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Ultrasound Localization and Percutaneous Electrical Stimulation of the Hypoglossal Nerve and Ansa Cervicalis

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Abstract

Objective. Hypoglossal nerve stimulation for obstructive sleep apnea (OSA) can be effective for appropriately selected patients, but current patient selection criteria are complex and still result in a proportion of nonresponders. Ansa cervicalis stimulation of the infrahyoid cervical strap muscles has recently been proposed as a new form of respiratory neurostimulation (RNS) therapy for OSA treatment. We hypothesized that percutaneous stimulation of both nerves in humans with temporary electrodes would make testing of the physiologic response to different RNS strategies possible.

Study Design. Nonrandomized acute physiology study.

Setting. Tertiary care hospital.

Methods. Fifteen participants with OSA underwent ultrasonography and placement of percutaneous electrodes proximal to the medial division of the hypoglossal nerve and the branch of the ansa cervicalis innervating the sternothyroid muscle (AC_{ST}). Procedural success was documented in each participant, as were any failures or procedural complication.

Results. The hypoglossal nerve was successfully localized in 15 of 15 (100%) participants and successfully stimulated in 13 of 15 (86.7%). The AC_{ST} was successfully localized in 15 of 15 (100%) participants and successfully stimulated in 14 of 15 (93.3%). Stimulation failure of the hypoglossal nerve was due to suboptimal electrode placement in 1 participant and electrode displacement in the other 2 cases. No complications occurred.

Conclusions. The hypoglossal nerve and AC_{ST} can be safely stimulated via percutaneous electrode placement. Larger trials of percutaneous stimulation may help to identify responders to different RNS therapies for OSA with temporary or permanent percutaneous electrodes. Techniques for electrode design, nerve localization, and electrode placement are described.

Keywords

hypoglossal nerve stimulation, ansa cervicalis, respiratory neurostimulation, ultrasound, obstructive sleep apnea

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Obstructive sleep apnea (OSA) is a common disorder characterized by repetitive airflow limitation during sleep due in part to changes in neuromuscular tone in vulnerable pharyngeal anatomy.[1] Pharyngeal patency is maintained by a complex and finely tuned balance of many muscle groups.[2-7] The general hypotonia of sleep, as well as the decline in coordinated tension among different muscle forces, increases the risk of airway collapse.[1]

Upper airway surgical therapies for OSA have historically been designed to reduce collapsibility by statically increasing cross-sectional area. Hypoglossal nerve stimulation (HNS) instead improves airway patency by dynamically altering pharyngeal dilator muscle function, primarily by increasing tone in the genioglossus muscle.[2] HNS can be highly effective in appropriately selected individuals, but a substantial proportion of patients who undergo implantation are nonresponders to therapy.[8,9]

Stimulation of the branch of the ansa cervicalis to the sternothyroid muscle (AC_{ST}) has recently been proposed as a potential ancillary neurostimulation therapy to HNS for OSA treatment.[10] The paired sternothyroid muscles pull the pharynx caudally via thyroid cartilage attachments and may mimic the effects of tracheal traction on the airway during diaphragmatic contraction and subsequent lung expansion. Caudal tracheal traction is a well-documented method for increasing pharyngeal patency by stretching the pharynx longitudinally, reducing pharyngeal wall compliance.[11-17]

The ability to percutaneously stimulate the hypoglossal nerve and AC_{ST} would enable minimally invasive physiologic experiments in humans to assess their response to different respiratory neurostimulation (RNS) interventions. Techniques for blind percutaneous hypoglossal nerve localization have

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been proposed but demonstrate a degree of error that complicates effective stimulation.[18,19] Nevertheless, both nerves can be localized with standard diagnostic ultrasound (US) equipment.[20,21] We hypothesized that both could also be stimulated percutaneously under US guidance, and we recently published results of an acute neurostimulation experiment in patients with OSA.[10] Here we describe in detail procedural techniques and equipment for successful nerve localization and stimulation. Reproducible percutaneous stimulation of the hypoglossal nerve and AC_{ST} creates new opportunities for diagnostic and therapeutic RNS procedures.

Methods

Study Design

This study was approved by the Vanderbilt University Medical Center Institutional Review Board (181078). Participants were recruited from a group of patients with OSA previously scheduled for drug-induced sleep endoscopy as part of their regular clinical care.

Anatomic Considerations

Hypoglossal Nerve. The hypoglossal nerve is responsible for motor innervation of the intrinsic and extrinsic musculature of the tongue aside from the palatoglossus muscle. It exits the cranial base through the hypoglossal canal and descends between the carotid artery and internal jugular vein, deep to the digastric muscle and submandibular gland as it traverses the carotid space at the level of the mandibular angle. It is approximately 2 mm in diameter as it enters the sublingual space between the mylohyoid and hyoglossus muscles, separating into a lateral division that largely innervates the retrusor muscles of the tongue (styloglossus and hyoglossus) and a medial division that innervates the genioglossus muscle and intrinsic muscles of the tongue as well as the suprahyoid musculature.[20,23,24] The medial division of the hypoglossal nerve was targeted for stimulation in this study.

Ansa Cervicalis. The ansa cervicalis is a loop of nerves innervating the infrahyoid strap muscles that receives contributions from the primary rami of cervical nerves 1 through 4.[25] Its mean diameter ranges from 0.8 to 2.2 mm.[26] The superior root contains contributions from C1 and C2. It joins with the extracranial portion of the hypoglossal nerve, branching away and coursing inferiorly over the carotid sheath as the latter loops underneath the occipital artery. The anatomy of the inferior root is more variable. Contributions can originate from C1 to C4 and combine in a variety of patterns, deep or superficial to the inferior jugular vein.[27] Much of the superior root is composed of retrograde fibers originating in the inferior root that innervate the suprahyoid strap muscles.[28]

Despite the overall variability in ansa cervicalis morphology, the innervating branch to the sternothyroid muscle is constant and reliable.[25] It is the only infrahyoid strap muscle composed of a single belly with a single point of innervation. Fibers from both roots combine into a common trunk that branches from the summit loop in the area of the omohyoid tendon and enter the sternothyroid muscle 1 to 2 cm above the clavicle at the lateral border.[25,27] The branch of the AC_{ST} was targeted for stimulation in this study.

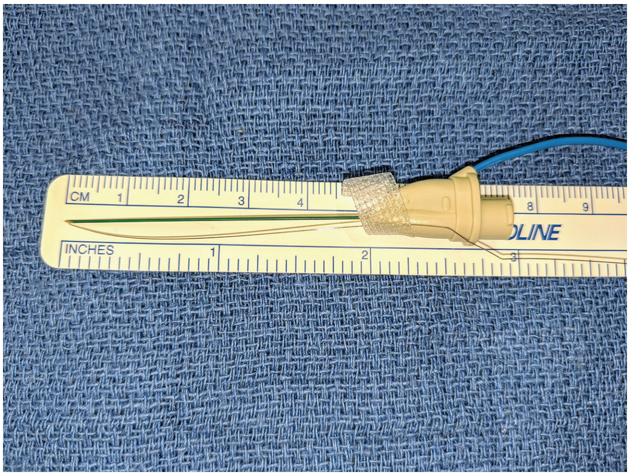

Figure 1. A custom-designed percutaneous electrode. A perfluoroalkoxy-coated, stainless-steel monofilament hook wire of 0.008-in diameter was inserted into the distal end of a 25-guage, 50-mm electromyography needle and taped before ethylene oxide gas sterilization.

Neurostimulation Equipment

Pulse Generator. A Grass S88 stimulator unit (Grass Instruments Co) was used as a pulse generator for synchronous and asynchronous stimulation of both nerves.

Stimulation Electrodes. Perfluoroalkoxy-coated, 0.008-in diameter, stainless-steel monofilament wire (A-M Systems) was fashioned into a hook wire monopolar electrode by stripping the nonconductive coating from the distal 5 mm and acutely bending it (**Figure 1**). The hook was inserted into the distal end of a 25-guage, 50-mm perfluoroalkoxy-coated electromyography (EMG) needle (Natus Medical Inc). The wire was secured under mild tension to the exterior of the needle hub with surgical tape. Electrodes were sterilized with ethylene oxide gas after construction.

Ultrasonography. US images were acquired with a Philips CX50 US scanner (Philips Healthcare) equipped with a linear transducer (3-12 MHz).

Experimental Procedures

Procedure Setup. Experiments were conducted in conjunction with a standard clinical drug-induced sleep endoscopy examination based on previously described methods.[29] Electrodes were placed prior to sedation because large excursions of the pharynx can occur during flow-limited inspiration as accessory respiratory muscles are recruited. It also ensured participant compliance with verbal instructions.

Participants were placed supine on a hospital gurney with the head supported by a foam ring and the surgeon above the head of the bed. A 12-mm subdermal ground needle electrode (Medtronic Xomed, Inc) was inserted into the skin of the

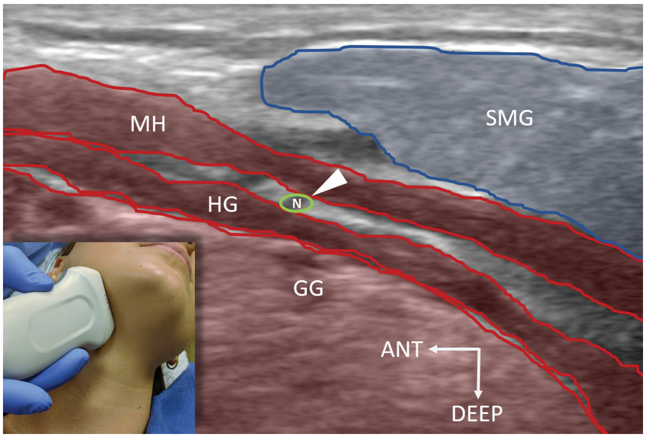

Figure 2. Ultrasound image of right hypoglossal nerve on cross section in a paracoronal plane traversing between the mylohyoid and hyoglossus muscles. Green circle and white arrow indicate hypoglossal nerve. ANT, anterior; GG, genioglossus; HG, hyoglossus; MH, mylohyoid; N, hypoglossal nerve; SMG, submandibular gland.

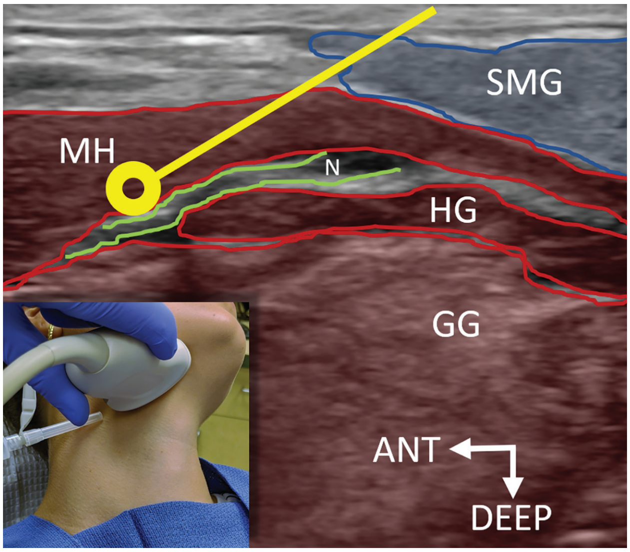

Figure 3. Ultrasound image of the right hypoglossal nerve in a parasagittal plane traversing between the mylohyoid and hyoglossus muscles. Electromyography needle course in yellow. ANT, anterior; GG, genioglossus; HG, hyoglossus; MH, mylohyoid; N, hypoglossal nerve; SMG, submandibular gland.

shoulder or chest, secured with tape, and connected to the pulse generator isolation unit. EMG needles were connected to the pulse generator isolation unit at this time to make them immediately available to the operator without loss of nerve visualization during US procedures.

Hypoglossal Nerve Localization and Electrode Placement. Each participant was asked to rotate the head left and comfortably extend the neck to help deliver the hypoglossal nerve from beneath the shadow of the mandible. The hypoglossal nerve was easiest to initially localize under US as a hypoechoic ovoid structure in a paracoronal plane anterior to the submandibular gland as it traversed between the mylohyoid and hyoglossus muscles (**Figure 2**).[20] The hypoechoic nerve contrasts well against the surrounding hyperechoic plane of fat between the muscles.

Once the nerve was identified, the US transducer was rotated into a parasagittal plane to visualize it on its long axis as it traversed the sublingual space over the anterior border of the hyoglossus muscle (**Figure 3**). This plane could be approximated by a line from the genial tubercle of the mandible to the lesser cornu of the hyoid bone. Imaging the nerve on its long axis enabled in-plane US needle localization at any desired location along its length, including where the medial and lateral divisions separate at the anterior border of the hyoglossus muscle.

Approximately 1 to 2 mL of xylocaine 1:100,000 buffered in a 9:1 ratio with 8.4% sodium bicarbonate was injected at the posterior in-plane edge of the US transducer, in the vicinity of the greater cornu of the hyoid bone. Anesthetic was injected under in-plane US guidance down to the level of the mylohyoid muscle but was not injected deeper to avoid anesthetizing the hypoglossal nerve. The submandibular gland often lay on the needle trajectory, especially in older patients with a more ptotic gland. Transient anesthetic blockade of the marginal mandibular branch of the facial nerve was not uncommon and resolved in all patients without issue.

After local anesthesia, the EMG needle was advanced along the same trajectory until it lay proximate to the medial division of the hypoglossal nerve at the anterior border of the hyoglossus muscle. Care was taken to avoid passing the needle deep into the underlying genioglossus muscle, as this caused significant participant discomfort. The genioglossus was easily visualized on US and through tactile feedback from the EMG needle as more dense tissue with significant resistance to further needle penetration. Brief stimulation pulses (pulse width, 300 μs at 3 Hz) at 1.0 to 1.5 mA confirmed hypoglossal nerve activation with ipsilateral tongue protrusion. Clinical inspection of tongue movement ensured that there was no activation of styloglossus and hyoglossus muscles causing ipsilateral retrusion and dipping of the oral tongue inferiorly.

Once the hypoglossal nerve was adequately localized, the hook wire was released and the EMG needle withdrawn. The wire was secured at the skin with surgical tape with approximately 1 cm of slack length to enable free travel with target muscle tissue contraction during stimulation. The hook wire was connected to the pulse generator isolation unit, and 1-second bursts of stimulation with a pulse width of 300 microseconds at 30 Hz were used to confirm nerve recruitment with desired tongue protrusion and absence of retrusor activation.

Ansa Cervicalis Nerve Localization and Electrode Placement. Each participant was asked to return the head to midline and comfortably extend the neck to help deliver the point of sternothyroid muscle innervation superiorly from beneath the shadow of the clavicle. The AC_{ST} runs in a primarily

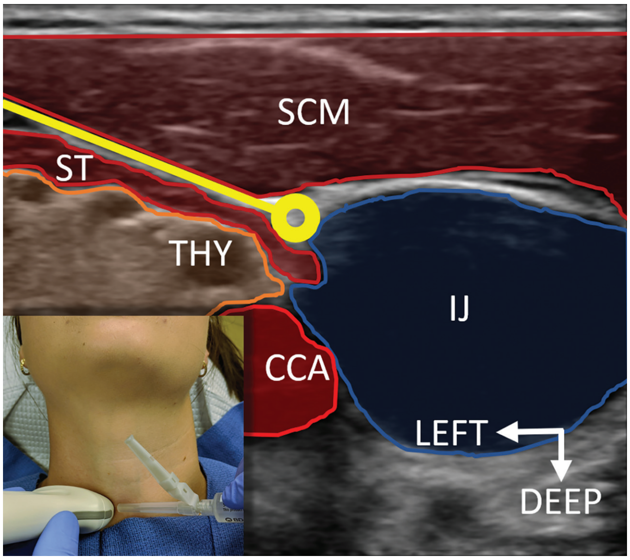

Figure 4. Ultrasound localization of ansa cervicalis innervation of the right sternothyroid muscle in the axial plane. Electromyography needle course in yellow. CCA, common carotid artery; IJ, internal jugular vein; SCM, sternocleidomastoid muscle; ST, sternothyroid muscle; THY, thyroid gland.

rostrocaudal direction over the surface of the internal jugular vein after branching from the summit loop of the ansa cervicalis near the omohyoid tendon. The nerve was localized on cross section in the transverse plane as the clavicle and mandible obstructed EMG needle access from inferiorly and superiorly, respectively. Transverse placement of the US transducer 1 to 2 cm above the clavicle enabled the electrode to be inserted in plane from medial to lateral along a trajectory between the sternocleidomastoid muscle (SCM) and the deeper infrahyoid strap muscles (**Figure 4**). The hypoechoic AC_{ST} could often be difficult to visualize against the much larger hypoechoic internal jugular vein, but it could be easily localized by its position relative to surrounding structures.

Local anesthetic was injected down to the level of the lateral sternohyoid muscle border. The EMG electrode was advanced under the medial border of the SCM and over the strap muscles until the lateral border of the sternothyroid muscle was achieved anteromedial to the internal jugular vein. Test stimulation pulses at 1.0 to 1.5 mA confirmed sternothyroid muscle activation. If the muscle did not adequately activate, the electrode was partially withdrawn and angled several millimeters superiorly or inferiorly. Following the tip of the partially out-of-plane needle protected against internal jugular venipuncture. Care was taken during stimulation pulse testing to be sure that the SCM and sternohyoid muscle were not contracting instead of the sternothyroid muscle. The SCM does not pull the pharynx caudally, and activation of only the inferior belly of the sternohyoid muscle does not generate significant caudal traction because the unstimulated superior belly stretches passively. The hook wire was secured after its EMG needle was removed. Single-second bursts of stimulation were again used to confirm nerve recruitment with descent of the thyroid notch and sternothyroid muscle contraction confirmed by US.

Table 1. Demographic Information for Participants.

	Mean (SD)
Age, y	54.5 (10.4)
Sex, male:female, No.	12:3
Body mass index	31.3 (2.8)
Apnea-hypopnea index	44.3 (14.6)

Drug-Induced Sleep Endoscopy and Neurostimulation

Sedation was begun after electrode placement and maintained with a manually titrated propofol infusion. A bispectral index score <50 was occasionally required to prevent arousal during neurostimulation procedures.

Neurostimulation. Stimulation amperage was titrated upward in 0.1- to 0.5-mA increments for each nerve. HNS was increased until maximal right tongue protrusion was achieved or the participant was aroused in response to stimulation. Arousal was identified from clinical response to noxious stimuli or elevation of bispectral index monitor values. The process was repeated with AC_{ST} stimulation, with effect confirmed by observation of thyroid notch descent. Nerves were stimulated with a pulse width of 300 microseconds at a frequency of 30 Hz. A series of previously described neurostimulation experiments followed.[10]

Data Analysis. Successful localization and stimulation procedures for each nerve were considered variables of interest, as was documentation of any intraoperative complication, including neuropraxia or internal jugular venipuncture. Localization was considered successful if tetanic muscle contraction was observed clinically and under US visualization during EMG needle placement. Weak or intermittent target muscle contraction without the desired clinical effect (eg, tongue protrusion or thyroid notch descent) was not considered successful. Stimulation of the hypoglossal nerve and AC_{ST} was considered successful if equivalent muscle contraction was observed with activation of the monofilament hook wire electrode after EMG needle withdrawal.

Results

Fifteen participants with OSA underwent study procedures (**Table 1**). Participants were mostly older, overweight men. The mean ± SD AHI was 44.3 ± 14.6 events/h, and the average BMI was 31.3 ± 2.8 kg/m^2.

The hypoglossal nerve was successfully localized in 15 of 15 (100%) participants and successfully stimulated in 13 of 15 (86.7%). It was harder to localize in 1 participant with substantial fat deposition around the neck. Stimulation with the EMG needle resulted in substantial muscle contraction; however, hook wire stimulation caused only a modest degree of genioglossus muscle contraction, and there were no appreciable effects during subsequent sedated experiments (data not shown). The second participant's hypoglossal nerve was localized and stimulated, but the hook wire was displaced during needle removal and he declined an attempt at replacement.

The AC_{ST} was successfully localized in 15 of 15 (100%) participants and successfully stimulated in 14 of 15 (93.3%). In 1 participant it was successfully localized and stimulated during electrode placement, but after sedation only the inferior belly of the sternohyoid was observed to contract on US. Replacement was not attempted.

No internal jugular venipuncture was observed by US visualization of a hematoma or by bleeding from the EMG needle cannula during electrode placement. No neuropraxia was observed after procedural completion in any patient.

Discussion

Our results demonstrate that the hypoglossal nerve and AC_{ST} can both be localized and stimulated percutaneously under US guidance. Stimulation produced characteristic movements of anatomic structures that confirmed accurate electrode placement. Percutaneous stimulation of these nerves creates an opportunity for several new RNS applications, including physiologic studies, diagnostic evaluations of airway response prior to permanent device implantation, and percutaneous placement of temporary or permanent electrodes.

Anatomic Approach

Prior reports of techniques for blind percutaneous hypoglossal nerve localization based on anatomic landmarks result in localization errors of several millimeters.[18,19] Nevertheless, neurostimulation requires sufficient current density to generate an action potential, and current density decreases exponentially with distance to the third power from the stimulating electrode. Localization errors of only a few millimeters will fail to stimulate a target nerve or will require substantial amperage that causes pain and patient awakening. Therefore, blind electrode placement risks inefficient capture of the target nerve and does not offer a mechanism for refining placement if the nerve fails to activate. Our US-guided technique provides anatomic information to guide electrode placement and protect against injury to surrounding structures.

Electrode Design

The design of our stimulating electrode serves several functional purposes. Monofilament wire has greater tensile strength than multifilament of the same gauge, permitting wire flexing without deformation and migration during muscle contraction.[30] The nonconductive EMG needle coating increases echogenicity and allows only the distal tip to act as a stimulating element, preserving current density and enabling highly accurate nerve localization. Placing the wire outside the needle with the hook inside the distal cannula also carries several advantages. Modern EMG needles are crimped at the base, significantly reducing the caliber of wire that can be easily passed through the bore. Smaller-caliber wire has insufficient tensile strength to prevent against hook deformation and migration, and it generates a smaller field for nerve activation, making it less forgiving of errors in nerve localization. Placing the wire electrode outside the needle enabled a larger wire gauge to be passed with a smaller EMG needle, reducing participant discomfort and protecting against current density losses associated with tissue edema from larger needle trauma. Placing the hook inside the needle also enabled needle repositioning without tearing and injury of soft tissue by an exposed hook. Finally, our electrode design additionally minimized the risk of hook displacement during needle withdrawal, as friction from sliding the needle over the entire length of the wire could pull the wire from its desired location. Even with these advantages, wire electrode displacement still occurred in a few early cases. Slow and careful EMG needle withdrawal prevented recurrence of this issue in later cases.

Potential Complications and Special Considerations

Several theoretical risks and potential modifications should be considered when a percutaneous RNS protocol is organized with our approach. First, electrode placement in the vicinity of the internal jugular vein carries a theoretical risk of iatrogenic venipuncture, but this complication was not observed in our cohort. If it had occurred, it would have been expected to resolve easily with external compression, as this protects against hematoma after central line removal. Second, although a nerve could theoretically be injured by EMG needle placement, no neuropraxia was observed in this cohort, suggesting that the risk is low. While electrodes were placed in awake participants in this protocol, they could also be placed under deep sedation without participant awareness if the airway is adequately supported. Other measurements tools could be combined with this procedure, such as endoscopy, spirometry, upper airway manometry, or polysomnography. It could also be modified for specific investigations during natural sleep.

Implications

This technique has several immediate and practical applications in the evaluation of RNS therapies. We recently published pilot data assessing the impact of AC_{ST} stimulation with and without HNS on flow-limited inspiration during propofol sedation, highlighting its value for physiologic research.[10] Acute response testing of different RNS modalities may be a useful diagnostic tool for selecting the most appropriate device for implantation if multiple therapeutic options become available. Precedent for this approach is provided by devices for other clinical conditions, such as overactive bladder. When responses to neurostimulation therapy are variable, temporary placement of a removable, percutaneously placed electrode provides an opportunity to assess therapeutic efficacy before committing to a fully implantable device.[31] Our protocol makes percutaneous implantation of similar removable electrodes feasible for future RNS devices.

Further studies are needed to determine the value of this technique for percutaneous electrode implantation or as a diagnostic screening tool.

Author Contributions

David T. Kent, conception and design, data acquisition, data analysis and interpretation, drafting the manuscript and final approval, agreement to be accountable for all aspects; **Alan R. Schwartz**, data analysis and interpretation, drafting the manuscript and final approval, agreement to be accountable for all aspects; **David Zealear**, conception and design, data acquisition, data analysis and interpretation, drafting the manuscript and final approval, agreement to be accountable for all aspects.

Disclosures

Competing interests: Alan R. Schwartz is a consultant for LivaNova, Nyxoah, Respironics, and Respicardia.

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References

1. Eckert DJ. Phenotypic approaches to obstructive sleep apnoea: new pathways for targeted therapy. *Sleep Med Rev*. 2018;37: 45-59. doi:10.1016/j.smrv.2016.12.003
2. Schwartz AR, Eisele DW, Hari A, Testerman R, Erickson D, Smith PL. Electrical stimulation of the lingual musculature in obstructive sleep apnea. *J Appl Physiol*. 1996;81(2):643-652. doi:10.1152/jappl.1996.81.2.643
3. Smith PL, Schwartz AR, Eisele DW, Rowley JA, McWhorter AJ. The effect of tensor veli palatini stimulation on upper airway patency. *Arch Otolaryngol Head Neck Surg*. 2013;125(9): 937. doi:10.1001/archotol.125.9.937
4. Tangel DJ, Mezzanotte WS, White DP. Influences of NREM sleep on activity of palatoglossus and levator palatini muscles in normal men. *J Appl Physiol*. 2017;78(2):689-695. doi:10.11 52/jappl.1995.78.2.689
5. Kuna ST. Respiratory-related activation and mechanical effects of the pharyngeal constrictor muscles. *Respir Physiol*. 2000; 119(2-3):155-161. doi:10.1016/S0034-5687(99)00110-3
6. Hillman DR, Walsh JH, Maddison KJ, et al. The effect of diaphragm contraction on upper airway collapsibility. *J Appl Physiol*. 2013;115(3):337-345. doi:10.1152/japplphysiol.01199.2012
7. Oliven R, Cohen G, Somri M, Schwartz AR, Oliven A. Relationship between the activity of the genioglossus, other peri-pharyngeal muscles and flow mechanics during wakefulness and sleep in patients with OSA and healthy subjects. *Respir Physiol Neurobiol*. 2020;274:103362. doi:10.1016/j .resp.2019.103362
8. Strollo PJ, Soose RJ, Maurer JT, et al. Upper-airway stimulation for obstructive sleep apnea. *N Engl J Med*. 2014;370(2): 139-149. doi:10.1056/NEJMoa1308659
9. Thaler E, Schwab R, Maurer J, et al. Results of the ADHERE upper airway stimulation registry and predictors of therapy efficacy. *Laryngoscope*. Published online September 14, 2019. doi: 10.1002/lary.28286
10. Kent DT, Zealear D, Schwartz AR, Ansa cervicalis stimulation: a new direction in neurostimulation for obstructive sleep apnea. *CHEST*. Published online October 13, 2020. doi:https://doi.org/ 10.1016/j.chest.2020.10.010
11. Squier SB, Patil SP, Schneider H, Kirkness JP, Smith PL, Schwartz AR. Effect of end-expiratory lung volume on upper airway collapsibility in sleeping men and women. *J Appl Physiol*. 2010;109(4):977-985. doi:10.1152/japplphysiol.00080.2010
12. Thut DC, Schwartz AR, Roach D, Wise RA, Permutt S, Smith PL. Tracheal and neck position influence upper airway airflow dynamics by altering airway length. *J Appl Physiol (1985)*. 1993;75(5):2084-2090. doi:10.1152/jappl.1993.75.5.2084
13. Rowley JA, Permutt S, Willey S, Smith PL, Schwartz AR. Effect of tracheal and tongue displacement on upper airway airflow dynamics. *J Appl Physiol*. 1996;80(6):2171-2178. doi:10. 1152/jappl.1996.80.6.2171
14. Hoffstein V, Zamel N, Phillipson EA. Lung volume dependence of pharyngeal cross-sectional area in patients with obstructive sleep apnea. *Am Rev Respir Dis*. 2018;130(2):175-178. doi:10.1164/arrd.1984.130.2.175
15. Stadler DL, McEvoy RD, Bradley J, Paul D, Catcheside PG. Changes in lung volume and diaphragm muscle activity at sleep onset in obese obstructive sleep apnea patients vs healthy-weight controls. *J Appl Physiol*. 2010;109(4):1027-1036. doi:10.1152/japplphysiol.01397.2009
16. Heinzer RC, Stanchina ML, Malhotra A, et al. Lung volume and continuous positive airway pressure requirements in obstructive sleep apnea. *Am J Respir Crit Care Med*. 2005; 172(1):114-117. doi:10.1164/rccm.200404-552OC
17. Stanchina ML, Malhotra A, Fogel RB, et al. The influence of lung volume on pharyngeal mechanics, collapsibility, and genioglossus muscle activation during sleep. *Sleep*. 2003;26(7): 851-856. doi:10.1093/sleep/26.7.851
18. Bassiri Gharb B, Tadisina KK, Rampazzo A, et al. Microsurgical anatomy of the terminal hypoglossal nerve relevant for neurostimulation in obstructive sleep apnea. *Neuromodulation*. 2015;18(8):721-727. doi:10.1111/ner.12347
19. Benbassat B, Cambronne C, Gallini A, Chaynes P, Lauwers F, de Bonnecaze G. The specific branches leading to the genioglossus muscle: three-dimensional localisation using skin reference points. *Surg Radiol Anat*. 2020;42(5):547-555. doi:10. 1007/s00276-019-02390-w
20. Meng S, Reissig LF, Tzou CH, Meng K, Grisold W, Weninger W. Ultrasound of the hypoglossal nerve in the neck: visualization and initial clinical experience with patients. *Am J Neuroradiol*. 2016;37(2):354-359. doi:10.3174/ajnr.A4494
21. Chang KV, Lin CP, Hung CY, Özçakar L, Wang TG, Chen WS. Sonographic nerve tracking in the cervical region: a pictorial essay and video demonstration. *Am J Phys Med Rehabil*. 2016;95(11):862-870. doi:10.1097/PHM.0000000000000557
22. Zaidi FN, Meadows P, Jacobowitz O, Davidson TM. Tongue anatomy and physiology, the scientific basis for a novel targeted neurostimulation system designed for the treatment of obstructive sleep apnea. *Neuromodulation*. 2013;16(4):376-386. doi:10.1111/j.1525-1403.2012.00514.x
23. Mu L, Sanders I. Human tongue neuroanatomy: nerve supply and motor endplates. *Clin Anat*. 2010;23(7):777-791. doi:10.10 02/ca.21011

24. Banneheka S. Morphological study of the ansa cervicalis and the phrenic nerve. *Anat Sci Int*. 2008;83:31-44. doi:10.1111/j.1447-073x.2007.00201.x
25. Loukas M, Thorsell A, Tubbs RS, et al. The ansa cervicalis revisited. *Folia Morphol (Warsz)*. 2007;66(2):120-125.
26. Chhetri DK, Berke GS. Ansa cervicalis nerve: review of the topographic anatomy and morphology. *Laryngoscope*. 1997;107(10):1366-1372. doi:10.1097/00005537-199710000-00014
27. Banneheka S. Anatomy of the ansa cervicalis: nerve fiber analysis. *Anat Sci Int*. 2008;83(2):61-67. doi:10.1111/j.1447-073X.2007.00202.x
28. Charakorn N, Kezirian EJ. Drug-induced sleep endoscopy. *Otolaryngol Clin North Am*. 2016;49(6):1359-1372. doi:10.1016/j.otc.2016.06.002
29. Zealear D, Li Y, Huang S. An implantable system for chronic in vivo electromyography. *J Vis Exp*. 2020;(158):60345. doi:10.3791/60345
30. Shakuri-Rad J, Cicic A, Thompson J. Prospective randomized study evaluating ultrasound versus fluoroscopy guided sacral InterStim lead placement: a pilot study. *Neurourol Urodyn*. 2018;37(5):1737-1743. doi:10.1002/nau.23502