Laryngeal elevation achieved by neuromuscular stimulation at rest

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Laryngeal elevation achieved by neuromuscular stimulation at rest. J Appl Physiol 94: 128–134, 2003; 10.1152/japplphysiol.00406.2002.—During swallowing, airway protection is achieved in part by laryngeal elevation. Although multiple muscles are normally active during laryngeal elevation, neuromuscular stimulation of select muscles was evaluated to determine which single muscle or muscle pair best elevates the larynx and should be considered during future studies of neuromuscular stimulation in dysphagic patients. Hooked-wire monopolar electrodes were inserted into mylohyoid, thyrohyoid, and geniohyoid muscle regions in 15 healthy men selected for having a highly visible thyroid prominence for videotaping. During trials of single, bilateral, and combined muscle stimulations, thyroid prominence movements were video recorded, digitized, and normalized relative to elevation during a 2-ml water swallow. Individual muscle stimulation induced ~30% of the elevation observed during a swallow and ~50% of swallow velocity, whereas paired muscle stimulation resulted in ~50% of the elevation and ~80% of the velocity produced during a swallow. Paired muscle stimulation produced significantly greater elevation than single muscle stimulation and could assist with laryngeal elevation in dysphagic patients with reduced or delayed laryngeal elevation.

Laryngeal elevation is essential for airway protection during the pharyngeal phase of swallowing; it aids apposition of the arytenoids to the base of the epiglottis for laryngeal vestibule closure and helps shape the aryepiglottic sinuses to divert the bolus laterally around the vestibule (13, 18). Anterior movement of the hyoid in conjunction with laryngeal elevation helps to pull open the relaxed upper esophageal sphincter so that food or liquid may be propelled through it and into the esophagus (21).

Pathologically reduced or delayed laryngeal elevation is the most common cause of aspiration in persons with dysphagia (6–8, 14), either as the primary swallowing dysfunction or as a part of a composite of kinematic and temporal deficiencies (15, 17). Reduced elevation may result from a traumatic brain injury or a cerebrovascular accident affecting central control (3), partial laryngeal resection (10, 12), tissue injury caused by external-beam radiation treatment of the larynx (11), or nerve injury during cervical spinal surgery with an anterior approach (9).

Ligament and muscle attachments suspend the thyroid and cricoid cartilages of the larynx between the hyoid bone above and the sternum below (1). For this reason, any suprahypoid muscle activity that raises the hyoid may consequently raise the larynx, given the absence of opposition by the infrahyoid muscles: the omohyoid, sternohyoid, and sternothyroid. Suprahypoid muscles that may elevate the larynx are the mylohyoid, geniohyoid, stylohyoid, and anterior belly of the digastric. The thyrohyoid muscle, depending on the cooperative action of its neighbors, may also raise the larynx by decreasing the distance between the hyoid bone and the thyroid cartilage. Thus combined stimulation of suprahypoid muscles with the thyrohyoid muscle might have cooperative actions on the hyoid bone and laryngeal suspension from the hyoid bone.

Many suprahypoid and infrahyoid muscles are simultaneously active early in the pharyngeal phase of swallowing, when laryngeal elevation begins (2, 4). Geniohyoid, mylohyoid, and digastric muscles are used selectively by different individuals, with some individuals using all three muscles at the onset of swallowing and others using different pairs (16). In addition, the temporal association between submental muscle contractions differs across individuals (5). Thus the degree to which individual muscles elevate the larynx is not known. If neuromuscular stimulation is to be used to assist dysphagic patients, individual muscles or muscle combinations must be evaluated to determine their effect on laryngeal elevation.

Our long-term goal is to assist patients with chronically delayed or deficient laryngeal elevation by using implanted functional electrical stimulation devices. The first step toward that goal is to select the best muscle or muscle combination to consider for planned studies in patients. However, not every possible laryngeal elevator muscle could be evaluated. In clinical
research with healthy volunteers who did not stand to personally benefit from invasive procedures, great caution had to be taken to minimize discomfort or risk of injury to major vessels or nerves in the head and neck region. Also, because cost, risks of infection, and discomfort increase as more hardware is implanted, we anticipated that only a few functional electrical stimulation devices would be implantable in any one patient. For these reasons, we aimed in this study to identify which single muscle or muscle pair has the greatest potential to assist laryngeal elevation and to quantify the amount of elevation that can be achieved relative to normal swallowing. Because many different muscles and muscle combinations were to be studied in healthy volunteers, external video recording was used to measure laryngeal movement relative to the amount of movement during swallowing. This allowed us to avoid extended radiation exposure during videofluoroscopy and helped minimize the invasiveness of this study.

The mylohyoid, geniohyoid, and thyrohyoid muscles were selected for investigation on the basis of their potential action, as indicated by their anatomical orientations, as well as by their accessibility for possible surgical implantation in patients. The stylohyoid was not investigated because of its inaccessibility. The anterior belly of the digastric was not selected for study because it is inactive during swallowing in ~25% of individuals (5), and its contraction could lower the jaw, which would interfere with swallowing (19, 20). The mylohyoid, geniohyoid, and thyrohyoid muscles were stimulated one at a time to determine the individual effects of each. In addition, the right and left mylohyoid and thyrohyoid muscles were synchronously stimulated as bilateral and ipsilateral pairs. It was hypothesized that paired ipsilateral stimulation of the mylo-

hyoid and thyrohyoid muscles would have the greatest effect on laryngeal elevation because of the potential for synergistic action offered by their mutual attachments to the hyoid bone. Although greater laryngeal movement was anticipated with multiple stimulation sites, no more than two muscles were stimulated simultaneously to allow us to come to a realistic solution for future implantation in patients.

METHODS

Fifteen healthy men, each selected for his highly visible thyroid prominence, participated in this study. Average age was 42 yr (range: 28–62 yr). Normal laryngeal structure and function were confirmed on fiber optic laryngeal examination by an otolaryngologist (E. Mann). Each participant also had normal blood pressure and electrocardiogram readings, no known neurological disorders, and no history of injury or surgery to the head or neck. The National Institute of Neurological Disorders and Stroke Institutional Review Board approved the study, and informed consent was obtained from each individual before participation.

Participants were seated in a partly reclined examination chair that was equipped with an adjustable headrest. As a safety precaution, an electrical grounding pad was adhered to the participant’s back, electrocardiography was used to monitor heart rate, and inductive plethysmographic bands were placed at the rib cage and abdomen to monitor breathing (Non-Invasive Monitoring Systems, Miami Beach, FL).

A lateral view of the neck surface was video recorded during each trial for data analysis. To aid later video data analysis, a 5-cm × 3-mm strip of white tape was adhered to the left side of the participant’s neck parallel to the direction of movement of the thyroid prominence during swallowing (see Figs. 1 and 2). Placement of the tape was sufficiently lateral to assure that the underlying skin did not move in conjunction with the prominence during swallowing.

Local subcutaneous 0.1-ml injections of 2% lidocaine HCl solution were used to anesthetize the skin before insertion of needle electrodes into the muscles. Neuromuscular stimula-

Fig. 1. Anterior view photograph of participant showing the locations of electrode insertions. Circles were drawn on the image to facilitate identification of geniohyoid (GH), right (r) and left (l) mylohyoid (MH), and right and left thyrohyoid (TH) sites. Ink marks on the neck indicate the estimated location of the hyoid cartilage (top line), the thyroid notch (V), and the superior anterior border of the cricoid cartilage (bottom line).

Fig. 2. Lateral view digitized video image of participant showing the measurement technique. The line on the neck was drawn during analysis with the aid of a strip of tape positioned parallel to the superior movement of the thyroid prominence during swallowing. This line was used to estimate the postural angle of the participant. The camera was rotated ~90° during this trial for display purposes.
tion was delivered with a Nicolet Viking IV system (Madison, WI) by using two independently controlled bipolar electrical stimulators. Optimal electrode position and depth were estimated by using anatomical landmarks and were tested by neuromuscular stimulation (0.5–4.0 mA, 200-μs biphasic pulses at 30 Hz lasting 1–2 s) with a monopolar stimulating needle electrode paired to a surface reference electrode adhered to the participant’s neck or arm. Electrode placement was determined physiologically on the basis of predicted patterns of movement during stimulation. Mylohyoid stimulation was defined as stimulation that resulted in both thyroid prominence elevation and submental tissue retraction. Geniohyoid stimulation was defined as stimulation that resulted in an inferior-anterior bulking of submental tissue without producing tongue movement or jaw lowering. Thyrohyoid stimulation was defined as stimulation that resulted in elevation and a slight diagonal twisting of the thyroid prominence contralateral to the side of stimulation.

Once the desired physiological action was produced, the monopolar needle was withdrawn and a 0.002-in. diameter hooked-wire electrode was inserted in its place using a 27-gauge needle. The tip of the hooked-wire electrode was bare of insulation for 1–2 mm, and both the needle and electrode wire were gas sterilized before use. Figure 1 shows typical electrode placements for mylohyoid, thyrohyoid, and geniohyoid stimulation. Placement of the hooked-wire electrode was confirmed by using the previously described criteria, and, if satisfactory, stimulation amplitude was gradually increased from 0.5 mA to a level that achieved marked movement without report of discomfort by the participant, usually between 3 and 6 mA. The maximum stimulation amplitude delivered to any site was 7 mA.

Video recordings were made by using a Panasonic KS152 video camera positioned on a tripod ~0.8 m on the left and level with the participant, which provided a lateral view of the entire neck and jaw region (Fig. 2). For display purposes, a time stamp (Horita TRG-50PC) was mixed with the video signal, and a grid of 6-mm squares was placed ~10 cm to the right of the participant’s neck during each trial to facilitate observation of prominence movement.

Trials were videotaped during stimulation of each mylohyoid, thyrohyoid, and geniohyoid muscle, during synchronous stimulation of an ipsilateral mylohyoid and thyrohyoid muscle pair, during bilateral mylohyoid stimulation, and during bilateral thyrohyoid muscle stimulation. In addition, reference recordings were made of each participant while swallowing 2 ml of water. We conducted three recordings of each condition to ensure that at least one would be acceptable for data analysis. Trial sequence varied across participants.

Analysis. The second of the three video recordings for each stimulation site was digitally captured, unless shadows, clothing, or an examiner obscured the image. In such cases, another of the three recordings was captured. Digitization was done by using a personal computer equipped with a video capture board at 60 fields/s with a frame size of 608 × 456 pixels. Each video sequence began while the participant was at rest, ~1 s before the onset of stimulation or swallow, and ended after the cessation of movement and a return to rest. Motus 2000 software (Peak Performance Technologies, Englewood, CO) was used to extract kinematic measures from the digitized video. With the use of a cursor, points were manually placed onto each video frame to mark the peak of the thyroid prominence as well as two points along a rostral-caudal line, which approximated the postural angle of the participant, guided by the strip of white tape adhered to the side of the neck. Thus, during data acquisition, vertical movement was on the y-axis coordinate frame parallel to the participant’s postural angle (Fig. 2). Measures were converted from pixels to millimeters for each recording by using either the grid or the measured strip of tape as a calibration marker, with one method applied for each participant. Kinematic data were then smoothed by using a low-pass Butterworth filter with a cutoff frequency of 3 Hz, and then were exported to a spreadsheet for graphing and statistical analysis.

The amount of elevation achieved on a swallow was the difference in millimeters between the thyroid position at rest and the peak value, computed as the mean of three data points immediately before and three points after the peak (7 data points over 100 ms; Fig. 3A). Elevation on stimulation was the difference in millimeters between the position of the thyroid prominence at rest and its position during a 500-ms period of stimulation when the thyroid position was most steady (Fig. 3A). Thyroid prominence velocity was calculated as the peak of the first derivative of its position (Fig. 3B). To normalize the data, all stimulation measures for each participant were converted to a percentage of the movement or velocity achieved during that participant’s 2-ml water swallow (% swallow elevation or % swallow velocity).

![Graphical example of mean elevation (A) and peak velocity (B) measurements during swallow and stimulation trials.](https://www.jap.org)
Two examiners familiar with the purpose of the experiment performed the data analyses. Intraexaminer reliability was determined by comparing measures made on two separate analyses of eight randomly selected trials (including both swallow and stimulation trials). Interexaminer reliability was determined by comparing the values obtained by each examiner on 24 different recordings (3 trials of 8 participants). A paired-sample t-test was performed to determine significance.

The six muscle stimulation conditions (3 single and 3 paired) were not independent of one another because the pairs were comprised of the same muscles that were stimulated singly. For this reason, paired muscle stimulation conditions were statistically analyzed separate from single stimulation conditions. First, a multivariate ANOVA was computed to compare the effect of muscle type (mylohyoid, thyrohyoid, and geniohyoid) on the elevation and velocity achieved during stimulation. Then, two repeated-measures ANOVAs, one for elevation and the other for velocity, were computed to compare the effect of stimulating two muscle sites (paired) vs. single stimulation of the same muscles. Values are written as means ± SE. A Bonferroni corrected P value of 0.05/3 = 0.017 was used to determine significance.

RESULTS

Measures of thyroid prominence movement during 2-ml water swallows by the 15 participants averaged 17.56 ± 4.17 mm, with an average velocity of 72.67 ± 29.98 mm/s. The mean intrarater difference was 0.59 mm for examiner 1, and 0.70 mm for examiner 2 (Student’s t = 0.47). The mean interrater difference between measures was 1.59 mm. The mean percent measurement error, therefore, was 3.67% within examiners and 9.05% between examiners on measures of swallow. The mean difference between examiners was 1.2% swallow elevation (standard deviation = 6.58%). Measures obtained by the two examiners were not significantly different (t = 0.67, P = 0.52).

Single-site stimulation. Stimulation was conducted in 28 mylohyoid sites and 30 thyrohyoid sites across the 15 participants. Geniohyoid stimulation was in 12 sites in nine participants. Despite the distinct criteria used to define electrode placement in the mylohyoid, thyrohyoid, and geniohyoid muscles, individual stimulation of those muscles did not produce significantly different thyroid prominence elevation or velocity (Wilks’ lambda = 0.965; F = 0.599; degrees of freedom (df) = 4, 134; P = 0.664; Fig. 4). Mean laryngeal elevation for these three muscles during stimulation was 5.08 ± 3.81 mm or 28.30 ± 19.76% of the elevation produced by the same participants during a 2-ml water swallow. Mean movement velocity for the three muscles was 27.49 ± 15.53 mm/s or 49.69 ± 31.29% of the velocity produced during a swallow.

Single vs. paired-site stimulation. Bilateral mylohyoid stimulation was recorded in 12 participants, bilateral thyrohyoid was recorded in 9 participants, and combined ipsilateral mylohyoid and thyrohyoid stimulation was recorded in 11 participants. Repeated ANOVAs compared paired stimulation with single-muscle stimulation only in those participants who had received both. For example, the mean of right and left single thyrohyoid stimulation was compared with bilateral thyrohyoid stimulation, and the mean of right mylohyoid and right thyrohyoid single muscle stimulation was compared with paired ipsilateral stimulation of those same muscles. A significant within-subjects effect was found for elevation (F = 24.96, df = 1, P < 0.0001), indicating that paired-muscle stimulation yielded greater laryngeal elevation than single-muscle stimulation for the three muscle pairings (right and left mylohyoid; right and left thyrohyoid; and ipsilateral thyrohyoid and mylohyoid; Fig. 5A). Mean elevation achieved by paired-muscle stimulation was 8.90 ± 5.50 mm or 49.07 ± 27.49% of swallow elevation, compared with 5.52 ± 3.22 mm or 30.14 ± 17.52% achieved by stimulation of those same muscles individually (Fig. 5B). Despite these group effects, no effect of muscle between subjects was found for elevation (F = 0.51, df = 2, P = 0.608). Thus the bilateral mylohyoid, bilateral thyrohyoid, and ipsilateral thyrohyoid and thyrohyoid stimulation results did not differ.

Movement velocity was also significantly greater when produced by paired-muscle stimulation than by single-muscle stimulation of those same muscles (P = 26.23, df = 1, P < 0.0001). During paired-muscle stimulation, laryngeal movement velocity averaged 51.94 ± 23.22 mm/s or 82.08 ± 43.86% of swallow movement.
velocity. Those same thyrohyoid and mylohyoid muscles stimulated one at a time produced an average movement velocity of 33.39 ± 11.86 mm/s or 54.92 ± 31.79%. No significant muscle effect was found (F = 1.54, df = 2, P = 0.231). Thus no muscle pair studied produced faster thyroid prominence movement when stimulated than any other.

**DISCUSSION**

Stimulation in the regions of the mylohyoid, geniohyoid, or thyrohyoid muscles with the use of a monopolar hooked-wire electrode produced elevation of the thyroid prominence that was ~30% of the elevation normally produced when a small amount of liquid is swallowed. Stimulation of bilateral mylohyoid, bilateral thyrohyoid, or an ipsilateral combination of the mylohyoid and thyrohyoid muscles produced ~50% of the laryngeal elevation that occurs during a normal swallow. This suggests that implantation of one or two muscles for neuromuscular stimulation might be adequate to assist with the onset and extent of laryngeal elevation and should be evaluated during swallowing in patients with dysphagia.

Our hypothesis was that combined stimulation of the mylohyoid and thyrohyoid muscles would produce the greatest amount of laryngeal movement because of their mutual attachments to the hyoid bone. The thyroid cartilage is attached to the hyoid via ligaments. Thus when the hyoid is raised by the mylohyoid muscle contraction, the entire larynx is elevated. The thyrohyoid may further raise the larynx by reducing the distance between the thyroid cartilage and hyoid bone. This hypothesis was not supported by the results; no differences were found between the combined stimulation of the mylohyoid and thyrohyoid on one side and the bilateral stimulation of the mylohyoid or thyrohyoid. One explanation for this finding may be that the twisting motion produced by unilateral thyrohyoid stimulation gave the appearance of minimal upward or even downward laryngeal movement when viewed from the side, although elevation could be seen when viewed from the front. This paradoxical observation...
did not occur when thyrohyoid stimulation was bilateral, likely because any twisting caused by one muscle was opposed by the twisting of its contralateral partner. Another explanation may be that the contraction produced by unilateral mylohyoid stimulation was insufficient to anchor the hyoid in an elevated position during thyrohyoid stimulation. We did not evaluate the effect of combined bilateral stimulation of mylohyoid and thyrohyoid muscles because of feasibility constraints, but it is reasonable to hypothesize that this could have better raised the hyoid and resisted any downward pull by the thyrohyoid muscles, and perhaps have achieved greater laryngeal elevation. Although no support for a synergistic relationship was found between the mylohyoid and thyrohyoid muscles during ipsilateral paired stimulation, it cannot be concluded that the expected synergistic relationship does not exist for bilateral mylohyoid and thyrohyoid muscle contraction.

Stimulation of individual muscles resulted in different amounts of laryngeal elevation in each of the participants. For example, bilateral thyrohyoid stimulation achieved the greatest laryngeal elevation in one participant, whereas in another it produced the least effect. Although normal variation in anatomy might underlie some individual differences, variation in electrode placement from participant to participant was the most likely cause. Electrode stimulation close to nerve endings has a greater effect than distant stimulation. Also, stimulation to some muscle areas may produce movement of a different direction than stimulation to other areas of the same muscle. The results of this study indicate that no one muscle or muscle pair achieves the greatest laryngeal elevation in all individuals. The implication is that a case-by-case method will be needed to determine the optimal stimulation site when use of neuromuscular stimulation to aid dysphagic patients is attempted.

The velocity of thyroid prominence movement induced by the combined stimulation of two muscles averaged 80% of the velocity achieved during a 2-ml wet swallow. Because the speed of movement with stimulation approximated that of a swallow, neuromuscular stimulation could be used to initiate earlier movement onset in patients whose laryngeal elevation is delayed. In this experiment, an examiner controlled stimulation while the participant was at rest, and the duration was sustained long enough to produce a stable period of maximum effect that could be accurately measured later. During attempts to swallow, a volitional, patient-operated switch could provide laryngeal elevation at the appropriate time. However, it will be important to consider individual cognitive and motor abilities when the best means of coordinating stimulation with swallowing is determined.

The measures of laryngeal elevation in millimeters obtained in this study are not as accurate as measures derived from videofluoroscopic images. Identification of the peak of the thyroid prominence was subjective and at times difficult because of masking by the overlying submandibular tissue, particularly at the peak of swallowing-related movement. Given these issues, it is not surprising that our measurement technique yielded peak laryngeal elevation values that were lower and more variable than those of Logemann et al. (13a). Tracking the posterior-superior corner of the subglottal air column on videofluoroscopy, Logemann et al. reported that the average peak laryngeal elevation in healthy men was 34 mm for those 21–29 yr of age. In this study, the mean elevation measured was 17 mm in subjects between 28 and 62 yr of age. However, measurement of laryngeal elevation from an external, lateral view of thyroid prominence was a reliable means of determining relative differences between muscle stimulation sites.

The next step in the development of a laryngeal functional electrical stimulation system for swallowing will be to evaluate in detail the laryngeal kinematics of paired neuromuscular stimulation by using videofluoroscopy to track anterior and vertical movements of the hyoid bone and the subglottic air column. Once the detailed effects of stimulation are known, it will be possible to select muscles on the basis of the specific needs of individual patients with dysphagia. It is envisioned that after a “fitting period” of training and fine tuning of stimulation duration to suit individual needs, patients might learn to use volitional control of the stimulator to overcome delayed onset of laryngeal elevation as well as to augment laryngeal elevation while swallowing. After training, it would be appropriate to evaluate the temporal and kinematic interactions of stimulation with volitional swallowing. Given the possibility of additive integration of self-generated and stimulated muscle contraction, it is encouraging to find that stimulation at rest could result in 50% of the movement that occurs during normal swallowing.

In conclusion, ~30% of the laryngeal elevation and ~50% of the velocity normally produced during a swallow were achieved with unilateral intramuscular stimulation of the mylohyoid, thyrohyoid, or geniohyoid muscle. Paired neuromuscular stimulation of the mylohyoid and/or thyrohyoid muscles produced ~50% of the laryngeal elevation with ~80% of the velocity that normally occurs during a swallow. Thus paired stimulation of these muscles should be evaluated in detail during swallowing as a possible means of augmenting laryngeal elevation and improving airway protection in patients with dysphagia.

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