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# Biomechanical Analysis of the Pharyngeal Swallow in Postsurgical Patients With Anterior Tongue and Floor of Mouth Resection and Distal Flap Reconstruction

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The purpose of this study was to examine changes in the biomechanics of pharyngeal swallow after surgery in eight patients (six men and two women) with anterior tongue and floor of mouth resections with distal flap reconstruction. Eight normal age-matched subjects were also studied. Swallowing performance was assessed following a standardized protocol with videofluoroscopy preoperatively and at 1 and 3 months postoperatively for the oral cancer patients. The normal subjects received a single videofluoroscopic study. Computer-assisted biomechanical analysis was used to mark the movements of specific oropharyngeal structures over time throughout the swallow of calibrated boluses. Statistical analyses revealed that tongue base, pharyngeal wall, hyoid, laryngeal, and cricopharyngeal movements during the swallow were altered significantly after surgery for the cancer patients. Some oropharyngeal structural movements differed from those of normal control subjects before surgery. In this study, biomechanical measures indicated that there was recovery in some aspects of the pharyngeal swallow in this patient group. The duration of tongue base to pharyngeal wall contact, which was significantly reduced preoperatively and at 1 month after surgery, increased significantly to within normal levels by the 3-month postoperative evaluation. Duration of laryngeal closure and the onset of laryngeal closure relative to cricopharyngeal opening also improved significantly to within normal levels by the 3-month postoperative evaluation.

**KEY WORDS: dysphagia, biomechanical, postsurgical, oropharyngeal cancer, recovery**

The tongue has been identified as the primary element in bolus propulsion through the oral cavity and oropharynx (Cerenko, McConnel, & Jackson, 1989; Kahrilas & Logemann, 1993; Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993; Kennedy & Kent, 1985; Logemann, 1989a; Shawker, Sonies, Hall, & Baum, 1984; Shawker, Sonies, Stone, & Baum, 1983; Stone & Shawker, 1986; Wein, Bockler, & Klajman, 1991). Bolus transit has been described as the result of the synergistic action of the oropharyngeal propulsion pump, in which the tongue is the major force generating bolus driving pressure, and the hypopharyngeal suction pump, the negative pressure preceding the bolus during laryngeal elevation (Cerenko et al., 1989). Ultrasound studies of the swallow in midsagittal view have described bolus propulsion as a wave down the center of the tongue, ending with a posterior thrust of the back of the tongue contacting the posterior pharyngeal wall, resulting in the injection of the bolus into the pharynx (Shawker et al., 1983). In a biplane fluoroscopic-manometric study of deglutitive tongue function, Kahrilas et al. (1993) found that complex, graded oral and base of tongue movements were necessary for bolus propulsion. During a normal swallow, the tongue tip is anchored against the anterior alveolar ridge and hard

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palate, while the periphery of the tongue surface is sealed against the lateral alveolar ridge, forming a pulsion chamber between the midtongue and palate (Hamlet, 1989; Kahrilas et al., 1993; Stone & Shawker, 1986). The central portion of the oral tongue exhibits first centripetal (away from the palate) followed by centrifugal (toward the palate) motion to produce propulsion of the bolus from the mouth into the pharynx (Kahrilas et al., 1993; Stone & Shawker, 1986; Wein, Bockler, & Klajman, 1991). When the bolus tail reaches the top of the tongue base, the initial pharyngeal bolus driving force is generated by the tongue base moving rapidly posteriorly, acting like a plunger; pharyngeal wall contraction then begins with the posterior and lateral walls moving inward toward the posteriorly moving tongue base, so that the tongue base and pharyngeal walls make contact (Jacob, Kahrilas, Logemann, Shah, & Ha, 1989; Shawker et al., 1983). The pharyngeal wall contraction then continues progressively downward to the upper esophageal sphincter (Kahrilas, Logemann, Lin, & Ergun, 1992).

Postoperative oral and oropharyngeal cancer patients may experience a range of tongue function disturbances, including impaired tongue control of the bolus and reduced oral tongue to palate contact, lateralization, and tongue base movement (Hamlet, Jones, Mathog, Bolton, & Patterson, 1988; Haribhakti, Kavarana, & Tibrewala, 1993; Logemann, 1983, 1989a, 1989b). Inability to anchor the resected tongue along the perimeter of the alveolar ridge would prevent the formation of the oral cavity chamber required for bolus propulsion and eventual onset of pharyngeal propulsion. Given the importance of tongue function in the transport of the bolus through the oral cavity and pharynx, it would seem likely that patients with anterior tongue resections should demonstrate some disruption of both the oral and pharyngeal swallow. Previous temporal analysis of videofluoroscopic assessments of oropharyngeal swallowing (Pauloski et al., 1993) revealed that patients with resections of the anterior tongue and floor of mouth reconstructed with distal flap closure demonstrated a significant and severe impairment in swallowing function after surgery, with no significant recovery of function by 3 months post-healing. Significantly increased oral transit times and large amounts of oral residue indicated a marked reduction in the ability of the tongue to effectively clear food from the oral cavity; pharyngeal transit time, pharyngeal delay time, and pharyngeal residue, however, did not differ as a function of evaluation point, suggesting that surgery in the anterior oral cavity did not disrupt pharyngeal function. Patients also experienced essentially no aspiration. In the presence of oral dysfunction in these patients, does the lack of disturbance of the pharyngeal swallow suggest that these patients experience no pharyngeal impact of the oral surgical procedure or that they are using some sort of compensatory pharyngeal strategy? The present study used computer-aided biomechanical analysis to measure swallow-related movements in the pharynx before and after surgery in patients with anterior tongue and floor of mouth resections with distal flap reconstruction to investigate this question.

## Method

### *Subjects*

From a total of 17 patients who had undergone anterior tongue and floor of mouth resection with distal flap reconstruction and were followed longitudinally from before their operations to 3 months postoperatively, 8 patients had preoperative and at least 1 postoperative videofluorographic studies of sufficient quality to be analyzed biomechanically. Criteria for videotape quality included visualization of the structures of interest (discussed below) in the lateral plane throughout the entire swallow and sufficient radiographic contrast to view areas of both high and low density, such as the cervical vertebrae and the subglottic air column.

Eight patients, 6 men and 2 women, were analyzed for this study. All patients had resection of the anterior floor of mouth and anterior tongue. Distal flaps of various origins were used to reconstruct the surgical patients. No patient had a tracheostomy tube in place at any of the evaluations. Table 1 summarizes the surgical data for the individual subjects. In addition to anterior tongue and floor of mouth resection, each

**TABLE 1. Sex, age, surgical, and radiation data for individual patients.**

| Pt. no. | Age | Sex | Tumor stage | Resection volume (cm³) | Additional* resected structures | % Oral tongue resected | % Tongue base resected | Flap origin | Postop. radiation (rads) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 71 | M | T3N2cM0 | 108 | MRND | 50 | 0 | pect. maj. | 5940 |
| 2 | 69 | M | T2N0M0 | 63 | MRND | 20 | 0 | nasolabial | 0 |
| 3 | 54 | F | T2N1M0 | 140 | MRND mandibular alveolar ridge | 10 | 0 | pect. maj. | 0 |
| 4 | 30 | F | T3N2M0 | 59 | RND | 15 | 0 | cervical | 6000 |
| 5 | 44 | M | T3N1M0 | 24 | RND | 50 | 50 | pect. maj. | 5800 |
| 6 | 66 | M | T4N1M0 | 96 | MRND mandibular alveolar ridge | 20 | 0 | pect. maj. | 0 |
| 7 | 53 | M | T2N0M0 | 36 | MRND | 15 | 0 | pect. maj. | 6000 |
| 8 | 56 | M | T4N0M0 | 540 | RND mandibular alveolar ridge | <5 | 0 | pect. maj. | 5000 |

*Note.* RND = radical neck dissection; MRND = modified radical neck dissection; pect. maj. = pectoralis major.
*All patients had resections of both the anterior tongue and floor of mouth.

patient had either a radical or modified radical neck dissection. Three patients had marginal resections of the mandibular alveolar ridge. The hypoglossal nerve (CN XII) was sacrificed on the right side in 2 patients, and remained intact bilaterally in the 6 other patients. No other cranial nerves were affected. Five of the 8 patients received postoperative radiation therapy, with an average total dose of 5748 rads. The majority of the irradiated patients began treatment just before the 1-month postoperative swallowing evaluation; treatment lasted an average of 39 days, which put completion of radiation therapy at approximately 2 weeks before the 3-month evaluation. No patient in this group received preoperative radiation therapy.

Eight normal subjects, sex and age-matched within 5 years to the surgical patients, were also measured specifically for this study. The normal subjects had no history of medical or neurological problems that may have caused a swallowing disorder.

## Data Collection and Reduction

Swallowing performance was assessed with videofluorography preoperatively and at 1 and 3 months postoperatively for the 8 oral cancer patients. The normal subjects received a single videofluorographic study. The swallow study protocol for all subjects consisted of two trials each of 1 ml liquid barium, 1 ml barium paste, and a small piece of a shortbread cookie coated with barium paste. All boluses were administered from a teaspoon. These bolus types are part of the standard clinical protocol for assessing patient behavior with various food consistencies. The bolus sizes were chosen for ease of administration and to reduce the likelihood of aspiration of large amounts. Not all surgical patients were able to swallow two trials of each consistency at each evaluation point. A patient may have refused to attempt one or both trials of a consistency because of known or suspected difficulty with it; the speech-language pathologist also may have judged it a clinical risk to introduce or continue with a specific consistency during the videofluorographic evaluation.

Fluoroscopic data were recorded on ¾ inch videotape at 30 frames per second. During the study, the fluoroscopy tube was focused on the lips anteriorly, the cervical vertebrae posteriorly, the soft palate superiorly, and the bifurcation of the esophagus and airway inferiorly.

Biomechanical analysis was used to mark the movements of specific oropharyngeal structures over time. Each video frame (1/30 sec intervals) from the liquid, paste, and masticated swallows was digitized, using a Gateway 2000 80486 computer equipped with a Data Translation Image Digitizing Board (model DT2861) with interactive software (Logemann, Kahrilas, Begelman, Dodds, & Pauloski, 1989). The following points, lines, and angles were marked on each digitized video frame: (1) a point on the anterior-inferior corner of C4, which served as an "anchor point," the origin of the x-y coordinate system against which movement of the other structures was measured; (2) a line along the vertical length of C3 from the anterior-superior corner to the anterior-inferior corner, to serve as the reference distance from which absolute movement in was measured and to compensate for radiographic magnification; (3) the angle of the subject's head tilt from true vertical, measured from the anterior-inferior aspect of C4 to the anterior-inferior corner of C2; (4) a point on the posterior-superior corner of the subglottic air column to represent laryngeal movement; (5) a point on the most anterior-superior aspect of the hyoid bone to represent vertical and horizontal hyoid movement; (6) a line from the anterior-superior tip of the arytenoid to the point on the posterior surface of the epiglottic base immediately anterior to the arytenoid to represent laryngeal closure at the vestibule; (7) a line between the anterior and posterior walls of the cricopharyngeal region approximately 5 mm below the under surface of the true vocal folds to represent cricopharyngeal opening; and (8) a line from the anterior-inferior corner of C2 to a point on the posterior pharyngeal wall and a point on the tongue base at that level to measure posterior tongue base movement and anterior movement of the posterior pharyngeal wall. These measures are illustrated in Figure 1.

The reference distance was used to correct for fluoroscopic magnification across digitized images and as an index of movement of oropharyngeal structures. Mathematical correction for optical distortion of the entire image was not available. Although a reference marker of known length, such as a coin, is routinely used for fluoroscopic studies intended for biomechanical analysis, the patient data were taken from archived videofluorographic studies that were not intended

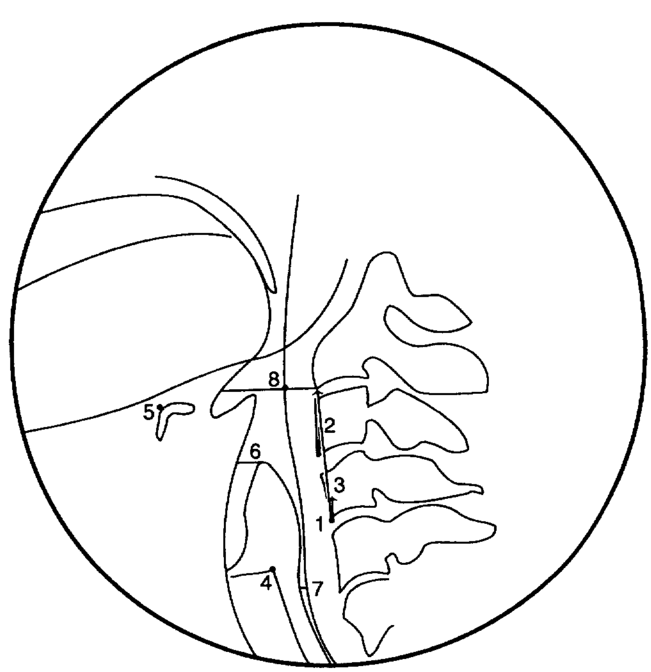


**FIGURE 1. Lateral view from videofluoroscopy of swallow study with marked points identified including (1) anterior-inferior corner of C4; (2) C3 from the anterior-superior corner to the anterior-inferior corner; (3) postural angle; (4) posterior-superior corner of the subglottic air column; (5) most anterior aspect of the hyoid bone; (6) anterior-superior tip of the arytenoid to the point opposite on posterior epiglottis; (7) anterior and posterior walls of the cricopharyngeal region; and (8) anterior-inferior corner of C2 to the tongue base and a point on the posterior pharyngeal wall at that level.**

originally for biomechanical analysis and a marker of known length was not placed in the radiographic field when the patient studies were completed. In order to make comparisons of extent of movement of oropharyngeal structures between patients and normal control subjects, the third cervical vertebra was used as the reference distance for all studies and assigned a value of 15 units. This value was derived from our calculations of the average length of C3 (15 mm), based upon our measurements of several cervical vertebrae from skeletons in our anatomy laboratory and of cervical vertebrae from videofluorographic studies in which a known reference distance was available.

Plots of structural movement over time were generated from the digitized and marked images of each subject's swallows. Figure 2 shows a set of composite graphs for one subject's structural movements. From the graphs of each subjects' swallows, the following outcome measures were made: (a) extent of posterior tongue base movement (units); (b) extent of anterior bulging of the posterior pharyngeal wall (units); (c) duration of tongue base contact to posterior pharyngeal wall (sec); (d) extent of anterior laryngeal movement (units) at onset of cricopharyngeal opening; (e) extent of vertical laryngeal movement (units) at onset of cricopharyngeal opening; (f) extent of anterior hyoid movement (units) at onset of cricopharyngeal opening; (g) extent of vertical hyoid movement (units) at onset of cricopharyngeal opening; (h) extent of epiglottis retraction (units) during closure of the laryngeal vestibule; (i) extent of anterior arytenoid movement (units) during closure of the laryngeal vestibule; (j) duration of laryngeal closure (sec); (k) width of cricopharyngeal opening (units); (l) duration of cricopharyngeal opening (sec); (m) onset of laryngeal closure relative to onset of cricopharyngeal opening (sec); and (n) onset of posterior tongue base movement relative to cricopharyngeal opening (sec) (Jacob et al., 1989; Kahrilas et al., 1992; Logemann et al., 1992). Both patient and normative data were measured by the same research assistants. In order to assess reliability of measurement, 10% of all data were remeasured by the same research assistant and measured by a second research assistant. Reliability of measurement assessed with Pearson correlation coefficients ranged from .81 to .97 for intrajudge and .81 to .93 for interjudge reliability.

The biomechanical data for the postsurgical patients were analyzed statistically using repeated measures analysis of variance (ANOVA) to assess change in the outcome measures over time (Winer, Brown, & Michels, 1991). The structural model used in the analysis consisted of two repeated factors (evaluation point and consistency) and their interaction. Because subjects swallowed multiple trials of each consistency, replicate measures were averaged in order to produce a subject mean that was used in the statistical analysis. In the presence of a significant interaction between evaluation point and bolus consistency ($p < .05$), the effect of evaluation point was tested separately for each of the bolus consistencies. If there were no significant interactions for a variable, the main effects of evaluation point and bolus consistency were evaluated using pooled data. Post hoc *t*-tests were performed to isolate the source of significance for any variables with main effect ANOVAs that had *p*-values of less than .05. A significance level of .017 (.05/3 comparisons) was used to assess the post hoc tests in order to minimize the experiment-wise error rate.

Biomechanical data from the normal subjects was compared to that of the surgical patients at each of their three evaluation points using ANOVA with factors for consistency, group (controls and patients at each of the three evaluation points), the interaction of consistency and group, and pair. The mean of multiple trials for each subject on each bolus consistency was used in the statistical analysis. For variables with a significant interaction, the main effect of group was tested separately for each bolus condition. For variables with no interaction, the test for the main effect of group (i.e., normal subjects versus surgical subjects preoperatively, and 1 and 3 months postoperatively) used data pooled across bolus consistency. When a significant main effect was detected, Dunnett's test (Steel & Torrie, 1980) was used to assess the significant pairwise comparisons between the normal subjects and the surgical data. Dunnett's test is a multiple comparison procedure that controls the error rate for the collection of the three comparisons at .05. All statistical analyses were performed with the General Linear Model (GLM) procedure in SAS (SAS/STAT, 1990).

## Results

All eight surgical patients received the preoperative and 1- and 3-month postoperative videofluoroscopy studies. The archived videotapes for one of the patients' 1-month studies and another of the patients' 3-month studies were of insufficient quality for digitization. Videotapes from all eight control subjects were analyzable.

### *Analysis of Evaluation and Consistency Effects in Surgical Patients*

***Main effect of evaluation point.*** The interaction effect of evaluation point and bolus consistency was not significant for any of the swallowing measures for the surgical patients, indicating that the patients demonstrated the same pattern of behavior on the bolus consistencies at the various evaluations. The main effect of evaluation point was then tested, pooled across bolus consistency. Duration of tongue base contact to posterior pharyngeal wall, extent of anterior bulging of the posterior pharyngeal wall, duration of cricopharyngeal opening, width of cricopharyngeal opening, duration of laryngeal closure, extent of thickening of the epiglottic base during closure of the laryngeal vestibule, onset of laryngeal closure relative to onset of cricopharyngeal opening, extent of vertical laryngeal movement at onset of cricopharyngeal opening, and extent of vertical hyoid movement at onset of cricopharyngeal opening demonstrated a significant difference across evaluation points. In the presence of a significant evaluation effect, three post hoc *t*-tests were performed: (a) preop versus 1 month, (b) preop versus 3 months, and (c) 1 month versus 3 months. Means, standard errors, ANOVA test results for the main effect and post hoc tests are summarized in Table 2.

The duration of tongue base contact to the posterior pharyngeal wall decreased slightly 1 month after surgery but

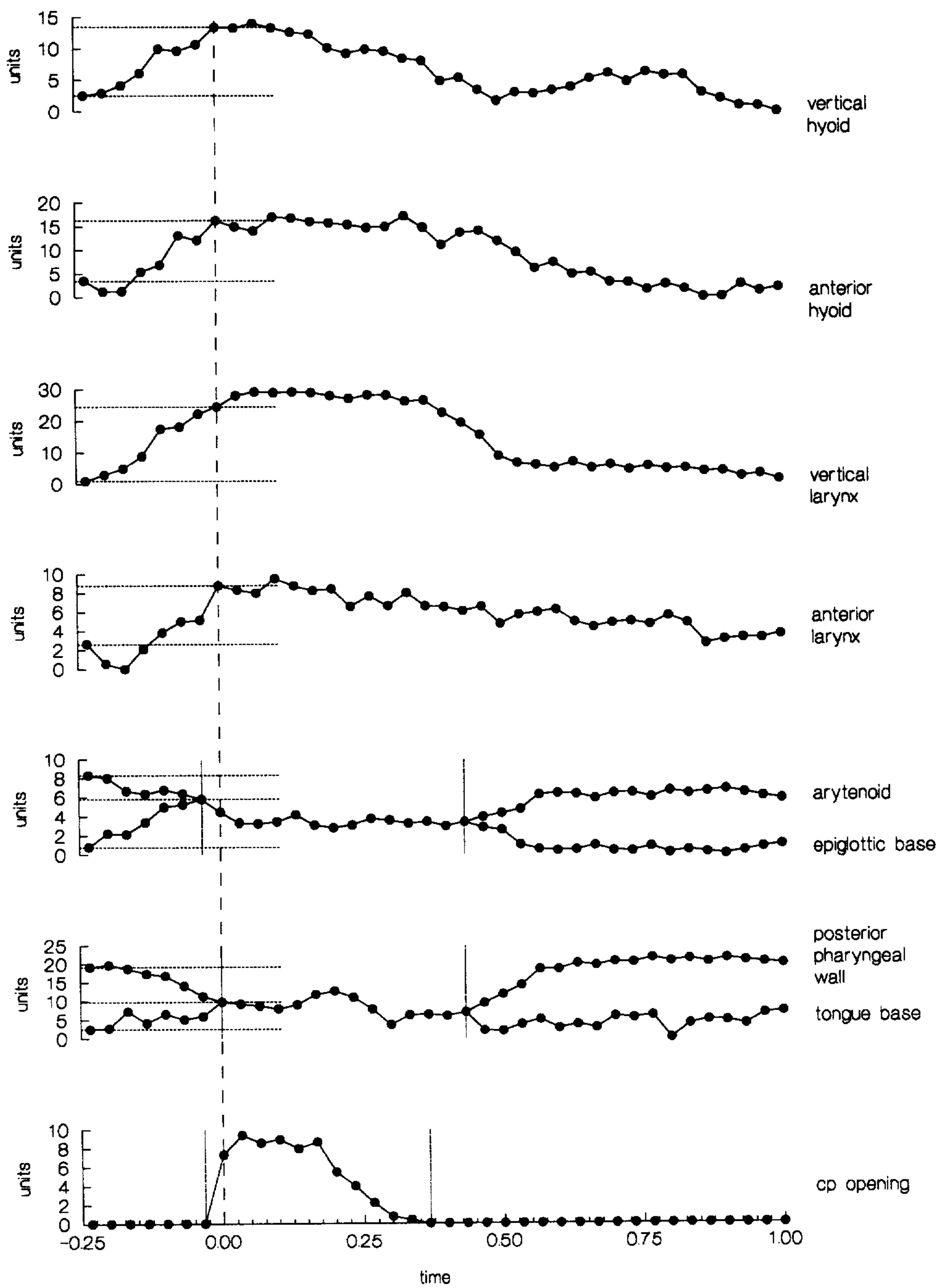


**FIGURE 2. Composite graph of movement in units of pharyngeal structures over time during a paste swallow of one patient. Time 0 (vertical dashed line) represents first cricopharyngeal opening. Extent of movement of each structure is measured relative to the structure's rest position. Movement data for each variable are measured between the dashed horizontal lines; timing data for each variable are measured between the solid vertical lines.**

by the 3-month evaluation had increased significantly beyond 1-month levels. The extent of posterior tongue base movement diminished after surgery, although not significantly. The degree of anterior bulging of the posterior pharyngeal wall increased steadily and significantly by the 3-month postoperative evaluation. The onset of posterior tongue base retraction relative to cricopharyngeal opening did not differ as a function of evaluation point.

The duration of cricopharyngeal opening decreased significantly after surgery between the preoperative and 3-month evaluations. Maximum width of cricopharyngeal opening also decreased after surgery at the 1-month evaluation, with no significant change between 1 and 3 months postsurgery, although this measure at 3 months was not significantly different from preoperative values.

Duration of laryngeal closure at the vestibule remained steady after surgery but increased significantly between the 1- and 3-month postoperative evaluations, accounted for by

**TABLE 2. Means and standard errors (in parentheses) by evaluation point (pooled across consistency), evaluation point ANOVA results, and post hoc test results for variables with a significant main effect for evaluation point (*n* equals number of consistencies swallowed by the subjects studied at each evaluation point).**

| | Preop | 1 month | 3 month | ANOVA *F* obs(2,40)* | *p*-value | post hoc[a] *t*-tests |
|---|---|---|---|---|---|---|
| | $n = 20$ | $n = 16$ | $n = 16$ | | | |
| Tongue base to pharyngeal wall contact (sec) | .26 (.03) | .17 (.03) | .32 (.04) | 5.03 | .01 | 3 |
| Extent of posterior tongue base movement (units) | 4.39 (.55) | 3.85 (.62) | 2.81 (.54) | 1.27 | .29 | NA |
| Extent of anterior bulge of PPW (units) | 9.89 (.71) | 12.93 (1.81) | 16.24 (1.48) | 12.67 | <.0001 | 2, 3 |
| Onset of posterior movement of tongue base re: CP opening (sec)[b] | −.06 (.02) | −.04 (.07) | −.08 (.02) | .29 | .75 | NA |
| Cricopharyngeal opening duration (sec) | .42 (.02) | .36 (.02) | .32 (.03) | 3.72 | .03 | 2 |
| Cricopharyngeal opening width (units) | 10.01 (.75) | 6.95 (.67) | 7.78 (.64) | 10.39 | .0002 | 1 |
| Laryngeal closure duration (sec) | .44 (.03) | .39 (.06) | .54 (.06) | 4.68 | .01 | 3 |
| Extent of posterior movement of the epiglottic base (units) | 7.39 (.67) | 7.47 (1.48) | 3.38 (.50) | 5.21 | .01 | 2, 3 |
| Extent of arytenoid anterior movement (units) | 5.58 (.68) | 6.39 (.97) | 6.74 (.57) | 1.02 | .37 | NA |
| Onset of laryngeal closure re: CP opening (sec)[b] | −.04 (.02) | .02 (.03) | −.11 (.03) | 7.40 | .002 | 3 |
| Laryngeal elevation (units) at CP opening | 19.59 (1.32) | 11.54 (1.27) | 8.34 (.90) | 31.53 | <.0001 | 1, 2 |
| Anterior laryngeal movement (units) at CP opening | 3.48 (.48) | 4.81 (.72) | 3.93 (.47) | .94 | .40 | NA |
| Hyoid elevation (units) at CP opening | 9.06 (.97) | 6.22 (.95) | 5.04 (.42) | 5.60 | .007 | 1, 2 |
| Anterior hyoid movement (units) at CP opening | 8.88 (.92) | 7.10 (1.15) | 7.35 (.77) | 1.26 | .30 | NA |

[a]1: $p < .017$ for preop vs. 1 month
2: $p < .017$ for preop vs. 3 month
3: $p < .017$ for 1 month vs. 3 month
NA: not applicable when ANOVA $p > .05$
[b]A negative value indicates that the event occurred before cp opening.
*$F_{crit(2,40,p < .05)} = 3.23$

significantly earlier laryngeal closure in relation to cricopharyngeal opening at 3 months postoperatively. The extent of posterior thickening of the epiglottic base, a component of laryngeal closure at the vestibule, did not differ between the preoperative and 1-month postoperative evaluations; by the 3-month evaluation, extent of posterior epiglottic movement had decreased significantly. Anterior arytenoid movement, the second component of laryngeal closure at the vestibule, increased slightly after surgery and between 1 and 3 months postoperatively, but did not change significantly across the evaluation points.

Elevation of the hyolaryngeal complex decreased significantly after surgery. Extent of both laryngeal and hyoid elevation decreased between the preoperative and 1-month evaluations, with no significant changes by 3 months postsurgery. Extent of anterior movement of these structures did not vary as a function of evaluation point.

***Main effect of bolus consistency.*** The main effect of bolus consistency for the surgical patients was tested, pooled across evaluation point. Only duration of laryngeal closure demonstrated a significant difference across bolus consistencies. Three post hoc *t*-tests were performed for this measure:

**TABLE 3. Means and standard errors (in parentheses) by bolus consistency (pooled across evaluation point), bolus consistency ANOVA results, and post hoc test results for variables with a significant main effect for bolus consistency (*n* equals number of evaluation points pooled over the subjects at each bolus consistency).**

| | Liquid | Paste | Cookie | ANOVA $F$ obs(2,40)* | $p$-value | post hoc[a] $t$-tests |
|---|---|---|---|---|---|---|
| | $n = 22$ | $n = 20$ | $n = 10$ | | | |
| Laryngeal closure duration (sec) | .45 (.05) | .49 (.04) | .40 (.05) | 5.69 | .007 | 2,3 |

[a]1: $p < .017$ for liquid vs. paste
2: $p < .017$ for liquid vs. cookie
3: $p < .017$ for paste vs. cookie
*$F_{crit(2,40,p<.05)} = 3.23$

(a) liquid versus paste, (b) liquid versus cookie, and (c) paste versus cookie. Means, standard errors, ANOVA test results for the main effect and post hoc tests are summarized in Table 3. Duration of laryngeal closure at the vestibule remained constant for liquid and paste boluses but decreased significantly on masticated material.

## *Comparison of Surgical Patients and Normal Control Subjects*

***Interaction of subject group by bolus consistency.*** The interaction between subject group (normal control subjects, surgical patients preoperatively, surgical patients at 1 month, and surgical patients at 3 months) and bolus consistency was significant only for duration of cricopharyngeal opening ($F_{obs} = 2.98$, $F_{crit(6,57,p<.05)} = 2.26$). Because of the significant interaction, the main effect of group was interpreted separately for each consistency. Table 4 includes the means and standard errors by bolus consistency for each group, the test for the main effect of group for each consistency, as well as the Dunnett's post hoc test results.

For liquid and masticated boluses, duration of cricopharyngeal opening did not differ significantly as a function of group. For the paste consistency, cricopharyngeal opening duration for the normal subjects did not differ from that of the surgical patients preoperatively, but was significantly longer than the patients' measures after surgery.

***Main effect of subject group.*** The main effect of subject group, pooled across bolus consistency, was tested for those variables that did not have a significant group by bolus interaction. Dunnett's test was performed to determine when the normal subjects differed significantly from the surgical patients: (a) normal controls versus patients preoperatively, (b) normal controls versus patients at 1 month postoperatively, and (c) normal controls versus patients at 3 months postoperatively. Table 5 summarizes the means, standard errors, ANOVA test results for the main effect, and Dunnett's post hoc test results.

Duration of tongue base contact to the posterior pharyngeal wall for the normal subjects was significantly longer than that of the surgical patients preoperatively and at 1 month postoperatively; at the 3-month evaluation, the patients did not differ from the normal subjects on this measure. Degree of posterior tongue base movement was significantly greater for the normal subjects than for the surgical patients at any evaluation point; extent of anterior bulging of the posterior pharyngeal wall was significantly smaller for the normal subjects when compared to the surgical patients after surgery. The onset of tongue base retraction relative to cricopharyngeal opening time started significantly earlier for

**TABLE 4. Means and standard errors (in parentheses) by group and consistency, group ANOVA results, and Dunnett Test results for duration of cricopharyngeal opening (*n* equals number of subjects analyzed for a given group and bolus consistency).**

| | Control subjects | Patients preop | Patients 1 month | Patients 3 month | ANOVA $F$ obs | $p$-value | Dunnett post hoc[a] tests |
|---|---|---|---|---|---|---|---|
| Liquid | .33 (.02) | .42 (.04) | .38 (.04) | .37 (.04) | 1.83[b] | .18 | NA |
| *n* | 8 | 8 | 7 | 7 | | | |
| Paste | .49 (.03) | .44 (.04) | .35 (.03) | .30 (.04) | 6.94[c] | .003 | 2, 3 |
| *n* | 8 | 7 | 7 | 6 | | | |
| Cookie | .40 (.02) | .41 (.06) | .31 (.06) | .26 (.06) | .68[d] | .59 | NA |
| *n* | 8 | 5 | 2 | 3 | | | |

[a]Joint significance level of $p < .05$. Significant difference from control is indicated by numeral:
1: Control vs. patients preop
2: Control vs. patients 1 month
3: Control vs. patients 3 month
NA: not applicable when ANOVA $p > .05$
[b]$F_{crit(3,19,\ p<.05)} = 3.13$
[c]$F_{crit(3,17,\ p<.05)} = 3.20$
[d]$F_{crit(3,7,\ p<.05)} = 4.35$

**TABLE 5. Means and standard errors (in parentheses) by group (pooled across consistency), group ANOVA results, and Dunnett Test results for variables with a significant main effect for group with no interaction (*n* equals number of consistencies swallowed by the subjects studied in each group).**

| | Control subjects | Patients preop | Patients 1 month | Patients 3 month | ANOVA* *F* obs(3,63) | *p*-value | Dunnett post hoc[a] tests |
|---|---|---|---|---|---|---|---|
| | $n = 24$ | $n = 20$ | $n = 16$ | $n = 16$ | | | |
| Tongue base to pharyngeal wall contact (sec) | .40 (.02) | .26 (.03) | .17 (.03) | .32 (.04) | 12.19 | <.0001 | 1, 2 |
| Extent of posterior tongue base movement (units) | 9.30 (.59) | 4.39 (.55) | 3.85 (.62) | 2.81 (.54) | 31.46 | <.0001 | 1, 2, 3 |
| Extent of anterior bulge of PPW (units) | 6.88 (.45) | 9.89 (.71) | 12.93 (1.81) | 16.24 (1.48) | 17.18 | <.0001 | 2, 3 |
| Onset of posterior movement of tongue base re: CP opening (sec)[b] | −.32 (.04) | −.06 (.02) | −.04 (.07) | −.08 (.02) | 9.27 | <.0001 | 1, 2, 3 |
| Cricopharyngeal opening width (units) | 7.74 (.56) | 10.01 (.75) | 6.95 (.67) | 7.78 (.64) | 4.23 | .009 | 1 |
| Laryngeal closure duration (sec) | .60 (.05) | .44 (.03) | .39 (.06) | .54 (.06) | 11.68 | <.0001 | 1, 2 |
| Extent of posterior movement of the epiglottic base (units) | 8.08 (.52) | 7.39 (.67) | 7.47 (1.48) | 3.38 (.50) | 5.38 | .002 | 3 |
| Extent of arytenoid anterior movement (units) | 6.14 (.59) | 5.58 (.68) | 6.39 (.97) | 6.74 (.57) | .74 | .53 | NA |
| Onset of laryngeal closure re: CP opening (sec) | −.12 (.03) | −.04 (.02) | .02 (.03) | −.11 (.03) | 5.89 | .001 | 2 |
| Laryngeal elevation (units) at CP opening | 25.46 (1.33) | 19.59 (1.32) | 11.54 (1.27) | 8.34 (.90) | 34.08 | <.0001 | 1, 2, 3 |
| Anterior laryngeal movement (units) at CP opening | 8.54 (.66) | 3.48 (.48) | 4.81 (.72) | 3.93 (.47) | 15.34 | <.0001 | 1, 2, 3 |
| Hyoid elevation (units) at CP opening | 16.36 (1.09) | 9.06 (.97) | 6.22 (.95) | 5.04 (.42) | 35.97 | <.0001 | 1, 2, 3 |
| Anterior hyoid movement (units) at CP opening | 15.21 (.69) | 8.88 (.92) | 7.10 (1.15) | 7.35 (.77) | 20.99 | <.0001 | 1, 2, 3 |

[a]Joint significance level of $p < .05$. Significant difference from control is indicated by numeral:
1: Control vs. patients preop
2: Control vs. patients 1 month
3: Control vs. patients 3 month
NA: not applicable when ANOVA $p > .05$
[b]A negative value indicates that the event occurred before cp opening.
*$F_{crit(3,63,\ p < .05)} = 2.75$

the normal subjects than for the patients at any evaluation point.

Maximum width of cricopharyngeal opening was significantly smaller for the normal subjects when compared to the surgical patients preoperatively; at 1 month and 3 months postoperatively, the surgical patients did not differ from the normal subjects on this measure.

Duration of laryngeal closure at the vestibule was significantly longer for the normal subjects when compared to the patients preoperatively and at 1 month postoperatively. Laryngeal closure duration for the patients at 3 months after surgery did not differ from that of the normal subjects. The patients and normal subjects were similar in their extent of posterior movement of the epiglottic base preoperatively and 1 month postoperatively; at the 3-month evaluation, the patients had significantly less epiglottic base movement than did the normal subjects. The extent of anterior arytenoid movement did not differ between the normal subjects and the patients at any evaluation. The onset of laryngeal closure relative to cricopharyngeal opening occurred significantly earlier for the normal subjects when compared to the patients at 1 month after surgery, but did not differ from the patients preoperatively and at the 3-month evaluation.

Extent of vertical and anterior movement of the larynx and hyoid was significantly greater for the normal subjects compared to the surgical patients at all evaluation points.

## Discussion

Biomechanical analysis of the oropharyngeal swallow of eight oral cancer patients with resections of the anterior tongue and floor of mouth and distal flap reconstruction revealed that tongue base, pharyngeal wall, laryngeal, hyoid, and cricopharyngeal movements during the swallow were altered significantly after surgery. Some oropharyngeal structural movements differed from those of normal control subjects even before surgery, perhaps as a result of the tumor burden.

When compared to normal subjects, the patients in this study had significantly reduced extent of posterior tongue base movement both preoperatively and postoperatively. The onset of posterior movement of the tongue base relative to cricopharyngeal opening time was also significantly delayed for the patients, further indicating the degree of tongue base impairment. The patients did not improve after resection and in fact had consecutively less movement of the tongue base over time, although this reduction was not significant. However, even though they had limited tongue base movement, the patients did demonstrate a significant improvement in the duration of tongue base to pharyngeal wall contact by the 3-month evaluation. This contact was achieved by significantly increased anterior movement of the posterior pharyngeal wall. Figure 3 illustrates the changes in movement of the posterior pharyngeal wall over each of the evaluation points. Preoperatively, the patients did not differ from the control subjects in extent of anterior bulging of the posterior pharyngeal wall; however, the extent of tongue base retraction was significantly reduced, and several of the patients could not achieve base of tongue to posterior pharyngeal wall contact. After surgery, posterior pharyngeal wall bulging increased well beyond normal, and by the 3-month evaluation, all patients were able to achieve tongue base to pharyngeal wall contact. Movement of the tongue

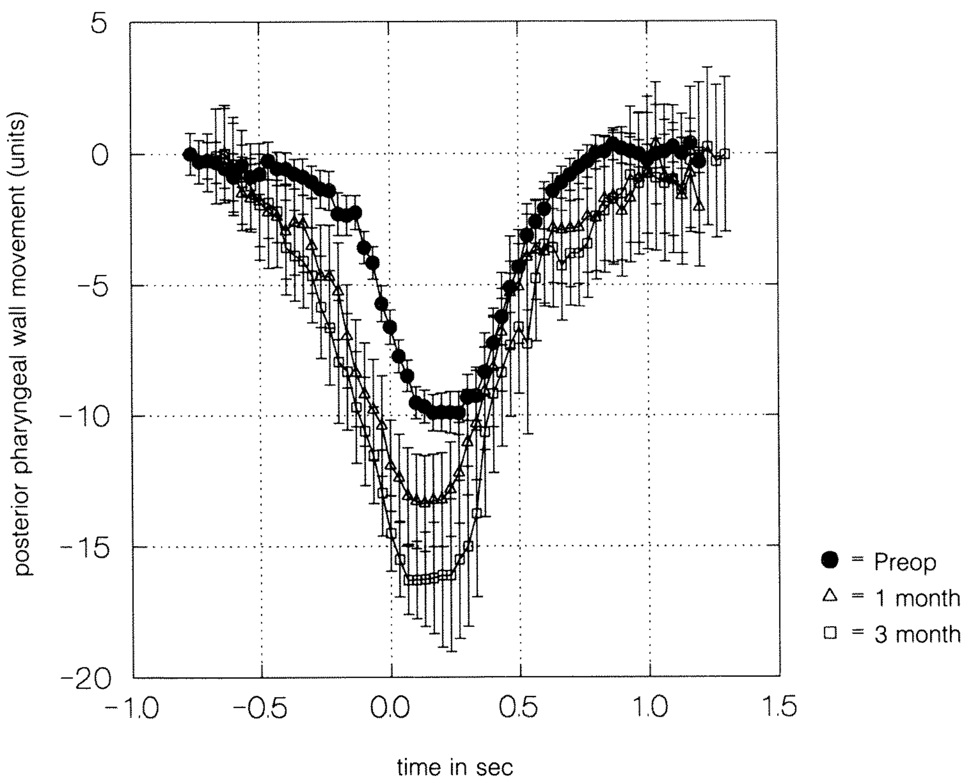


**FIGURE 3. Movement over time graph of the anterior bulge of the posterior pharyngeal wall at the level of the tongue base averaged across swallows of liquid, paste, and masticated materials for the eight surgical patients preoperatively, and at 1 and 3 months postoperatively. Time 0 equals first cricopharyngeal opening; 0 units equals rest position of posterior pharyngeal wall.**

base and posterior pharyngeal wall toward each other until full contact is achieved is the key element in producing pharyngeal bolus driving pressure (Jacob et al., 1989; Shawker et al., 1983). In the presence of reduced tongue base movement, the other component of pressure generation, the pharyngeal walls, appeared to compensate to maintain bolus propulsion through the pharynx. Compensation of this type was postulated by Buchholz, Bosma, and Donner (1985) and may have occurred in these surgical patients. Increased movement of the lateral pharyngeal wall also may have contributed to the improved pharyngeal dynamics, although lateral wall movement could not be measured from the lateral fluoroscopic view analyzed for this study. A review of individual patient data revealed no relationship between extent of oral tongue resected and degree of posterior pharyngeal wall bulging; however, it is of interest that the one patient who had an extension of his resection to the tongue base demonstrated the greatest posterior pharyngeal wall bulge at 3 months postsurgery. An analysis of patients with a posterior loci of resection may reveal similar results.

Hyoid and laryngeal elevation and anterior movement were significantly reduced both pre- and postoperatively in the surgical patients when compared to normal subjects. Preoperative differences in hyolaryngeal movement may have been the result of infiltration of the tumor into the floor of mouth muscles (i.e., the mylohyoid, geniohyoid, and anterior belly of the digastric) that assist in elevation and anterior movement of the hyoid and larynx. Postoperatively, hyoid and laryngeal elevation were significantly reduced relative to preoperative levels and continued to diminish by 3 months after surgery; however, anterior movement of these structures did not change significantly over time. Because none of the patients had a tracheostomy in place at the time of any of their evaluations, reduced elevation of the larynx and hyoid is not the result of traction caused by a tracheostomy tube. Impaired neural stimulation, abnormal muscle contraction, or decreased tissue compliance may result in decreased hyoid and laryngeal movement (Dodds, Man, Cook, Kahrilas, Stewart, & Kern, 1988). Although two patients had unilateral resection of the hypoglossal nerve, neither demonstrated any greater impairment of vertical or anterior movement of the hyoid and larynx than the rest of the patients. A loss of tissue compliance from increased surgical scarring over time and postoperative radiation may have limited the extent to which the hyoid and larynx could elevate during the swallow. The postsurgical changes in hyoid and laryngeal elevation also may have occurred as a result of surgical detachment of the anterior attachment of the floor of mouth muscles. These muscles are generally considered responsible for the forward and upward movement of the hyoid and larynx. Cutting or damaging these muscles may have significantly changed their line of pull upward on the hyoid and larynx but not the anterior pull on these structures. Figure 4 illustrates the changes in hyoid and laryngeal elevation over time.

Width of cricopharyngeal opening may have increased as a result of the increased pharyngeal wall movement. Cricopharyngeal opening is created by the elevation and anterior movement of the hyolaryngeal complex (Kahrilas, Dodds, Dent, Logemann, & Shaker, 1988; Kahrilas, Logemann, Krugler, & Flanagan, 1991; Kahrilas & Logemann, 1993); the width of cricopharyngeal opening is related to bolus pressure (Jacob et al., 1989; Dantas et al., 1990). Preoperatively, the patient group demonstrated a significantly greater cricopharyngeal opening width when compared to the normal control subjects. The patients had significantly greater hyoid and laryngeal elevation before surgery than they did postoperatively, along with an anterior bulge of the posterior pharyngeal wall that was larger than that of the normal subjects (9.89 units vs. 6.88 units), although this difference was not significant. The pull of the elevating larynx on the relaxed cricopharyngeus along with the greater activity of the posterior pharyngeal wall potentially increasing pressure on the bolus may have combined to produce a cricopharyngeal opening width that was significantly larger than normal. After surgery, the degree of hyoid and laryngeal elevation was significantly diminished; however, significantly increased movement of the pharyngeal wall may have created sufficient pressure on the bolus for it to distend the cricopharyngeus to a width within normal limits. Further evidence for this hypothesis is the small amount of pharyngeal residue observed in these types of patients (Pauloski et al., 1993). Figure 5 illustrates the changes in cricopharyngeal opening width over time.

The mechanism for laryngeal closure showed some changes as well. Laryngeal closure at the level of the vestibule, as measured in this study, is achieved by the approximation of the arytenoids and the base of the epiglottis (Logemann et al., 1992). Extent of epiglottic base movement did not differ for the patients between the preoperative and 1-month postsurgery evaluations, and anterior arytenoid movement did not differ from normal at any evaluation. Posterior movement of the epiglottic base may occur as a biomechanical result of tongue base retraction and/or thickening of the epiglottic base as the larynx elevates. Although reduced below normal levels, the onset and extent of tongue base retraction did not change significantly over time for the patients. Because the patients had a delayed onset and reduced extent of tongue base retraction, they may have needed to rely on a combination of tongue base retraction and laryngeal elevation at the preoperative and 1-month evaluations to increase the thickening of the epiglottic base to make contact with the arytenoids. Later onset of laryngeal closure relative to cricopharyngeal opening was necessary in order to achieve closure as the patient waited for the tongue base to retract and the larynx to elevate sufficiently to produce the epiglottic bulge. The later onset of laryngeal closure translated into laryngeal closure durations that were shorter than normal for the patients preoperatively and 1 month after surgery. By the 3-month postoperative evaluation, laryngeal elevation had diminished to half that of preoperative levels (8.34 units vs. 19.59 units). Without adequate laryngeal elevation, the reduced extent of tongue base retraction was insufficient to produce the degree of posterior epiglottic base movement that was observed preoperatively and at 1 month. Figure 6 illustrates the changes in posterior movement of the epiglottic base over time. Two patients with the largest oral tongue resections were unable to achieve epiglottic base to arytenoid contact at the 3-month evalua-

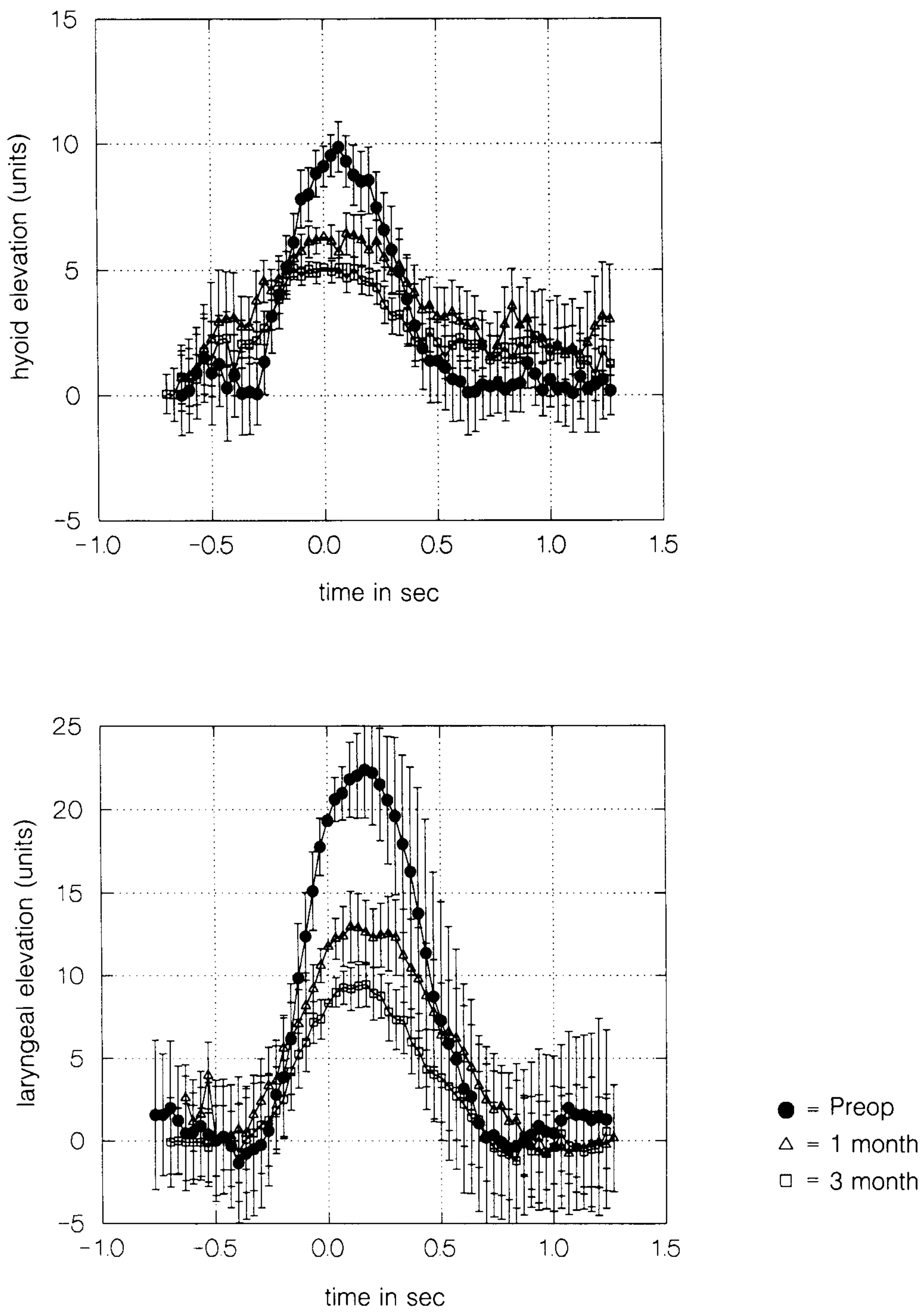


**FIGURE 4. Movement over time graphs of hyoid and laryngeal elevation averaged across swallows of liquid, paste, and masticated materials for the eight surgical patients preoperatively, and at 1 and 3 months postoperatively. Time 0 equals first cricopharyngeal opening; 0 units equals rest position of the structures.**

tion; however, neither of them aspirated, probably because they maintained closure of the true vocal cords despite inadequate closure at the vestibule. Closure of the true cords currently cannot be assessed with biomechanical analysis of the lateral fluoroscopic view. The six other patients were able to initiate and maintain closure of the laryngeal vestibule within normal limits.

The influence of bolus consistency on the biomechanical measures also was investigated in these patients. Previous studies have documented changes in the oropharyngeal swallow with increases in bolus viscosity in normal subjects. These include increased duration of tongue base to pharyngeal wall contact, increased cricopharyngeal opening duration, increased oral and pharyngeal residues, and increased hyoid and laryngeal movements (Dantas et al., 1990; Lazarus et al., 1993). For the surgical patients in this study,

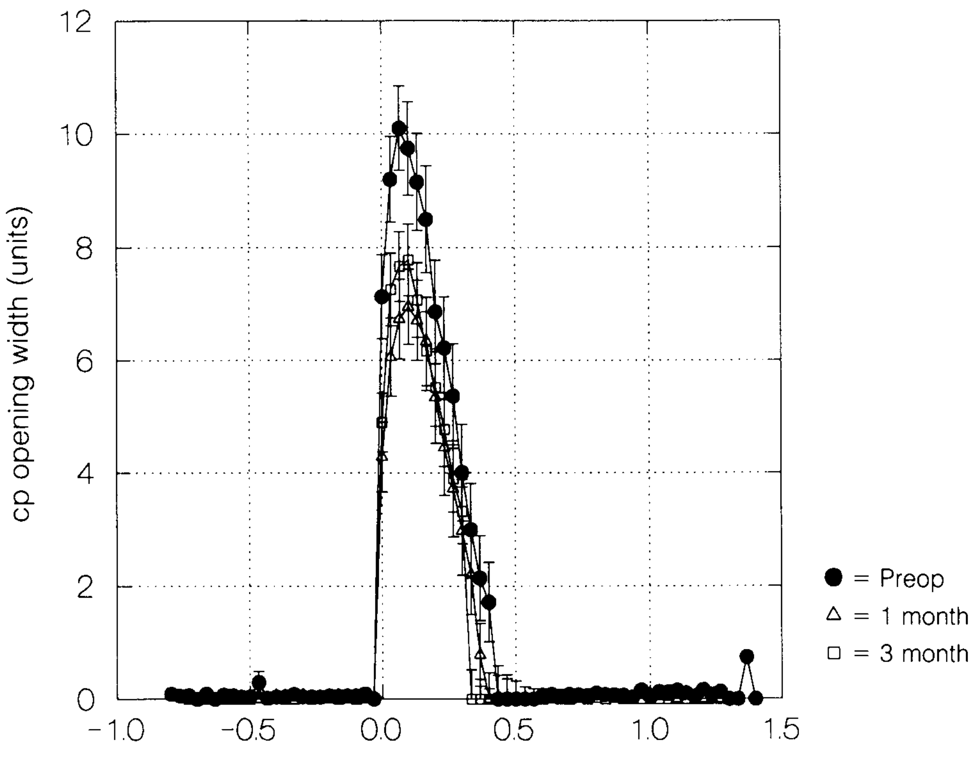


**FIGURE 5. Graph of cricopharyngeal opening width over time averaged across swallows of liquid, paste, and masticated materials for the eight surgical patients preoperatively, and at 1 and 3 months postoperatively. Time 0 equals first cricopharyngeal opening.**

duration of laryngeal closure decreased significantly from liquid to masticated boluses. Although these results are contrary to the trend in normal subjects, the decreased duration may actually be a bolus volume, rather than bolus viscosity, effect. In normal subjects, duration of laryngeal closure increases with increasing bolus volume (Kahrilas et al., 1988; Kahrilas & Logemann, 1993; Lazarus et al., 1993; Logemann et al., 1992; Logemann et al., 1993). Bolus residue in the oral cavity increases greatly with increased bolus viscosity in this patient population (Pauloski et al., 1993); therefore, a smaller percentage of the bolus is available to enter the pharynx. The shortened laryngeal closure duration for the patients in this study appears to be the result then of a smaller bolus volume reaching the pharynx. A similar effect was observed for left basal ganglion stroke patients for this duration measure (Logemann et al., 1993).

Previous analysis of swallowing function in patients with anterior tongue and floor of mouth resection with distal flap reconstruction revealed no significant improvements in the temporal aspects of the oropharyngeal stages of swallow over time (Pauloski et al., 1993). In this study, biomechanical measures indicate that there was recovery in some aspects of the pharyngeal swallow in this patient group. The duration of tongue base to pharyngeal wall contact, which was significantly reduced preoperatively and at 1 month after surgery, increased significantly to within normal levels by the 3-month postoperative evaluation. As discussed previously, contact was achieved through the significantly increased anterior movement of the posterior pharyngeal wall. Even after the completion of postoperative radiation, this possibly compensatory mechanism for bolus transport was not disrupted, indicating the strength of this adaptation. Duration of laryngeal closure and the onset of laryngeal closure relative to cricopharyngeal opening also improved significantly to within normal levels by the 3-month postoperative evaluation.

Pauloski et al. (1993) cited the small amount of swallowing therapy that their patients received as potentially having an impact on the lack of recovery observed in their study. If the changes in tongue base retraction and posterior pharyngeal wall movement observed in this study are compensatory in nature, then therapy maneuvers and exercises patterned after the changes in structural movement observed in this study may be used to improve swallow functioning even further. Therapy for increasing tongue base to pharyngeal wall contact has focused on improving posterior movement of the tongue base. Although specific exercises to increase posterior pharyngeal wall movement have not been identified, this kind of therapy is potentially beneficial for all patients with tongue dysfunction, especially patients with posterior tongue resections who may never be able to achieve adequate posterior movement of the tongue base because of their surgery. A new technique for enhancing pharyngeal wall movement is being tested currently at this institution with promising preliminary results.

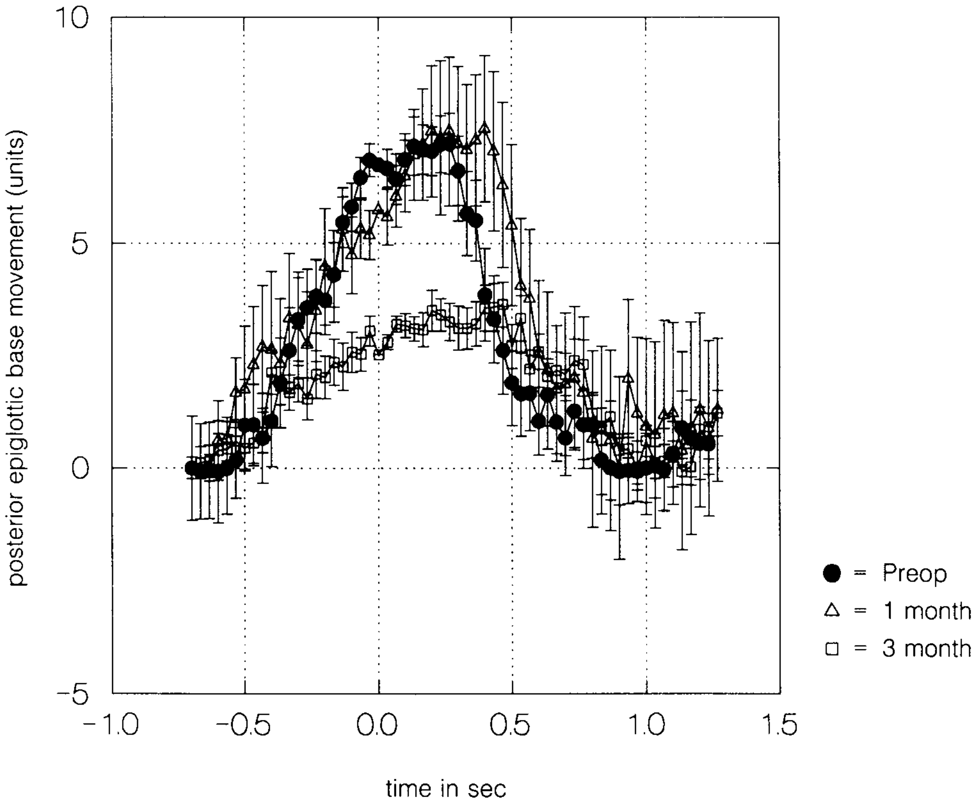


**FIGURE 6. Movement over time graphs of posterior movement of the epiglottic base averaged across swallows of liquid, paste, and masticated materials for the eight surgical patients preoperatively, and at 1 and 3 months postoperatively. Time 0 equals first cricopharyngeal opening; 0 units equals rest position of the structures.**

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