertical (y) motion was greater than horizontal (x) motion. There were individual differences with respect to the precise direction of pellet motion. The most striking of

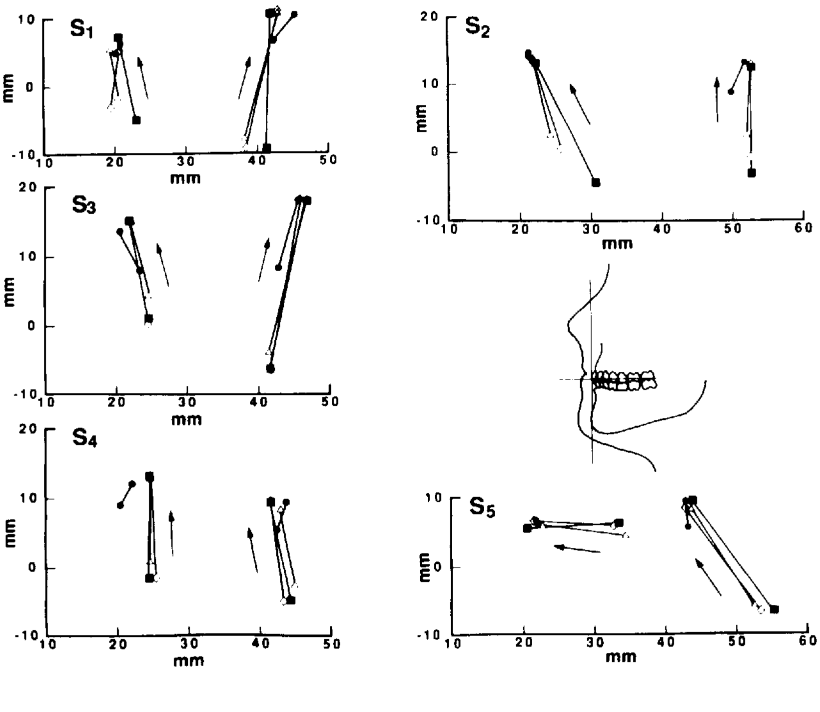

Fig. 4. Direction and extent of midsagittal tongue motion in lingual propulsive activity. Dark circles are for dry swallows, light triangles for 5 ml water swallows, light diamonds for 10 ml water swallows, and dark squares for 15 ml water swallows. Axes of the measurement space were located relative to each subject's maxillary dentition.

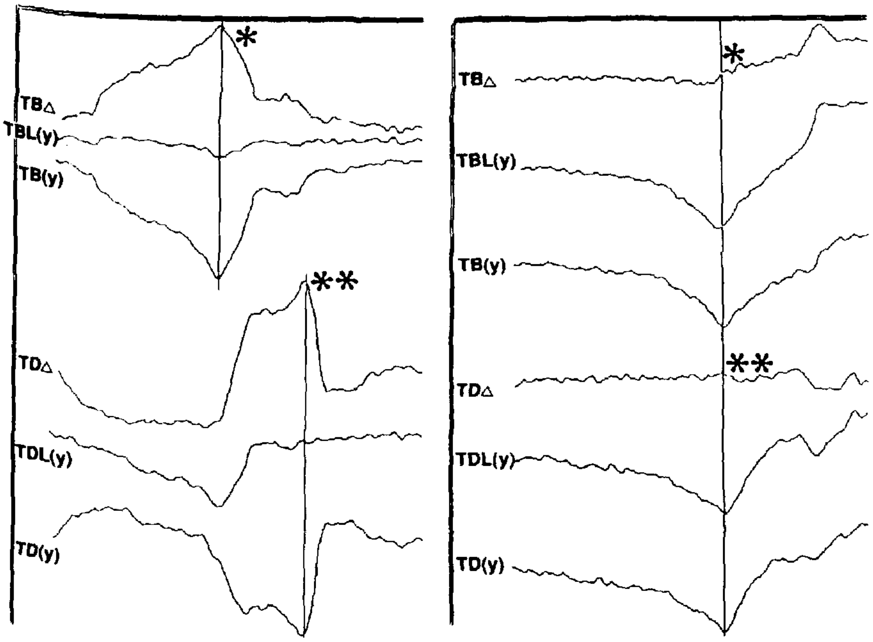

Fig. 5. Patterns of tongue grooving (TB Δ and TD Δ) in relation to lingual propulsive activity. Subject 2 showed the typical pattern with extent of grooving tending to mirror the lowering of midsagittal pellets (TB[y] and TD[y]). The onset of lingual propulsive activity started earlier for the tongue blade (*) than for the tongue dorsum (**). The unique pattern for subject 5 indicated minimal changes in cross-sectional tongue contour for lingual propulsive activity, with the midsagittal (TB[y] and TD[y]) and lateral (TBL[y] and TDL[y]) portions of the tongue moving as a unit, and the activity of the tongue blade and dorsum occurring simultaneously (* and **).

these individual differences was displayed by subject 5, who showed very little vertical motion for the tongue blade pellet, but over 10 mm in anterior motion for this pellet during water swallows. This subject evidently had a reverse swallowing pattern (tongue thrust), although this was not apparent in the limited range of motion present for her dry swallows.

In most cases, the overall direction of pellet motion appeared similar for different bolus volumes. Exceptions were data for subject 1, and for dry swallows in general. The pellet trajectories for dry swallows were more extreme angular versions of the trajectories for the water boluses: an exception is subject 4, who had upward and backward trajectories for dry swallows.

Tongue Grooving. Tongue grooving was determined by subtracting the midsagittal pellet vertical (y) position from the corresponding lateral pellet vertical position. This subtraction was done by computer for all sampling points in the data record and the result displayed as a graphic trace of groove magnitude through time. The maximum in this trace (most extreme grooving) was noted for tongue motion associated with lingual propulsive activity.

For most of the subjects maximum tongue grooving was found to occur near the onset of lingual propulsive activity [9]. In fact, the temporal measurement points for maximum grooving and midsagittal tongue posture at onset of lingual propulsive activity were virtually identical, except for subject 5. Figure 5 shows a comparison of traces for tongue grooving and tongue dorsum vertical position for subject 2, who showed the typical pattern. These traces appear to be mirror images of each other. The interpretation of such a pattern is that the lowering of the midsagittal pellet at the onset of lingual propulsive activity was in fact a progressive tongue grooving, with the lateral margins of the tongue remaining relatively stationary to achieve a lateral seal.

The pattern for subject 5 (the reverse swallower) was quite distinct in respect to the tongue grooving measure. She did not consistently groove the tongue during a swallow, but varied its conformation between flat and humped, and the most nearly grooved (least humped) conformation of the tongue did not occur at a particular portion of the swallow. Figure 5 shows corresponding midsagittal tongue pellet position and tongue grooving traces for this subject also.

There were marked individual differences in the extent of tongue grooving, and in the degree to which tongue grooving varied with bolus volume. Table 1 summarizes these data. The major individual difference was attributable to subject 5. Mean data for this subject did not show grooving of either the tongue blade or tongue dorsum during the swallow. The humped conformation of the tongue did not vary with bolus volume, except for the tongue blade measure for the dry swallow: the tongue blade dorsum was *less* humped for the dry swallow.

The remaining subjects all showed a difference

Table 1. Extent of tongue grooving at the onset of lingual propulsive activity.

Subject		Bolus volume (ml)			
		Dry	5	10	15
1	Blade	−6.6 (3.6)*	−0.0 (2.0)*	3.8 (3.1)	2.7 (3.0)
	Dorsum	−2.7 (1.9)*	7.7 (3.2)	7.9 (2.8)	4.4 (4.1)
2	Blade	−12.3 (1.0)*	−3.8 (2.4)*	−2.2 (2.2)	1.5 (1.5)*
	Dorsum	−4.8 (1.5)*	−2.1 (1.8)*	−0.4 (4.5)	2.1 (3.2)*
3	Blade	−10.0 (3.1)*	−4.7 (5.8)*	−1.0 (2.0)*	−1.9 (2.8)
	Dorsum	0.3 (2.9)*	7.5 (3.6)	8.8 (3.4)	9.2 (3.3)
4	Blade	−7.0 (4.1)*	−2.7 (1.9)	0.5 (3.2)	−0.5 (4.9)
	Dorsum	−7.0 (3.1)*	−0.5 (3.1)	2.5 (3.6)	1.5 (3.4)
5	Blade	−5.1 (3.3)*	−9.1 (2.9)	−9.4 (4.3)	−10.5 (3.2)
	Dorsum	−0.4 (2.0)	−0.3 (4.3)	−1.2 (3.1)	−1.8 (1.5)

Mean values (mm) are given with standard deviations in parentheses. Negative values indicate tongue humping, positive values indicate central grooving. See text for discussion of statistically significant differences (*).

in tongue grooving on dry swallows for both of the pellets: the tongue was relatively more humped for the dry than for the liquid swallows. Among the liquid swallows there were individual differences in the extent to which volume affected the extent of grooving or humping. For the tongue blade, the conformation was flat or humped in all subjects for the 5 ml amount. Subjects 2 and 3 showed a greater degree of grooving of the tongue blade for one, but not both, of the larger volumes. For the tongue dorsum only one subject (subject 2) revealed a difference in extent of grooving among the liquid swallows: he had a humped conformation for the dry swallow, less humped for the 5 ml swallow, flat for the 10 ml, and slightly grooved for the 15 ml.

The bulk of the evidence for tongue grooving shows differences only between dry swallows and liquid swallows. Although there were evident trends for larger volumes to be associated with a greater extent of grooving, there were not consistent statistically significant incremental differences as a function of volume of liquid swallows. Dry swallows had a humped or flat conformation of the tongue in all subjects, whereas in the liquid swallows four of the subjects showed tongue grooving for at least the larger volumes.

Propulsive Effects

Velocity. Maximum velocity during lingual propulsive activity showed individual variability, so individual subject data are reported. Table 2 provides mean values and standard deviations for this measure.

Table 2. Peak velocity (mm/s) for tongue blade and tongue dorsum pellets as a function of bolus volume.

Subject		Bolus volume (ml)			
		Dry	5	10	15
1	Blade	–	49 (25)	79 (34)	83 (35)
	Dorsum	46 (15)*	102 (29)*	128 (19)	138 (43)
2	Blade	–	76 (14)	91 (42)	97 (43)
	Dorsum	70 (18)*	161 (35)	175 (53)	207 (32)*
3	Blade	45 (13)	90 (35)	102 (42)	85 (29)
	Dorsum	136 (41)	143 (27)	179 (63)	166 (63)
4	Blade	67 (35)	129 (32)	130 (35)	131 (42)
	Dorsum	69 (25)*	147 (31)	145 (49)	147 (39)
5	Blade	34 (7)	113 (18)	116 (18)	110 (27)
	Dorsum	54 (12)*	109 (20)	122 (24)	106 (25)

Mean values are given with standard deviations in parentheses. See text for discussion of statistically significant differences (*).

The data set for the tongue blade pellet is incomplete, because no measurable motion was present in subjects 1 and 2 for the dry swallows. The remaining subjects showed markedly lower velocity of the tongue blade for dry swallows than for any of the liquid swallows. Four of the subjects also demonstrated lower tongue dorsum velocity for the dry swallows in comparison to any of the water swallows.

Among the liquid swallows there were occasional trends for greater bolus volume to be associated with higher velocity of tongue motion, but few of these differences were statistically significant. Subject 1 had lower tongue blade and dorsum velocity for the 5 ml volume than for the other

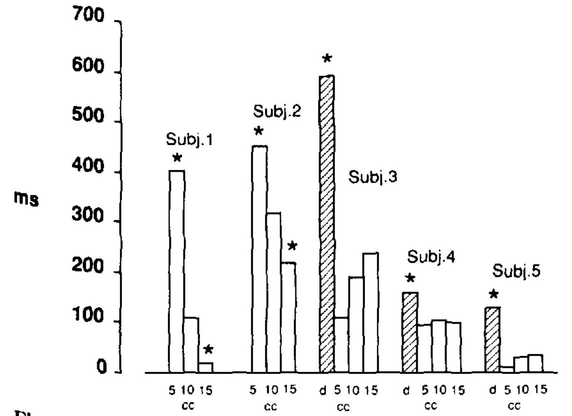

Fig. 6. Time difference between peak velocity for the tongue blade and dorsum pellets as a function of bolus volume.

liquid boluses. Subject 2 had a higher mean tongue blade velocity for the 15 ml swallows than for the other volumes.

Based on this data set it must be concluded that dry swallows differ from water swallows in respect to tongue velocity during linqual propulsive activity, but among water swallows of these volumes there was not a general monotonic increase in velocity of motion as a function of bolus volume.

Temporal Progression. It was hypothesized that in order to provide a greater propulsive force, the sequence of motion from the tongue blade pellet to the tongue dorsum pellet would be more nearly simultaneous for the larger bolus volumes. The most confident temporal measurements could be made by noting time of peak velocity for the two midsagittal pellets, so the measure of temporal progression was obtained by taking the time difference between peak velocity for the tongue blade and tongue dorsum pellets.

This measure also showed individual variability (Figs. 5 and 6). It was not possible to compute temporal progression for dry swallows in subjects 1 and 2, because no measurable tongue blade motion was present, but in the remaining three subjects it was clear that lingual propulsive activity was much slower for the dry swallows than for any water swallow. Among the water swallows, statistically significant temporal differences were only found for subjects 1 and 2 (in both cases only between the 5 ml and 15 ml conditions).

The results for temporal progression present a picture similar to those for velocity of motion. Dry swallows differ by showing a slower sequence of lingual propulsive activity, but within the liquid swallows of the volumes tested there was no consistent incremental effect across subjects.

Discussion

Two major findings emerge from the present investigation: Dry swallows differ from liquid swallows, and there is significant swallow-to-swallow variability and individual differences, which overshadow many differential effects of bolus volume, at least for the range of liquid volumes used here.

Lingual propulsive activity for purposeful dry swallows differed from that for liquid swallows in the following respects:

1. Range of movement of the tongue blade was small and sometimes unmeasurable, and movement of the tongue dorsum was likewise less than for the liquid swallows.
2. Onset of movement for lingual propulsive activity in dry swallows was initiated from a tongue blade and dorsum position well above the incisal plane, whereas tongue position for those points in liquid swallows was generally below the incisal plane.
3. The direction of motion in lingual propulsive activity for dry swallows tended to be a more extreme angular version of the trajectory for liquid swallows, and in some subjects a unique direction of motion was revealed.
4. The cross-sectional contour of the tongue was humped or flat for dry swallows.
5. Peak velocity of motion was less than for the liquid swallows.
6. The progression of activity from tongue blade to dorsum in lingual propulsive activity took longer for dry swallows. This comparison could not be made in all subjects, however.

Procedural differences used by different investigators studying the effects of bolus volume on swallowing characteristics make it especially important to scrutinize any apparent discrepancies reported in summary conclusions. The range of water bolus volumes differed from that used in some other studies, most of which used a broader range (e.g., 1–20 ml). The swallows investigated here were all purposeful. The dry swallows were thus not necessarily the same as inadvertent and unconscious swallows of secretions, even though the bolus size may have been equivalently minimal. Nor can these dry swallows necessarily be considered similar to swallows of a very small amount of liquid (e.g., 1 ml) introduced into the mouth, because when material is introduced the subject is expecting to swallow "something," and characteristic adjustments may be made based on that expectation. If we were to assume that a dry swallow was mechanically equivalent to that for 1–2 ml of liquid, our conclusions would be different, because all the differences between dry and liquid swallows would be considered differential effects of bolus volume.

We chose to sample 5, 10, and 15 ml of water. All of those swallows should have been within the moderate, comfortable range of bolus sizes for adults. The choice of bolus volumes in this study also probably predisposed to results leading to conservative conclusions, that is, few consistent differences in swallow characteristics attributable to the influence of different bolus volumes.

Among 5–15 ml liquid swallows, the differences found involved primarily spatial effects. Tongue blade and dorsum position at the onset of lingual propulsive activity was lower for the larger liquid volumes than for the 5 ml amount. The interpretation is that in forming the bolus and preparing to channel it centrally into the pharynx, both of which are voluntary functions, sensory feedback on the nature of bolus volume was used.

What might be the consequences of starting lingual propulsive activity from a different tongue posture? Tongue position just before the onset of lingual propulsive activity may serve as a sensory indication of how much muscular activity will be needed in the swallow for efficient passage of the bolus. If a bolus is to pass rapidly through the pharynx, there should be minimal resistance from a constricted pharynx. Greater extent of hyoid motion for larger bolus volumes would be consistent with this principle [10]. Lower pharyngeal resistance, as well as a wider and longer opening of the upper esophageal sphincter, would explain a differential effect of bolus velocity as it enters the esophagus.

Rapid passage of a bolus could also be effected by a differentially greater lingual propulsive force. In such a case more extensive motions of pharyngeal structures might in part be a passive effect, or related to an integrated composite lingual/hyoid gesture. Propulsive effects were not found to be systematically different across 5–15 ml bolus volumes in this study, although there was some evidence for this mechanism being used in isolated subjects. In general the hypothesis was not supported that tongue velocity of motion would be higher for larger bolus volumes to provide a greater impetus for the bolus. This is not consistent with the finding of a higher tongue velocity for larger volumes in other reported work [8], although a larger range of bolus sizes investigated may have contributed to those conclusions. Our results are consistent with the finding of no difference in force of "oral peristaltic contraction" for different bolus volumes [8].

Taken as a whole, the evidence does suggests that differences in the pharyngeal swallow as a function of bolus volume are not merely secondary effects of differences in the dynamics of lingual propulsive activity. The implication is rather that the motor activity during the pharyngeal swallow is directly modified as a result of sensory information processed during the early oral stages of bolus formation and containment.

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References

1. Kennedy JG, Kent RD: Anatomy and physiology of deglutition and related functions. *Semin Speech Lang 6*:257–272, 1985
2. Miller AJ: Neurophysiological basis of swallowing. *Dysphagia 1*:91–100, 1986
3. Hrychshyn AW, Basmajian JV: Electromyography of the oral stage of swallowing in man. *Am J Anat 133*:335–340, 1972
4. Jacob P, Kahrilas PJ, Logemann JA, Tracy K, Lazarus C, McLaughlin B: Bolus viscosity and volume affect strap muscle EMG activity during swallowing. *Gastroenterology 95*:873, 1988
5. Fisher MA, Hendrix TR, Hunt JN, Murrills AJ: Relation between volume swallowed and velocity of the bolus ejected from the pharynx into the esophagus. *Gastroenterology 74*:1238–1240, 1978
6. McConnel FMS: Analysis of pressure generation and bolus transit during pharyngeal swallowing. *Laryngoscope 98*:71–78, 1988
7. Tracy JF, Logemann JA, Kahrilas PJ: Effects of bolus size and age on oropharyngeal deglutition. *ASHA 30*:133, 1988
8. Dodds WJ: Physiology of swallowing. Presented at the Johns Hopkins Second Symposium on Dysphagia, March 1988, Baltimore, MD
9. Kahrilas P, Dodds W, Dent J, Logemann J, Shaker R: Upper esophageal sphincter function during deglutition. *Gastroenterology 95*:52–62, 1988
10. Dodds W, Man K, Cook I, Kahrilas P, Stewart S, Kern M: Influence of bolus volume on swallow induced hyoid movement in normal subjects. *AJR 150*:1307–1309, 1988
11. Ekberg O, Olsson R, Sundgren-Borgstrom P: Relation of

bolus size and pharyngeal swallow. *Dysphagia 3:*69 72, 1988

12. Stone M, Shawker TH: An ultrasound examination of tongue movement during swallowing. *Dysphagia 1:*78–83, 1986
13. Hamlet S, Jones L, Mathog R, Bolton M, Patterson R: Bolus propulsive activity of the tongue in dysphagic cancer patients. *Dysphagia 3:*18–23, 1988
14. Abbs JH, Nadler RD, Fujimura O: X-ray microbeams track the shape of speech. *SOMA January:*29–34, 1988
15. Westbury JR, Xue Q: Three-dimensional articulatory kinematics from x-ray microbeam data. *J Acoust Soc Am 84:*s127, 1988
16. Hamlet SL, Nelson R, Patterson R: Sounds of swallowing. *J Acoust Soc Am 83:*s23, 1988
17. Jones P, Work C: Volume of a swallow. *Am J Dis Child 102:*427, 1961
18. Saylor J: Volume of a swallow: role of orifice size and viscosity. *Vet Hum Toxicol 29:*79–83, 1987
19. Hamlet SL, Stone M, Shawker TH: Posterior tongue grooving in deglutition and speech: preliminary observations. *Dysphagia 3:*65–68, 1988