Closure mechanisms of laryngeal vestibule during swallow

JERI A. LOGEMANN, PETER J. KAHRILAS, JOAN CHENG, BARBARA ROA PAULOSKI, PATRICIA J. GIBBONS, ALFRED W. RADEMAKER, AND SHEZHANG LIN
Departments of Communication Sciences and Disorders, Medicine and Cancer Center, Northwestern University, Evanston, Illinois 60208

Logemann, Jeri A., Peter J. Kahrilas, Joan Cheng, Barbara Roa Pauloski, Patricia J. Gibbons, Alfred W. Rademaker, and Shezhang Lin. Closure mechanisms of laryngeal vestibule during swallow. *Am. J. Physiol.* 262 (*Gastrointest. Liver Physiol.* 25): G338–G344, 1992.—This study examined the temporal effects of bolus volume on closure of the laryngeal vestibule at the arytenoid to epiglottic base and the mobile portion of the epiglottis, the temporal relationships between these levels of airway closure and cricopharyngeal opening for various bolus volumes, and the mechanisms responsible for these two levels of airway protection during deglutition. Closure of the laryngeal vestibule progressed inferiorly to superiorly at all bolus volumes. Duration of closure of the airway at the arytenoid to epiglottic base increased systematically with bolus volume, as did the duration of descent of the epiglottis below horizontal. Closure at the arytenoid to epiglottic base occurred earlier in relation to maximal laryngeal elevation as bolus volume increased. In contrast, descent of the epiglottis to horizontal and the temporal relationship between closure of the airway at the arytenoid to epiglottic base and cricopharyngeal opening were independent of bolus volume. These findings indicate a tightly organized neural program for some pharyngeal swallow events with systematic variability with volume in other pharyngeal events, possibly modulated by afferent input from the periphery. The neuromuscular mechanisms responsible for closure of the airway at the arytenoid to epiglottic base and at the mobile epiglottis appear to be quite different. Closure at the arytenoid to epiglottic base is apparently under direct neural control by active anterior tilting of the arytenoid cartilage and posterior projection of the epiglottic base as the larynx elevates, whereas epiglottic downward movement to closure is the biomechanical effect of hyolaryngeal movement, downward bolus movement, and tongue base retraction. In swallows of larger volumes, the leading edge of the bolus had passed the airway inlet before the airway closed at the epiglottic and arytenoid levels. Deviation of the bolus laterally around the airway, from the valleculae to the pyriform sinuses, is clearly a contributor to airway protection.

airway closure; laryngeal motion; hyoid motion; videofluoroscopy

LARYNGEAL FUNCTION DURING deglutition is usually considered the primary and most critical aspect of laryngeal physiology, providing protection for the airway from the entrance of food and liquid. This protection involves cessation of respiration with closure of the airway. Using radiographic examination, several investigators have observed a sequence of laryngeal closure during a swallow beginning with approximation of the true vocal folds, followed by closure at the level of the false folds and the superior tip of the arytenoid to the epiglottic base, and finally the mobile superior portion of the epiglottis (1–3, 6, 15, 18, 20, 22). However, because these investigators did not control the volume of material swallowed, systematic effects of bolus volume on duration of airway closure or the temporal organization of airway closure have not been defined.

Various control mechanisms have been hypothesized to underlie the various levels of airway closure (10, 14–17, 21). Epiglottic movement during a swallow has been thought to result from hyolaryngeal elevation and posterior movement of the tongue base. As the hyoid bone and larynx elevate, carrying the root of the epiglottis upward, and the tongue base retracts, the epiglottis is thought to fold over the top of the supraglottic area (7). Apposition of the arytenoids to the base of the epiglottis has been postulated to result from anterior tilt of the arytenoids (1). Laryngeal elevation, which carries the arytenoids upward, was thought to contribute to closure at this level. All of these hypotheses are derived from observations of radiographic studies of swallow, without quantitative analyses. Measurements of hyoid and laryngeal movement in relation to epiglottic position and tongue base retraction throughout the swallow should provide data to support or reject these theories. Similarly, measurements of the anterior movement of the arytenoid cartilage and the posterior bulge of the base of the epiglottis as they oppose one another to close the larynx at the false vocal fold level during the swallow can define the relative role of each structure in this level of airway protection. Also, quantified analyses of these levels of airway closure should contribute to our further understanding of the neural versus biomechanical mechanisms underlying control of each of these levels of laryngeal closure.

This study was undertaken with the goal of determining the temporal and biomechanical characteristics of laryngeal vestibular closure during a swallow as observed on videofluoroscopy in the lateral plane, and the systematic effects of bolus volume on these measures. Specifically, we were attempting to identify the mechanisms by which two levels of laryngeal closure are accomplished: epiglottic coverage of the larynx and supraglottic closure at the level of the arytenoid to the epiglottic base. It is these two levels of airway protection that are consistently visible on lateral fluoroscopy and prevent the entry of food to the true vocal fold level (1, 23).

METHODS

Eight young adult men between the ages of 22 and 28 yr without present or past history of swallowing problems served as subjects for this study. Concurrent videofluoroscopic and manometric studies of swallowing were conducted late in the afternoon at least 4 h after a meal. The study protocol was approved by the Northwestern University Institutional Review Board.

During recording sessions, subjects were seated in a chair fitted with a headrest similar to that of a dental chair, minimizing head movement throughout the study. A 3-mm diam flexible catheter containing two radio opaque markers spaced 3 cm apart was positioned transnasally so that both markers

were visible in the pharynx throughout the study (see Fig. 1). Lateral videofluoroscopic studies were completed with the fluoroscopic tube focused on the tip of the tongue anteriorly, the cervical vertebra posteriorly, the hard palate superiorly, and the subglottic air column inferiorly (11). A lead letter "x" was taped to the skin over C6 and included in the fluoroscopic field to serve as the stationary origin of an image based *x-y* coordinate system used in the analysis of swallow-related laryngeal movements from fluoroscopy. The fluoroscopic image was displayed on a monitor and recorded with a video cassette recorder (Sony U-matic, model VO-5600) at 60 fields/s. Temporal information was encoded on the videotape with a counter-timer at 0.01-s intervals (Thalner Electronics). Each subject completed two swallows each of 1, 5, 10, and 20 ml of liquid barium (E-Z Paque Barium Sulfate Suspension, E-Z EM, Westbury, NY) mixed with water in a two-thirds barium to one-third water formula. The liquid barium was placed in the mouth with a syringe, and subjects were instructed to hold the barium over the tongue until the swallow command at which time they should swallow it as a single bolus. If a subject double swallowed, aspirated, experienced bolus penetration into the laryngeal inlet, or technical problems occurred, an additional swallow of the same volume was obtained. Aspiration was seen on one swallow, and penetration occurred on two swallows of these normal young adults. These swallows were not included in the analysis.

Four types of measures were made from the videofluoroscopic recordings of each swallow: *1*) the timing of key movements of the epiglottis in relation to closure of the airway at the arytenoids to epiglottic base and onset of opening of the cricopharyngeal region or upper esophageal sphincter (UES); *2*) extent and timing of tongue base movement toward the posterior pharyngeal wall; *3*) location of the bolus head at key points of airway closure and reopening; and *4*) spatial analysis of hyolaryngeal movements.

Timing of epiglottic movement, initial cricopharyngeal opening, and initial closure of the arytenoid to epiglottic base. The videofluoroscopic images of each swallow were examined in slow motion to obtain timing information on the following epiglottic movements: *1*) onset of downward movement, *2*) horizontal position, *3*) maximally lowered position, *4*) onset of upward movement, *5*) return to horizontal, and *6*) return to rest. The onset of closure of the arytenoid to epiglottic base was also noted. Timing of these key epiglottic movements was then correlated with the onset of closure of the airway at the arytenoid to epiglottic base established as time 0.0 s. Thus epiglottic movements that occurred before first closure at the arytenoid to epiglottic base were given negative times, whereas those occurring after the arytenoid to epiglottic base closure were given positive times. Onset of cricopharyngeal (UES) opening was also measured relative to the onset of closure of the arytenoid to epiglottic base.

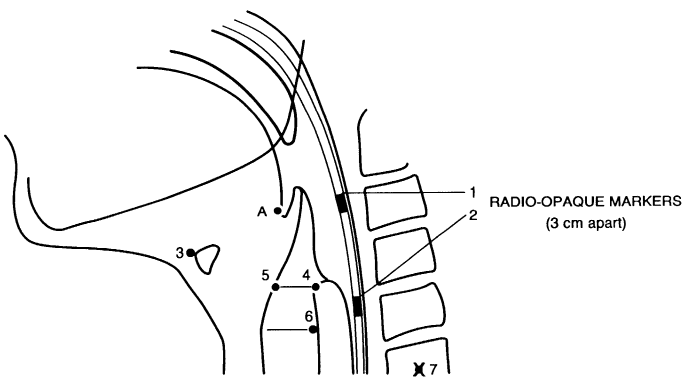

Fig. 1. Tracing from a videoprint of oral cavity and pharynx (lateral radiographic view) with anatomic points of interest marked and labeled, including *1–2*) anterior-superior corner of 2 radiopaque markers (3 cm apart); *3*) anterior superior corner of hyoid bone; *4*) anterior superior corner of arytenoid cartilage; *5*) posterior surface of epiglottis; *6*) posterior-superior corner of subglottic air column; and 7) anchor point (center of lead letter "x" taped to subject's neck). *A*: point on tongue base that was tracked as it moved posteriorly to pharyngeal wall. *Points 4* and *5* were tracked over time to define closure of laryngeal vestibule at arytenoid (*4*) to epiglottic base (*5*).

Extent of tongue base movement. On a videoframe showing the oropharynx at rest with no bolus in the mouth, the distance between the tongue base at a level 3 mm above the vallecular pit and the posterior pharyngeal wall was measured for each subject. The absolute distance toward the pharyngeal wall achieved by the tongue base as it retracted over the bolus in the pharynx during each swallow was calculated on the video frames showing the epiglottis in each of the following positions: *1*) horizontal; *2*) maximal lowering; *3*) first upward movement from maximal lowering; and *4*) return to horizontal. Position of the tongue base at each of these epiglottic positions was then calculated for each patient as a percentage of the total distance between their tongue base and the pharyngeal wall at rest. One hundred percent tongue base movement indicated contact with the pharyngeal wall. The location on the tongue base at which these measurements was made is indicated in Fig. 1 as *point A*.

Bolus location. The position of the leading edge of the bolus (the bolus head) was identified at the moment when the epiglottis initiated its downward movement, when the epiglottis reached horizontal, at the first closure of the arytenoid to epiglottic base, and at the moment at which the arytenoid to epiglottic base reopened after the swallow. The position of the end of the bolus (the bolus tail) when the arytenoid to epiglottic base reopened was also noted.

Spatial analysis. Spatial analysis of the videofluoroscopic swallowing sequences was accomplished using an interactive computer program written to enable *x-y* coordinate determination of selected structures on each video frame (13). For each swallow, 50 sequential frames (at 1/30 s intervals), selected so as to encompass critical events in the pharyngeal swallow, were analyzed. Each of these video images was digitized using an IBM PC-AT computer equipped with an image digitization board (Data Translation Frame Grabber, model DT 2851, IBM, Marlboro, MA.). The digitized image had a configuration of 512×512 pixels with 8 bits per pixel, thereby allowing for 256 increments on a gray scale. The program allowed the user to position a cross-hair cursor on anatomic points of interest on each video frame and then mark these points for subsequent calculations. The position of the two radiopaque markers 3 cm apart in the catheter corrected for fluoroscopic magnification by providing distance calibration in the midline of the pharynx, against which movement of pharyngeal structures could be measured. For this analysis, the following points were marked, as illustrated in Fig. 1: *1–2*) the anterior-superior corner of the two radiopaque markers, which were 3 cm apart; *3*) the anterior-superior corner of hyoid bone; *4–5*) the laryngeal entrance at the anterior superior corner of the arytenoid cartilage and the posterior surface of the epiglottis opposite the anterior superior corner of the arytenoid; *6*) the posterior superior corner of the subglottic air column; and 7) the anchor point (center of the lead letter "x" taped to the subject's neck).

After these data points were marked on each digitized video image, the coordinates were computed. The origin of the coordinate system was taken as the anchor point, which moves with the subject. The angle defined by the radiopaque markers on the catheter established the vertical axis of the coordinate system. Thus the analysis yielded the x and y coordinates of each data point (in mm) on each digitized frame of the swallow sequence corrected for magnification, head tilt, and head movement. Identifying these data points allowed us to track, plot,

and measure vertical and anterior hyoid and laryngeal position throughout the swallow, as well as closure of the airway at the level of the arytenoid to epiglottic base. The onset of downward epiglottic movement, horizontal epiglottic position, and location of the tongue base and bolus at specific times during each swallow were then marked on these plots of hyoid and laryngeal movement.

For all measures, numerical data across swallows of the same volume were averaged and expressed as means ± SE. Statistical comparisons among conditions or parameters were done with analysis of variance and correlational analysis as appropriate (19). In all cases, significance levels of 0.05 were considered statistically significant.

RESULTS

Previous investigators have described laryngeal closure as occurring inferiorly to superiorly (1–3, 6, 15, 18, 20, 22). Therefore, airway closure was first examined at the arytenoid to epiglottic base, and timing of movements of the epiglottis was examined in relation to closure at this level.

Effects of bolus volume on airway closure. The durations of laryngeal closure at the arytenoid to the epiglottic base during swallows of four volumes of liquid barium are presented in Table 1. Duration of laryngeal closure at this level increased significantly with bolus volume increase. Closure at this level of the airway occurred earlier relative to maximal laryngeal elevation as bolus volume increased (Table 1). Differences between 1 vs. 10 ml and 5 vs. 20 ml volumes were statistically significant ($P = 0.05$ level). The relatively large standard error in the timing of arytenoid to epiglottic base closure relative to the onset of maximal laryngeal elevation reflects a large intra- and intersubject variability. Reopening of the airway at the arytenoid to epiglottic base occurred at a relatively constant 0.06–0.09 s (±0.02) after the larynx began to descend from maximal elevation for all bolus volumes. Onset of cricopharyngeal opening always occurred within one videoframe (±0.03 s) of closure of the airway at the arytenoid to epiglottic base, regardless of bolus volume.

Table 2 presents the timing of epiglottic descent from rest position in relation to closure of the airway at the arytenoid to epiglottic base at each bolus volume. The epiglottis began its descent 0.11 to 0.14 s before closure of the airway at the arytenoid to epiglottic base was accomplished independent of bolus volume. Duration of epiglottic descent to horizontal was also independent of bolus volume. The epiglottis reached horizontal within 0.02 s of airway closure at the arytenoid to epiglottic base, regardless of bolus volume. In contrast, maximal lowering of the epiglottis occurred increasingly later than closure of the arytenoid to epiglottic base as bolus volume increased, as did the initiation of upward epiglottic movement, its return to horizontal, and the moment when the epiglottis was first free of the contact with the posterior pharyngeal wall. Once the epiglottis was free of contact with the posterior pharyngeal wall, it consistently returned to its vertical rest position within 0.03 s.

Position of bolus at time of closure of laryngeal vestibule. The position of the bolus head at the initial descent of the epiglottis and the first closure of the arytenoid to epiglottic base were similar over the eight subjects examined and changed systematically with an increase in bolus size. With 1-ml boluses, the bolus head was high in the pharynx, 16.5 mm (±5.4) above the pit of the valleculae, at the time of initial epiglottic descent. With 5-ml boluses, the leading edge of the bolus reached the superior surface of the arytenoid cartilage 1 mm (±2.2) above the vallecular pit when the airway closed at the arytenoid to epiglottic base. The most marked change of position was noted between 5- and 10-ml boluses. During 10-ml swallows, the leading edge of the bolus was consistently located at the middle of the hypopharynx, 21 mm (±3.2) below the valleculae, and with 75% of the 10 ml swallows, the bolus head had reached the open pharyngoesophageal (PE) junction when the airway closed at the arytenoid to epiglottic base. The leading edge of the bolus had always reached the PE junction on 20-ml swallows at the time of initial closure of the arytenoid to epiglottic base, 26 mm (±4.2) below the valleculae. In all cases, the entire bolus had passed through the cricopharyngeal segment when the arytenoid to epiglottic base reopened after the swallow.

Closure at arytenoid to epiglottic base. Movement of the arytenoid cartilage and epiglottic base toward each other to achieve closure of the airway at this level is plotted from the spatial analysis for small (1 ml) and large (20 ml) volume boluses for the eight subjects in Fig. 2. Spatial analysis of the 5- and 10-ml swallows revealed the same pattern. The average anterior-posterior distance between the arytenoid and the posterior surface of the epiglottis in these eight young adult male subjects was 19.5 ± 1.1 mm. Anterior tilting of the arytenoid accounted for one-third to one-half of the closure. Reopening of the airway occurred as a result of the arytenoid tilting back to its rest position and the epiglottic base diminishing in thickness, as shown in Fig. 2. Figure 2 also illustrates the

Table 1. *Duration of laryngeal closure from arytenoid to epiglottic base, timing of onset of maximal laryngeal elevation, and timing of onset of cricopharyngeal opening in relation to initial closure of larynx at arytenoid to epiglottic base for swallows of 4 vol for 8 subjects*

	1-ml swallow	5-ml swallow	10-ml swallow	20-ml swallow
Duration of laryngeal closure, s*	0.48(±0.05)	0.50(±0.02)	0.61(±0.06)	0.58(±0.03)
Relationship to onset of maximal laryngeal elevation*	−0.06(±0.02)	−0.08(±0.02)	−0.11(±0.02)	0.15(±0.02)
Onset of cricopharyngeal opening	0.02(±0.03)	0.00(±0.03)	0.02(±0.02)	0.00(±0.03)

Values are means ± SE. Negative value indicates that arytenoid to epiglottic base closed before larynx first reached maximal elevation.
* $P < 0.05$ by 2-way analysis of variance.

Table 2. *Effect of bolus volume on timing of epiglottis excursion relative to closure at arytenoid to epiglottic base (time 0.0 s)*

Epiglottic Position	Bolus Volume, ml			
	1	5	10	20
Starts descent	−0.11(±0.01)	−0.12(±0.01)	−0.13(±0.01)	−0.14(±0.02)
Reaches horizontal	−0.01(±0.02)	−0.02(±0.01)	−0.01(±0.02)	0.01(±0.02)
Maximally lowered*	0.09(±0.02)	0.14(±0.02)	0.13(±0.02)	0.18(±0.02)
Starts upward*	0.19(±0.02)	0.22(±0.02)	0.36(±0.03)	0.41(±0.04)
Returns to horizontal*	0.49(±0.02)	0.55(±0.02)	0.62(±0.03)	0.65(±0.03)
First free of pharyngeal wall*	0.57(±0.03)	0.60(±0.03)	0.67(±0.03)	0.72(±0.03)
Returns to rest*	0.60(±0.04)	0.62(±0.03)	0.70(±0.04)	0.75(±0.03)

Values reported are means ± SE. * $P < 0.05$ by 2-way analysis of variance.

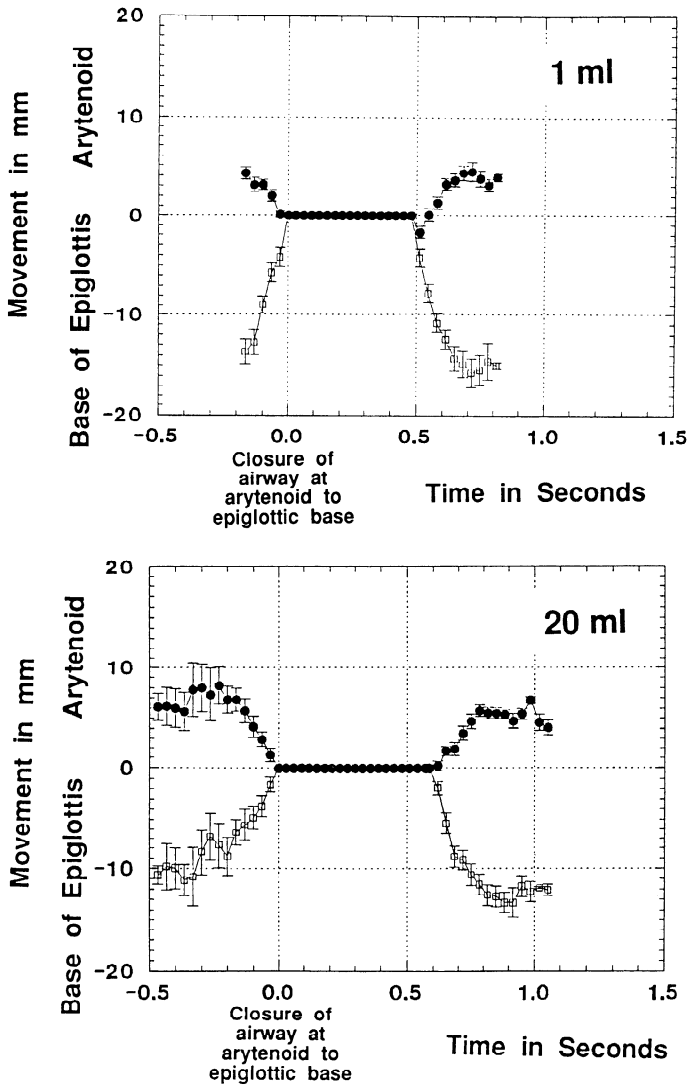

Fig. 2. Pattern of closure and reopening (means ± SE) of airway at level of epiglottic base and arytenoid for 1- and 20-ml swallows. Filled circles, position of arytenoid; open squares, position of base of epiglottis. *Time 0.0*, onset of closure of airway at this level. *Position 0* is coordinate of closure. Pattern of closure seen on these 2 vol was representative of that seen on 5- and 10-ml swallows.

prolonged duration of closure of the airway at the arytenoid to epiglottic base on swallows of larger volume. Closure at this level did not begin earlier but persisted longer for the larger volume (Fig. 2).

Mechanisms of epiglottic movement. Analysis of epiglottic movement in relation to movement patterns of the hyoid, larynx, and tongue throughout the swallow revealed three distinct major components of epiglottic movement: *1*) onset of descent to horizontal, *2*) movement below horizontal and return to horizontal, and *3*) return to rest position.

Onset of descent to horizontal. To determine the factors most highly correlated with onset of downward epiglottic movement to a horizontal position, a Pearson correlation matrix (19) was generated for each bolus volume. The anterior and vertical position of the hyoid and larynx and bolus position at the time of onset of epiglottic descent were used, because these factors have been hypothesized to affect epiglottic descent (7). Results of this correlation matrix for each bolus volume are presented in Table 3. Different factors correlated with the onset of epiglottic descent during swallows of small and large volume. With 1- and 5-ml boluses, the anterior and vertical position of the larynx and the position of the bolus head when the epiglottis began its descent were significantly correlated with the onset of downward epiglottic movement. At the 10- and 20-ml volumes, only bolus position was significantly correlated with the onset of epiglottic descent. As bolus volume increased to 10 and 20 ml, the bolus had progressed lower in the pharynx at the time the epiglottis began its descent and so exerted greater influence on epiglottic movement than did hyoid or laryngeal position.

Descent below horizontal and return to horizontal. Figure 3 gives the relationship between tongue base retraction to the posterior pharyngeal wall and epiglottic descent below horizontal and return to rest. The epiglottis always moved just below horizontal when the tongue base was retracted 67% (±2) of the distance toward the posterior pharyngeal wall. The epiglottis was maximally lowered when the tongue base achieved 100% contact

Table 3. *Correlation coefficients between initiation of epiglottic descent and onset of movement of hyoid, larynx, and bolus*

Onset of Movement	1 ml	5 ml	10 ml	20 ml
Vertical hyoid	0.44	0.04	0.11	0.17
Anterior hyoid	0.17	0.11	0.21	0.41
Vertical larynx	0.61*	0.69*	0.43	0.38
Anterior larynx	0.72*	0.57*	0.47	0.22
Bolus head	0.88*	0.83*	0.60*	0.70*

* $P < 0.05$.

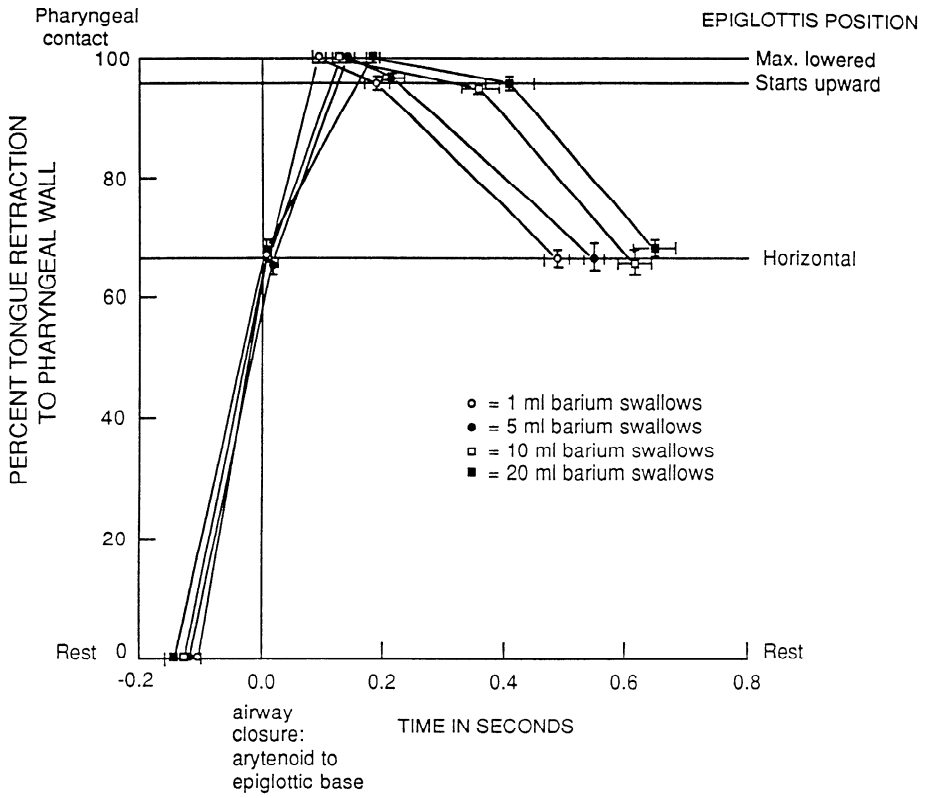

Fig. 3. Epiglottic descent to horizontal, maximal lowering and return to horizontal in relation to timing of percent (means ± SE) of tongue base retraction across pharyngeal space for all volumes and onset of airway closure at arytenoid to epiglottic base (*time 0.0*). Rest position of tongue base is scored as 0, whereas contact of tongue base to pharyngeal wall is scored as 100% retraction.

with the posterior pharyngeal wall. As the tongue base retracted 4% (± 0.5) from the posterior pharyngeal wall toward its rest position, the epiglottis began its ascent. The epiglottis returned to just below its horizontal position when the tongue base returned to the location 66% (±2) of the way from its rest position regardless of bolus volume. Tongue base retraction to the pharyngeal wall always occurred later for larger bolus volumes and corresponded to the temporal changes observed in epiglottic descent below horizontal as a result of changes in bolus volume as shown in Fig. 3. Apparently, the retraction of the tongue base to the pharyngeal wall determined the time of epiglottic descent below horizontal by pushing the epiglottis further downward against the posterior pharyngeal wall and accounted for the longer epiglottic descent below horizontal as bolus volume increases.

Return to rest. The return to rest position of the epiglottis began when the tip of the epiglottis was free of contact with the pharyngeal wall. From that time until the epiglottis returned to its rest position was 0.03 to 0.06 s (see Table 2), and was accomplished entirely as a result of the elastic properties of the cartilage.

DISCUSSION

Timely and complete closure of the airway is vital to successful swallowing. This investigation was designed to examine the temporal characteristics and mechanics of airway closure at the laryngeal vestibule, i.e., the epiglottis and arytenoid to epiglottic base, during swallow. Our results support previous observations that airway closure during deglutition progresses inferiorly to superiorly, in that arytenoid to epiglottic base closed first, followed rapidly by the epiglottis reaching maximal lowering (1–3, 6). However, the epiglottis begins its downward descent at least a tenth of a second before closure at the arytenoid to epiglottic base.

In swallows of larger volumes, the leading edge of the bolus had passed the airway inlet before the airway closed at the epiglottic and arytenoid levels, but penetration of liquid into the airway is a relatively unusual event. The concept of sphincteric laryngeal closure as the only protection for the airway (1–3, 6, 15) is too simplistic to account for this phenomenon. The deviation of the bolus laterally around the airway, from the valleculae to the pyriform sinuses, is clearly a contributor to airway protection.

Bolus volume affected a number of measures of closure of the laryngeal vestibule. Duration of airway closure at the arytenoid to epiglottic base increased with larger bolus volumes and occurred earlier relative to maximal laryngeal elevation as bolus volume increased. Movement of the epiglottis below horizontal occurred significantly later as bolus volume increased. This latter change was apparently mediated by posterior tongue base retraction that also occurred later on larger volumes. We have also observed progressively later tongue base retraction with larger volumes in a previous study (8). Systematic change in timing of tongue base retraction is necessary to accommodate the passage of a large bolus, because tongue base retraction occurs after the entire bolus is in the pharynx below the tongue base. Discrepancies in the literature regarding the influences of the bolus vs. biomechanics on epiglottic movement are probably the result of not having controlled bolus volume.

Previous investigators have documented other aspects of the pharyngeal swallow, which increase with increasing bolus volume, including UES opening and vertical

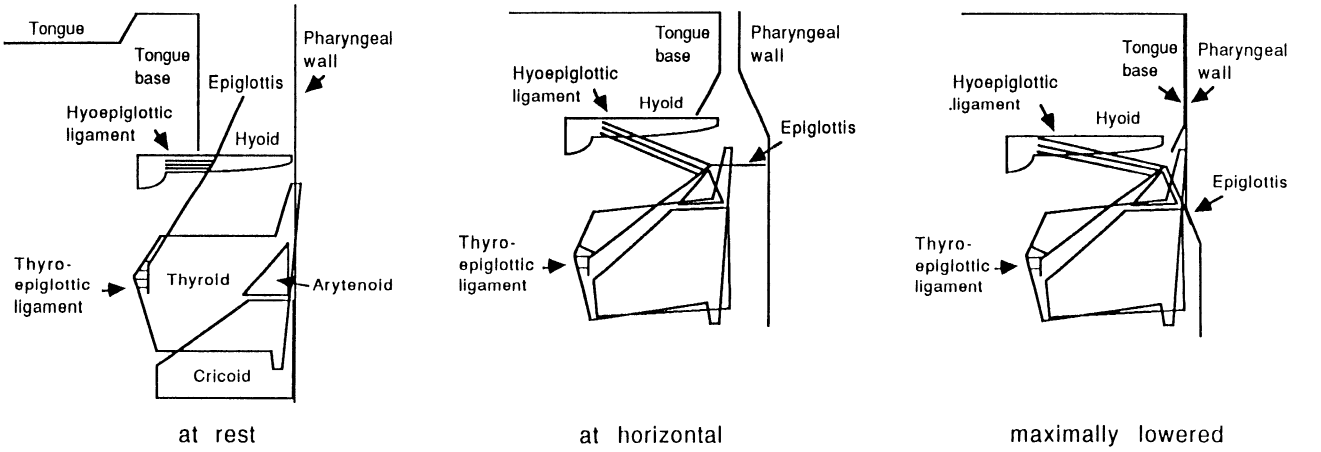

Fig. 4. Schematic drawing of descent of epiglottis from rest to maximal lowering, illustrating ligamentous attachments of epiglottis to thyroid cartilage and hyoid bone. Larynx has elevated and moved anteriorly as epiglottis reaches horizontal. Epiglottis appears to fold over apex of arytenoid cartilage and is maximally lowered when tongue base is in contact with pharyngeal wall.

laryngeal movement (5, 9). The systematic effects of bolus volume are hypothesized to be modulated by afferent input from the oral cavity, perhaps from proprioceptive receptors in the tongue, because the tongue is contoured differently to accommodate larger volumes of material.

Although several key aspects of closure of the airway at the arytenoid to epiglottic base and movement of the epiglottis below horizontal were affected by bolus volume, timing of the descent of the epiglottis from rest to horizontal did not change with bolus volume. These results are similar to those of Cook et al. (4), who found that some aspects of the opening mechanisms of the upper esophageal sphincter were not affected by bolus volume, whereas other factors were affected systematically by bolus size.

Cricopharyngeal (UES) opening always occurred within ±0.03 s of airway closure at the level of the arytenoid to the epiglottic base, regardless of bolus volume. Duration of both measures increased systematically with larger bolus volumes. UES opening and airway closure apparently are a portion of the tightly organized neural swallow program elicited at the brain stem swallow center.

The mechanisms controlling the two levels of airway closure examined here (closure of the arytenoid to epiglottic base and epiglottic descent) appear to be quite different. Closure at the arytenoid to epiglottic base appears to be related to active neuromuscular control, because it requires active anterior tilting of the arytenoid, probably the result of contraction of thyroarytenoid and supraglottic musculature. The posterior bulging at the base of the epiglottis is likely the biomechanical result of thickening of the epiglottis as the larynx elevates and of the increased posterior tilt of the epiglottis at the more superior level. These data are corroborated by observations of anterior arytenoid tilting to the epiglottic base made with simultaneous endoscopy and videofluoroscopy by Shaker et al. (22). The observation that closure at the arytenoid to epiglottic base occurs earlier in relation to onset of maximal laryngeal elevation as bolus volume increases and that this timing varies greatly within and between subjects suggests that closure of the airway at the arytenoid to epiglottic base is under active neuromuscular control rather than the biomechanical effect of laryngeal elevation. If laryngeal elevation were responsible for closing the airway at the arytenoid to epiglottic base, closure would always occur at the same time relative to maximal elevation, which it did not.

In contrast with the presumably active neuromuscular closure at the level of the arytenoid to epiglottic base, evidence from this study indicates that epiglottic descent to horizontal is the biomechanical effect of laryngeal elevation and anterior movement, bolus pressure, and tongue base retraction. The biomechanical effects of vertical and anterior laryngeal movement are likely created by the ligamentous attachments of the epiglottis to the thyroid cartilage, as shown in Fig. 4. The base of the epiglottis is attached to the thyroid cartilage at the thyroid angle. Approximately two-thirds of the way up from this inferior attachment, the epiglottis attaches to the hyoid by the hyo-epiglottic ligament. During a swallow, as the larynx moves forward the base of the epiglottis moves with it, contributing to the onset of the downward tilt of the epiglottis toward horizontal. As the larynx lifts and the bolus descends onto the upper half of the epiglottis, the result is a "foldover effect" on the mobile upper half of the epiglottis. Once the epiglottis reaches horizontal, its movement further downward and back to rest are no longer related to hyolaryngeal position. At the time the epiglottis is horizontal, it is carried posteriorly by the retracting tongue base, which brings the tip of the epiglottis in contact with the posterior pharyngeal wall. As the tongue base continues to retract, the epiglottis is crushed between the pharyngeal wall and the tongue base, forcing the epiglottis to its maximally lowered position. As shown in Fig. 4, the epiglottis appears to fold over the superior tip of the arytenoid cartilage. Return to rest position of the epiglottis depends on the release or anterior movement of the tongue base as it

returns to rest and the elastic properties of the epiglottic cartilage. Timing of the epiglottic return to rest once free of the pharyngeal wall may provide a test of cartilage pliability.

Findings from this study suggest that movements of the epiglottis are secondary biomechanical effects of laryngeal and bolus movement and tongue base retraction, whereas airway closure at the arytenoid to epiglottic base is under direct neural control as a part of the pharyngeal swallow complex initiated at the medullary swallow center.

Identification of those pharyngeal swallow events that are under direct neural control and those movements that are the secondary or biomechanical effects of other events and the temporal relationships of these events in normal swallowing will facilitate the development of new treatment techniques and maneuvers for dysphagic patients (12), as well as provide new insights into the neural control of deglutition.

This project was supported by National Cancer Institute Grant P01-CA-40007.

Address for reprint requests: J. A. Logemann, Northwestern Univ., Dept. of Communication Sciences and Disorders, 2299 Sheridan Rd., Evanston, IL 60208.

Received 1 March 1991; accepted in final form 9 September 1991.

REFERENCES

1. **Ardran, G. M., and F. H. Kemp.** The protection of the laryngeal airway during swallowing. *Br. J. Radiol.* 25: 406–416, 1952.
2. **Ardran, G. M., and F. H. Kemp.** The mechanism of the larynx II. The epiglottis and closure of the larynx. *Br. J. Radiol.* 40: 372–389, 1967.
3. **Ardran, G. M., and F. Kemp.** Closure and opening of the larynx during swallowing. *Br. J. Radiol.* 29: 205–208, 1956.
4. **Cook, J., W. J. Dodds, R. O. Dantas, B. Massey, M. K. Kern, I. M. Lang, J. G. Brasseur, and W. J. Hogan.** Opening mechanisms of the human esophageal sphincter. *Am. J. Physiol.* 257 (*Gastrointest. Liver Physiol.* 20): G748–G759, 1989.
5. **Dantas, R., M. Kern, B. Massey, W. J. Dodds, P. Kahrilas, J. Brasseur, I. Cook, and I. Lang.** Effect of swallowed bolus variables on oral and pharyngeal phases of swallowing. *Am. J. Physiol.* 258 (*Gastrointest. Liver Physiol.* 21): G675–G681, 1990.
6. **Ekberg, O.** Closure of the laryngeal vestibule during deglutition. *Acta Otolaryngol.* 93: 123–129, 1982.
7. **Ekberg, O., and S. Sigurjonsson.** Movement of the epiglottis during deglutition. *Gastrointest. Radiol.* 7: 101–107, 1982.
8. **Jacob, P., P. Kahrilas, J. Logemann, V. Shah, and T. Ha.** Upper esophageal sphincter opening and modulation during swallowing. *Gastroenterology* 97: 1469–1478, 1989.
9. **Kahrilas, P. J., W. J. Dodds, J. Dent, J. A. Logemann, and R. Shaker.** Upper esophageal sphincter function during deglutition. *Gastroenterology* 95: 52–62, 1988.
10. **Logemann, J. A.** *Evaluation and Treatment of Swallowing Disorders.* San Diego: College Hill, 1983.
11. **Logemann, J. A.** *Manual for the Videofluorographic Study of Swallowing.* San Diego: College Hill, 1986.
12. **Logemann, J. A., and P. J. Kahrilas.** Relearning to swallow post CVA: application of maneuvers and indirect biofeedback: a case study. *Neurology* 40: 1136–1140, 1990.
13. **Logemann, J. A., P. J. Kahrilas, J. Begelman, W. J. Dodds, and B. R. Pauloski.** Interactive computer program for biomechanical analysis of videoradiographic studies of swallowing. *Am. J. Roentgenol.* 153: 277–280, 1989.
14. **Mosher, H. P.** X-ray study of movements of the tongue, epiglottis, and hyoid bone in swallowing, followed by a discussion of difficulty in swallowing caused by retropharyngeal diverticulum, postcricoid webs and exostoses of cervical vertebrae. *Laryngoscope* 37: 235–62, 1927.
15. **Negus, V. E.** *Comparative Anatomy and Physiology of the Larynx.* London: Heinemann, 1949.
16. **Negus, V. E.** *The Mechanism of the Larynx.* St. Louis, MO: Mosby, 1929.
17. **Pressman, J. J., and G. Kelemen.** Physiology of the larynx. *Physiol. Rev.* 35: 506–554, 1955.
18. **Ramsey, G. H., J. W. Watson, R. Gramiak, and S. A. Weinberg.** Cinefluorographic analysis of the mechanism of swallowing. *Radiology* 64: 498–518, 1955.
19. **Rosner, B.** *Fundamentals of Biostatistics* (2nd ed). Boston, MA: Duxbury, 1986, p. 409, 444.
20. **Rushmer, R. F., and J. A. Hendron.** The act of deglutition: a cinefluorographic study. *J. Appl. Physiol.* 3: 622–630, 1951.
21. **Sasaki, C. T., and G. Isaacson.** Functional anatomy of the larynx. *Otolaryngol. Clin. North Am.* 21: 595–612, 1988.
22. **Saunders, J. B., C. Davis, and E. G. Miller.** The mechanism of deglutition (second stage) as revealed by cineradiography. *Ann. Otorhinol.* 60: 897–918, 1951.
23. **Shaker, R., W. Dodds, R. Dantas, W. Hogan, and R. Arndorfer.** Coordination of deglutitive glottic closure with oropharyngeal swallowing. *Gastroenterology* 98: 1478–1484, 1990.