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Hyoid Bone and Larynx Movements During Electrical Stimulation of Motor Points in Laryngeal Elevation Muscles: A Preliminary Study

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Objectives: This study aimed to determine the laryngeal elevation muscle motor points, evaluate the movement of hyoid bone and larynx during stimulation of the motor points, and examine the potential for treating severe dysphagia by functional electrical stimulation.

Methods: The motor points of the laryngeal elevation muscles were anatomically determined from four cadavers. Those motor points in two healthy subjects and one lateral medullary syndrome patient were electrically stimulated by surface or implanted electrodes.

Results: The movements elicited by electrical stimulation of the motor points were greater in implanted than in surface electrodes. Elevation of the hyoid bone and the larynx in a lateral medullary syndrome patient were achieved with the implanted electrodes, but the upper esophageal sphincter opening was not obtained unless an additional cricopharyngeus muscle block was provided.

Conclusion: The hyoid bone and larynx were elevated by electrically stimulating the motor points of the laryngeal elevation muscles.

Keywords: Dysphagia, functional electrical stimulation, hyoid bone, larynx, motor point

Conflict of Interest: The authors reported no conflicts of interest.

INTRODUCTION

Functional electrical stimulation (FES) is a technology used to restore lost motor functions of muscles by providing electrical currents (1–3). Numerous studies of FES for upper and lower extremities have been reported since 1961, when Liberson et al. (4) introduced FES for the common peroneal nerve in hemiplegic patients. Recently, laryngeal elevation by FES has been reported for patients with reduced laryngeal elevation. Freed et al. (5) placed surface electrodes on the skin on the digastric or the thyrohyoid muscles, resulting in restoration of normal swallowing function in 35% of patients with most severely dysphagia caused by stroke after less than a week of daily treatment. Leelamanit et al. (6) placed surface electrodes on the skin overlying the submandibular gland to detect the timing of swallowing, and others on the skin overlying the thyrohyoid muscle, 1 cm lateral to the midline and just below the hyoid bone. Marked improvements were observed in 20 of 23 patients following FES of the thyrohyoid muscle during swallowing. They suggested that stimulation of the thyrohyoid muscle caused laryngeal elevation and this helped to open the upper esophageal sphincter (UES). However, the thyrohyoid muscle is thin and is overlain with the sternohyoid muscle. As the surface electrodes are placed on the skin, the current density is greatest in the superficial muscles and correspondingly reduced in the deep muscles. Thus, it is unlikely that the thyrohyoid muscle can be stimulated by surface electrodes without simultaneously stimulating the sternohyoid muscle. Inferior movements of the hyoid bone and the larynx at rest and during swallowing are reported following surface electrode stimulation (7,8). On the other hand, Burnett et al. (9) stimulated geniohyoid, mylohyoid, and thyrohyoid muscles using implanted monopolar hooked-wire electrodes in healthy volunteers. Laryngeal elevation was achieved for each individual muscle stimulation, and approximately 50% of

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the laryngeal elevation during a normal swallow occurred with bilateral mylohyoid, bilateral thyrohyoid, or ipsilateral mylohyoid and thyrohyoid muscle stimulation. In the above studies, the electrodes were placed at various positions, but maximum muscle contractions were obtained when the motor points of the muscles were stimulated. However, to the best of our knowledge the motor points of the laryngeal elevation muscles have not been investigated. Thus, the objective of this preliminary study was to determine the laryngeal elevation muscle motor points, evaluate the movement of the hyoid bone and the larynx during stimulation of the motor points, and examine the potential for treating severe dysphagia by FES.

METHODS

Motor Points of the Muscles Used for Laryngeal Elevation

The suprahyoid and the thyrohyoid muscles are used for laryngeal elevation. The suprahyoid muscles, consisting of the geniohyoid, mylohyoid, digastric, and stylohyoid muscles, elevate the larynx by pulling the hyoid bone superiorly. However, the posterior belly of the digastric and the stylohyoid muscles are difficult to stimulate because they are near the carotid artery, jugular vein, and facial nerve. The thyrohyoid muscle is an infrahyoid muscle and causes a downward movement of the hyoid bone, but elevates the larynx. Motor points, which are often determined by trial and error methods, are specific areas on muscles that produce a maximal contraction when electrically stimulated. However, they are anatomically defined as a surface spot on a muscle belly at the point of penetration of the motor nerve fiber through the epimysium (10). We identified the skin area above the anatomically defined motor points of the geniohyoid, the mylohyoid, the anterior belly of digastric, and the thyrohyoid muscles from formalin-hardened cadavers. The right sides of four cadavers (two men and two women, average 74 years of age [52–95] at death and 157 cm height [150–167 cm]) were used to examine anatomically the motor points of the muscles.

FES in Healthy Subjects

Motor points of the muscles for laryngeal elevation in healthy subjects were electrically stimulated by surface or implanted electrodes and the movements of the hyoid bone and larynx were evaluated using videofluoroscopic (VF) examination of swallowing at 30 frames/sec in lateral projection. The electrical stimulation unit (Neuropack, Nihon Kohden, Tokyo, Japan) provided two channels of monopolar electrical stimulation at a fixed pulse width of 200 µsec and a frequency of 20 Hz. Stimulation intensity was increased until the subjects indicated any further increase would become uncomfortable, yielding the maximum tolerance level. The subjects were two healthy men (25 and 32 years old) who gave written informed consent. The Institutional Review Board approved this study. The bilateral geniohyoid muscle, the mylohyoid/anterior belly of the digastric muscles, and the thyrohyoid muscles were stimulated at rest. The surface electrodes used were 1.5 cm in diameter, disc-shaped, and positioned on the skin above the motor point. The implanted electrodes used were 0.1-mm diameter wire electrodes and were inserted into the skin above the motor point. The depths of the motor points were determined by trial and error. Duration of stimulation was 5 sec, during which we asked the subjects not to swallow. We identified the target muscles by carefully observing the movement of the larynx and the hyoid bone. The geniohyoid and the mylohyoid/anterior belly of the digastric muscles elevate the larynx by pulling the hyoid bone superiorly; by contrast, the thyrohyoid muscle causes downward movement of the hyoid bone but still elevates the larynx. The lower posterior corners of the fourth and fifth cervical vertebral bodies were marked and a line drawn through these two points served as the vertical axis in VF lateral view. The horizontal axis was a perpendicular line to the vertical axis. The marker placed on the surface of the thyroid cartilage was hypothesized to indicate the position of the larynx. The position of the anterior-inferior point of the hyoid bone and the center of the larynx marker were measured and the movement between on- and off-stimulation positions calculated.

FES in a Lateral Medullary Syndrome Patient

A 70-year-old man who had suffered lateral medullary syndrome was referred to our hospital for swallowing rehabilitation a half year later. At admission, the patient had tube feeding only from the percutaneous endoscopic gastrostomy. The head-raising exercise (Shaker's exercise) (11), Mendelsohn maneuver, and other exercises were performed for three months but no marked changes occurred. Elevation of the hyoid bone and the larynx were still weak, and the opening of the UES during swallowing was insufficient to pass a bolus, even after the cricopharyngeus muscle block. FES for laryngeal elevation was planned after the Institutional Review Board approval and written informed consent from the patient was obtained. First, electromyography (EMG) of the laryngeal elevation muscles was performed to exclude the possibility of damage to peripheral nerves of the target muscles. Next, 0.1-mm diameter wire electrodes were inserted into the skin above the motor points of the bilateral geniohyoid, the mylohyoid/anterior belly of digastric muscles, and the thyrohyoid muscles. The electrical stimulation unit (Neuropack, Nihon Kohden, Tokyo, Japan) provided two channels of monopolar electrical stimulation at a fixed pulse width of 200 µsec and a frequency of 20 Hz. Stimulation intensity was increased until the patient indicated any further increase would become uncomfortable, yielding the maximum tolerance level. Duration of stimulation was 5 sec, during which we asked the patient not to swallow. We identified the target muscles by carefully observing the movement of the larynx and the hyoid bone. The geniohyoid and the mylohyoid/anterior belly of the digastric muscles elevate the larynx by pulling the hyoid bone superiorly; by contrast, the thyrohyoid muscle causes downward movement of the hyoid bone but still elevates the larynx. The lower posterior corners of the fourth and fifth cervical vertebral bodies were marked and a line drawn through these two points served as the vertical axis. The horizontal axis was a perpendicular line to the vertical axis. Instead of the larynx marker, the position of the superior posterior corner of the thyroid cartilage was hypothesized to indicate the position of the larynx as the calcified thyroid cartilage of this patient could be observed by fluoroscopy. The position of the anterior-inferior point of the hyoid bone also was measured to determine the movement of the hyoid bone. VF at 30 frames/sec in lateral projection were recorded and the movement of the hyoid bone and the larynx between on- and off-stimulation were measured. Electrical stimulation of the laryngeal elevation muscles was then added for 15 sec after 4 mL of thick liquid was placed in the oral cavity of the patient. When the movement of the larynx and the hyoid bone under electrical stimulation reached a maximum level, the patient, with or without cricopharyngeus muscle block using 1% lidocaine, was asked to swallow.

RESULTS

Motor Points of the Muscles Used for Laryngeal Elevation

The skin area above the motor point of the geniohyoid muscle was 2.1 ± 0.6 cm superior from the superior end of the hyoid bone and 0.8 ± 0.3 cm lateral from the midline (mean ± SD). At this point, the motor branch penetrated through the epimysium of the geniohyoid muscle. The motor point of the mylohyoid and the anterior belly of the digastric muscles were the same; the mylohyoid nerve branch passed between both muscles and penetrated the epimysium from the back of the anterior belly of the digastric muscle and the front of the mylohyoid muscle at 2.3 ± 0.6 cm superior from the superior end of the hyoid bone and 2.2 ± 0.6 cm lateral from the midline (Fig. 1). The motor point of the thyrohyoid muscle was just lateral and inferior of the superior thyroid tubercle. The skin areas above the motor points are shown in Figure 2.

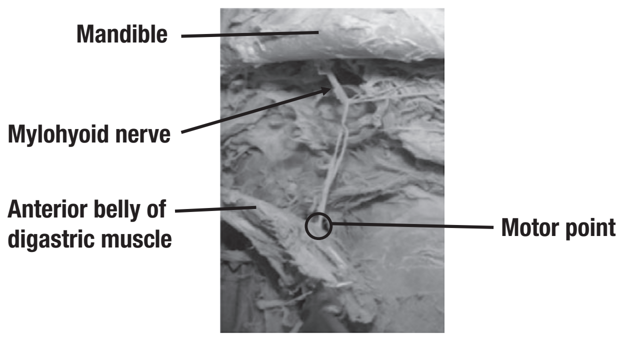

Figure 1. The motor point of the anterior belly of the digastric muscle. The branch of the mylohyoid nerve penetrated the epimysium from the back of the anterior belly of the digastric muscle.

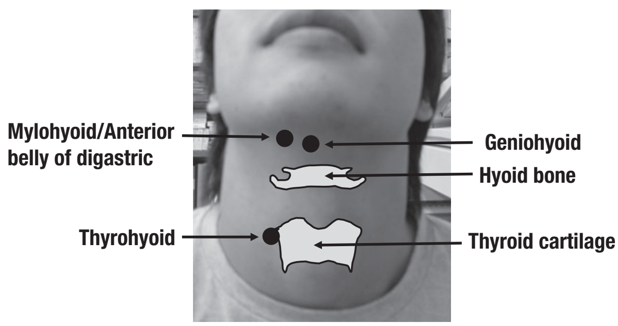

Figure 2. The skin areas above the motor points of the geniohyoid, the mylohyoid, the anterior belly of digastric, and the thyrohyoid muscles in the right sides.

Electrical Stimulation by Surface Electrodes in Healthy Subjects

The surface electrodes were placed on the skin areas above the motor points as shown in Figure 2. Stimulation of the motor points of the bilateral geniohyoid muscles resulted in 0.4 ± 0.5 mm superior and 2.7 ± 0.1 mm anterior movement of the hyoid bone line (mean ± SD). Stimulation of the bilateral mylohyoid/anterior belly of the digastric muscles resulted in 1.2 ± 0.1 mm superior and 0.7 ± 1.0 mm anterior movement of the hyoid bone on average. Stimulation of the mylohyoid and the anterior belly of the digastric muscles was unable to be distinguished because both muscles had the same motor points. However, stimulation of the motor points of the bilateral thyrohyoid muscles resulted in 16.5 ± 7.4 mm inferior movement of the hyoid bone and 5.5 ± 1.4 mm inferior movement of the larynx.

Electrical Stimulation by Implanted Electrodes in Healthy Subjects

The implanted electrodes were inserted perpendicular to the skin above the motor points as shown in Figure 2. The tip of the electrodes was placed where the maximum muscle contractions were obtained; at about 2–2.5 cm in depth. Stimulation of the bilateral geniohyoid muscles resulted in 4.5 ± 0.5 mm superior and 14.9 ± 6.0 mm anterior movement of the hyoid bone (mean ± SD). Stimulation of the bilateral mylohyoid/anterior belly of the digastric muscles resulted in 2.6 ± 0.7 mm superior and 3.0 ± 1.5 mm anterior movement of the hyoid bone. Stimulation of the bilateral thyrohyoid muscles resulted in 1.7 ± 2.4 mm lower and 2.1 ± 3.0 mm anterior movement of the hyoid bone and 7.6 ± 1.5 mm superior movement of the larynx.

Electrical Stimulation in a Lateral Medullary Syndrome Patient

EMG analysis revealed no positive sharp waves or fibrillation potentials at rest in the investigated muscles. The implanted electrodes were inserted perpendicular to the skin above the motor points as shown in Figure 2. They were implanted to the depth that the maximum muscle contractions were obtained. The movement of the hyoid bone and the larynx can be seen in Table 1 and Figure 3. Elevation of the hyoid bone and the larynx were obtained with various settings for the electrical stimulation. The maximum elevation was obtained when the geniohyoid muscles were stimulated followed by thyrohyoid muscle stimulation. A thick liquid was given during the combined stimulation of the bilateral geniohyoid and the thyrohyoid muscles, but most of the liquid did not pass the UES. However, after adding cricopharyngeus muscle block the thick liquid passed the UES during electrical stimulation. The patient felt somewhat uncomfortable during swallowing under electrical stimulation, but this feeling was less than the maximum tolerance level.

Table 1. The Movements of the Hyoid Bone and Larynx During Electrical Stimulation at Rest by Implanted Electrodes.

Stimulated muscles	Hyoid bone	Larynx
Geniohyoid	5.7 mm superior, 10.4 mm anterior	
Mylohyoid/anterior belly of digastric	2.7 mm superior, 2.4 mm anterior	
Thyrohyoid	3.0 mm inferior, 0 mm anterior	6.5 mm superior, 1.3 mm anterior
Geniohyoid and thyrohyoid simultaneously	2.2 mm superior, 9.8 mm anterior	6.2 mm superior, 6.5 mm anterior
Geniohyoid followed by thyrohyoid	5.9 mm superior, 14.3 mm anterior	12.0 mm superior, 9.8 mm anterior

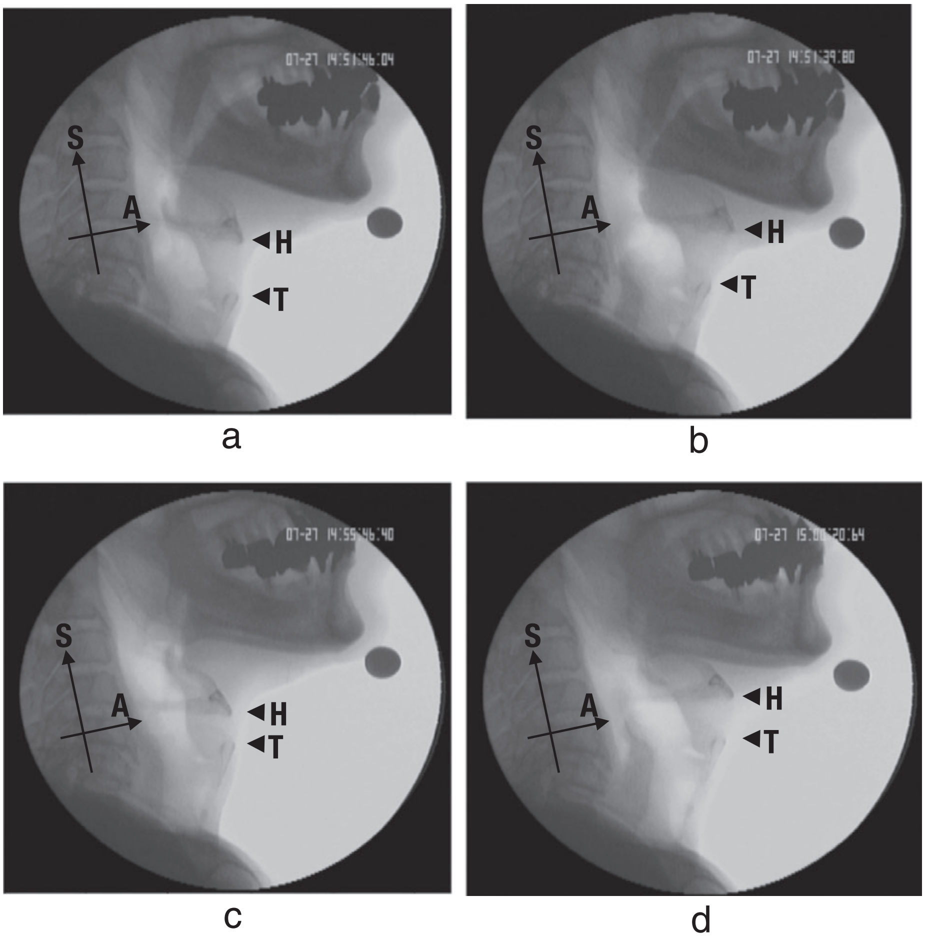

Figure 3. The movements of the hyoid bone and the larynx without and with electrical stimulation at rest by implanted electrodes. Elevation of the hyoid bone and the larynx were obtained with electrical stimulation. The maximum elevation was obtained when the geniohyoid muscles were stimulated followed by thyrohyoid muscle stimulation. a. Without stimulation. b. Geniohyoid stimulation. c. Thyrohyoid stimulation. d. Geniohyoid stimulation followed by thyrohyoid stimulation. A, anterior; H, hyoid bone; S, superior; T, thyroid cartilage.

DISCUSSION

We determined the motor points of the laryngeal elevation muscles from studying cadavers. In a study of healthy subjects, we stimulated the motor points determined from our cadaver study. We used implanted electrodes in a lateral medullary syndrome patient because the movements elicited by this electrical stimulation were greater with than those from surface electrodes. Our aim was to achieve maximum laryngeal elevation and selective thyrohyoid muscle contraction.

Motor Points of the Muscles Used for Laryngeal Elevation

In the present study, we determined the skin areas above the motor points of the geniohyoid, the mylohyoid, the anterior belly of the digastric, and the thyrohyoid muscles using cadavers. Some anatomic studies of motor points have been previously performed. For instance, Liu et al. (12) detected the nerve entry points into the epimysium of the forearm from ten cadavers, and Botte et al. (13) determined the motor points of the gluteus medius muscle that responded maximally to an applied electric current during surgery for pressure sores in the gluteal region. The present study is the first to report the motor points of the laryngeal elevation muscles; although determining the depth of the motor points from the skin is difficult from cadaver studies. However, in healthy subjects we found the depth of the motor points to be approximately 2–2.5 cm from the skin when laryngeal elevation muscles were stimulated by implanted electrodes. An accurate position of the muscle motor points is useful to obtain maximum muscle contractions using electrical currents.

Surface vs. Implanted Electrodes

Stimulation of the skin areas above the motor points of the thyrohyoid muscle by surface electrodes resulted in inferior movement of the hyoid bone and the larynx, probably because of the simultaneous contraction of the sternohyoid muscle that totally overlays the thyrohyoid muscle. Surface electrodes are noninvasive, easily applied, and provide good recruitment of superficial muscles, but stimulation of a specific or a deep muscle is difficult (14). Similar to reports by Humbert et al. (7) and Ludlow et al. (8), selective stimulation of the thyrohyoid muscle by surface electrodes was impossible. On the other hand, although implanted electrodes are invasive and have a risk of infection (14), we could selectively stimulate the thyrohyoid muscles, which resulted in inferior movement of the hyoid bone and superior movement of the larynx. Moreover, the movements elicited by electrical stimulation of the geniohyoid and the mylohyoid/anterior belly of the digastric muscles were greater with implanted than with surface electrodes. We believe that the use of the implanted electrodes is thus the better option for the restoration of reduced laryngeal elevation. However, surface electrodes are still useful because of their handiness when maximum laryngeal elevation is not required.

FES in a Lateral Medullary Syndrome Patient

We used implanted electrodes because we wanted to achieve maximum laryngeal elevation and selective thyrohyoid muscle contraction. The larynx was elevated by stimulation of the geniohyoid, the mylohyoid/anterior belly of the digastric muscles, and the thyrohyoid muscles using implanted electrodes. In normal swallowing, onset of activation of suprahyoid muscles occurred earlier than thyrohyoid muscle activation (15,16). The average hyoid displacements during normal swallowing of 10-mL liquid were 6.5 mm superior and 12.9 mm anterior, while for solid foods were 11.9 mm superior and 12.2 mm anterior (17). The average movement of the thyroid prominence during swallowing of 2-mL liquid was 17.56 mm (9). Maximum hyoid bone and laryngeal elevation was achieved by stimulation of the geniohyoid muscles followed by the thyrohyoid muscles. In this manner, the 5.9 mm superior and 14.3 mm anterior movement of the hyoid bone and the 12.0 mm superior and 9.8 mm anterior movement of the larynx (i.e., 15.5 mm larynx movement from the Pythagorean theorem) were obtained. The hyoid bone and the larynx movements could be reconstructed by FES to almost the same degree as those observed during liquid drinking in healthy subjects. However, UES opening was not obtained irrespective of the elevation of the hyoid bone and the larynx in this lateral medullary syndrome patient. The UES consists of the cricopharyngeus muscle, the lower fibers of the inferior pharyngeal constrictor, and the upper circular fibers of the esophagus; however, the cricopharyngeus muscle is the main component (18). The cricopharyngeus muscle usually contracts and then relaxes to pass a bolus. An additional cricopharyngeus muscle block was required to pass the bolus. Opening of the UES during swallowing is determined by the combined effect of the relaxation and the distensibility of the cricopharyngeus muscle and distraction of the cricoid cartilage caused by contraction of the UES opening muscles, consisting of the geniohyoid, the digastric muscles, and the thyrohyoid muscles (11). Anterior laryngeal movement causes a fall in pressure at the UES, which ensures smooth passage of a bolus from the pharynx to the esophagus (19). Patients with lateral medullary syndrome show lower motor neuron dysfunction of the pharynx and the larynx (20), and the cricopharyngeus muscle, which is innervated by the vagus nerve, appears to have motor neuron damage. Although we applied FES to only one patient, results suggested that elevation of the hyoid bone and the larynx is insufficient to open the UES in patients with motor neuron dysfunction of the UES. Additional procedures to relax the UES are required to pass the bolus.

Before applying FES to the patient in the present study, the potential for lower motor neuron dysfunction of the target muscles was examined, as a muscle contracts primarily by excitation of the intramuscular nerves, and only 3–7% of the muscle twitch force is produced by direct stimulation of muscle fibers (21). Muscles with a damaged supplying nerve are not a good indication for FES, but EMG analysis of this lateral medullary syndrome patient revealed no lower motor neuron dysfunction for the laryngeal elevation muscles. The geniohyoid and the thyrohyoid muscles are innervated by fibers from the first cervical spinal nerve, and the mylohyoid and the anterior belly of digastric muscles are supplied by the branch of the inferior alveolar nerve from the mandibular nerve (22). These nerves did not seem damaged by lateral medullary syndrome, although EMG studies in target muscles are needed before applying FES to exclude patients with lower motor neuron damage as there were very few EMG abnormalities in subjects who did not have lower motor neuron dysfunction (20).

Limitations of the Present Study

This study has several limitations. We were able to determine the motor points as areas of skin on the laryngeal elevation muscles using cadavers, although trial-and-error methods were still required to find the exact depth of a motor point when we used implanted electrodes. We found the depth of the motor points to be approximately 2–2.5 cm from the skin in healthy subjects. Understanding the areas of skin above the motor points was very useful as it saved much time achieving good muscle contractions. Stimulation of the motor points of the hyoid bone and the larynx elevation muscles produced elevations to almost the same degree as those observed during liquid drinking in healthy subjects. However, when the same muscles but not the motor points are stimulated, only about 50% of the laryngeal elevation produced during a normal swallow occurs (9). Moreover, it is difficult to time the stimulation of the laryngeal elevation muscles with the act of swallowing. We placed a thick liquid in the oral cavity of the patient and then instructed him to swallow after the electrically stimulated movement of the larynx and the hyoid bone reached a maximum level. If electrical stimulation can be well timed, a bolus may pass the UES. This was a preliminary report, and as we stimulated only two healthy subjects and one lateral medullary syndrome patient, the findings could be seen as being very weak. A further trial will confirm whether or not the elevation of the hyoid bone and the larynx is insufficient to open the UES in patients who have motor neuron dysfunction of the UES.

CONCLUSIONS

We identified the motor points of the laryngeal elevation muscles. Selective thyrohyoid muscle stimulation was only possible using implanted electrodes. Hyoid and larynx elevation, such as during drinking liquid, were reconstructed in a lateral medullary syndrome patient by electrically stimulating the motor points of the laryngeal elevation muscles.

Authorship Statements

Drs. Kagaya, Baba, Okada, and Yokoyama designed and conducted the study, including patient recruitment, data collection, and data analysis. Dr. Kagaya prepared the manuscript draft with important intellectual input from Drs. Saitoh and Muraoka. All authors approved the final manuscript.

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COMMENTS

This study consists of three portions; using cadaver, normal subjects and a lateral medullary syndrome patient. From the cadaver study, the motor points of the laryngeal elevation muscles were determined. The motor points in a study of healthy subjects were stimulated using surface and implanted electrodes from the results of cadaver study, and implanted electrodes were used in a lateral medullary syndrome patient. It would be clinically useful for laryngeal elevation FES as a preliminary study.

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Comments not included in the Early View version of this paper.