Vagal Nerve Stimulation: Overview and Implications for Anesthesiologists

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Vagal nerve stimulation is an important adjunctive therapy for medically refractory epilepsy and major depression. Additionally, it may prove effective in treating obesity, Alzheimer's disease, and some neuropsychiatric disorders. As the number of approved indications increases, more patients are becoming eligible for surgical placement of a commercial vagal nerve stimulator (VNS). Initial VNS placement typically requires general anesthesia, and patients with previously implanted devices may present for other surgical procedures requiring anesthetic management. In this review, we will focus on the indications for vagal nerve stimulation (both approved and experimental), proposed therapeutic mechanisms for vagal nerve stimulation, and potential perioperative complications during initial VNS placement. Anesthetic considerations during initial device placement, as well as anesthetic management issues for patients with a preexisting VNS, are reviewed.
(Anesth Analg 2006;103:1241–9)

Vagal nerve stimulation with surgical placement of an easily programmable, wholly implanted medical device has become an important treatment modality for medically refractory epilepsy. In 1985, Dr. Jacob Zabara, a neurophysiologist in Philadelphia, first suggested that electrical vagus nerve stimulation might be used to treat patients with medically refractory seizure disorders by disrupting hypersynchronous electroencephalographic (EEG) activity (1,2). This theory, based on animal studies demonstrating central nervous system effects from peripheral vagus nerve stimulation (3,4), led to the development of an experimental vagal nerve stimulator (VNS). This device, based on cardiac pacemaker design, was first placed in 1988 in a patient with intractable epilepsy (5). Since then, the device has undergone further manufacturer modifications. It is currently approved as an adjunct therapy for medically refractory epilepsy and major depression. Additional indications for vagal nerve stimulation currently under investigation include obesity, Alzheimer's disease, chronic pain syndromes, and some neuropsychiatric disorders.

As the number of approved indications increases, more patients will be eligible for VNS placement and will require anesthesia for these procedures. Additionally, patients with these implantable devices may present for other surgical procedures requiring anesthetic management. This review will focus on the indications for VNS placement, proposed mechanisms for VNS action, anesthetic considerations during initial device placement and additional issues that arise with an indwelling device. Potential perioperative complications in this patient population will also be discussed. Because currently the Neurocybernetic Prosthesis (Cyberonics, Houston, TX) is the only VNS approved by the Food and Drug Administration (FDA), this review focuses only on this particular system for vagal nerve stimulation.

EFFICACY DATA

Despite major medical and surgical therapeutic advancements, poorly controlled seizures remain a major clinical problem affecting 150,000–300,000 patients in the United Sates alone (6). Vagal nerve stimulation has been shown to be effective for seizure reduction in epileptic patients. In a multicenter, prospectively randomized, parallel, double-blind study, patients reported a statistically significant reduction in seizure frequency (31% of patients in the "high stimulation" group had a more than 50% decrease in seizure frequency compared with 11% of patients in the "low stimulation" group); however, only a small fraction of these patients were rendered seizure-free (7). In this study, "low stimulation levels (levels that were thought to be less than therapeutic on the basis of data from animal studies)" were used as controls, rather than patient groups not undergoing stimulation, as the electrical stimulus can be felt by the patients (8). Prospective studies of long-term efficacy of vagal nerve stimulation have shown a 34% reduction at 3 mo and a 45% reduction at 12 mo in total number of seizures (6,9). Vagal nerve stimulation has also been shown to be effective in children aged 3–18 yr (10),

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Accepted for publication August 24, 2006.

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DOI: 10.1213/01.ane.0000244532.71743.c6

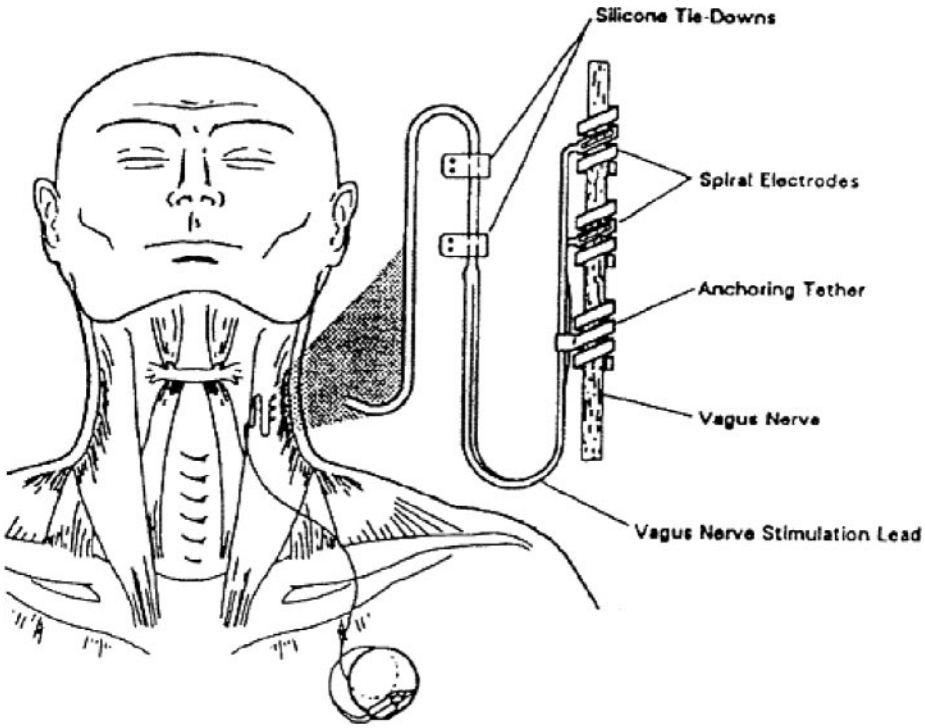

Figure 1. Diagram of vagal nerve stimulator placement. Reprinted with permission from Cyberonics, Inc.

with median reductions in seizure frequency at 3, 6, 12, and 18 mo of 23%, 31%, 34%, and 42% respectively. Magnet application over the VNS, which causes activation of vagal nerve stimulation, after seizure onset has also been shown to shorten seizure duration or intensity 40%–60% of the time (8).

VNS SYSTEM DESCRIPTION

The VNS consists of a constant current pulse generator/stimulator, a single subcutaneously placed lead wire, and a silicone rubber-imbedded platinum electrode wrapped around the left vagus nerve (Fig. 1). The combined pulse generator/stimulator delivers an electrical stimulation burst based on programmed parameters. The VNS does not monitor central nervous system electrical or peripheral muscle activity, and therefore, cannot respond to potential seizure activity.

The VNS generator/stimulator is noninvasively programmed via an externally placed programming wand and software on a standard personal computer or personal digital assistant. Radio frequency signals are used to communicate with the implanted VNS generator/stimulator. By placing the programming wand on the skin overlying the generator/stimulator, the VNS can then be accessed for programming, data retrieval, device interrogation, and diagnostics.

The optimal programmable stimulation parameters have not been documented and likely are patient-dependent (7). In general, the generator/stimulator provides a pulse of electrical current (1–2 mA) for a very brief time period (0.5 ms), which is repeated over a short time interval (20–30 Hz for 30 s every 5 min) throughout the day. Programmable parameters of the generator/stimulator include output current, frequency, pulse width, and stimulation on-time and off-time. Additionally, if the generator/stimulator is appropriately programmed, placement of a magnet can provide additional stimulation cycles to allow patients and companions to activate the device to prevent seizures preceded by aura or to halt an ongoing seizure (10).

PROPOSED MECHANISM OF ACTION

How electrical stimulation of the vagus nerve modifies seizures risk in epileptic patients is not completely understood. Most researchers, however, believe that VNS electrical stimulation creates action potentials within the cervical vagus nerve that modulate cerebral neuronal excitability, either through activation of the limbic system, noradrenergic neurotransmitter systems, or generalized brainstem arousal systems (1,11). This effect may be through induction or inhibition of electrical signals by altering neuronal electrical or chemical properties.

Understanding vagus nerve anatomic connections and pathways may help explain the VNS's mechanism of action, complications during initial placement, and complications from chronic indwelling devices. The vagus nerve (tenth cranial nerve) itself is a complex mixed nerve, containing both afferent and efferent fibers with myelinated A and B-fibers, and unmyelinated C-fibers. Approximately 80% of vagus nerve fibers carry afferent information about visceral, somatic, and taste sensations (12). The visceral organs of the thorax and abdomen (i.e., heart, lungs, aorta, and the gastrointestinal system) project these afferent fibers primarily to the Nucleus Tractus Solitarius (NTS),

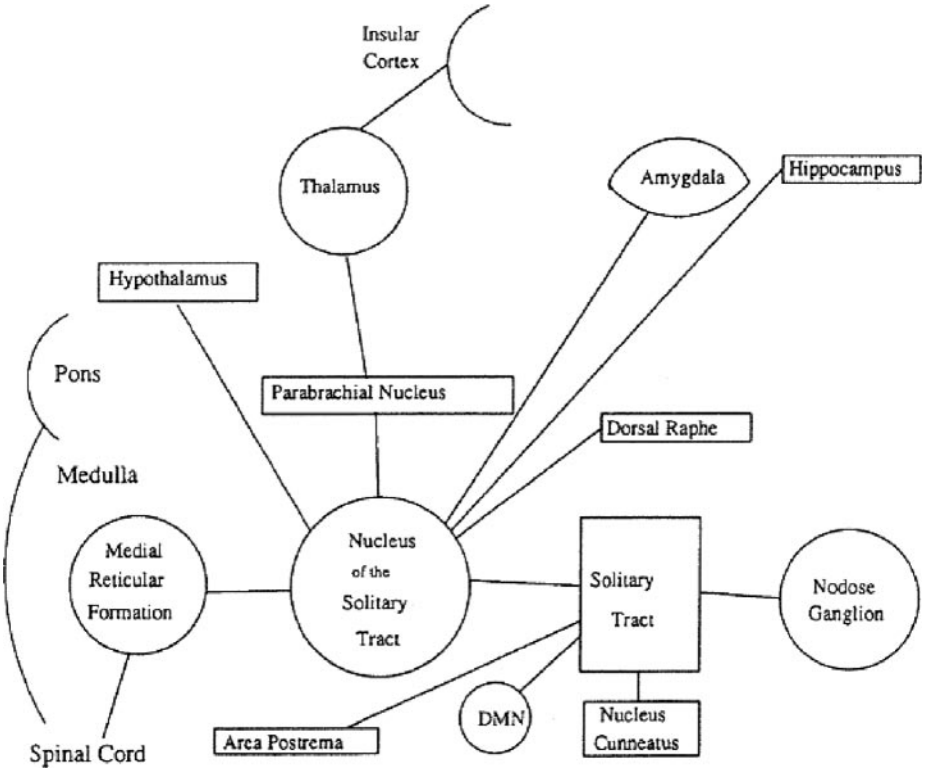

Figure 2. Diagram of potential vagal nerve pathways for mechanism of action in epilepsy therapy. Reprinted with permission from Blackwell Publishing, Ltd.

which receives afferent information from many other sources, including cranial nerves (V, VII, and IX), the spinal cord, and multiple brainstem, and cerebral structures.

Because the NTS then sends information to the reticular formation and the parabrachial nucleus (which connects to the hypothalamus, thalamus, sensory, and visceral motor cortices), the NTS may have an important role in seizure modulation in VNS therapy (13). Additionally, other medullary centers—the medial reticular formation, the area postrema, and the nucleus cuneatus—may also receive direct afferent projections from the vagus nerve and may condition the efficacy of vagal nerve stimulation (12–14). The NTS has projections to many higher brain centers (Fig. 2), including the amygdala, the dorsal raphe, the nucleus ambiguous, the dorsal motor nucleus of the vagus, the parabrachial nucleus, the hypothalamus, and the thalamus (14–17). These central projections represent important neural pathways that influence activities of the autonomic nervous system, various motor systems (such as those subserving posture and coordination), ascending visceral and somatic sensory pathways, and the local arousal system and likely serve as the underlying mechanism for VNS efficacy (11).

Generation, propagation, and maintenance of seizures is a complex pathophysiologic process requiring activation and interaction of multiple brain centers to affect duration and spread of the seizure. Despite intensive, continuing research, at present, the mechanism of action of vagal nerve stimulation is still not fully known.

SURGICAL PLACEMENT OF THE VNS

After general anesthesia induction, the patient is positioned supine with the head turned to the right with neck extension (similar to patient positioning for left carotid endarterectomy). An incision is made in the skin of the left neck overlying the lower portion of the anterior border of the sternocleidomastoid muscle at the level of the crico-thyroid membrane. The underlying subcutaneous tissues are then carefully dissected to the layer of the carotid sheath. The left vagus nerve is exposed within the carotid sheath between the jugular vein and carotid artery; injury to either vessel or the trachea can result in serious intraoperative or postoperative complications. The left is preferred over the right vagus nerve for VNS placement because of the greater number of cardiac efferent fibers from the right vagus nerve (18), whose stimulation may result in more frequent adverse cardiac complications. Exposure of approximately 3 cm of the vagus allows for proper electrode attachment.

After vagus nerve isolation, a pocket for generator placement is created above the pectoralis fascia via an anterior left chest incision. With a tunneling approach, the connector lead from the vagus electrodes is pulled into the chest incision. The coils of the electrode array are then wound around the vagus nerve (Fig. 1).

The generator is then connected to the electrode array and placed into the subcutaneous chest pocket. The generator is interrogated using a programming wand in a sterile sleeve placed over the chest incision. Lead impedance and all connections are verified, and

a short test of system integrity may be performed. Additionally, the generator may now be programmed and vagal nerve stimulation begun; however, some centers may choose to program the device in the recovery room or at a follow-up appointment.

ANESTHETIC CONSIDERATIONS FOR THE VNS PLACEMENT PROCEDURE

Patients presenting for VNS placement generally have poorly controlled recurrent seizures requiring multiple antiepileptic drugs (AEDs), which may impact perioperative management. Current recommendations include continuation of AEDs through the morning of surgery (19). Preoperative assessment includes the type and frequency of seizure and the presence or absence of aura and triggers.

The use of preoperative AEDs may have significant impact on anesthetic management. Cytochrome p450 enzyme induction by AEDs (e.g., phenytoin) may alter the metabolism of anesthetic drugs. These patients may have resistance to neuromuscular blocking drugs and require larger opioid dosages (20,21). AEDs may also affect neuromuscular relaxants by causing acetylcholine receptors to be up-regulated at the neuromuscular junction (22,23). Additionally, metabolism of other medications may be significantly accelerated by hepatic enzyme induction caused by chronic AED therapy.

VNS placement is performed under general anesthesia with endotracheal intubation. Mechanical ventilation should be adjusted to maintain normocarbia, as hyperventilation may precipitate seizures. IV access should allow for rapid transfusion and fluid resuscitation because of the potential for hemorrhage from the carotid artery and/or the jugular vein. Packed blood cell availability should be based on institution preferences and experience.

Anesthetic management during VNS placement requires knowledge of the pro- and anticonvulsant properties of IV and inhaled anesthetics under varying conditions. Only a brief review of anesthetics effects on the seizure threshold follows, as extensive reviews are available (21,24).

Anesthetics have different effects on seizure threshold. IV induction drugs such as propofol and thiopental, have depressant EEG effects thus decreasing the likelihood of seizures (25,26). In contrast, ketamine may trigger seizure activity and thus should probably be avoided (27,28).

Opioid administration may produce EEG epileptiform activity. In animal models, large doses of fentanyl (200 mcg/kg) and sufentanil (>40 mcg/kg) have induced EEG-documented cortical seizure activity (29–31). In a rat model, clinically relevant large-dose remifentanil produced dose-related EEG activation, whereas in humans, large-dose remifentanil (bolus of 1 mcg/kg with subsequent infusion of 1–3 mcg $\cdot$ kg^{-1} $\cdot$ min^{-1}) activated the limbic system without inducing clinical seizures (32). Fentanyl and sufentanil in moderate (25 and 2.5 mcg/kg respectively) to large doses (100 and 10 μg/kg respectively) have been shown to cause epileptiform EEG activity in patients without epilepsy undergoing coronary artery revascularization (33). In epileptic patients undergoing depth electrode implantation for localization of seizure focus, epileptiform activity was induced by alfentanil in the depth electrodes, with no activity recorded from the scalp electrodes (34). These factors should be considered during anesthetic planning, particularly in epileptic patients.

All modern inhaled anesthetics, with the exception of halothane, can produce EEG burst suppression at hemodynamically acceptable doses. Isoflurane, although used as a therapy in status epilepticus (32), has also been associated with epileptiform EEG activity in epileptic patients (35). Epileptiform EEG activity has been reported during sevoflurane induction with spontaneous ventilation in both pediatric (36) and adult (37) populations. Sevoflurane has also been shown to induce epileptogenic EEG activity in nonepileptic patients during surgical levels of anesthesia (38) as well as epileptic patients (39). Additionally, enflurane produces predictable EEG changes, especially in children (40,41). For these reasons, it seems prudent to avoid both sevoflurane and enflurane for VNS surgery in patients with an underlying seizure disorder.

The use of specific intraoperative physiologic monitoring is determined by the patient's medical conditions. In addition to American Society of Anesthesiologists (ASA) routine monitors (42), more invasive monitoring should be based on the severity of underlying cardiovascular or respiratory conditions. EEG monitoring is not routinely indicated; intraoperative awareness monitoring should be based on ASA published guidelines (43).

Important postoperative complications include seizures, peritracheal hematoma (from damage to the carotid artery or jugular vein), vocal cord paralysis and hoarseness (from damage to the vagus nerve and its branches, the recurrent laryngeal and superior laryngeal nerves). Seizures should be considered in patients with delayed awakening from anesthesia and changes in postoperative mental status, or frank seizures in the recovery room can occur. Appropriate pharmacologic therapy (benzodiazepines, etc.) should be administered to treat these seizures and endotracheal intubation performed for airway protection. Early AED resumption should be considered in these patients.

Postoperative respiratory distress and/or increasing neck circumference should raise concern for peritracheal hematoma. Treatment may require emergent endotracheal intubation or wound exploration and hematoma evacuation to relieve tracheal compression. Left vagal surgical nerve damage may cause unilateral hoarseness and dyspnea. Direct or fiberoptic laryngoscopy may be used to diagnose this potential complication.

COMPLICATIONS DURING VNS PLACEMENT AND PERIOPERATIVE PERIOD

Although intraoperative complications were rare during several large multicenter trials involving 261 patients, some complications may be life threatening during the perioperative period for VNS placement (6,44).

Animal and human studies have shown that vagal nerve stimulation at high intensities has a complex chronotropic effect on the heart (45). Bradycardia, complete atrio-ventricular block, and ventricular asystole after initial left vagus nerve intraoperative stimulation have been reported in four patients (46). The asystolic periods in these patients ranged from 10–45 s after initial stimulation and responded to therapies including IV epinephrine, atropine and brief external cardiac compression. In three of the four patients, the surgical procedure was aborted after successful resuscitation; subsequent cardiology evaluation revealed no intrinsic cardiac dysfunction (46). In one case of bradycardia during initial VNS testing, normal cardiac rhythm was spontaneously restored after cessation of stimulation; however, repeat stimulation caused asystole which required atropine and brief external cardiac compression (47). The procedure was terminated and the VNS removed. The original multicenter VNS trials of 261 patients did not report cardiac arrhythmias. Because of the potential impact of VNS on cardiac rhythm, preoperative electrocardiogram (ECG) and cardiology consultation may be warranted in selected patients with preexisting conduction system defects. Additionally, during initial intraoperative VNS testing and use, continuous ECG monitoring with resuscitative therapies should be available.

Lower facial muscle paralysis and laryngeal dysfunction may occur postoperatively. Large multicenter trials reported three patients (approximately 1% of patients) who developed postoperative lower facial muscle paralysis. This paralysis resolved spontaneously in all three patients (6,44). Three other patients (approximately 1%) developed postoperative left vocal cord paralysis, in two of whom it resolved spontaneously. The other patient had a generator malfunction producing intense vagus nerve stimulation for more than 4 h with minimal long-term symptom resolution (44). One patient (0.5%) developed hoarseness, thought to be caused by the stimulating electrode compressing the vagus nerve, which resolved spontaneously. Vocal cord and laryngeal muscle dysfunction may increase the risk of aspiration and postoperative patients should be monitored closely for this complication.

COMPLICATIONS AFTER VAGAL NERVE STIMULATOR PLACEMENT

Chronic vagal nerve stimulation may lead to significant side effects in patients presenting for other surgical procedures. For example, chronic vagal nerve stimulation can cause significant respiratory side effects. In animal studies, vagal nerve stimulation has been shown to increase the risk of various respiratory abnormalities, including respiratory arrest (48); although, this complication has not been reported in humans. Although neither tidal volume nor respiratory rate has been shown to be affected by vagal nerve stimulation in awake patients, consistent decreases in airway flow and respiratory effort were documented in four patients when vagal nerve stimulation occurred during sleep (49,50).

Approximately one-third of patients with refractory epilepsy have baseline obstructive sleep apnea (OSA) in addition to their other medical problems (51). Vagal nerve stimulation may worsen OSA symptoms during stimulation intervals. During polysomnography studies in patients undergoing VNS therapy, measured airflow significantly decreased, whereas respiratory effort was generally preserved during vagal nerve stimulation (52). These findings suggested, in one case, that airway obstruction occurs during periods of vagal nerve stimulation with additional support from continuous esophageal pressure monitoring. Respiratory events resolved with titration of continuous positive airway pressure (52). Although in a small series of patients, the combination of OSA and vagal nerve stimulation, especially with the addition of the effects of various anesthetics, could become significant postoperatively.

VNS's influence on respiration may involve both central and peripheral mechanisms. Suggested mechanisms include effects on the central respiratory centers from nerve projections from the reticular formation of the medulla (53) or the medial pontine reticular formation (54). Peripheral stimulation of vagal afferents may also activate motor efferents in the dorsal motor nucleus of the vagus nerve and nucleus ambiguous, resulting in altered neuromuscular transmission to laryngeal and pharyngeal muscles, and causing upper airway narrowing (55).

If a patient presents with OSA that developed after placement of VNS, potential options include turning off the VNS during the high-risk perioperative period. The VNS can also be programmed to lower stimulation frequencies, prolonged stimulator off-time, decreased stimulus intensity or turned completely off, which have all been shown to decrease respiratory events (51). Although there are no specific recommendations about perioperative narcotic usage in patients with VNS, all patients with OSA are at increased risk of perioperative apneic and hypopneic episodes. Anesthetic management should minimize postoperative respiratory complication risks, and strategies may include non-opiate analgesic regimens such as nonsteroidal antiinflammatory drugs. Other options include administering supplemental oxygen and the close monitoring of these patients in the recovery room within the ASA OSA guidelines (56). Although there is

Table 1. Side Effects of Chronic Vagus Nerve Stimulation[a]

	Low "Placebo" stimulation[b] (%)	High "Therapeutic" stimulation[c] (%)
Voice alteration	30.1	66.3
Cough	42.7	45.3
Pharyngitis	25.2	34.7
Pain	30.1	28.4
Dyspnea	10.7	25.3
Headache	23.3	24.2
Dyspepsia	12.6	17.9
Vomiting	13.6	17.9
Paresthesia	25.2	17.9
Nausea	20.4	14.7
Accidental injury	12.6	12.6
Fever	18.4	11.6
Infection	11.7	11.6

[a] From Ref. (6).

[b] Low stimulation: 0.25–2.75 mA (current), 1–2 Hz (frequency), 130 μs (pulse width), 30 s on-time, 60–180 min off-time.

[c] High stimulation: 0.25–3.0 mA (current), 20–50 Hz (frequency), 500 μs (pulse width), 30–90 s on-time, 5–10 min off-time.

insufficient literature, patients who experience respiratory episodes in the recovery room or who have risk factors for OSA should be closely monitored and may require continuous positive airway pressure or noninvasive positive pressure ventilation in the immediate postoperative period.

Chronic VNS use may also lead to various types of laryngopharyngeal dysfunction, including voice alteration, cough, pharyngitis, throat discomfort, and dyspnea (6). In three patients, continuous vocal cord adduction during stimulation intervals has been documented by fiberoptic laryngoscopy (57). In another small case series of laryngeal dysfunction with VNS, all examined patients had endoscopically documented vocal cord paresis, with varying severity of glottic obstruction and aspiration during the stimulation intervals (58). Therefore, in patients undergoing surgery and after chronic VNS therapy, there may be an increased risk for aspiration, and appropriate measures may include preoperative nonparticulate antacid administration, rapid sequence anesthetic induction and endotracheal intubation.

There has also been one report of significant periodic airway obstruction in a patient with an implanted VNS during general anesthesia with a laryngeal mask airway. This obstruction was presumably caused by vagal nerve stimulation, as the left arytenoid and aryepiglottic fold were fiberoptically visualized during VNS stimulation to be pulled across the midline, causing near complete glottic obstruction. Although improved, obstruction failed to completely resolve during the nonstimulation periods (59). Endotracheal intubation may be required to prevent this complication if an indwelling VNS is to be active intraoperatively.

In addition to these significant laryngopharyngeal complications, headache, nausea, vomiting and dyspepsia have also been commonly reported (6). Table 1 lists the documented side effects and their reported incidences from a large multicenter trial.

There is also one case report of chronic diarrhea associated with VNS that ceased after VNS therapy was terminated (60). Patients presenting for surgery with this complication may have significant electrolyte imbalances that would affect the conduct of anesthesia, and serum electrolyte analysis may be warranted.

The effect of chronic vagal nerve stimulation on the proconvulsant activity of specific anesthetics has not been studied. The use of medications which may lower the seizure threshold should probably be avoided in patients with epilepsy treated with chronic vagal nerve stimulation.

Dyspnea and voice alteration are significantly worse with higher levels of stimulation. If these symptoms become intolerable, changing stimulation intensity may decrease the symptoms while still providing therapy. Most other side effects seem not to correlate with stimulation levels.

ADDITIONAL ANESTHETIC CONSIDERATIONS WITH AN INDWELLING VNS

External defibrillation and electrical cardioversion may damage the generator circuitry. If external defibrillation is required, the VNS manufacturer (Cyberonics, Houston, TX) recommends using the lowest amount of appropriate energy during each electrical current delivery and placing the defibrillation paddles as far removed from the generator and implanted lead as possible (10). Paddles should be placed so that current will travel in a vector perpendicular to the VNS system.

Electrocautery or radio frequency ablation may damage the generator. Although the VNS does not need to be deactivated or inhibited (via magnet placement) during surgery, recommended maneuvers to minimize damage to the electrical circuitry from electrocautery include positioning grounding pads (similar to pacemaker recommendations) so as to prevent current flow through the system and as far away from the VNS generator as possible (10). The correct functioning of the VNS system may need to be confirmed after the procedure.

During certain magnetic resonance imaging (MRI) procedures, heat production may result in thermal injury to the vagus nerve or adjacent structures. Magnetic and radiofrequency fields induced during MRI may deactivate or alter programmable functions of the VNS device. If MRI is indicated, the VNS Physician's Manual should be consulted for a list of imaging procedures and systems appropriate for use with the VNS (10).

Transmission of shockwave energy during extracorporeal shockwave lithotripsy may damage the pulse generator. If this procedure must be performed, patient positioning considerations include avoiding

generator submersion in the water bath and minimizing the generator's exposure to ultrasound therapy.

The VNS pulse generator could potentially affect the operation of other implanted devices, including cardiac pacemakers and implanted cardiac defibrillators. VNS may also produce ECG artifact, causing these devices to malfunction. Although no cases could be located in a Medline search, the potential for this complication should be considered. After any of the above, the generator should be tested to ensure its proper functioning.

MAGNET ACTIVATION

The use of the magnet supplied with the VNS is somewhat complex, and differs from pacemaker magnet application. Unlike the donut-shaped magnet used with conventional pacemakers, the VNS magnet is bar-shaped providing 50 gauss at 1 in., and available in either a watch or pager style. An understanding of proper magnet placement is important to prevent inadvertent damage to both the generator and vagus nerve, and permit proper perioperative therapeutic usage.

When a magnet is in close proximity, the generator may respond with several different actions (10). If a magnet is placed over the generator for more than 1 s and then quickly removed, the generator will deliver a burst of vagal nerve stimulation on the basis of programmed settings. This may prevent or shorten a seizure. This maneuver can be repeated if needed. The generator returns to its previous mode of action after the magnet-initiated burst stimulation.

In contrast, when a magnet is placed over the generator either during stimulation or for more than 65 s, output from the generator will be inhibited. This can be clinically monitored by loss of episodic side effects, such as voice alteration or pain. Magnet removal results in resumption of previous VNS output settings.

Although it is not recommended by the manufacturer, and there is currently no literature, one potential option that might be considered if deactivation was required during surgery with an indwelling VNS might be magnet application throughout the operative procedure. If the magnet were to be applied throughout the operative procedure, it would seem prudent to test the generator to ensure proper functioning ideally immediately postoperatively.

FUTURE INDICATIONS FOR OTHER APPLICATIONS FOR VNS

Initially approved in 1997 for treatment of refractory epilepsy, the VNS also received additional FDA approval for the adjunctive treatment of depression in 2005. This indication evolved when patients using VNS for epilepsy showed signs of elevated mood and further studies revealed efficacy in treatment-resistant depression (61–63).

Obesity may also be amenable to vagal nerve stimulation therapy due to the effects of vagal afferents on multiple aspects of satiety and eating behavior (64). Clinical studies on VNS efficacy in obesity are expected in the near future (65).

Many additional proposed uses for VNS, including its application for obesity and neuropsychiatic disorders (obsessive-compulsive disorder, panic disorder, and posttraumatic stress disorder) are under investigation (64). There may be a role for vagal nerve stimulation in the treatment of pain syndromes. In rats, vagal nerve stimulation has been shown to have antinociceptive effects in experimental pain models (66,67). Additionally, original investigations into the antiinflammatory role of electrical vagal nerve stimulation, especially in the setting of hemorrhagic (68) and septic shock (69), have also been published.

SUMMARY

Vagal nerve stimulation with the VNS is approved by the FDA for medically refractory epilepsy and major depression. This relatively simple operative procedure, however, has significant anesthetic considerations during both placement procedures and for procedures in patients with indwelling devices. During the operative procedure, complications including dysrhythmias such as asystole and bradycardia may occur. Chronic vagal nerve stimulation may cause laryngopharyngeal dysfunction including vocal cord paresis which may cause partial or complete airway obstruction in the nonintubated, spontaneously ventilated patient during anesthesia. The risk of aspiration may also be increased in patients with laryngopharyngeal dysfunction. Chronic vagal nerve stimulation may also depress postoperative respiratory efforts and increase the risk of obstructive airway episodes throughout the postoperative period.

As vagal nerve stimulation is used for more indications, patients are now beginning to present for non-VNS anesthetic procedures with an implantable VNS. Preoperative preparation for these patients should include identification of the generator location and response to magnet application (should therapeutic magnet application become necessary). The effects of electrical energy from electrocautery or external defibrillation should also be understood.

In conclusion, vagal nerve stimulation with the VNS can be a safe and efficacious treatment modality for epilepsy in many patients. Anesthesiologists must understand the physiologic implications of this device during both implantation procedures and procedures in patients with preexisting VNS devices who may present in high-risk situations such as extracorpeal shock wave lithotripsy.

ACKNOWLEDGMENTS

The authors extend their appreciation to Shilpa Thadiangada and Ashley Stockwell for their assistance with manuscript preparation.

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