OBSTRUCTIVE SLEEP APNEA: ELECTRICAL STIMULATION TREATMENT

MESUT SAHIN
JINGTAO HUANG
Louisiana Tech University
Ruston, Louisiana

1. INTRODUCTION

Obstructive sleep apnea (OSA) is an intermittent occlusion of the upper airways (UAW) resulting in frequent arousals during sleep (Fig. 1) (1). OSA is a prevalent problem among middle-aged overweight males. Surgical approaches offer only partial relief and the outcome of the surgery is not predictable preoperatively. No drug therapy exists that is effective for the long-term (2). The best therapy currently available is a nasal mask that applies a continuous positive airway pressure (CPAP) to keep the airways open. Most common complications of OSA are restless sleep, excessive daytime sleepiness, job-related accidents, impaired short-term memory, hypertension, congestive heart failure, and decreased libido. Personality disorders and other psychological problems may further complicate the situation in the long run.

OSA is recognized at an increasing rate as more sleep centers open around the world. In most epidemiology studies, the severity of the OSA is rated by the number of obstructive apnea and hypopnea (intermittent within a breath) episodes per hour of sleep (apnea-hypopnea index, AHI). In a recent review, it was estimated that roughly 1 out of every 5 adults has at least mild OSA (defined by AHI ≥5) and 1 out of 15 has at least moderate OSA (defined by AHI ≥15) in predominantly white populations (3). Another report concluded that 1–4% of the male population in Sweden suffers from OSA (4). In a small town in Western Australia, at least 8.5% of the men and 4% of the women had evidence of sleep-disordered breathing for at least one-third of the night (5). In another study conducted in Australia, the prevalence of sleep-disordered breathing (AHI > 15) in a sample of 2,202 subjects between the ages of 35 and 69 was at least 3.6% (5.7% in men and 1.2% in women) (6). These statistics demonstrate that OSA is a prevalent sleep disorder in all parts of the world.

The pathogenesis of OSA has been extensively studied and reviewed (1,7–11). The current research suggests that along the secondary variables like excessive weight, gender, age, and the use of drugs that depress the upper airway tone, mainly two factors render the upper airways vulnerable for obstructions: the anatomical and neuro-muscular factors. Some of the anatomical factors that reduce the size of the air passage are extra adipose tissue in the pharynx and a small or recessed lower jaw.

The fall in the tonic and phasic activity of the UAW muscles during sleep increases the UAW collapsibility and results in the closure of the pharynx in the face of unfavorable anatomical measures. Earlier, the phasic genioglossal (GG) activity in OSA patients was shown to be approximately three times that of normal patients during wakefulness to compensate for the anatomic restriction of the flow (12). In a more recent report, the OSA patients had higher tonic, phasic, and peak phasic GG activity than control subjects for a wide range of epiglottic pressure changes during wakefulness (13). As the slope of the GG activity versus the epiglottic pressure was the same for both groups, this report concluded that the high GG activity in patients was a product of increased tonic activation of the muscles, combined with increased negative-pressure generation during inspiration. On the other hand, it has been shown that GG and tensor palatini muscle activities had significantly larger decrements than controls during alpha-theta transition at the sleep onset (12,14–17) [although the decrease in the GG activity was not always present (18)]. The large decrease in the UAW muscle activity from its elevated level renders the UAWs more collapsible compared with normal subjects. The GG activity further decreases during a transition from non rapid eye movement (NREM) to REM sleep (19). Finally, because the negative airway pressure created by the

Figure 1. A typical pattern of upper-airway occlusion (AO) in a patient. Although present, the genioglossal (GG) activity is low during the occlusions while the pressure swings in the airways are maximal. An arousal occurs just prior to the termination of the occlusive phase, as indicated by the EEG, and the inspiration resumes with a large peak in the GG activity. The patient relapses back into occlusions after a few breaths until the next arousal (1).
diaphragm muscle during inspiration is not sufficiently balanced by the dilating forces of the UAW muscles, the airways collapse at the most vulnerable sites: the soft palate (nasopharynx or velopharynx) or behind the tongue (i.e. oropharynx) (20). It is worth noting that central apnea differs from obstructive apnea in its origin and form. As the respiratory drive ceases in the central apneas completely, breathing does not occur even if the upper airways are open. This article deals only with OSA.

These reports cited above present a scenario that can potentially be corrected by direct activation of the muscles involved using small electric currents. After all, the OSA patients are able to keep their airways open voluntarily during wakefulness or resume breathing upon arousal from sleep. The extra dilating forces needed to keep the airway patency during sleep can potentially be provided by electrical stimulation of the UAW muscles or the nerves that innervate them. The objective then becomes finding the right set of muscles or nerves that can dilate the site of obstruction maximally with minimum disturbance to the subject. The sensation caused by the electrical stimulation, however, should not even cause micro-arousals. Otherwise, the main objective would be defeated by reducing the total amount of time that the patient spends in deep stages of sleep.

The discussion above leads to the conclusion that the hypoglossal nerve (HG) and the tongue muscles that are supplied by the HG nerve are potential targets for stimulation (Fig. 2) (21). The HG nerve innervates the extrinsic muscles of the tongue (i.e., the genioglossus (GG), styloglossus and the hyoglossus), the intrinsic muscles that reshape the tongue, and the geniohyoid muscle. The tongue is the structure with the largest displacement in the region and can potentially relieve the naso- and oropharynx with its forward movement. In addition to the dilation function, activation of the tongue muscles can increase the stiffness of the airways and therefore reduce the collapsibility during the negative pressure swings of inspiration. The GG, the fan-shaped muscle underneath the tongue, is the tongue protrusor and its activity is responsible for anterior positioning of the tongue, whereas the styloglossus and hyoglossus are considered as retractor muscles (Fig. 2). The genioglossus fibers normally contract during inspiration as part of a reflex that is elicited by the negative pharyngeal pressure. Therefore, the studies have concentrated around augmenting this phasic contraction either by direct activation of the GG or selective stimulation of the medial branch of the HG nerve that results in GG activation. Those efforts are summarized in the next section below.

2. CURRENT APPROACHES TO ACTIVATE THE TONGUE MUSCLES

2.1. Genioglossal Stimulation

A study conducted in nine OSA patients demonstrated that unilateral GG stimulation with acutely implanted wire electrodes could increase the inspiratory airflow at moderate levels of nasal positive airway pressure (CPAP) without arousing the patients from sleep (22). The GG activation increased the maximum inspiratory flow rates significantly (although the flow limitation was not completely abolished) whereas the retractor muscle (hyoglossus and styloglossus) stimulation decreased it. The repetitive GG stimulation in four of those patients decreased the AHI from 65.6 \pm 11.5 to 9.0 \pm 5.8 episodes/h. In another study, electrical stimulation via percutaneously inserted bipolar-hooked wires successfully increased the diameter of the hypopharyngeal airway as much as 284% of the resting diameter during wakefulness in nine of the 14 patients studied (23). In seven awake healthy subjects, the UAWs

[Figure 2. The hypoglossal nerve and the muscles that it innervates: the intrinsic and extrinsic muscles of the tongue and the geniohyoid. Genioglossus is considered as the main tongue protrusor of the extrinsic muscles and the hyoglossus and styloglossus as the retractor muscles (21). (This figure is available in full color at http://www.mrw.interscience.wiley.com/ebe.)]
were first partially occluded by applying an external pressure to the submental hyoid region. Then, the transmucosal stimulation of the tongue base, which presumably activated the GG, effectively reduced the pharyngeal resistance (about 42%), despite the fact that submental stimulation (see below) did not generate any statistically significant changes in the same study (24). Another group tested the effects of direct GG stimulation on UAW resistance in anesthetized dogs (25). Upper airway resistance (Rua) increased during both inspiration and expiration when the tracheal negative pressure was switched from 5 to 20 cmH2O. Airway resistance was significantly reduced by stimulation of the GG. The effect of stimulation on airway resistance varied remarkably with the stimulation frequency and reached a plateau above 50 Hz.

These reports suggest that the GG activation alone is capable of improving the airway patency. Nevertheless, chronic implantation of wire electrodes in the tongue is not feasible for this approach to become a clinical tool. A possible alternative paradigm for direct GG stimulation is to use a floating type of microelectrode without interconnects to the outside world, such as the BION®. The results of the BION® implants in OSA patients have not been reported yet (see (26) for a preliminary report) and no other floating stimulators are being tested for this purpose, to our knowledge.

2.2. Submental Stimulation

Similar to the direct GG stimulation, it is the GG muscle again that is targeted with transcutaneous stimulations with electrodes placed underneath the mandible, the lower jaw. Miki et al. (27) examined the effects of submental electrical stimulation in six patients. The stimulations decreased the frequency of apneic episodes, apnea time/total sleep time, the longest apnea duration, and the number of times that oxygen saturation dropped below 85% per hour significantly compared with those control nights. The stimulations neither caused arousals, nor affected the blood pressure or the heart rate significantly. Hida et al. reported in 13 patients that submental stimulation reduced the frequency and duration of apneic episodes with an improvement in the sleep quality and daytime sleepiness (28). These effects remained for at least two nights following the five successive stimulation nights. None of the patients was awakened by the stimulation and none complained of pain or any other discomfort caused by stimulations. Another report by this group demonstrated that the effect of submental stimulation on upper airway collapsibility was similar to that of hypoglossal nerve stimulation in anesthetized dogs (29), which was to decrease the collapsibility and expand the UAW size.

A controversial study was reported by Edmonds et al. (30) in eight male patients with OSA that submental and subhyoidal transcutaneous electrical stimulations failed to prevent sleep-disordered breathing or to improve sleep architecture. Transcutaneous stimulation did not enlarge the upper airways during wakefulness, nor did it prevent the upper airways from collapsing during sleep. Decker et al. (31) reported that submental stimulation had inconsistent effects in seven OSA patients, terminating only 22% of the apneas. The submental stimulation was discomforting during wakefulness. Nonetheless, the stimulus intensity producing arousal during sleep was significantly greater than that producing barely tolerable discomfort during wakefulness. Schnall et al. (24) tested the dilatory effects of upper airway muscle contractions induced by transcutaneous electrical stimulation in awake subjects. Only sublingual stimulation produced measurable tongue protrusion, which was believed to be the effect of GG activation, and helped preserve the upper airway patency while a pressure load was applied exogenously. Neither submental (geniohyoid) nor paralaryngeal (sternohyoid and sternothyroid) muscle stimulation, no matter alone or combined, could cause any tongue protrusion.

In summary, the reports on submental stimulation are controversial, which can be explained by nonspecific activation of the GG because of the tissue present between the stimulating electrodes and the target site. The electrode size and the position can play a significant role on the muscle recruitment function with transcutaneous stimulation. The submental approach is attractive because of its non-invasiveness and ease of application. The success rate and the severity of the OSA cases that can benefit from this approach remains to be seen in a larger-scale study.

2.3. Hypoglossal Nerve Stimulation

Electrical nerve stimulation has a number of advantages over muscle stimulation. The electrode interface is mechanically more stable during activation and, therefore, the recruitment characteristics are better defined. Neural stimulation requires much less energy than muscle stimulation. Thus, the HG nerve stimulation should be preferred over GG activation if the same function can be achieved. Furthermore, HG is mainly a motor nerve. Although it is not known exactly how many afferent fibers are present in the human HG nerve, the experience in clinical trials suggests that HG nerve stimulation at moderate levels does not cause pain to the subject during wakefulness and the threshold for arousal is even higher during sleep (31). Direct hypoglossal nerve stimulation in UAW isolated dogs caused a remarkable decrease of upper airway compliance (29), defined as the slope of the pressure-volume (P-V) curve. With chronic implants in dogs, it has been shown that unilateral hypoglossal nerve stimulation can increase the peak upper-airway flow from 0.1 L/s to 1.6 L/s tested over a 3-month period (32). Histological examination revealed no nerve damage resulting from chronic stimulation. In humans with intraoperative acute nerve-cuff implants on the HG nerve, the pharyngeal size at the level of the tongue base was increased to twice the size of the intubation tube in one study (33), and the flow of inspired air was doubled in another (34). Stimulation of the medial branch was nearly as good and was superior to stimulation of other branches in the latter study (34). Hypoglossal nerve stimulation at both loci during sleep consistently resulted in increased inspiratory airflow without arousals from sleep. Stimulation of the distal HG nerve to the GG caused protrusion and contralateral deviation of the tongue in another study by the same group (35).
former group noted that the current amplitude needed to open the obstructed airways was below the level to cause tongue protrusion (33).

Decker et al. (31) reported that the HG nerve stimulation with percutaneously inserted wire electrodes provided tongue protrusion at minimal discomfort in humans terminated only 23% of the apneic events. Stimulation with bipolar needle electrodes by another group was shown to interrupt obstructions in human subjects without arousals (36). As discussed by the former group, the inefficiency of the stimulations with wire electrodes could be because of misplacement of the wires around the nerve trunk resulting in the recruitment of retractor muscles before the protruser muscles of the tongue.

The most advanced efforts on HG stimulation has been lead by a group at Johns Hopkins University and their collaborators from other research centers and Medtronics Inc., MN. In an international collaboration effort, this group chronically implanted eight OSA patients with a device that stimulated the hypoglossal nerve unilaterally (37). The device consisted of an implantable intrathoracic pressure sensor for synchronization with breathing, a programmable pulse-generating device, and a stimulating half-cuff nerve electrode (Fig. 3) placed around the medial branch of the HG nerve. Electrical stimulation was delivered for the entire night after the onset of sleep and significantly reduced the mean apnea-hypopnea index in NREM and REM sleep stages and reduced the severity of oxyhemoglobin desaturations. The long-term stimulation at night was tolerated by all the patients without any adverse effects. Apnea was eliminated entirely in all patients, but the intermittent inspiratory flow limitation (snoring) remained. The stimulation seemed to be most effective for patients with retroglossal obstruction. Poor synchronization, electrode breakage, and sensor malfunction prevented the continuation of the study in some patients.

In summary, HG nerve stimulation seems to be a promising treatment method for OSA. Different levels of success in the cited reports are most likely because of anatomical variations across the subjects, the site of obstruction, and the site of electrode implantation. Room for improvements exists before this approach can become a clinical tool. One of these techniques that offers a potential for improvement, selective nerve stimulation, is discussed below.

2.4. Selective Stimulation of the Hypoglossal Nerve

Selective nerve stimulation is a technique that has been developed to improve the motor function obtained with electrical stimulation of the peripheral nerves with cuff electrodes. This technique was recently applied to the HG nerve for more effective removal of UAW obstructions (38,39). A flat-interface-nerve electrode (FINE) with multiple contacts (40) was used for selectively activating the fascicles inside the HG nerve trunk. A FINE with nine contacts was implanted on the proximal hypoglossal nerve trunk in a dog (38). The data showed that genioglossus or geniohyoid could selectively be activated from the main HG trunk by delivering small currents through selected contacts. A 17-contact FINE implanted immediately proximal to the branching point (Fig. 4) generated selective activation of the protrusor (genioglossus) or the retractor muscles (hyoglossus and styloglossus), although selective activation of the styloglossus or the hyoglossus muscle was not possible (39).

Huang et al. imaged the upper airways in anesthetized beagles to assess the effects of selective stimulation of the main HG nerve trunk (41). A fiberoscopy lead (diam. 5 mm) was inserted through the cut end of the trachea cephalad and positioned immediately past the proximal rim of the trachea while the head was fixed at either 30° or 60° from the horizontal. Transoral images showed that stimulations delivered through various electrode contacts could generate different activation patterns of the tongue muscles (Fig. 5) (41), including medial or lateral dilation or constriction of the oropharynx at the root of the tongue. Some of these tongue-activation patterns translated into a substantial increase in the oropharyngeal size whereas others did not have any effect (41), which suggests that multiple muscle-activation patterns can be generated with selective HG stimulation, and some of these patterns may be more effective than others for removing the UAW obstructions. This result may, in turn, increase the size of the patient population that can benefit from the HG nerve stimulation as a treatment method for OSA.

3. CONTINUOUS VERSUS CLOSED-LOOP STIMULATION

An important question, still unanswered, is if a feedback signal to synchronize the stimulations with breathing is necessary. Can the stimulations be applied continuously without causing muscle fatigue overnight? The current literature shows that the stimulation level needed for functional results is much lower than the maximum recruitment level of the muscles, and this level is not discomforting to the patients during wakefulness. An open-loop, continuous stimulation paradigm may reduce the number of apnea/hypopnea episodes in a mild OSA patient by merely decreasing the UAW compliance, which
suggests that continuous stimulation may be an acceptable paradigm, eliminating the need for a feedback signal. However, reducing the total time of muscle stimulation may still be of interest because intensive activation may result in conversion of the fatigueable fibers to fatigue-resistant ones in the long term. The contribution of this change to the upper airway patency remains to be seen. Thus, the use of a feedback signal has the potential to improve the overall success of the device.

In addition, the starting point of the pulse train within each breath may be a critical parameter for the best results. It may be much easier to keep the airways open through the inspiratory cycle by turning the stimulus train on prior to the onset of the inspiratory phase rather than trying to dilate the airways against the surface tension of the lining liquid after they collapse (42), which is particularly true if the “delayed activation of the upper airway inspiratory muscles” plays a role in the

**Figure 4.** Placement of the flat-interface-nerve electrode on the hypoglossal nerve for selective stimulation (39).

**Figure 5.** Tongue (top row) and pharyngeal images (bottom row) captured simultaneously to compare the effects of medial and lateral contact stimulation with the flat-interface-nerve electrode in an anesthetized beagle. The head was 30° from the horizontal with the mouth open to image the tongue. Top row, left to right: the control image at rest, stimulation through the lateral, and medial contacts of the FINE. The tongue area that is activated by the stimulation is marked with a circle in each image. The bottom row shows the corresponding pharyngeal images taken with a 5 mm fiberoscopy lead inserted through the cut end of the trachea cephalad and placed immediately past the rim of the trachea. The septum in the middle is the caudal end of the soft palate (the arrow in the bottom-left image). The nasopharynx is the opening below the soft palate and the oropharynx is the one above (dog is in supine position). The lateral contact stimulation dilates the oropharynx toward the ipsilateral side and the medial contact stimulation dilates the oropharynx bilaterally (41). (This figure is available in full color at http://www.mrw.interscience.wiley.com/ebe.)
pathogenesis of the obstructions, as suggested by Hudgel and Harasick (43).

4. DETECTION OF OBSTRUCTIONS TO SYNCHRONIZE STIMULATIONS

If it is determined that the closed-loop approach is advantageous, a reliable method for detection of obstructive breaths will have to be developed to apply the stimulus pulses only when needed. A few detection methods have been proposed to synchronize the electrical stimulation with breathing while some others have been described as a part of an experimental procedure without evaluating its contribution to the overall success of the stimulation paradigm. Among those physiological variables are the hypopharyngeal (22), esophageal (35), and intrathoracic (37) pressure; airflow detected with a thermistor near the nose or mouth (28); tracheal breath sounds (44); tracheal interring distance measured with a strain gauge (36); abdominal movements; and EEG signal. (A) The rectified-integrated phasic HG activity (normalized) is plotted against the breath number. The force transition maneuver in NREM sleep. The traces from top to bottom are the submental force, esophageal pressure, rectified-averaged HG activity, abdominal movements, and EEG signal. (B) The average of 23 trials showing the rate of increase in the HG response. The rectified-integrated phasic HG activity (normalized) is plotted against the breath number. The force transition maneuvers take place within the sixth and seventh breaths (45).

It was proposed that the coupling between the UAW mechanics and the HG nerve activity should be stronger than any other secondary variable to be used for detection of obstructions (45). This technique eliminates the need for implantation of a separate sensor if the HG nerve is implanted with a cuff electrode for stimulation. Two beagles with cylindrical cuff electrodes were implanted to record the HG activity as a response to loading of the UAWs during sleep. The loading paradigm was a remotely controlled force applied to the submental region externally. The phasic HG activity increased immediately in the following breath as a response to the submental force and stayed at an elevated level as long as the force was applied (Fig. 6a) (45). The baseline signal increased slightly with the submental force in one of the animals, but the increase in the baseline did not interfere with detection of the phasic component. The phasic HG signal began to increase before the esophageal pressure with an average time difference of 17 ± 196 ms (mean ± SD, 220 breaths). The HG activity was detectable even at very low levels of UAW loading in this dog model (47). It remains to be seen if the obstructive breaths are detectable in OSA patients using the cuff electrode recordings of the HG nerve’s activity.

5. EVALUATION OF CURRENT APPROACHES

5.1. Stimulation Paradigms

In general, reports cited above are aimed at activating the GG directly or via stimulation of the medial branch of the HG nerve. Activation of the medial branch alone seems to be as efficient as the main trunk of the HG nerve in a group of patients (35). Can this be generalized to the rest of the population with the given variations in the UAW anatomy and the degree of OSA severity? The tongue movements have a large degree of freedom as manifested during mastication and swallowing. It is also a unique organ that is capable of changing its shape voluntarily with the recruitment of vertically and transversely located intrinsic muscles (48). Can a stimulation paradigm be found that uses these capabilities of the tongue for removal of obstructions in a more effective way than single-branch stimulation can provide? Can such an advanced stimulation paradigm also provide multiple modes of muscle activation so that a control algorithm can be designed to switch between these modes when the patient changes his/her position in the bed?

To speculate on some of these questions, a paradigm aiming to recruit only the GG muscle and the whole
muscle at once is not likely to be the optimum solution for the following reasons: (1) Genioglossus is a fan-shaped muscle attaching to the ventral side of the tongue along its longitudinal axis, the hyoid bone on one end and the mandible on the other end (Fig. 2). Activation of the whole muscle at once, rather than some selected portions of it, can produce agonist forces and not a net force in the forward direction to pull the tongue out of the pharyngeal cavity. (2) The forces generated by the tongue muscles are context-dependent (i.e., neck position). For certain positions of the neck, the retractor muscles and the geniohyoid can also be recruited to augment the pharyngeal dilation obtained with the GG alone. (3) Coordinated activation of the GG, the retractor, and the intrinsic muscles can generate forces not only to pull the tongue forward but also push it downward to relieve the nasopharynx. (4) Coactivation of the antagonistic muscles can reduce the collapsibility of the UAWs by stiffening the whole structure. In animal and human experiments, the net result of protrusor (genioglossus) and retractor (styloglossus and hyoglossus) muscle coactivation is a retraction of the tongue (35,48–50). Nevertheless, experiments in patients demonstrated that coactivation of these muscles causes increased inspiratory flow rates (35). The question then becomes what is the stimulation paradigm or the right set of muscles to be activated that will maximize the functional outcome and thereby the patient population who can benefit from this treatment method?

5.2. Functional Assessment Tools

It is evident that a single-dimensional measure like upper airway resistance or airflow is not sufficient as a functional assessment tool for the HG or GG stimulation. The evaluation methods for the electrical stimulation should reflect the details of what happens to the UAW size and shape in its various compartments in addition to the measurements of collapsibility. Recent reports on HG/GG stimulation have used UAW imaging as an assessment tool. In some studies, techniques that allow imaging of the pharyngeal lumen directly with insertion of an endoscopic camera were used (41,51–54). Imaging techniques that can take a transverse section and make cross-sectional and volumetric measurements, such as magnetic resonance imaging (55–58), computer tomography (59), and fluoroscopy (59), were also used. The endoscopic methods have the disadvantage of having a lead (rigid or flexible) inside the UAWs that may disturb the muscle function. On the other hand, they are easy to use and do not require an expensive imaging facility. The noninvasive techniques, however, provide more precise area and volume measurements at user-selected depths of the airways without disturbing the structures being imaged. In general, these recent reports reflect the attempts for acquiring more functional information about exactly what the stimulations do in various compartments of the pharynx. Upper-airway mechanical resistance, compliance of the pharyngeal passage, or the critical pressure at which the airways collapse should still be measured independently. Despite the fact that these are single-dimensional variables and provide information only on the overall structure, it is still necessary to use these measures along with the imaging tools for an accurate assessment of the function.

5.3. Animal Models

Appropriateness of the animal models and extrapolating data from these models to answer questions regarding a neural prosthesis for humans should be evaluated carefully. Major anatomical differences exist between the human and the common animal models used in these studies; primarily the cat and the dog. Across the species, variance in the shape of the hyoid bone and its attachments is one example. The relative size and the scale of the structures may also introduce a difference in the passive mechanical properties of the muscles. For instance, the critical pressure at which the airways collapse in an animal model may be significantly different than that of a human in an otherwise comparable study. Anesthesia (e.g., chloralose, halothane, ketamine, and pentobarbital) suppresses the HG activity drastically (60). Decerebration is often used to eliminate the effects of anesthesia. It is still questionable, however, how appropriate it is to extrapolate the data from a decerebrate model to make conclusions about the condition of the UAWs during sleep. These deviations from the human case limit the use of animal models for studying the consequences of the electrical stimulation of the UAW muscles or at least make it difficult to translate the results to the humans.

5.4. What More …

Before electrical stimulation of the tongue muscles can become a clinically available neuroprosthetic device, the longevity of the implanted electrodes at the site of the HG nerve, which experiences significant rotations and translations, should be tested with chronic implants. With the recent advances in electrode technology, we anticipate that this testing will not be a major challenge in the near future. The set of tongue muscles to be activated and the patterns of activation need to be studied carefully in human patients to maximize the functional benefit. Selective stimulation of the HG nerve may be the tool to use for generation of these patterns. A method of detection for the obstructive breaths and a closed-loop control algorithm that is robust enough to work in all sleep stages and respiratory patterns should be developed. A unique approach is needed for the REM sleep because of its chaotic nature. A diagnostic measure is needed to predict the outcome of the HG nerve implants preoperatively. Sublingually inserted wire electrodes that can activate the GG may have a utility as a diagnostic tool in this regard (61). Finally, one should not expect that every OSA patient will benefit from such a neuroprosthetic device even after all the problems are resolved. In most severe cases, it may not be possible to generate the combination of forces necessary to keep the UAW patency before arousing the patient from sleep.

BIBLIOGRAPHY

8 OBSTRUCTIVE SLEEP APNEA: ELECTRICAL STIMULATION TREATMENT


FURTHER READING

ON PATHOGENESIS OF OSA


ON EPIDEMIOLOGY OF OSA

ON ELECTRICAL STIMULATION IN OSA


ON UAW IMAGING IN OSA