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Electrical Stimulation for the Management of Aspiration during Swallowing

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Abstract— **Protection of the airway during swallow is often compromised following stroke and other neurological diseases. If a patient fails to recover airway protection with standard therapy, they are often left with few if any options to avoid repeated pneumonia resulting from aspiration. For them, the only option is no food by mouth and a PEG-tube for nutrition. Functional electrical stimulation offers possible solutions for restoring airway protection. Here we report the capabilities of transtracheal stimulation for vocal fold closure and selective stimulation of the XII cranial nerve to produce elevation of the hyolaryngotracheal complex. These stimulation locations add to our toolbox for managing swallowing difficulties and allow patients to maintain oral feeding.**

I. Introduction

According to a recent review [1], the reported incidence of dysphagia after stroke ranges from 37% to 78%. Primary consequences of post-stroke dysphagia include malnutrition [2], dehydration [3], and respiratory complications, most notably aspiration pneumonia [1], [4], [5] due to airway penetration of bacteria-laden aspirant. Of the 730,000 [6] stroke survivors each year in America, aspiration will occur in between 19% to 38% of the cases, or about 150,000 patients [7–9]. Approximately 12% of aspirating patients will develop pneumonia, a 20-fold increase over those who do not aspirate [9], [10].

Any disruption to the swallowing process jeopardizes airway protection. Dysphagia (difficulty swallowing) is identified in nearly 10 million Americans every year. Aspiration pneumonia is the third-leading cause of mortality in elderly and stroke survivors and represents a significant problem [11], [12]. Unfortunately for many patients who have failed standard therapy by the speech language pathologist, the only option remaining is prohibition of oral intake. In such cases, nutrition must be supplied enterally, e.g. through a percutaneous endoscopic gastrostomy tube (PEG-tube) or a jejunostomy (J-tube). Loss of oral feeding with required enteral nutrition has a negative impact on quality of life. Further, even when oral intake is eliminated, an individual will typically swallow a liter or more of secretions in the course of a typical day, which still places these patients within an elevated risk for aspiration-pneumonia [13], [14].

Electrical stimulation for the restoration of airway protection by eliciting laryngeal elevation during swallow has been performed using surface electrodes on the neck [15–17] or via intramuscular electrodes [18], [19]. While showing promise, the evidence is not sufficient to support that surface or intramuscular stimulation is sufficient to protect the airway and return a patient to an oral diet [20–22]. Protection of the airway with vocal fold adduction has been demonstrated by direct stimulation of the recurrent laryngeal nerve (RLN) with implanted electrodes [23], [24].

These studies and data support the idea that a functional electrical stimulation approach to prevention of aspiration will require a balanced approach of both laryngeal elevation and vocal fold closure. The purpose of this paper is to provide evidence, in a canine model, of two possible novel locations for stimulation to restore laryngeal function. Specifically, the hypothesis is that it is possible to stimulate the RLN with electrodes against the tracheal wall to produce sustained, controlled vocal fold closure and that stimulation with a nerve electrode directly on the XII cranial nerve can produce strong elevation of the hyo-laryngeal complex.

II. Methods

A. Animal Model

All experiments were performed in seven mongrel canines weighting between 11 and 18 kg. Animals were initially sedated with pentothal and anesthesia was maintained with inhalation isofluorane at 1-4%. Heart rate, temperature, end-tidal CO_2, pO_2, and respiration rate were monitored to ensure depth of anesthesia throughout the procedure. An arterial line was place in the femoral artery to measure blood pressure and provide a patent conduit for medication as necessary. IV fluids with glucose were provided continuously through the forelimb. Body temperature was maintained with a circulating water heating pad and the animal was ventilated for the entire procedure through an endotracheal tube inserted between the 3rd and 4th tracheal rings. This allowed for visualization of the vocal folds with a flexible endoscope through the mouth. Fine-wire EMG electrodes were placed into the intrinsic muscles of the larynx, including the posterior cricoarytenoid (PCA), lateral cricoarytenoid (LCA), thyroarytenoid (TA), and cricothyroid (CT) muscles, and the extrinsic muscles, including the mylohyoid (MH), thyrohyoid (TH), genioglossus (GG), and geniohyoid (GH). The electrodes were placed at the neuromuscular junction for each muscle. At the end of the procedure, the animal was euthanized with an IV overdose of Euthasol. All procedures were reviewed and approved by the

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Case Western Reserve University Institutional Animal Care and Use Committee.

B. *Trans-tracheal stimulation of RLN for VFAd*

Trans-tracheal stimulation was provided by attaching aluminum tape foil contacts to the balloon of a standard endotracheal tube and connecting to an external stimulator via perfluoroalkoxy (PFA)-coated stainless-steel leads (**Figure 1**). The contacts were arranged in columns of two or three at a 45° annular spacing around the balloon. This electrified tracheostomy tube was inserted between the 3rd and 4th tracheal rings and the ventilator was connected to the tube to maintain anesthesia. Supra-threshold current controlled stimulation pulses up to 5 mA were applied to the contacts in a bipolar configuration between the top and bottom contacts of a column to induce tetany of the intrinsic laryngeal muscles.

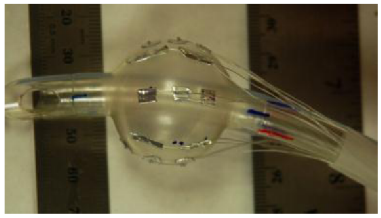

Figure 1. Electrodes attached around the balloon of a tracheal tube provided the electrical stimulation conduit to stimulate the RLN through the tracheal wall.

Vocal fold adduction was recorded on video via flexible fiberoptic endoscope inserted through the mouth and recorded at 30 frames/sec. Following the experiment, the area of the glottal opening was measured frame-by-frame in arbitrary units. The area of the opening was compared as a percentage of size without stimulation and with stimulation. Stimulation was applied unilaterally and bilaterally for comparison. The tracheostomy tube was rotated in 15° increments and stimulated to test 24 different annular locations around the trachea. A flat interface nerve electrode (FINE) was placed on the RLN to compare the functional result of direct nerve stimulation to trans-tracheal RLN stimulation.

C. *Stimulation of CN XII*

Flat Interface Nerve Electrodes (FINEs) were place at three nerve locations (**Figure 2**) including the common CN XII (ProxXII) which contains neural fibers to the TH, GH, and other tongue muscles; just distal to the branching of the XII on the branch to the TH only (THXII) and one on the branch to all the tongue muscles (DistXII). The fine-wire electrodes in the intrinsic and extrinsic muscles recorded EMG in response to stimulation and also provided an electrode for stimulation of the muscle to compare function with the CN XII direct stimulation.

Markers were affixed to the thyroid cartilage, hyoid cartilage, and arch of the mandible. The animal was supine. The lower jaw was held in place with a tie and the motion of the markers was recorded on video at 30 frames/sec. A scale was captured with the video for calibration. Following the experiment the video was analyzed frame-by-frame and the locations of the markers relative to the arch of the mandible were recorded.

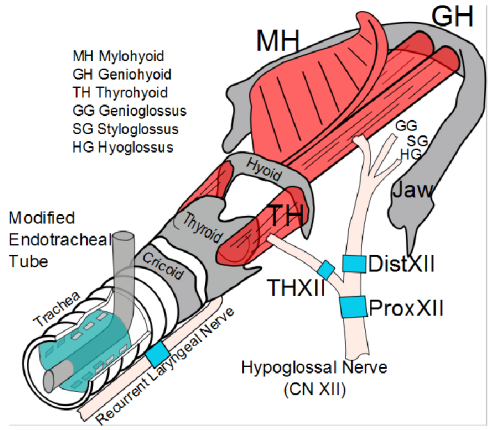

Figure 2. Placement of the FINEs on the XII CN and its branches; the RLN; and the placement of the transtracheal tube.

III. Results

A. *Trans-tracheal stimulation of RLN for VFAd*

Simulation through the FINE on the RLN produced complete closure of the vocal folds (**Figure 3a**). Unilateral trans-tracheal stimulation produced nearly complete closure, and bilateral trans-tracheal stimulation produced complete closure, but with less variability that unilateral stimulation (**Figure 3b**). There was no significant difference between unilateral and bilateral transtracheal stimulation ($p >> 0.2$, ANOVA). Direct nerve stimulation caused a median of

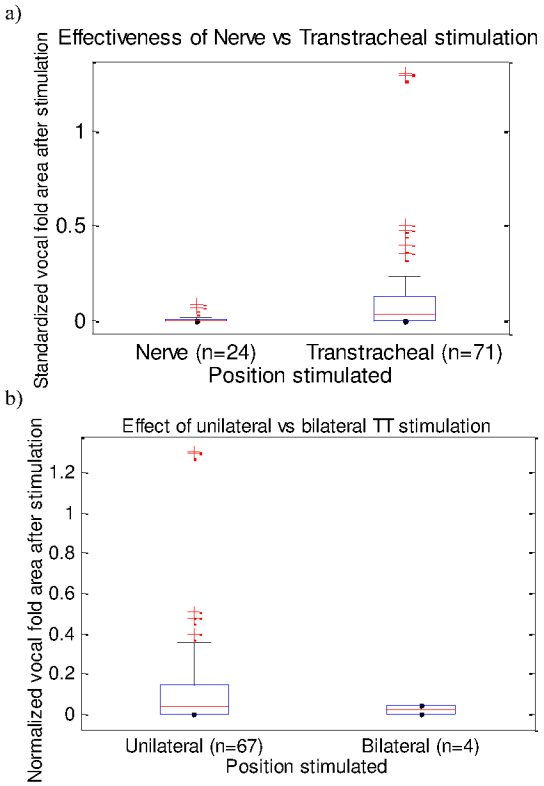

Figure 3. Opening area within the vocal folds during supra-threshold tetanic stimulation as a percentage of the opening area without stimulation. a) Direct nerve stimulation with the FINE compared to unilateral transtracheal stimulation. b) Unilateral compared to bilateral transtracheal stimulation.

100% glottal closure, significantly more than trans-tracheal stimulation (p=0.031, ANOVA), which caused a median of 96.5% closure.

The preferred location of the electrodes, defined as the point with the lowest threshold, was 99.7° to the left and 127.6° to the right of midline where 0° is defined as the anterior, center of the trachea (**Figure 4**). This location was consistent between experiments. Further, if the best location was shifted on one side, the best location on the other side was shifted an equal amount. Therefore, the separation between the two optimal locations was consistent between experiments. The separation of optimal locations is 230 ± 27.1 degrees.

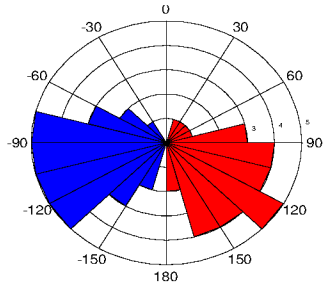

Figure 4. Histogram of annular count of contact locations that had a current threshold less than 5 mA. Blue is for left stimulation sites and red is for right side locations. 0° is set as the anteriocenter of trachea. (Rings represent counts of 1 – 5.)

The vocal fold adduction is dependent on the anesthesia level and stimulation frequency. The closure at 1% and 2% isofluorane were not statistically different, but at 2%, there is a higher variability in the response. At isofluorane levels above 2%, stimulation resulted in opening of the vocal folds (**Figure 5a**). Similarly, stimulation frequency of less than 30 Hz resulted in opening of the vocal folds and stimulation of 40 Hz or higher resulted in closure of the vocal folds (**Figure 5b**).

B. CN XII Stimulation

The CN XII or the intramuscular electrodes in the extrinsic laryngeal muscles for elevation were stimulated at 40 Hz. The displacement was measured at the plateau of the motion (**Figure 6a**) and the velocity was measured for the first half second of stimulation. Stimulation of the CN XII produced both more motion (**Figure 6b**) and faster motion than the intramuscular stimulation (**Table 1**).

The proximal CN XII stimulation results in an upward displacement of the thyroid and of the hyoid. The distance between the thyroid and hyoid is diminished.

Motion [mm (std)]	ProxXII	DistXII	THXII	TH IM	GH IM	MH IM
Laryngeal Elevation	17.4* (5.6)	18.8* (5.9)	0.1 (4.6)	3.8* (3.4)	5.2* (2.8)	8.7* (3.1)
Hyoid Elevation	9.7* (9.1)	17.3* (6.1)	-4.8† (3.8)	-3.1† (3.2)	8.5* (3.4)	12.5* (3.2)
Thyroid-Hyoid Decr.	7.7* (6.0)	1.4 (6.2)	4.8* (2.5)	6.9* (3.5)	-3.3† (3.2)	-3.8† (0.5)

Table 1. Summary of all motions for various stimulation locations. (*significant *(p<0.05)* motion in direction of normal swallowing, † significant *(p<0.05)* motion opposite to normal swallowing.)

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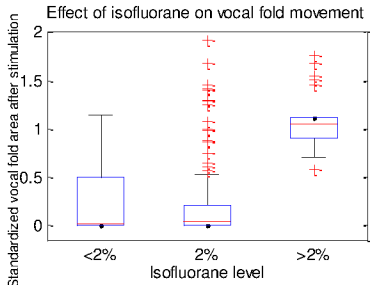

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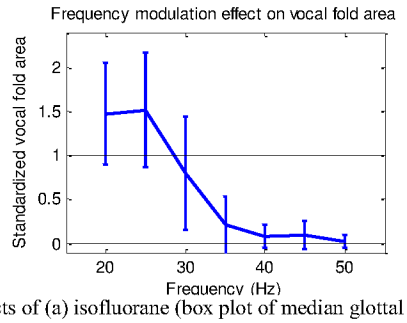
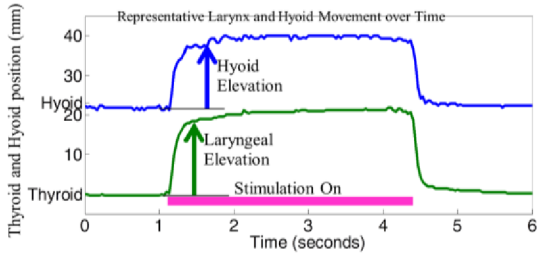


Figure 5. Effects of (a) isofluorane (box plot of median glottal area and quartiles) and (b) stimulation frequency (mean glottal area, bars show the standard deviation) on the opening area of the vocal folds during tetanic supra-threshold stimulation. Area greater than one demonstrated vocal fold opening and less than one demonstrates vocal fold closure.

Stimulation of the branch to the geniohyoid results in elevation of the thyroid and hyoid, but distance between the hyoid and thyroid is also increased. Stimulation of the branch to the thyrohyoid muscle results in a downward displacement of the hyoid and shortening of the distance between the thyroid and hyoid. This response is similar to intramuscular stimulation of the thyrohyoid muscle. The

a)



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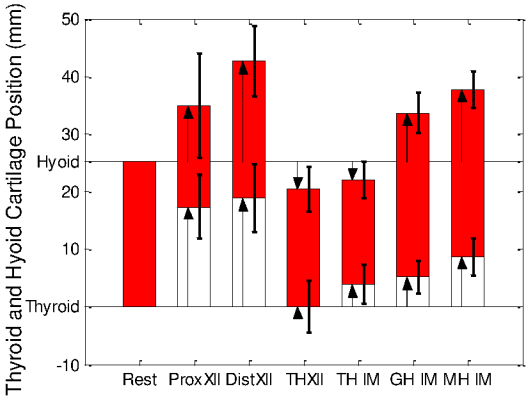

Figure 6. a) Example of the motion of the thyroid and hyoid during one stimulation train. b) Average with standard deviation of the thyroid and hyoid motions for all experiments as a function of cuff location and intramuscular stimulation.

velocity of the motion is also significantly higher ($p < 0.05$) with direct nerve stimulation compared to intramuscular stimulation.

In all of the experiments, it was possible to selectively stimulate the common CN XII, i.e. the ProxXII electrode, to avoid unwanted motion of the tongue. Further, trans-tracheal stimulation of the RLN was not affected by laryngeal elevation.

IV. Discussion

In this paper, we report on the several different stimulation paradigms to restore the important actions that protect the airway during swallowing, vocal fold closure and hyo-laryngeal elevation. We demonstrate that trans-tracheal stimulation produces nearly complete vocal fold closure comparable to direct stimulation of the recurrent laryngeal nerve.

Stimulation of the CN XII is able to produce greater elevation of the hyo-laryngeal complex than intramuscular stimulation of a single muscle. We did not compare nerve stimulation with simultaneous intramuscular stimulation of multiple muscles, which might produce equally robust motion. The nerve stimulation did produce more rapid motion than intramuscular stimulation, which might be important for airway protection during swallow.

These results provide a broader toolbox of methods for restoring airway protection. From these, we can devise more complete electrical stimulation systems for airway protection in dysphagic patients and offer the possibility of improved systems that may be able to provide adequate airway protection such that feeding by a PEG-tube is no longer necessary.

The next steps will be to verify the selectivity and function in humans via intraoperative trials for the CN XII stimulation. Trans-tracheal stimulation will be tested by acute trials with patients already having tracheostomies. One significant unknown related to trans-tracheal stimulation is whether or not there is undesired sensation associated with this stimulation.

In summary, we have demonstrated new stimulation paradigms and approaches that offer significant promise for the management of dysphagia.

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