Dysphagia 2006: 1–10
DOI: 10.1007/s00455-006-9029-4

Dysphagia

Effects of Surface Electrical Stimulation Both at Rest and During Swallowing in Chronic Pharyngeal Dysphagia

Christy L. Ludlow, PhD,[1] Ianessa Humbert, PhD,[2] Keith Saxon, MD,[1] Christopher Poletto, PhD,[1] Barbara Sonies, PhD,[3] and Lisa Crujido, MS[4]

[1]Laryngeal and Speech Section, National Institute of Neurological Disorders and Stroke, Bethesda, Maryland; [2]Departments of Medicine and Radiology, Geriatric Research Education and Clinical Center (GRECC), University of Wisconsin-Madison, Wm. S. Middleton Veterans Hospital, Madison, Wisconsin; [3]Department of Rehabilitation of the Clinical Center, National Institutes of Health, Bethesda, Maryland; and [4]Department of Speech and Hearing Science, Arizona State University, Tempe, Arizona, USA

Abstract. We tested two hypotheses using surface electrical stimulation in chronic pharyngeal dysphagia: that stimulation (1) lowered the hyoid bone and/or larynx when applied at rest, and (2) increased aspiration, penetration, or pharyngeal pooling during swallowing. Bipolar surface electrodes were placed on the skin overlying the submandibular and laryngeal regions. Maximum tolerated levels of stimulation were applied while patients held their mouth closed at rest. Videofluoroscopic recordings were used to measure hyoid movements in the superior-inferior and anterior-posterior dimensions and the subglottic air column position while stimulation was on or off. Patients swallowed 5 ml liquid when stimulation was off, at low sensory stimulation levels, and at maximum tolerated levels (motor). Speech pathologists, blinded to condition, tallied the frequency of aspiration, penetration, pooling, and esophageal entry from videofluorographic recordings of swallows. Only significant ($p = 0.0175$) hyoid depression occurred during stimulation at rest. Aspiration and pooling were significantly reduced only with low sensory threshold levels of stimulation ($p = 0.025$) and not during maximum levels of surface electrical stimulation. Those patients who had reduced aspiration and penetration during swallowing with stimulation had greater hyoid depression during stimulation at rest ($p = 0.006$). Stimulation may have acted to resist patients' hyoid elevation during swallowing.

Key words: Deglutition — Deglutition disorders — Hyolaryngeal movement — Aspiration — Penetration — Sensory stimulation — Resistance — Transcutaneous neuromuscular stimulation.

The research was performed at the Laryngeal and Speech Section, National Institute of Neurological Disorders and Stroke, Bethesda, Maryland, and supported by the Intramural Research Program of the National Institute of Neurological Disorders and Stroke, Project No. Z01 NS 02980.
Correspondence to: Christy L. Ludlow, PhD, 10 Center Drive MSC 1416, Bldg. 10 Rm. 5D38, Bethesda, MD, 20892, USA e-mail: ludlowc@ninds.nih.gov

Although surface electrical stimulation has received increased attention as an adjunct to swallowing therapy in dysphagia in recent years [1–4], little is known about the effects of transcutaneous stimulation on swallowing physiology. It has been hypothesized that electrical stimulation may assist swallowing either by augmenting hyolaryngeal elevation [1,2] or by increasing sensory input to the central nervous system to enhance the elicitation of swallowing [3,4].

When electrical stimulation is applied to the skin or oral mucosa at low current levels, it activates the sensory nerve endings in the surface layers providing sensory feedback to the central nervous system. With increased current amplitude, the electric field may depolarize nerve endings in muscles lying beneath the skin surface [5] and may spread with diminishing density to produce muscle contraction.

When electrodes are placed in the submental region, therefore, the current density is greatest at the skin surface and diminishes with depth through the platysma underlying the skin and subcutaneous fat [6]. Accordingly, as the current is increased in amplitude, increasingly deeper muscles may be recruited, albeit with less efficiency. Such muscles include the anterior belly of the digastric, which can either lower the mandible or pull the hyoid upward depending on whether the mouth is held closed. Deeper still are the mylohyoid and geniohyoid muscles, which pull the hyoid bone upward and toward the mandible, respectively. These muscles are much less likely to be activated by surface stimulation, however, because of their greater depth.

Similarly, when electrodes are placed on the skin overlying the thyroid cartilage in the neck, the current will be greater at the skin with less intensity to the underlying platysma muscle with further reduction to the underlying sternohyoid and omohyoid muscles [6], which pull the hyoid downward and backward toward the sternum. The electrical field strength would be even further diminished if the current reaches the deeper thyrohyoid muscle, which brings the larynx and hyoid together, and the sternothyroid muscle, which lowers the larynx toward the sternum. Given that the sternohyoid muscle is larger and overlies the thyrohyoid and sternothyroid, we expect that high levels of surface electrical stimulation on the neck could pull the hyoid downward because of stimulation of either the sternohyoid or the underlying sternothyroid but would be much less likely to raise the larynx toward the hyoid bone as occurs in normal swallowing.

In VitalStim®Therapy [7] electrodes are simultaneously activated over the submental and laryngeal regions on the throat, with the aim of producing a simultaneous contraction of the mylohyoid in the submental region (to elevate the hyoid bone) and the thyrohyoid in the neck (to elevate the larynx to the hyoid bone). However, because these muscles lie deep beneath the anterior belly of the digastric, sternohyoid, and omohyoid muscles, we hypothesized that simultaneous transcutaneous stimulation with two pairs of electrodes at rest would cause (1) the hyoid bone to descend in the neck (due to sternohyoid muscle action), (2) the hyoid bone to move posteriorly (due to the omohyoid muscle activity), and (3) the larynx to descend (if current activates either the sternohyoid or sternothyroid muscles). Furthermore, we hypothesized that in severe chronic dysphagia, (4) when the same array is used at low levels of stimulation just above the sensory threshold, sufficient for sensation but without muscle activation, swallowing might improve as a result of sensory facilitation, while (5) at higher levels required for motor stimulation, the descent of the hyoid might interfere with swallowing causing increased penetration and aspiration.

Methods

Participant Selection

The protocol for the study was approved by the Institutional Review Board before initiating the research. Participant selection criteria included chronic stable pharyngeal dysphagia, at risk for aspiration for 6 months or more, a score of 21 or greater on the Mini-Mental State Examination [8], a severely restricted diet and/or receiving nutrition through enteric feeding, and medically stable at the time of the study. To be included for study, all participants had to demonstrate a risk of aspiration for liquids on videofluoroscopy during the screening portion of the study.

Procedures

Participants were administered informed consent, and had to correctly answer ten questions to demonstrate that they understood the content of the consent before participating. VitalStim® electrodes (Chattanooga Group, Hixson, TN, No. 59000) and the VitalStim Dual Channel Unit were used for the study. Two sets of electrodes were used. The top set was placed horizontally in the submental region over the region of the mylohyoid muscle above the hyoid bone (Fig. 1). The bottom set was placed on the skin over the thyroid cartilage on either side of the midline over the region of the thyrohyoid muscle medial to the sternocleidomastoid muscle. This electrode array was recommended as effective during certification training of the first two authors [7]. A ball-bearing with a diameter of 19 mm was taped to the side of the neck for measurement calibration.

After familiarizing the participant with the device, we identified the sensory threshold as the lowest current level at which the participant reported a "tingling" sensation on the skin. Stimulation at the sensory threshold level did not produce movement on videofluoroscopic recordings and was the lowest level at which participants sensed stimulation on the skin. Movement was first observed when participants first reported a "tugging" sensation, usually around 7 or 8 mA. The maximum motor level was the highest current level a participant could tolerate without discomfort during stimulation on the neck. We determined the sensory and motor levels independently for each set of electrodes. The VitalStim device cycles automatically from "on" to "off" to "on" again for 1 s every minute. Because the change in stimulation is ramped, this cycling process takes up to 4 s. For the stimulation-at-rest trials, the participant was told to keep the teeth clenched to prevent jaw opening and the stimulation was simultaneously set at the maximum tolerated levels for both sets of electrodes. When the stimulation duration reached 55 s, videofluoroscopy was turned on and we recorded the fluoroscopic image on S-VHS videotape while the participant was in the resting position and the device automatically cycled from "on" to "off" and then "on" again. The examiner pressed a button at the time of stimulation offset to place a visible marker on the videotape.

During the videofluoroscopic screening examination, we determined which volume, either 5 or 10 ml, of liquid barium bolus was more challenging and put a participant at risk of aspiration for use during testing. During testing, between one and three swallows were recorded in each of the following conditions in random order: (1) with no stimulation, (2) with both electrode sets on at the sensory threshold level, and (3) with both sets at the maximum tolerated stimulation level. Stimulation remained on before, during, and after the stimulated swallows. The videotaped recordings included an auditory channel for documen-

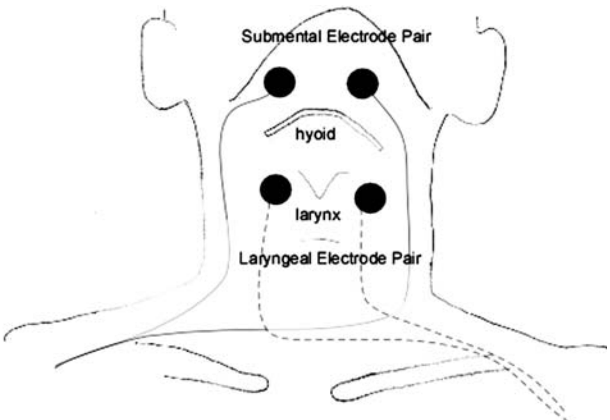

Fig. 1. Schematic of the placement of the surface electrodes over the submental region and the laryngeal region relative to palpation of the hyoid bone and the thyroid cartilage in the neck.

tation and a frame counter display for identifying when stimulation changed.

Because radiation exposure during this study was administered for research purposes only and was not necessary for medical care, the Radiation Safety Committee limited us to a short exposure time per participant for the total study. Therefore, depending on radiation exposure time in each part of the study, we were able to conduct between only one and three trials per condition in addition to stimulation at rest for each participant.

Movement Analysis

The video of each trial was captured offline using Peak Motus 8, a 2D motion measurement system (ViconPeak, Centennial, CO). The system was equipped with a video capture board [capture rate approximately 60 fields/s (~30 frames/s) and frame size 608 × 456 pixels]. The radius of the ball-bearing (9.5 mm) was used for all measurement calibrations in the horizontal and vertical directions. An investigator used a cursor to identify the points on the most anterior-inferior corner of the second and fourth vertebrae on each video frame and a straight line was drawn between these two points to define the y axis. When either the second or the fourth vertebra was not visible, the bottom anterior-inferior corner of the first and third vertebrae were used in the same fashion. A line perpendicular to the y axis at the anterior-inferior corner of the lower vertebra served as the x axis. The x and y coordinates for all points were determined (in mm) relative to the anterior-inferior corner of the second vertebra, which served as the origin with anterior and superior points being positive and posterior and inferior points being negative for direction of movement of the hyoid. Four points were marked for each frame, the anterior-inferior points of the two interspersed vertebrae, the anterior-inferior point of the hyoid bone, and the most posterior and superior point in the subglottal air column (to track the position of the larynx).

The time series plots of the x and y points of the hyoid bone and the y coordinate of the larynx were exported from Peak Modus into Microsoft Excel and then into Systat 11 (Systat Software, Inc., Richmond, CA) for analysis. The frame when the stimulation cycled from "on" to "off" was added to the file and used to sort measures into stimulation "on" and stimulation "off." All of the position data was then corrected to place the starting position at zero on both the x and y axes for each subject and then the mean hyoid (x,y) and larynx (y) positions were computed for the stimulation "on" and stimulation "off" conditions for each subject.

Dysphagia Ratings

Four experienced certified speech pathologists initially examined the screening videotapes of randomly selected subjects to decide on a rating system. After assessing several swallows with the Rosenbek Penetration-Aspiration (Pen-Asp) scale [9], it was noted that many of the participants who were on enteric feeding because of their risk of aspiration could score within the normal range, a score of 1 on this scale. This occurred when no penetration or aspiration occurred, even though there was severe residual pooling in the pyriform sinuses and none of the bolus entered the esophagus. These participants regurgitated any residual material back into the mouth after a trial, not swallowing any of the liquid but scoring as normal because no material entered the airway. Because scores of 1 on the Pen-Asp scale were at ceiling (normal) and would not allow measurement of improvement, this scale could measure only a worsening in swallowing in these patients. Therefore, another scale was developed that did not have a ceiling effect. The NIH Swallowing Safety Scale (SSS) captured the abnormalities seen in this patient group, which involved pooling and a lack of esophageal entry with and without penetration and aspiration. When scoring a swallow, a score of 1 was assigned for the occurrence of each of the following abnormalities: pooling in the vallecula, penetration into the vestibule from the hypopharynx, pooling in the pyriform, and backup penetration from the pyriform into the laryngeal vestibule. The amount of the bolus material entering and clearing from the upper esophagus was rated as 3 if none entered, 2 if a minimal amount entered, 1 if a moderate amount entered, and 0 if all of the bolus was cleared through the upper esophagus. In addition, the total number of aspirations in each swallowing sample was counted. Only normal swallows received a total of 0 on this scale, and the maximum score could reach as high as 13 depending on the number of aspirations or other abnormalities in bolus flow that occurred in a single swallow.

All four speech pathologists viewed each videofluoroscopic recording without knowledge of condition and came to a consensus on all noted behaviors and the Pen-Asp rating before assigning the scores. After repeating ratings on 21 trials to establish reliability, differences in ratings of the same swallow were noted and a set of uniform rules was developed to be followed in assigning scores. These rules were subsequently used to assign ratings to each of the trials in this study. Another set of 18 trials was then repeated to determine the measurement reliability.

Statistical Analyses

To determine the reliability of the position measures, two examiners measured the position for the hyoid on the x and y axes and for the larynx on the y axis on each frame and then computed means for each during both the stimulated and nonstimulated conditions on four of the ten subjects. The output of the General Linear Model Systat 11 (Systat Software, Inc., Richmond, CA) was used to calculate the mean square differences for the within and between subject factors. The Intraclass Correlation Coefficient (ICC) was computed by taking the mean square difference between subjects and subtracting the mean square difference within subjects and then dividing the result by the sum of the mean square difference between subjects and the mean square difference within subjects [10].

To determine the reliability of the ratings made using the Pen-Asp scale and the NIH-SSS, ICCs were computed between the two sets of ratings on each scale from the first 21 trials that were reanalyzed. To identify the items that were unreliable, Cohen's kappa was computed for the two sets of ratings of each component item of the NIH-SSS using Systat 11. After developing rules for scoring those items that had low reliability, ICCs were computed on the second set of repeated ratings for both the Pen-Asp Scale and the NIH-SSS.

To address the first hypothesis that the hyoid bone would descend in the neck with maximal levels of stimulation at rest, a one-sample directional *t*-test was used to test for a lowering of the hyoid bone on the *y* axis between "off" and "on" stimulation. To address the second hypothesis that the hyoid bone would move posteriorly, a one-sample directional *t*-test was used to test for a retraction of the hyoid bone on the *x* axis in the "off" and "on" stimulation conditions within subjects. To determine if the larynx descended during stimulation, a one-sample directional *t*-test was used to test for a lowering of the subglottal air column between the two conditions.

To determine if swallowing improved due to sensory levels of stimulation, one-sample directional *t*-tests were used to test participants' mean changes in ratings between nonstimulated swallows and stimulated swallows within participants on the Pen-Asp scale and the NIH-SSS with a Bonferroni-corrected *p* value of $0.05/2 = 0.025$. Finally, to determine if swallowing worsened during maximum levels of motor stimulation, one-sample directional *t*-tests were used to test participants' mean changes in ratings between nonstimulated swallows and stimulated swallows within participants on the Pen-Asp scale and the NIH-SSS with a Bonferroni-corrected *p* value of $0.05/2 = 0.025$.

Pearson correlation coefficients using a Bonferroni-corrected *p* value of 0.025 for statistical significance were computed between both the participant's mean initial severity on the Pen-Asp scale and the NIH-SSS and changes in mean ratings during the sensory stimulation to determine if participant characteristics predicted the degree of benefit. Similarly, Pearson correlation coefficients were computed between the extent to which the hyoid was pulled down in the neck during stimulation at rest and the change in participants' mean ratings for swallowing on the Pen-Asp scale and the NIH-SSS using a Bonferroni-corrected *p* value of 0.025 for statistical significance.

Results

Participants

All 11 participants had chronic long-standing dysphagia (Table 1). Their disorder was either subsequent to a cardiovascular accident in six subjects (> 6 months after), postcraniotomy for a benign tumor in two (2 and 4 years after), or post-traumatic brain injury in two (2 and 3 years after). Only one patient had a chronic progressive neurologic disease, i.e., Parkinson's disease of more than 20 years with dysphagia for more than two years.

Ten of the 11 participants participated in the stimulation-at-rest trials; one did not because of time constraints. During swallow stimulation trials, one participant had severe aspiration on an initial swallowing trial and for safety reasons the study was discontinued. Therefore, we were able to include ten participants in the motor stimulation swallow trials. Because of time constraints, two of the participants did not participate in the low sensory levels of stimulation, leaving eight participants in the study.

Measurement Reliability

The ICCs for the movement of the hyoid bone on the *y* axis in the stimulation "on" and "off" conditions were 0.99 and 0.94, respectively, and for hyoid movement on the *x* axis were 0.94 and 0.87. The ICCs for the larynx on the *y* axis in the stimulation "on" and "off" conditions were 0.58 and 0.66, respectively, indicating much less reliability on these measures. Because the movement of the larynx was extremely small, ranging from a mean position of 0.4 mm in the stimulation "on" to 0.18 mm in the "off" condition, measurement variability contributed to the variance on this measure.

Movement Induced by Stimulation at Rest

To address the first hypothesis, a one-tailed directional *t*-test comparing the mean position between stimulation "off" and "on" conditions demonstrated a significant lowering of the hyoid position on the *y* axis ($t = -2.523$, $df = 9$, $p = 0.016$) (Fig. 2A, B). To address the second hypothesis that the hyoid bone would move posteriorly with stimulation at rest, a directional *t*-test comparing the mean positions in the stimulation "off" and "on" conditions within subjects was not significant ($t = -0.102$, $df = 9$, $p = 0.460$) (Fig. 2C). Similarly, a directional *t*-test found no descent in laryngeal position on the *y* axis during stimulation ($t = 0.696$, $df = 9$, $p = 0.748$) (Fig. 2D).

Reliability of Ratings on the Pen-Asp Scale and NIH-SSS

After the first set of 21 repeated ratings, the ICC was 0.965 on the Pen-Asp scale and 0.764 on the NIH-SSS. Because of concerns about the reliability of the NIH-SSS, we implemented more detailed judging rules for each item where disagreement occurred. A second set of 18 reliability measures using the new judging rules resulted in an ICC for the NIH-SSS that was 0.925, demonstrating adequate reliability when using the scale once the judging rules were developed and implemented.

Effects of Low Sensory Stimulation Levels During Swallowing

Due to time constraints, only eight of the ten participants completed the sensory condition. To address the fourth hypothesis that swallowing improved with sensory levels of stimulation, one-sample directional *t*-tests were computed to compare mean change in ratings between nonstimulated swallows and stimulated swallows within participants. The results were not significant on the Pen-Asp scale ($t = 0.336$, $df = 7$, $p = 0.373$) but were significant on the NIH-SSS ($t = 0.2.355$, $df = 7$, $p = 0.025$) using a Bonferroni-corrected p value of $0.05/2 = 0.025$. Six of the eight participants showed a reduction on the NIH-SSS with sensory stimulation during swallowing (Fig. 3A) while five of the eight participants showed a reduction on the Pen-Asp scale (Fig. 3B).

Effects of Motor Stimulation Levels During Swallowing

To address the fifth hypothesis that the risk for aspiration and swallowing safety worsened during stimulation, one-sample directional *t*-tests were computed to examine mean change in ratings between nonstimulated swallows and stimulated swallows within participants. The result was not significant on either the Pen-Asp scale ($t = 0.363$, $df = 9$, $p = 0.637$) or on the NIH-SSS ($t = -0.881$, $df = 9$, $p = 0.201$) at a Bonferroni-corrected p value of $0.05/2 = 0.025$. On the NIH-SSS, five of the ten participants had increased risk with motor levels of stimulation (Fig. 4A), while on the Pen-Asp scale, equal numbers of participants increased or decreased with motor levels of stimulation (Fig. 4B).

Relationship Between Severity of Dysphagia and Changes in Swallowing with Stimulation

The Pearson correlation coefficient between participants' initial severity on the Pen-Asp scale and change in swallowing with sensory stimulation was not significant ($r = 0.142$, $p = 0.737$). Similarly, participants' initial severity and change in swallowing with sensory stimulation on the NIH-SSS ($r = 0.701$, $p = 0.053$) was not significant using a Bonferroni-corrected α value of 0.025 for statistical significance. A Pearson correlation coefficient between both the participants' initial severity on the Pen-Asp scale and change in swallowing with motor stimulation was not significant ($r = -0.501$, $p = 0.140$), nor was the correlation between participants' initial severity on the NIH-SSS and change in swallowing with motor stimulation ($r = -0.190$, $p = 0.599$), using a Bonferroni-corrected α value of 0.025 for statistical significance.

Relationship of Movement During Stimulation at Rest with Changes in Swallowing with Stimulation

Pearson correlation coefficients were computed between the extent to which the hyoid was pulled down in the neck during stimulation at rest and the change in swallowing on the Pen-Asp scale and the NIH-SSS using a Bonferroni-corrected α value of 0.025 for statistical significance. No significant relationship was found between the degree of improvement on the NIH-SSS and the degree to which the hyoid bone was depressed during motor levels of stimulation at rest ($r = -0.388$, $n = 9$, $p = 0.302$) (Fig. 5A). The improvement in the Pen-Asp scale during motor stimulation was significantly inversely related to the degree to which the hyoid bone was depressed during motor levels of stimulation at rest ($r = -0.828$, $n = 9$, $p = 0.006$) (Fig. 5B). The relationship demonstrated that those with the greatest hyoid depression at rest had the greatest reduction on the Pen-Asp scale during motor levels of stimulation while swallowing.

Discussion

The first purpose of this study was to determine the physiologic effects of surface electrical stimulation on the position of the hyoid and larynx in the neck. We had predicted that when both the submental and laryngeal electrode pairs were stimulating at the participants' maximal tolerated levels, that the hyoid bone would be pulled downward, most likely because of stimulation of the sternohyoid muscle. The data supported this hypothesis; all but two participants had depression of the hyoid bone by as much as 5–10 mm during stimulation at rest (Fig. 2A, B). We also predicted that the hyoid bone might be pulled posteriorly; however, limited anterior-posterior movement occurred in the hyoid bone. Three participants had hyoid anterior movement, by as much as 5 mm in one case, while the others had minimal movement in the posterior direction. Whereas minimal ascending movement (2–3 mm) occurred in the larynx in two participants, none of the other participants experienced any appreciable laryngeal movement (Fig. 2D) and the 2–3-mm changes were potentially a result of measurement variation. To summarize these findings, the only appreciable motoric effect of surface electrical stimulation was to cause the hyoid bone to

Table 1. Participant characteristics and surface electrical stimulation levels

Subject	Sex	Age	Etiology	Time after onset (years)	Status	Sensory threshold upper/lower electrode (mA)	Motor threshold upper/lower Electrode (mA)
1.	M	66	Hemorrhage in vetebro-basilar circulation	2.5	PEG, bilateral sensory loss, pooling, previous aspiration pneumonia	3.5/2.0	8.0/8.0
2.	M	66	Parkinson's disease	20 years duration, severe dysphagia 2+ years	PEG for 2 years, swallowed own secretions, Recurrent pneumonia	6.0/2.5	10.0/10.0
3.	M	76	Stroke	1	PEG unable to handle secretions, Aspiration pneumonia × 3, normal sensation	4.0/2.0	14/7.0
4.	M	78	Brain stem stroke	5	PEG, frequent aspiration pneumonia, severe reduction in UES relaxation, normal sensation	7.0/7.0	14/14
5.	F	47	Left occipital and brain stem stroke	3	PEG, unable to handle secretions, bilateral sensory loss	3.0/4.0	10/10
6.	M	25	Closed brain injury	2	Aspiration on liquids, bilateral sensory loss	3.5/6.0	16.6/13.0
7.	M	48	Cerebellar hemorrhage with craniotomy	2	PEG, unable to handle secretions, aspiration pneumonia, pooling, normal sensation	3.0/2.5	18.0/18.0
8.	F	44	Subarchnoid hemorrhage left vertebral artery	2	Tracheostomy, PEG tube, Normal sensation bilateral, Pooling of secretions	4.0/2.0	12.5/9.5
9.	M	45	Traumatic brain injury	3	Chokes on saliva, eats soft foods, drooling, bilateral sensory loss	3.0/4.0	18.0/16.0
10.	M	61	Left hemisphere stroke	0.5	PEG, unable to handle secretions,Normal sensation on left, pooling, Botox® in UES	1.5/4.0	13.0/13.0
11.	M	47	Craniotomy for brain stem tumor	4	Severe aspiration, multiple aspiration pneumonia, bilateral sensory loss	1.5/1.5[a]	14/18

[a]Could not study effects of either sensory or motor stimulation during swallowing due to severe aspiration.

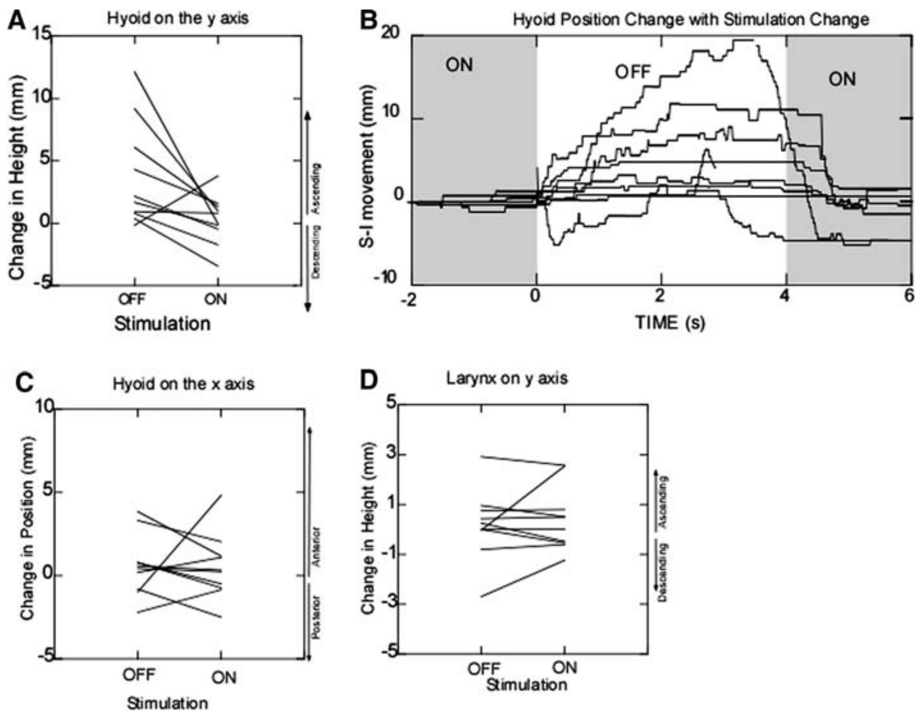

Fig. 2. Line graphs showing the mean values for each participant during the stimulation "off" and "on" conditions for (**A**) the hyoid position on the *y* axis. (**B**) Traces of hyoid position during stimulation "on," stimulation "off," followed by stimulation "on" for each participant in the study. Line graphs also show the mean values for each participant during the stimulation "off" and "on" conditions for (**C**) the hyoid position on the *x* axis and (**D**) the larynx position on the *y* axis.

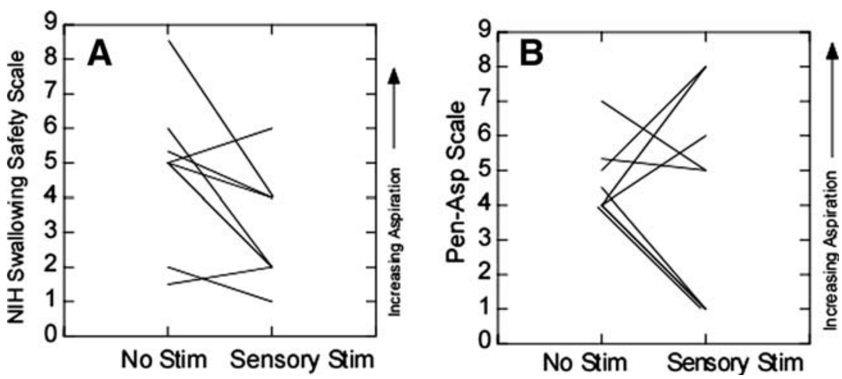

Fig. 3. Line graphs showing individual participants' ratings during the stimulated and nonstimulated swallows at sensory levels of stimulation on the (**A**) NIH Swallowing Safety Scale and the (**B**) Penetration-Aspiration scale.

descend in the neck, producing movement in the opposite direction from that required for swallowing.

These results suggest that when surface stimulation was applied to the neck at rest, stimulation was either too weak or not deep enough to stimulate axons that innervate the muscles that produce hyoid and laryngeal elevation such as the mylohyoid and the thyrohyoid muscles, respectively. No change in laryngeal position was observed with surface stimulation at rest.

The second purpose of this study was to determine the immediate effects of surface stimulation on swallowing in participants with chronic pharyngeal dysphagia. Based on previous use of sensory stimulation in the oral and pharyngeal cavities to augment patients' volitional control of swallowing [3,11], we compared sensory levels of electrical stimulation just above the participants' sensory threshold for detecting a tingling sensation on the skin and found a significant improvement on the NIH-SSS during swallowing but no change on the Pen-Asp scale (Fig. 3). The improvement on the NIH-SSS tended to be related to higher initial scores, i.e., the more severely affected patients were those who had the greatest improvement with stimulation. Because the NIH-SSS captures pharyngeal pooling and failed esophageal entry in contrast with the Pen-Asp scale, which measures only aspiration and penetration, sensory stimulation may be somewhat helpful in those patients who have reduced ability to clear the bolus from the airway.

Based on the expected lowering of the hyoid with motor levels of stimulation, we hypothesized that the group would have increased penetration and

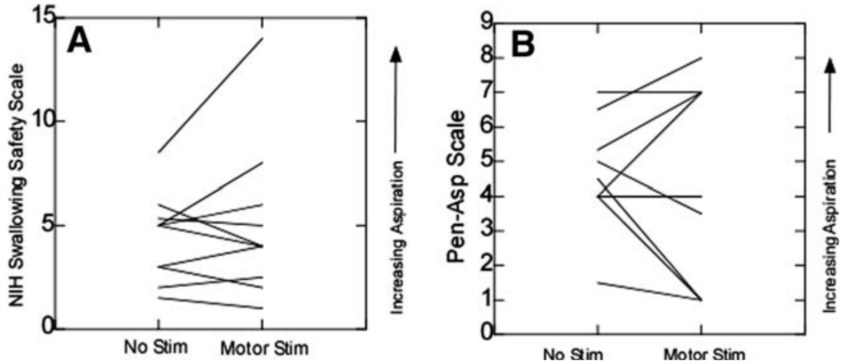

Fig. 4. Line graphs showing individual participants' ratings during the stimulated and nonstimulated swallows at motor levels of stimulation on the (**A**) NIH Swallowing Safety Scale and the (**B**) Penetration-Aspiration scale. These graphs are autoscaled to the range of the data in the two conditions; therefore, (A) is on a larger scale than (B).

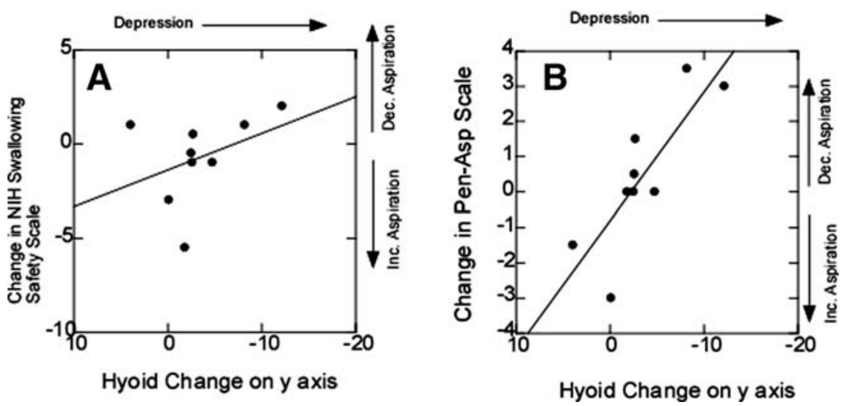

Fig. 5. Scatterplots with linear trend showing the relationship between improvements in swallowing and the extent of hyoid depression during stimulation at rest for the (**A**) NIH Swallowing Safety Scale and the (**B**) Penetration-Aspiration scale.

aspiration during swallowing with motor stimulation. No group change in aspiration was noted on either scale with motor levels of stimulation. When the degree of improvement on the Pen-Asp scale with motor levels of stimulation was examined relative to the degree of hyoid depression, we found an unexpected relationship indicating that patients with the greatest hyoid depression during motor levels of stimulation at rest had the greatest improvement during swallowing with the same levels of stimulation. When the hyoid was depressed with stimulation, a patient probably experienced a greater resistance to hyolaryngeal elevation during swallowing. Perhaps those patients who felt a greater downward pull on the hyoid, when stimulation was turned on at maximal levels, made a greater effort to elevate the hyolaryngeal complex when swallowing in an attempt to overcome the effects of the stimulation. It could also be that those patients who had greater residual power in their hyolaryngeal muscles would have not only experienced greater hyoid descent with stimulation but could also have greater residual power that they could recruit for hyolaryngeal elevation to counteract the stimulation-induced descent during swallowing.

This study did not address whether surface electrical stimulation aids dysphagia therapy in patients at risk of aspiration. A controlled clinical trial with random assignment to two groups with equal contact time to compare traditional therapy techniques and therapy using surface electrical stimulation with blinded outcome ratings is needed to answer this question. This study addressed the immediate physiologic effects of the use of surface electrical stimulation at rest and during swallowing. However, this study suggests that electrical stimulation should be used judiciously depending on a patient's type and degree of difficulty with swallowing. In those patients who already have some ability to raise the hyolaryngeal complex, hyoid depression with stimulation may serve as "resistance" during therapy. On the other hand, if a patient is unable to produce any hyolaryngeal elevation and, therefore, would not be able to resist the hyoid depression induced by stimulation, stimulation might put such a patient at greater risk of aspiration as the hyolaryngeal complex is held down during swallowing. This may have occurred in some of the more severely affected patients who increased in severity on the Pen-Asp scale and NIH-SSS with motor levels of stimulation, while those less impaired did not change (Fig. 4A, B).

In this study both submental and laryngeal pairs of electrodes were used simultaneously as is recommended for VitalStim Therapy. It is likely that the simultaneous stimulation resulted in hyoid lowering because the stronger stimulation to the more superficial and larger sternohyoid and sternothyroid muscles overcame any action that might have been induced by stimulation of the mylohyoid muscle in the submental region or the thyrohyoid muscle beneath the sternohyoid in the throat region. Some have proposed using submental stimulation alone to activate the anterior belly of the digastric and the mylohyoid muscles to pull the hyoid bone upward. However, elevation of the hyoid bone without simultaneous stimulation of the thyrohyoid to raise the larynx would leave the larynx down, resulting in further opening of the vestibule and increased risk of aspiration. Only if the mylohyoid and thyrohyoid muscles are activated together, without contraction of the sternohyoid, would both the hyoid and larynx be raised together as has previously been shown with intramuscular stimulation [12]. This cannot be achieved using surface stimulation because the larger sternohyoid muscle overlies the thyrohyoid and pulls the hyoid downward.

The finding that the group as a whole improved with sensory levels of stimulation alone on the Pen-Asp scale was somewhat unexpected. Previous research has shown that stimulation of the anterior and posterior faucial pillars was most effective for eliciting a swallow reflex in normal subjects [13]. Although not studied physiologically, stroking the throat region is known to assist spontaneous elicitation of swallowing in infants and some mammals. Stimulation of either the glossopharyngeal or the superior laryngeal nerves has been shown to elicit swallowing in animals [14], and bilateral chemical blockade of the superior laryngeal nerves disrupts swallowing in normal humans [15]. It has not been observed that sensory stimulation to the surface of the throat would reflexively trigger a swallow in adults; however, sensory levels of electrical stimulation on the skin in the throat may facilitate volitional triggering of swallowing in dysphagia. These preliminary results suggest that low levels of electrical stimulation on the skin might be beneficial in some patients. Because such low levels of electrical stimulation were not observed to induce hyoid depression, we posit that none of the patients would be put at increased risk for aspiration using lower sensory levels of stimulation. Careful systematic study is needed, however, before such low levels of stimulation could be considered an additional tool for dysphagia therapy.

This study has several limitations. Only one or two trials were evaluated in each patient in each condition because of the need to limit radiation exposure for research purposes in patients who were already receiving radiation for clinical purposes. In addition, the NIH-SSS had limited reliability when first used. This tool improved once rules for judging each of the categories were developed; however, further assessment of the individual items on this scale is needed. The results differed when using the Pen Asp scale and the NIH-SSS. Further research is needed to examine how these scales differ and what they reflect. However, the NIH-SSS was more useful for the severely affected patients in our study with chronic pharyngeal dysphagia . The assessment of pooling and esophageal entry was useful for assessing the particular deficits of patients who were on enteric feeding and had not ingested food for six months or more.

Despite these limitations, the results presented here may be helpful as a first step in developing a physiologic understanding of the immediate effects of surface electrical stimulation in dysphagia. Before such a tool is used in therapy, improved understanding of its immediate effects should be gained in the presence of specific types of swallowing difficulties before it is applied widely to a variety of patients regardless of their risk of aspiration with hyoid lowering. Before surface electrical stimulation is used, the patients should be carefully screened to determine whether they would be placed at increased risk of aspiration with a procedure that lowers the hyoid. Our results indicate that in some patients with dysphagia this form of stimulation could interfere with hyolaryngeal elevation required for airway protection during swallowing.

References

1. Freed ML, Freed L, Chatburn RL, Christian M: Electrical stimulation for swallowing disorders caused by stroke. *Respir Care 46(5)*:466–474, 2001
2. Leelamanit V, Limsakul C, Geater A: Synchronized electrical stimulation in treating pharyngeal dysphagia. *Laryngoscope 112(12)*:2204–2210, 2002
3. Park CL, O'Neill PA, Martin DF: A pilot exploratory study of oral electrical stimulation on swallow function following stroke: an innovative technique. *Dysphagia 12(3)*:161–166, 1997
4. Power M, Fraser C, Hobson A, Rothwell JC, Mistry S, Nicholson DA, Thompson DG, Hamdy S: Changes in pharyngeal corticobulbar excitability and swallowing behavior after oral stimulation. *Am J Physiol Gastrointest Liver Physiol 286(1)*:G45–G50, 2004
5. Loeb GE, Gans C: *Electromyography for Experimentalists*. Chicago: The University of Chicago, 1986
6. Sobotta J: Head, Neck, Upper limbs, Skin. Volume 1 of *Sobotta Atlas of Human Anatomy*, 11th English ed. Staubesand J (ed.) Baltimore: Urban & Schwarzenberg, 1990
7. Wijting Y, Freed ML: *VitalStim Therapy Training Manual*. Hixson, TN: Chattanooga Group, 2003

8. Folstein MF, Folstein SE, McHugh PR: "Mini-mental state." A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res 12(3):*189–198, 1975
9. Rosenbek JC, Robbins JA, Roecker EB, Coyle JL, Wood JL: A penetration-aspiration scale. *Dysphagia 11(2):*93–98, 1996
10. Fleiss JL: *The design and analysis of clinical experiments*. New York: John Wiley & Sons, 19991999, pp 1–11
11. Hamdy S, Jilani S, Price V, Parker C, Hall N, Power M: Modulation of human swallowing behaviour by thermal and chemical stimulation in health and after brain injury. *Neurogastroenterol Motil 15(1):*69–77, 2003
12. Burnett TA, Mann EA, Cornell SA, Ludlow CL: Laryngeal elevation achieved by neuromuscular stimulation at rest. *J Appl Physiol 94(1):*128–134, 2003
13. Pommerenke WT: A study of the sensory areas eliciting the swallowing reflex. *Am J Physiol 84(1):*36–41, 1927
14. Jean A: Control of the central swallowing program by inputs from the peripheral receptors. A review. *J Auton Nerv Syst 10:*225–233, 1984
15. Jafari S, Prince RA, Kim DY, Paydarfar D: Sensory regulation of swallowing and airway protection: a role for the internal superior laryngeal nerve in humans. *J Physiol 550(Pt 1):*287–304, 2003