Opening mechanisms of the human upper esophageal sphincter

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Cook, Ian J., Wylie J. Dodds, Roberto O. Dantas, Benson Massey, Mark K. Kern, Ivan M. Lang, James G. Brasseur, and Walter J. Hogan. Opening mechanisms of the human upper esophageal sphincter. Am. J. Physiol. 257 (Gastrointest. Liver Physiol. 20): G748–G759, 1989.—Our goals in this study were to evaluate the mechanisms operative in swallow-associated opening of the upper esophageal sphincter (UES) and to determine the dynamics of fluid flow across the sphincter. For this purpose, we obtained concurrent videofluorographic and manometric studies of 2- to 30 ml barium swallows in 15 normal subjects. We found that the resting UES high-pressure zone corresponded closely with the location of the cricopharyngeus. The findings indicated that manometric UES relaxation and anterior laryngeal traction on the larynx invariably preceded UES opening. With graded increases in bolus volume, progressive increases occurred in UES diameter, cross sectional area, flow duration, and transsphincteric flow rate. Intrabolus pressure upstream to the UES and within the UES at its opening during transsphincteric flow of barium remained within a narrow physiological range of <10 mmHg up to a bolus volume of 10 ml. With increases in bolus volume, anterior laryngeal movement, UES relaxation, and UES opening occurred sooner in the swallow sequence to accommodate the early entry of large boluses into the pharynx. We conclude that during swallowing 1) normal UES opening involves sphincter relaxation, anterior laryngeal traction, and intrabolus pressure, 2) volume-dependent adaptive changes in UES dimension accommodate large bolus volumes and flow rates with minimal requirement for increases in upstream, or intrasphincteric, intrabolus pressure or UES opening duration, and 3) volume-dependent changes in UES dimensions as well as timing of UES relaxation and opening indicate a sensory feedback mechanism that modulates some components of the swallow response generated by the brain stem swallow centers.

pharyngoesophageal sphincter; laryngeal motion; hyoid movement

THE UPPER ESOPHAGEAL SPHINCTER (UES) normally relaxes and opens during swallowing to permit passage of ingested material into the esophagus but otherwise remains closed except during belching and vomiting. Although observations of swallow-induced UES opening are made commonly during radiographic examination, minimal quantitative information exists about the specific mechanisms of deglutitive UES opening in humans (16, 23). Some investigators emphasize that the major mechanism associated with deglutitive UES opening is transient cessation of cricopharyngeal electrical activity (12, 20, 22). Other workers stress that actual UES opening is caused mainly by traction generated by anterior hyoid movement that pulls open a relaxed or partially relaxed sphincter (2, 11, 14). Another possible mechanism of UES opening is intrabolus pressure forces, mediated by an oncoming swallowed bolus (20). Our aims in this study were to 1) quantify the variables of UES opening associated with swallows of different bolus volumes and 2) analyze the specific mechanisms that govern UES opening and transsphincteric flow.

METHODS

We obtained concurrent videofluoroscopic and manometric studies of UES function during barium swallows in 15 healthy male volunteers with an average age of 29 ± 5 (SD) yr, range 18–38 yr. The study was approved by the Human Research Review Committee of the Medical College of Wisconsin.

The subjects were positioned sitting on a stool, turned laterally to a vertical X-ray table top and held their head in a neutral position. Swallow sequences were recorded at 30 frames/s on video tape with a 0.5-in. Beta video recorder (Sony SLHF 900). Using either a 6- or 9-in. intensifier magnification mode, we obtained concurrent videofluoroscopic and manometric recordings (4–6 s duration) of swallows of high-density barium (250% wt/vol; E-Z-hd barium sulfate, E-Z-EM, Westbury, NY). Swallow sequences were recorded for barium volumes of 0, 2, 5, 10, 20, and 30 ml. Each bolus was delivered to the mouth by a syringe. For “dry swallows” of 0 ml barium, small amounts of saliva and residual barium from prior swallows passed into the esophagus. For each swallowed volume, recordings over the pharynx and UES were made in duplicate for both the lateral and posterior-anterior (P-A) projections. A ruler with metal markers 3 cm apart, recorded in the plane of the UES for both the P-A and lateral projections, enabled distance correction for magnification. Recording of each swallow lasted 4–6 s. Fluoroscopy time was ≤2.5 min.

Manometry was done using several different transducer probes (Gaeltec, Medical Measurements, Hackensack, NJ) of 1.8-mm OD that contained two or three individual transducers spaced at 1.5- or 3-cm intervals, respectively. Before manometry, the transducers were balanced and calibrated in a water bath at 37°C. Transducer signals were processed through an eight-channel Beckman polygraph (Sensor Medics, Anaheim, CA) run at a speed of 100 mm/s. The videofluoroscopic and manometric recordings were synchronized using a clock timer (Thalner Electronics, Ann Arbor, MI) that indicates

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Subjects were divided into two groups. In group 1 (8 subjects), we obtained magnified images (6-in. mode) of the pharynx and UES to quantify the features of UES opening. In group 2 (7 subjects), we used a low-magnification mode (9-in. mode) to record concurrently the oral and pharyngeal phases of swallowing in order to determine the precise timing of UES opening during the oropharyngeal peristaltic sequence.

In the eight group 1 subjects, a single probe with three transducers spaced at 1.5-cm intervals was passed transnasally. After a UES pullthrough, the distal transducer was positioned within the proximal part of the sphincter. The transducers were oriented anteriorly and the probe taped to the subject's nose.

In the seven group 2 subjects we used two pressure probes. A probe with two transducers 3 cm apart was passed transnasally and positioned with the proximal transducer in the oropharynx at the level of the valleculae and the distal transducer in the hypopharynx. The transducers faced anteriorly. A second probe with two transducers 3 cm apart was passed transorally and positioned so that the distal transducer was located at the posterior tonsillar arch while the proximal transducer was located at the middle of the tongue. Lateral video images of the mouth and pharynx were recorded for barium swallows of 0, 2, 5, 10, and 20 ml.

In the group 2 subjects we also determined the resting axial and radial UES pressure profile using a four-lumen catheter that was passed transnasally. This catheter measured 2 x 4 mm OD. Lateral recording orifices were located at the same level, 5 cm proximal to the end of the assembly. The catheter lumens distal to each orifice were occluded with metal plugs of different lengths that permitted fluoroscopic determination of recording orifice orientation. During recordings, each catheter lumen was perfused with water at 0.5 ml/min (1). In each subject, three UES pullthroughs were done at 0.5 cm/s during concurrent videofluoroscopic and manometric recording while the subject refrained from swallowing.

We measured a large number of variables including the following: 1) resting location and pressure profile of the UES, 2) dimensions and timing of swallow-induced UES opening, 3) timing and magnitude of deglutitive movements of the hyoid, larynx, and tongue, and 4) pressure profile across the UES during swallowing. Duplicate measurements were averaged.

We determined pressure at 2-mm increments across the resting posterior and anterior UES pressure profile and related axial location of the pressure profile to the under surface of the vocal cords. On the videofluoroscopic recordings, this landmark was readily seen as a horizontal air-tissue interface. As shown in Fig. 1, the vocal cords attach posteriorly to the vocal process of each arytenoid and mark the superior margin of the cricoid lamina. The cricopharyngeus muscle is a horizontal band of muscle without a midline raphe that loops posteriorly around the pharyngoesophageal junction so that its arms attach to the lateral margins of the cricoid lamina like a C-clamp. Pressure values among pullthroughs and among subjects were normalized by indexing peak pullthrough pressure as 100%. Peak posterior pressure was located 1.6 ± 0.2 (SE) cm distal to the level of the vocal cords. The region of UES pressure ≥50% of peak averaged 1.3 cm in length. Peak pressure for the anterior axial pressure profile was located 3–4 mm proximal to that of the posterior pressure peak. These results were similar to our previous observation that the major portion of the functional UES high-pressure zone corresponds to the cricopharyngeus (19).

Analysis of deglutitive UES opening and transsphincteric barium flow was done on the video sequences by obtaining the time and sequential sphincter diameter from each video frame. Measured distances were corrected for magnification. We defined UES opening as the instant that the barium bolus head reached the central zone of the UES. In some sequences, barium or air entered the proximal few millimeters of the sphincter 0.03–0.09 s before opening of the central sphincter zone of maximal resting pressure. Sagittal sphincter diameter was measured ~1.6 cm distal to the cords. Time of UES closure was taken as the instant that the barium column disappeared from the sphincter zone. Transverse diameter of the UES was measured at the junction of the funnel-shaped pharynx with the tubular esophagus on the P-A video projections. The P-A dimensions of the UES were measured from the lateral video projections. For bolus volumes >10 ml, the barium column in the UES tended to slightly overlap the cervical spine, thereby indicating that the maximal P-A sphincter diameters were parasagittal rather than midline. Indeed, regional UES anatomy suggests that UES opening in the midline would be restricted by the cervical spine and posterior bulge of the cricoid plate (7). To estimate midline UES opening, we measured the change in distance of the posterior tracheal wall (1.6 cm distal to the vocal cords) to the spine. Maximal UES area during transsphincteric flow for a given barium volume was estimated from the maximal values of transverse, parasagittal, and midline sphincter diameter. Approximations of cross-sectional sphincter area were calculated using mathematical models for 1) an ellipse, ignoring the potential midline narrowing and 2) a "barbell" configuration that attempts to correct for midline narrowing (15).

To determine the superior and anterior components of deglutitive hyoid movement, we measured the sequential coordinates of the anterior-inferior hyoid margin. To measure superior laryngeal movement, we used the vocal cords as a marker (Fig. 1). Superior movement of the larynx is caused by hyoid elevation plus shortening of the thyrohyoid muscles (7). Thyrohyoid shortening was determined by subtracting superior hyoid movement from superior laryngeal movement. We determined the time of initial movement of the tongue tip against the posterior surface of the maxillary incisors, an event that represents the onset of lingual peristalsis (6). This event was used as the temporal reference for all other events. We also measured the timing and magnitude of tongue base movement. The onset of tongue base movement was taken as the initial forward or backward movement of
the tongue base, at a point just apart and above the vallecula. Generally, the initial movement was forward.

From the manometric tracings, we determined the relationship between the barium bolus tail and the peristaltic pressure wave, as peristalsis swept the bolus through the mouth (group 2 subjects) and pharynx (group 1 subjects). Resting UES pressure and deglutitive pressures above, within, and below the sphincter were referenced to atmospheric pressure. Manometric UES relaxation does not commence until after the sphincter approaches or reaches the apogee of its superior deglutitive excursion (17, 19). We observed radiographically in the group 1 subjects that the middle transducer, positioned 1.5 cm proximal to the upper margin of the resting UES, lay within the central zone of the sphincter during its deglutitive oral excursion. Therefore, we used the pressure tracing of the middle transducer to measure manometric UES relaxation. Measurements were made of the timing of relaxation onset, complete relaxation to atmosphere as zero, and termination of complete relaxation, coincident with the arrival of pharyngeal peristaltic pressure wave. We then calculated the duration of complete UES relaxation. Also measured were the absolute pressures above, within, and below the UES, coincident with the onset of sphincter opening (defined as opening pressure) and during the interval of maximal UES opening (defined as flow pressure). We also calculated the pressure difference across the UES during maximal sphincter opening. Upstream intrabolus pressure was taken from the hypopharynx 1 cm above the open UES while downstream intrabolus pressure was measured from the cervical esophagus 1 cm below the UES. Intraspincteric pressure was measured from within the UES.

Inferences regarding the statistical significance of changes in the timing or magnitude of peristaltic events associated with different swallowed bolus volumes were tested by analysis of variance for repeated measures. Composite data in the text is given as means ± SD unless designated otherwise.

RESULTS

The sequence of events during the oral and pharyngeal phases of swallowing for a 10-ml barium bolus is shown in Fig. 2. At swallow initiation the bolus is held in the anterior mouth with the tongue tip positioned against the upper incisors. The oral cavity is sealed off from the oropharynx by compression of the palate against the posterior-superior aspect of the tongue. With swallowing, the tongue moves superiorly against the palate, first its tip and then the base, to propel the bolus in a peristaltic fashion into the pharynx. During lingual peristalsis, the point of glossopalatal contact imparts a V-configuration to the tail of the barium bolus. At the onset of oral peristalsis, the tongue base moves forward to accommodate bolus entry into the pharynx, and the hyoid, larynx, and UES begin a superior and anterior excursion that widen the pharynx and shorten the axial distance that the bolus must travel. The UES segment opens generously during flow of the bolus into the esophagus. Transspincteric flow is completed during laryngeal descent toward its resting position. During swallowing the larynx is sealed by action of its intrinsic muscles and inversion of the epiglottis.

Maximal transverse and P-A dimensions of the UES during transspincteric flow of different swallow bolus volumes are given in Table 1. The maximal transverse and P-A diameters both showed a progressive increase for graded increases in bolus volume (P < 0.01). Also
FIG. 2. Sequential images obtained during swallowing of a 10-ml barium bolus in a normal subject. A: bolus position at the initiation of swallowing (time = 0). B: oral phase of swallowing (time = 0.01 s). Posterior movement of the tongue against the palate imparts a V-configuration to the bolus tail and propels the bolus into the pharynx. The hyoid and larynx begin to move superiority and then forward. C: pharyngeal phase of swallowing (time = 0.03 s). The tongue base moves forward to accommodate bolus entry in the pharynx. The central zone of the sphincter is located distal to the vocal cords. The larynx is starting to close. D: pharyngeal phase (time = 0.6 s). The pharyngeal contraction wave is in the oropharynx. The hyoid and larynx have reached their maximal anterior position. The UES is maximally open while barium flows freely into the esophagus.

TABLE 1. Maximal dimensions and calculated UES area during transsphincteric flow of different volumes of swallowed barium

<table>
<thead>
<tr>
<th>Volume of Swallowed Barium, ml</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Upper sphincter diameter, mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>18.9±3.5</td>
<td>20.7±3.7</td>
<td>21.0±3.7</td>
<td>22.3±3.3</td>
<td>29.9±3.4</td>
</tr>
<tr>
<td>Parasagittal</td>
<td>8.0±1.3</td>
<td>11.0±1.9</td>
<td>11.8±1.6</td>
<td>13.3±2.0</td>
<td>14.1±1.9</td>
</tr>
<tr>
<td>Midline</td>
<td>4.8±1.2</td>
<td>7.3±2.2</td>
<td>8.1±2.1</td>
<td>9.3±1.8</td>
<td>9.5±2.5</td>
</tr>
<tr>
<td>Area, mm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ellipse</td>
<td>118±31</td>
<td>181±59</td>
<td>195±45</td>
<td>230±51</td>
<td>264±46</td>
</tr>
<tr>
<td>Barbell</td>
<td>115±37</td>
<td>205±60</td>
<td>235±44</td>
<td>297±24</td>
<td>332±33</td>
</tr>
</tbody>
</table>

Values are means ± SD in mm of 8 group 1 subjects. Values for midline were estimated by anterior tracheal movement.

shown in Table 1 are the values for estimated maximal midline UES diameter during transsphincteric flow of different bolus volumes. These values were determined by the maximal change in the posterior trachea-to-spine distance during sphincter opening. The estimated midline diameter during maximal UES opening was invariably less than the maximal P-A diameter for all bolus volumes (P < 0.05). For graded increases in bolus volume, maximal midline UES diameter increased progressively to a bolus volume of 10 ml (P < 0.01) and then increased minimally for larger boluses. Calculated approximations of the maximal area of UES opening for different bolus volumes are given for both the ellipse and “barbell” mathematical models (Fig. 3). Although the calculated barbell-shaped areas were somewhat greater than the calculated ellipse areas, both sets of approximations showed a significant progressive increase in cross-sectional UES area for graded increases in swallowed vol-
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FIG. 3. UES area during transsphincteric flow for graded increases in swallowed bolus volume. Calculations (15) are shown for both the ellipse and barbell shapes. Data from 8 subjects are plotted as mean ± SE. For both models, significant increases in UES area occurred as a function of increases in bolus volume ($P < 0.01$).

Mean flow rate during UES opening was calculated by dividing the volume of swallowed barium by the interval of transsphincteric flow. For the 2-, 5-, 10-, 20-, and 30-ml barium boluses, respectively, the average transsphincteric flow rates were the following: 5 ± 0.3, 10 ± 0.6, 18 ± 1.8, 32 ± 1.9, and 46 ± 1.9 ml/s. Thus, as bolus volume was increased from 2 to 30 ml, mean transsphincteric flow rate increased nearly 10-fold.

The initiation of swallowing was heralded by a leading complex of three closely related events: movement of the tongue tip and tongue base and superior movement of the hyoid. These initial events were followed in order by superior movement of the larynx (vocal cords), anterior movement of the hyoid, onset of manometric UES relaxation, anterior movement of larynx (posterior tracheal wall), and UES opening. UES closure occurred coincident with the arrival of pharyngeal peristaltic wave at the sphincter. The onset of UES relaxation and subsequent UES opening occurred as the hyoid and larynx approached or reached the apogee of their superior excursions (Fig. 5). UES opening occurred shortly after the hyoid and larynx began to move anteriorly. In ~20% of swallows, detectable gas penetrated the UES 0.03–0.06 s before the barium bolus. This phenomenon was not dependent on bolus volume.

Increases in bolus volume were associated with progressive increases in maximal superior hyoid and laryngeal movement ($P < 0.01$) (Fig. 6). Superior laryngeal movement exceeded that of the hyoid. The shaded area indicates the magnitude of thyrohyoid shortening. Maximal anterior movement of both the hyoid and larynx also increased with bolus volume ($P < 0.05$). For each bolus volume, magnitude of anterior laryngeal movement was less than anterior hyoid movement.

With respect to the onset of swallow-induced lingual peristalsis, anterior hyoid and laryngeal movement, as well as UES opening, all moved forward significantly in time ($P < 0.05$) with increases in bolus volume (Table 3) (Fig. 7). UES opening invariably occurred during anterior laryngeal movement while closure occurred as the larynx returned to its initial resting position. As illustrated in Fig. 8, the forward temporal migration of UES relaxation and opening with respect to the onset of oral peristalsis accounted for the bolus-dependent increases in the duration of UES opening and transsphincteric flow. As bolus volume increased, the bolus head arrived at the UES sooner as a consequence of an increase in bolus length. Figure 9 shows that for each bolus volume, the onset of manometric UES relaxation began before the onset of anterior laryngeal movement, whereas complete UES relaxation and UES opening occurred during anterior movement of the hyoid and larynx.

The transit times of oral and pharyngeal peristalsis measured by videofluorography and manometry were nearly identical (Table 4). Whereas increases in bolus...
TABLE 2. Duration of transsphincteric flow and complete UES relaxation for different volumes of swallowed barium

<table>
<thead>
<tr>
<th>Volume of Swallowed Barium, ml</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trans-UES barium flow</td>
<td>0.41±0.03</td>
<td>0.48±0.05</td>
<td>0.55±0.05</td>
<td>0.62±0.07</td>
<td>0.65±0.04</td>
</tr>
<tr>
<td>Complete UES relaxation</td>
<td>0.46±0.14</td>
<td>0.50±0.14</td>
<td>0.56±0.12</td>
<td>0.65±0.12</td>
<td>0.64±0.18</td>
</tr>
</tbody>
</table>

Values are means ± SD in s for 8 group 1 subjects. For each volume, a significant difference did not exist between the duration of UES relaxation and transsphincteric barium flow.

volume were inversely related to the rate of oral transit ($P < 0.05$), bolus volume did not affect transit time in the pharynx. Although increases in bolus volume were associated with earlier UES closure, this trend did not reach statistical significance, except in group 2 (Table 3).

Swallowed bolus volume did not affect the interval between the onset of manometric UES relaxation (instant the pressure turns downward) and complete sphincter relaxation (decreases to zero pressure) or the interval between complete UES relaxation and the onset of transsphincteric bolus flow (Figs. 8 and 9). For a 5-ml bolus, these intervals were 0.13 ± 0.01 s and 0.05 ± 0.01 s, respectively, in the eight group 1 subjects.

Detailed analysis of manometric tracings established the interrelationship between intraluminal pressure and transsphincteric flow during swallowing. Resting pressure in the pharynx was zero relative to atmosphere. With a dry swallow, a slightly negative pressure of 2–4 mmHg commonly developed before the arrival of the peristaltic contraction wave. For wet swallows, a small step up of positive hypopharyngeal pressure preceded the peristaltic pressure wave (Fig. 10). The onset of this step up was coincident with the arrival of the bolus head at the hypopharyngeal recording site. The low-pressure plateau of intrabolus pressure corresponded to the interval during which the bolus flowed past the transducer.

Upstream intrabolus pressure at the onset of UES opening was invariably low, e.g., 6 ± 1.8 mmHg for a 10-ml swallowed bolus, but was directly dependent on bolus volume (Fig. 11). In contrast, at the instant of UES opening, downstream pressure in the cervical esophagus was slightly negative at about 6–8 mmHg and was independent of bolus volume (Table 5). Upstream bolus pressure during transsphincteric flow was 1–5 mmHg greater than opening pressure and was directly related to bolus volume. Intrasphincteric pressure during flow also increased with bolus volume (Fig. 8; Table 5). During transsphincteric flow, intrasphincteric pressure was ~3 mmHg less than upstream bolus pressure, while downstream bolus pressure in the cervical esophagus was 3–10 mmHg lower than hypopharyngeal pressure. The downstream pressure was slightly negative for the 2-ml bolus but increased to a value of 15.3 mmHg for the 30-ml bolus. The upstream to downstream pressure difference across the UES during sphincter opening was al-
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The study findings indicate that 1) the cricopharyngeus is the major contractile element of the UES and exhibits manometric relaxation just prior to sphincter opening; 2) UES traction by anterior deglutitive movement of the hyoid and larynx initiates normal sphincter opening and is the predominant mechanism that determines UES opening for dry swallows and wet swallows of low volume; 3) for swallowed volumes ≥5 ml, pressure forces within the bolus contribute substantially to the magnitude of UES opening; 4) graded increases in swallowed bolus volume cause adaptive increases of UES dimension that decrease flow resistance, thereby allowing a substantial increase in flow rate while maintaining a short duration of transsphincteric flow with only minimal increases in intrabolus pressure, and 5) modulation of swallowing by change in bolus volume exhibits adaptive accommodation by the pharynx and UES, whereas peristaltic propagation in the pharynx remains stereotyped and constant.

For our study, we selected anatomical markers that would satisfactorily identify UES location during deglutition. Manometric pullthroughs across the UES during videofluoroscopic recordings confirmed previous observations that the central UES high-pressure zone corresponds to the cricopharyngeus (18, 19). The inferior aspect of the vocal cords serves as a reliable radiographic marker for identifying the upper margin of the cricoid, which is located about 1–2 cm cephalad to the peak resting UES pressure. During swallowing, the hyoid and larynx make a pronounced superior and anterior excursion. We quantified these movements with temporal plots of the location of the hyoid, vocal cords, and posterior tracheal wall. Anterior tracheal movement was judged to approximate sagittal UES opening in the midline. To measure manometric UES relaxation, we positioned a transducer 1.5 cm above the proximal margin of the resting UES. During its deglutitive excursion, the UES rose to the level of the transducer. Manometric UES relaxation and sphincter opening occur while the sphincter approaches or reaches the apogee of its deglutitive oral excursion (17, 19).

Complete manometric sphincter relaxation as well as the onset of anterior hyoid laryngeal movement invariably preceded UES opening. UES opening was signaled by penetration of the sphincter segment by the head of the barium column. Generally, the barium penetration

Table 3. Temporal relationship of onset of hyoid and laryngeal movement, UES opening, and closure to initiation of swallow-induced oral peristalsis

<table>
<thead>
<tr>
<th>Swallowed Volume, ml</th>
<th>Interval From Onset of Lingual Peristalsis, s</th>
<th>Duration of UES Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UES opening</td>
<td>UES closure</td>
</tr>
<tr>
<td>0</td>
<td>0.84±0.07</td>
<td>1.14±0.07</td>
</tr>
<tr>
<td>2</td>
<td>0.73±0.07</td>
<td>1.08±0.07</td>
</tr>
<tr>
<td>5</td>
<td>0.61±0.06</td>
<td>1.07±0.06</td>
</tr>
<tr>
<td>10</td>
<td>0.44±0.04</td>
<td>0.93±0.04</td>
</tr>
<tr>
<td>20</td>
<td>0.36±0.03</td>
<td>0.91±0.03</td>
</tr>
</tbody>
</table>

Values are means ± SE in s and are composite data from 7 group 2 subjects. All columns showed a direct correlation with bolus volume (P < 0.001).
FIG. 7. Group mean data in group 1 patients showing the relationship between UES opening and anterior movement of the larynx for 2- to 20-ml bolus volumes. UES opening is indicated by open circles; closure is indicated by the closed circles. Plots demonstrate that maximal anterior hyoid movement increases in magnitude and moves leftward in time as bolus volume increases. For all volumes, UES opening invariably occurred after the onset of anterior laryngeal movement but before peak movement.

FIG. 8. Example from a single normal group 1 subject of the effect of increases in bolus volume on the timing of UES relaxation and opening during the swallowing sequence. DS, dry swallow. Initial pressure hump on each tracing is caused by superior movement of the unrelaxed UES to the level of the transducer positioned 1.5 cm proximal to the rest position of the sphincter. Onset of UES relaxation is defined as the instant the pressure hump turns downward. Arrows indicate the onset (*) and peak (+) of anterior laryngeal movement. Horizontal black bars indicate UES opening and interval of transsphincteric flow of barium. Vertical dashed line indicates UES closure. The manometric tracings of UES relaxations are aligned, or indexed, to the instant of UES closure because analysis of data from group 2 subjects indicated that the timing of UES closure in relation to the onset of the oral phase of swallowing was not significantly affected by bolus volume. In this example, the onset of UES relaxation, anterior laryngeal movement, and UES opening all migrate forward in the swallow sequence as a function of increases in swallowed bolus volume.

accurately defined the instant of UES opening, but occasionally air preceded the bolus head by 0.03–0.06 s. In either case, however, sphincter opening was always preceded by complete manometric UES relaxation. We judge that manometric UES relaxation likely reflects cessation of cricopharyngeal electromyogram activity, which is transiently switched off during swallowing (2, 10). The onset of manometric UES relaxation occurred prior to appreciable anterior laryngeal movement and thus does not appear to be caused by traction that might reduce UES pressure without true sphincter relaxation (2). Our data support the proposal that UES relaxation is a prerequisite for normal sphincter opening (21).

The second event associated with normal deglutitive UES opening is brisk anterior movement of the larynx. This forward laryngeal movement is generated by anterior movement of the hyoid during its superior excursion and to a lesser degree by thyrohyoid shortening. The timing of anterior hyoid and laryngeal movement support the conclusion that anterior traction is the predominant force responsible for the initiation of deglutitive UES opening as the sphincter snaps open. This initial opening of ~7 mm was independent of bolus volume. Further, sphincter opening elicited by anterior laryngeal movement occurs during a dry swallow when a fluid bolus is negligible. This conclusion is also supported by neural stimulation studies of the geniohyoid muscle in the opossum (2) and dog (unpublished observations). During anterior distraction of the cricoid, the posterior portion of the C-shaped cricopharyngeus is normally prevented from moving forward by the prevertebral fascia (7). This fascia allows the pharyngeal musculature to move freely in the longitudinal direction while allowing negligible anterior movement. During swallowing, shortening of the pharyngeal elevator muscles (e.g., stylopharyngeus) also elevate the larynx (7) and serve to widen transverse UES diameter. Transverse UES widening occurs because
FIG. 9. Composite data from 8 group 1 subjects showing the effect of swallowed bolus volume on the timing of anterior hyoid and laryngeal movement, UES relaxation, and UES opening within the swallow sequence. Data from magnified images of the pharynx in group 1 subjects is plotted using the incisor to UES opening intervals measured from group 2 subjects in whom UES relaxation was not recorded. Dotted curves represent manometric profile of UES relaxation. With increases in bolus volume, the onset and peaks of anterior hyoid and laryngeal movement as well as UES relaxation and opening shift to the left so that in effect the sphincter opens earlier. TB, initial movement of tongue base; SH-0, superior hyoid movement; SL-0, onset superior laryngeal movement; AH-O, onset anterior hyoid movement; AL-O, onset anterior laryngeal movement; AL-P peak anterior laryngeal movement; AH-P, peak anterior hyoid movement; SL-P, peak superior laryngeal movement; SH-P, peak superior hyoid movement. Horizontal shaded bars indicate duration of UES opening for liquid boluses. Duration of opening is shown above the bar. Duration also judged for UES opening for a dry swallow (DS). The later was identified when a thin coating of barium outlined the mucosa of the pharynx and UES.

TABLE 4. Comparison of oral-pharyngeal peristaltic transit times measured by videoradiography and intraluminal manometry

<table>
<thead>
<tr>
<th>Swallowed Mid Tongue → Fauces</th>
<th>Fauces → Hypopharynx</th>
<th>Fauces → UES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume, ml</td>
<td>Video Manometry</td>
<td>Video Manometry</td>
</tr>
<tr>
<td>2</td>
<td>0.20±0.05 0.26±0.06</td>
<td>0.56±0.04 0.53±0.05</td>
</tr>
<tr>
<td>5</td>
<td>0.12±0.02 0.18±0.03</td>
<td>0.56±0.03 0.52±0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.12±0.02 0.13±0.03</td>
<td>0.50±0.01 0.53±0.02</td>
</tr>
<tr>
<td>20</td>
<td>0.10±0.01 0.10±0.02</td>
<td>0.46±0.01 0.50±0.04</td>
</tr>
</tbody>
</table>

Values are means ± SE in s from 7 group 2 subjects.

the superior attachment of the stylopharyngeus is lateral to its insertion on the hypopharynx. Oral excursion of the larynx during swallowing not only facilitates opening of the UES but also enlarges the pharynx to receive a swallowed bolus, engulfs the bolus, shortens the distance the bolus must travel, and protects the larynx against aspiration (11). The hyoid and larynx elevation achieved during swallowing in adults transiently recapitulates the high resting position of these structures that exists during infancy (22).

Pressure forces imparted by a swallowed bolus also contribute to UES opening. Although intrabolus pressure is not needed for the initiation of UES opening, it contributes to the magnitude of sphincter opening for bolus volumes ≥5 ml in size. For bolus volumes ≤2 ml, intraluminal bolus pressure at the instant of UES opening was virtually zero (Fig. 11), and minimal increase in sagittal UES diameter occurred after that of the initial opening (Fig. 4). For bolus volumes ≥5 ml, however, modest progressive increases occurred in opening pressure, flow pressure (above and within the sphincter), and maximal UES diameter. The contribution of intrabolus pressure to the magnitude of UES opening was particularly evident for bolus volumes of 10 and 20 ml, which are within the upper physiological range of normal. For such bolus volumes, traction and intrabolus pressure may act in concert for 0.1–0.25 s to open the sphincter further after its initial opening. After 0.1–0.2 s, when traction becomes maximal, however, further increases in UES diameter are accounted for only by intrabolus pressure alone, which acts as a radially distending force within the sphincter lumen.

Intrabolus opening pressure 1 cm proximal to the UES at the instant of sphincter opening and during transsphincter flow are normally within a low range of 0–20 mmHg. The low deglutitive pressure difference between the bolus and trachea has little tendency to cause aspiration. An important distinction exists between intrabolus pressure, which is normally low, and the high contractile pressure of >100 mmHg (9) within the collapsed segment of the hypopharyngeal peristaltic contraction wave. Pressures within the bolus and trailing...
UES OPENING

FIG. 10. Example of intrabolus pressure ~1 cm upstream from the UES prior to sphincter opening and during transsphincteric flow. Tracings shown for 2-, 5-, 10-, 20- and 30-ml barium swallows. Black horizontal bars indicate period of UES opening and transsphincteric flow. Hatched area under each pressure tracing indicates interval during which the bolus flowed by the transducer. The upstroke onset of the peristaltic pressure wave corresponded to the disappearance of the bolus tail.

FIG. 11. Relationship of upstream opening pressure and flow pressure to swallowed bolus volume. Composite data from 8 group 1 subjects. Bars plotted as means; black bars indicate SE. Mean value is given at top of each bar.

### TABLE 5. Intrabolus pressure and pressure across the UES associated with sphincter opening for different volumes of swallowed barium

<table>
<thead>
<tr>
<th>Bolus Volume, ml</th>
<th>Pressure Onset UES Opening</th>
<th>Bolus Pressure at Maximal UES Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
</tr>
<tr>
<td>0</td>
<td>0.1±1.0</td>
<td>−8.2±2.4</td>
</tr>
<tr>
<td>2</td>
<td>0.5±0.6</td>
<td>−7.8±2.4</td>
</tr>
<tr>
<td>5</td>
<td>4.4±1.8</td>
<td>−6.6±2.2</td>
</tr>
<tr>
<td>10</td>
<td>6.0±1.3</td>
<td>−7.2±3.3</td>
</tr>
<tr>
<td>20</td>
<td>10.0±2.6</td>
<td>−8.4±3.1</td>
</tr>
<tr>
<td>30</td>
<td>17.0±5.4</td>
<td>−7.8±3.4</td>
</tr>
</tbody>
</table>

Values are means ± SE for 8 group 1 subjects. Upstream, 1 cm proximal to UES; downstream, 1 cm distal to UES.
contracting segment are within two distinct domains (5a). The leading edge between these two domains is the upstroke of the peristaltic pressure complex that imparts a V-configuration to the bolus tail (25, 26). Hence, peristaltic transit time may be determined accurately by either videofluoroscopy or intraluminal manometry. Our data suggest that normally a swallowed barium bolus does not fall through the pharynx by gravity (5a, 8, 24) but rather is mainly pushed by peristalsis.

Approximations of maximal cross-sectional UES area for different bolus volumes were calculated for elliptical and barbell shapes. The barbell approximation of the open UES likely corresponds more closely to the actual area because the central zone of the open UES is flattened by the cricoid plate and cervical spine (7). For larger bolus volumes, increases in sphincter area seem to occur mainly in the lateral lobes of the sphincter because the sagittal trachea-to-spine distance reached a maximum value for a 10-ml bolus, whereas the maximum parasagittal diameter of the barium column increased progressively for bolus volumes up to 30 ml. Cross-sectional UES areas calculated by the ellipsoid method showed a close correlation to those calculated by the barbell method, thereby suggesting that the ellipsoid method gives a reasonable approximation.

When swallowed bolus volume was increased from 2 to 30 ml, mean flow rate through the pharynx and across the sphincter increased ~10-fold, whereas the velocity of pharyngeal peristalsis remained unchanged. Flow duration and intrabolus pressure showed only modest change. Thus the substantial increase in flow rate was achieved primarily through an increase in UES cross-sectional area. The modest volume-dependent increase in intrabolus pressure immediately above and within the UES during transsphincteric bolus flow serves as a radially distending force to increase the cross-sectional area of the hypopharynx and UES.

The pressure difference between intrabolus pressure in the hypopharynx (1 cm proximal to the UES) and in the cervical esophagus (1 cm distal to the UES) was found to decrease as bolus volume was increased from 2 to 30 ml (Table 5). The implications of this decrease merit analysis. The pressure difference across a segment such as the open UES is associated with two additive effects: 1) a decrease in pressure due to frictional losses (Poiseuille's law) and 2) a difference in pressure associated with a difference in cross-sectional area at the two measurement ports (Bernoulli effect). Estimates of frictional loss in pressure account for negligible pressure drop across the UES because UES area increases so substantially with increase in bolus volume. Therefore, the measured decreases in pressure differences across the UES as bolus volume was increased from 2 to 30 ml are likely due to changes in cross-sectional area in the hypopharynx and cervical esophagus such as that the relative area of the hypopharynx increases more than that of the cervical esophagus. The dimensions of both these areas increased with increases in bolus volume but were not quantified due to the problem of simulating hypopharyngeal geometry, and the cervical esophagus was often cut off on the videofluoroscopic recordings. These measurements, however, merit further study.

With swallowing, transient negative subatmospheric pressures occurred in the hypopharynx, UES and cervical esophagus. We attribute these negative pressures to the pharyngeal expansion and elongation of the cervical esophagus that occur during swallowing. Our observations support the notion that the resultant suction forces may assist bolus transport through the pharynx (3, 4) but only for a short interval early in the swallow sequence. Transient-negative pressures in the hypopharynx were observed only for dry or 2-ml swallows, probably because the arrival of a larger bolus masks the phenomenon. The transient-negative deglutitive pressures in the cervical esophagus were bolus independent. They occurred during superior movement of the closed sphincter and disappeared with the onset of sphincter opening. The transient-negative pressures within the UES we attribute to hyoid traction on the sphincter. This negative pressure disappears concurrent with UES opening.

With increases in swallowed bolus volume, the onsets of anterior hyoid and laryngeal movement, manometric UES relaxation, and UES opening all moved forward in time with respect to the initiation of oral peristalsis. Oral transit decreased with increases in bolus volume. In contrast, the timing and velocity of pharyngeal peristalsis and the relationship of pharyngeal peristalsis to UES closure were not affected by bolus volume. Because larger bolus volumes cause earlier laryngeal movement and UES opening while having minimal effect on the timing of sphincter closure, increases in bolus volume caused increments in the duration of manometric UES relaxation and opening.

The finding that bolus volume affects the timing and magnitude of many events associated with swallowing has implications about the control mechanism that executes swallowing. Some evidence from canine studies suggests that the pharyngeal and late oral phase of swallowing are a stereotyped patterned response, unaffected by the type of swallowing, programmed by the medullary swallowing centers (13, 22). In contrast, data from rabbits suggests that duration of pharyngeal constrictor responses is altered by the type of swallowing (5). Our data show that the timing, duration, and magnitude of many deglutitive events are modulated by the volume of a swallowed liquid bolus, albeit velocity of pharyngeal peristalsis was not affected. Bolus modulation of hyoid movement and other events begins while the bolus is still in the mouth. At present, however, it is not clear whether bolus modulation of deglutitive events occurs during swallowing or whether the central nervous system modification of swallowing is modified before swallow initiation. We speculate that modification originates from mechanoreceptors in the tongue that are deformed by an intraoral bolus.

To summarize, our study findings indicate that normal swallow-induced UES opening is governed by four factors: 1) relaxation of resting UES tone, 2) traction caused by anterior laryngeal movement and pharyngeal shortening, 3) pressure forces generated within the oncoming swallowed bolus, and 4) low compliance of the relaxed
UES that allows the cricopharyngeus to be easily stretched open by traction and low intrabolus pressure. Although UES relaxation is determined by transient central inhibition of resting central nervous system cricopharyngeal stimulation (12), physical opening of the sphincter occurs passively by traction and intrabolus pressure that act on the relaxed sphincter.

Clinical abnormalities of UES opening may be related to impaired UES relaxation, diminished traction caused by feeble laryngeal movement, impaired pharyngeal peristalsis, or reduced compliance of the UES musculature. Functionally, these abnormalities, either singularly or in combination, may lead to absent or incomplete UES opening, laryngeal aspiration, and increased residual in the pharynx. Such patients generally complain of dysphagia or choking.

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