Diaphragmatic Pacing in Neuromuscular Respiratory Failure

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Abstract: Electrical activation of the diaphragm is a technology that allows the treatment of selected forms of respiratory failure. The diaphragmatic pacing is carried out by an implanted electrode and receiver with a pocket or tabletop external transmitter. The device electrically stimulates the phrenic nerves to contract the diaphragm rhythmically. The main indication for diaphragm pacing is for ventilator-dependent subjects after high cervical cord injury and patients with central alveolar hypoventilation. The clinical requirements are stable clinical condition and intact phrenic nerves, diaphragms, and lungs. In most patients, a training period is required to provoke a gradual conditioning effect, improving endurance to diaphragmatic fatigue. A cooperative patient, supportive family and friends, and a skilled care team are paramount conditions. Diaphragmatic pacing probably does not lengthen life, but it can increase the quality of life. Tracheostomy is usually required to overcome upper airway obstruction. Poor results are related to inadequate selection of patients, complications related to implantation, system failure, inappropriate pacing schedule, inadequate follow-up, or lack of patient compliance or family support. The long-term results of diaphragm pacing demonstrate its usefulness both in adult and pediatric patients when applied in the correct circumstances.

Key Words: diaphragmatic pacing, quadriplegia, central alveolar hypoventilation, conditioning, respiratory failure

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The respiratory system functions as a vital pump that moves air in and out of the lung gas-exchange units. The respiratory pump consists of central respiratory network, spinal cord, peripheral nerves, neuromuscular junctions, and respiratory muscles. The most important respiratory muscle is the diaphragm, which is innervated by cervical motor neurons C3-5 via the phrenic nerves. Diaphragm contraction decreases intrapleural pressure during inspiration, expands the rib cage, and thereby air moves into the lungs. Although the diaphragm performs most of the work, normal ventilation also requires the simultaneous contraction of accessory muscles (scalene, parasternal portion of the internal and external intercostals muscles, sternocleidomastoid, trapezius). Hypercapnic ventilatory failure can occur as the result of the failure of any of the vital pump components. As expected, its management differs according to the disease process and the affected ventilatory component. Thus, many therapeutic options are available, such as negative-pressure ventilators, glossopharyngeal breathing, positive-pressure ventilation, and expiratory muscle aids for assisted cough.

Diaphragmatic pacing (DP) is an infrequently used technology that allows the treatment of selected forms of respiratory failure particularly neuromuscular control dysfunction. An implanted electrode and receiver with a pocket or tabletop external transmitter is used. The device electrically stimulates the phrenic nerves to contract the diaphragm rhythmically.[1,2]

More than 1000 patients worldwide have been treated with DP.[3] Despite growing clinical experience with DP, most clinicians are unfamiliar with proper patient selection or with the use of this therapeutic tool.

HISTORICAL BACKGROUND

According to Chervin and Guilleminault,[4] it was Cavallo in 1777 who first proposed that electricity could be used for artificial respiration. Hufeland proposed applying electrical stimulation to the phrenic nerves of asphyxiated newborns in 1783. Ure used electricity to produce diaphragmatic contractions in the body of a criminal after hanging in 1818. In the 19th century, Duchenne in France and Remak in Germany established electrostimulation of phrenic nerves as an accepted technique of treating ventilatory insufficiency. In 1948, Sarnoff established the term "electrophrenic respiration" and demonstrated the possibility of achieving normal gas exchange in both animals and patients. The DP technique in use today was developed by the efforts of Glenn and coworkers. In 1959, they first employed radio frequency stimulation of the phrenic nerve.[1,2,5,6]

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DIAPHRAGM HISTOLOGY, PHYSIOLOGY, STRUCTURE, AND FUNCTION

Several pathologic conditions lead to diaphragmatic weakness or may render it ineffective and, therefore, lead to respiratory failure. The activation pattern of the diaphragm is unique in relation to most other skeletal muscles. Its duty cycle is 3 to 20 times higher than other mammals' limb muscles. Its stereotypical, continuous, repetitive activation is associated with unique contractile and metabolic fiber properties. Furthermore, the diaphragm may be especially responsive to disuse, and it is capable of adapting or maladapting to conditions of altered use.[7]

Diaphragmatic motor units can be classified into 4 different types based on standard physiologic criteria: (1) slow-twitch, fatigue resistant (type S or I); (2) fast twitch, fatigue resistant (type FR or IIa); (3) fast twitch, fatigue intermediate (type FInt or IIx); and (4) fast twitch, fatigable (type FF or IIb).[8] Forces generated by motor units depend on (1) innervation ratio (number of muscle fibers innervated by a motoneuron); (2) muscle fiber cross-sectional area; and (3) specific force (force per cross-sectional area of the entire muscle unit). To accomplish forces generated during ventilatory and nonventilatory behaviors, motor units in the diaphragm, type S motor units are recruited first, followed in order by FR, FInt, and FF units.

The long-term activation pattern of the diaphragm influences the contractile and metabolic muscle fiber properties. Studies employing chronic electrical stimulation have demonstrated dramatic changes in histochemical fiber composition, such as conversion of type II fibers to type I and corresponding alterations in the expression of myosin heavy chain isoforms. In response to inactivity, significant reductions in diaphragm strength and shortening velocity can occur as early as 1 to 3 days afterward, becoming more pronounced with time.[7,8]

INJURY AND DISEASE

Diaphragm Disease

A number of pathologic states may affect diaphragmatic function, including malnutrition, autoimmune diseases, and congenital myopathies such as Duchenne disease. The management is directed at medical reversal or palliation of the underling diseases. It should be pointed out that if the diaphragm atrophy is secondary to disuse but remains unaffected by disease per se, a favorable response to pacing can be expected.[9]

Lower Motoneuron and Phrenic Nerve Disease

Phrenic nerve injury can result from violent trauma, neck stretching, as a complication of chest surgery, chiropractic procedures, and attempts at central venous cannulation.[9] Examples of diseases involving anterior horn cells are amyotrophic lateral sclerosis, spinal muscular atrophy, and poliomyelitis and post-poliomyelitis. Although unilateral phrenic nerve dysfunction is often self-limited and clinically well tolerated, bilateral, complete, or prolonged injury does occur, with possible significant morbidity and even mortality. Injury of the phrenic nerve and damage of the anterior horn cells are not amenable to DP.

Upper Motoneuron Disease

Causes of upper motoneuron compromise include cerebral atrophy, hemiplegia (stroke), tumor, infection, and trauma. The 2 clinical conditions commonly seen and that comprise the majority of instances where DP is used are C1-C2 quadriplegia and central alveolar hypoventilation (CAH). Quadriplegia due to low cervical injury does not need DP.[10] Hypoventilation syndromes are an uncommon but important group of respiratory control disorders. Congenital central hypoventilation syndrome is the principal and most important example. No specific anatomic or biochemical mechanism has been yet identified.[11]

CLINICAL EXPERIENCE: INDICATIONS AND CONTRAINDICATIONS

Since their early pioneering studies, Glenn and colleagues have communicated their large clinical experience.[12–17] Other works have increased the amount of information on DP.[18–31]

DP has been used in several conditions such as high cervical quadriplegia, CAH (either the idiopathic [adult] or the congenital [pediatric] type), intracranial vascular lesions, tumors, infectious processes, primary alveolar hypoventilation, postpoliomyelitis, syringomyelia, cervical cordotomy, atlanto-occipital deformity, Hirschsprung's diseases, Arnold-Chiari Type II malformation, and Shy-Drager's diseases. According to the current clinical experience, recommendations about use of DP can be categorized as medically necessary, unnecessary, under investigation and contraindicated (Table 1).

The main indication for DP is in ventilator-dependent patients after high cervical cord injury (level C1-C2) usually caused by traffic, sporting, or diving accidents or gunshot wounds. DP is indicated in patients with no measurable vital capacity who cannot use mouthpiece and intermittent positive pressure ventilation. Approximately one third of such patients are suitable for this type of treatment.[3] The second important group is the one with CAH associated with central apneas (problems with central control of breathing). The use of a DP may be considered medically necessary for these patients, who have permanent, severe hypoventilation.

One of the most important criteria for DP is the need for ventilatory assistance during the day rather than just at night, when other less invasive methods can be used.[32] DP should only be considered for patients with stable chronic ventilatory

TABLE 1. Indications and Contraindications of Diaphragmatic Pacing

Category	Condition	Comments
Medically necessary	Quadaplegia; central alveolar hypoventilation syndrome	They should have permanent, severe hypoventilation. The patient must have an intact phrenic nerve and diaphragm.
Not medically necessary	Respiratory insufficiency is temporary.	Patient can subsist independently of a mechanical respirator.
Investigational/not medically necessary	Chronic obstructive pulmonary disease, hiccups, chest wall deformities or other pulmonary conditions	There is insufficient scientific, controlled evidence available that the expected health benefits from this procedure are clinically significant and/or provide a greater likelihood of benefit than other possible alternatives.
Contraindicated	Patient has another serious disorder that might affect nerve conduction, neuromuscular junction or myopathy that weakens the diaphragm; progressive neuromuscular and pulmonary disease.	Pre-operative screening tests do not demonstrate that phrenic nerves, lungs, and diaphragm can sustain ventilation by electrical stimulation.

failure and should not be undertaken in those likely to progressively deteriorate or to significantly recover.[3]

Patients with lesions of the phrenic nerve or its nucleus in spinal segments C3-C5 or weakness of the diaphragm not secondary to disuse atrophy are not suitable candidates. However, more recently, nerve transfer with end to end anastomoses from the intercostal to the phrenic nerve was reported. This allowed axonal regeneration in 8 of 10 procedures. A DP was implanted as part of the procedure distal to the anastomoses. All 8 successful transfers were able to tolerate DP.[33]

A multicenter study conducted by Glenn et al[17] reviewed 477 patients. The center group (6 experienced medical centers) studied 164 patients. At the time of follow-up, from a total of 157 available data, 64% of the patients lived at home, 23% in the hospital, and 13% in a rehabilitation unit, and less than 5% were in a nursing home. Eighty-two percent of those still being paced required minimal or no additional ventilatory support. Forty-two percent of the patients were working, were in school or were normally or moderately active; about 16% had retired and 39% were inactive. The longest period of pacing achieved was 18.3 years.

The latest international review of 64 patients (35 children and 29 adults) who underwent quadripolar electrode pacing revealed successful pacing in 94% of pediatric patients for a mean of 2.0 ± 1.0 years, and in 86% of adults for a mean of 2.2 ± 1.1 year.[34]

PREOPERATIVE ASSESSMENT

The cause of chronic ventilatory failure must be clearly demonstrated, and the level of any spinal cord injury and likelihood of damage to the phrenic nerve nucleus in the spinal cord or nerve roots should be assessed.

In quadriplegic patients under mechanical ventilation, peak inspiratory pressure, the (A-a) P_{O2} gradient and supplementary oxygen requirements will indicate whether adequate ventilation is likely to be achieved with DP.[3]

In all CAH patients, lung volumes and carbon monoxide transfer factor should be measured. Each infant should have a detailed recording in a pediatric respiratory physiology laboratory to evaluate spontaneous breathing during sleep (nonrapid and rapid eye movement) and wakefulness. The full sleep polysomographic recording montage should include at a minimum tidal volume (pneumotachograph), movement (respiratory inductance plethysmography) of the chest and abdomen, hemoglobin saturation with pulse waveform, end tidal carbon dioxide, and electrocardiogram.[35] These patients must have the diagnosis of persistent and continuous central apnea.

Phrenic nerve conduction time (PNCT) and tidal volume elicited by phrenic nerve stimulation must be measured.[36] Of 120 nerves in patients evaluated by transcutaneous phrenic nerve stimulation, test data correctly predicted nerve viability and diaphragmatic functioning in 116.[14] The normal PNCT is between 6 and 9 ms. A prolonged PNCT of more than 11-ms latency is consider pathologic.

Diaphragm muscle function should be recorded. Most of the test can be performed under fluoroscopy (preferable) or ultrasound[37] at the bedside in the intensive care unit and includes mouth pressure through maximal inspiratory pressure or snifflike maneuver and tidal volume or inspiratory flows developed during both unilateral and bilateral supramaximal electrical phrenic nerve stimulation in the neck. Transdiaphragmatic pressure provides a reliable measure of diaphragmatic paralysis in quadriplegic patients.[38] Recent painless technique using cervical magnetic stimulation of the phrenic nerves has been described.[39,40] This stimulation technique is a useful nonvolitional method of assessing diaphragm contractility. It is easy to perform and reproducible in the assessment of diaphragm contractility.

PACING EQUIPMENT

The 3 systems available share the same principles of external and internally implanted components (Fig. 1).[2,5,14–16]

1. a stimulating electrode which is applied to the phrenic nerve
2. an internal receiver (subcutaneously) attached to the electrode
3. an external coiled antenna placed on the skin over the internal receiver
4. the external transmitter connected to the antenna

The transmitter radio frequency signal is emitted from antennae placed on the skin overlying the subcutaneously implanted receivers. The receiver converts the radiofrequency signal to an electrical impulse, which is carried by the wires from the receiver to the stimulating electrode on the thoracic phrenic nerve. As a result of the electrical stimulation of the phrenic nerve, the diaphragm contracts. Each breath is triggered by a series of radiofrequency pulses of specified intervals, length, amplitude, and frequency. No equipment is left piercing the skin, as the stimulation current is generated inductively.

The Glenn-Avery system (Avery Laboratories, Inc., New York, NY) was the first system available and most widely used.[32] The Avery system involves a unipolar nerve-stimulating electrode and receiver for each paced nerve.

The MedImplant system (Vienna, Austria) has one multichannel receiver that serves both sides. Usually placed by sternotomy, stimulating electrodes are implanted in both phrenic nerves. Microsurgical techniques are used to attach 4 electrodes directly to the nerve. This technique is also known as carousel stimulation[41]

The Atrotech OY System (Tampere, Finland) has 1 receiver for each side and a 4-pole electrode that contacts each nerve without microsurgery.[41] This 4-pole electrode has been in use since 1986. This activation method seems more physiologic than the others stimulation techniques. Each of the 4 circumferential quadrants of the nerve is stimulated to trigger a paced breath.

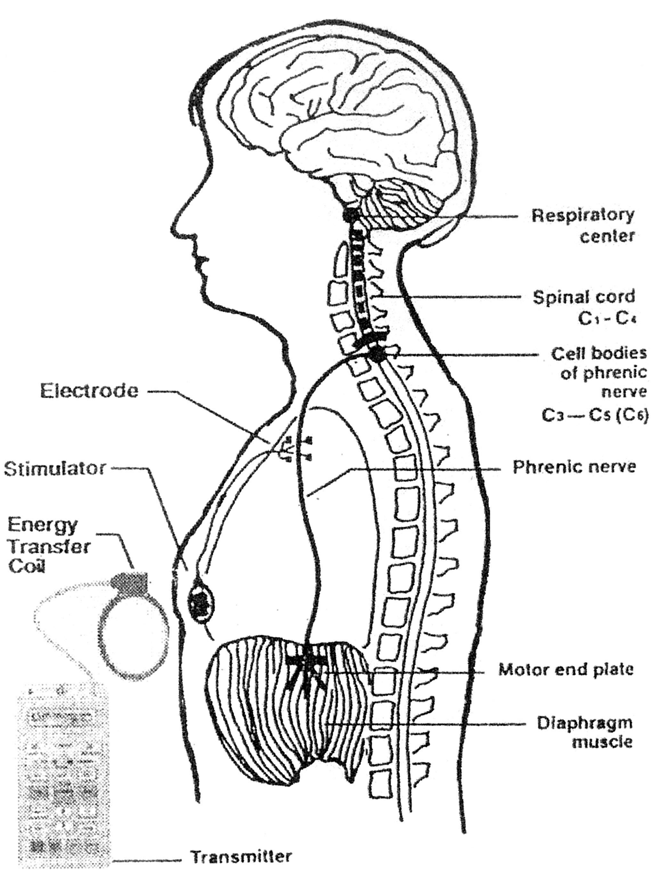

FIGURE 1. Diagram of external and internal components of a DP unit. (From Atrotech OY manual with permission)

SURGICAL PLACEMENT

In placing the electrode, extreme caution is taken in handling the nerve. Injury would preclude pacing. Electrodes may be applied to the nerve in the neck or in the thorax.[42,43] The cervical approach in the supraclavicular area remains controversial. It is technically easier for electrode placement, both sides can be paced in the same operation, and the operative morbidity may be lower.[14] The phrenic trunk is easily found over the anterior surface of the anterior scalene muscle; however, in as many as 76% of patients the phrenic nerve trunk is missing the contribution of the fifth cervical root, which does not join the nerve until it enters the thoracic cavity. In patients with tetraplegia, the neck has preserved sensitivity. Hence, adjacent nerve stimulation can induce severe pain, which will make patients prefer a mechanical ventilator to electroventilation.[44] The neck is also the only part these patients are able to move; thus, the electrode is prone to mechanical stress that may cause scar formation. The proximity to the tracheotomy makes this approach more prone to infection.

For these reasons, the thoracic approach seems preferable in patients with tetraplegia. The thoracic placement is carried out through a limited anterior thoracotomy in the second or third intercostal space. The phrenic nerve is identified as it courses anterior to the hilum, and a location is chosen superiorly where the electrode lies comfortably flat against the mediastinum. Two parallel incisions are made in the mediastinal pleura. The electrode is gently slipped behind the nerve (unipolar model) or behind and in front of the nerve (quadripolar model) and then secured to the pleura. The receiver is placed in a subcutaneous pocket, away from the skin incision. The contralateral unit is usually placed 2 weeks later. Thoracoscopic electrode placement is now used as an alternative to thoracotomy.[9]

Surgical complications include damage to the phrenic nerve, failure to achieve effective pacing, and infection. Infection makes it necessary to remove the implanted components.[16,44,45]

TRACHEOSTOMY

Pacing can induce extremely vigorous diaphragmatic contraction, which may cause upper airway obstruction if upper airway muscles lack coordination.[43] Almost every patient should be tracheostomized or retain a previous tracheostomy, even those who are on full-time continuous DP. Also in cases that positive pressure ventilation is needed, tracheostomy provides a rapid and safe airway. A Teflon tracheal button may be used to replace the conventional tracheostomy. This device maintains the airway; its presence is almost imperceptible in daily life. Tracheal irritation and injury are minimized with the button; the inner plug is removed at night to ensure an unobstructed airway during sleep.

Closure of the tracheostomy may be considered in some patients who have a lesion confined to the upper spinal cord, with preservation of the brain stem; in patients with some preserved spontaneous ventilation; and in patients adept at glossopharyngeal (frog) breathing.[32]

CONDITIONING

Nerve fatigue has been an important problem when continuous stimulation has been required. Electrodes stimulate the same motor units during each contraction, producing muscle fatigue. The fusion frequency is an important guide to plan stimulation strategy. The fusion frequency is the minimal stimulation frequency (Hz) required to produce smooth contractions (usually 20–30 Hz), which are dependent on the relaxation rate of the 4 different types of motor units. Electrical stimulation for up to fusion frequency predisposes to fatigue and does not substantially increase force generation.

The stimulus parameters most appropriate have been characterized as low stimulus frequency, short inspiratory time, and moderate respiratory rate.[27]

The quadripolar electrodes have reduced the stimulation frequency. Four-pole sequential nerve stimulation delays muscle fatigue when compared with unipolar stimulation and may help to achieve long-term full-time bilateral electroventilation. Four-pole sequential nerve stimulation also offers an opportunity to shorten the conditioning phase of the hypotrophic diaphragm from about 6 to 2 months.[46] This may give the patients earlier access to rehabilitation centers for spinal cord injuries and can diminish the workload of the personnel. Diaphragmatic fatigue is seldom a problem if DP is required only at night or only during the day, except if inappropriate pacemaker settings are used.[3]

There is no pacing schedule that is appropriate for all patients. In every case, the schedule requires repeated evaluation according to the ventilation achieved and the possibility of diaphragmatic fatigue. In all cases the procedure should follow a rationale that is based on some premise.

After surgery, there is inflammation or reaction to the trauma around the nerve. For that reason, stimulation is usually started 10 to 14 days after surgery.

As expected, quadriplegia produces more phrenic nerve atrophy than CAH, and atrophy predisposes to fatigue. The final pacing parameters should be achieved within 6 to 8 weeks in quadriplegia and much sooner in CAH where diaphragmatic atrophy is not a problem; fatigue is much less common.[3]

The diaphragm has a remarkable plasticity. Its fiber composition can change according to load and metabolic demands. Continuous low-frequency electrical stimulation avoids diaphragm fatigue and improves endurance. Prolonged low-frequency stimulation causes biochemical, structural, and physiologic changes in type II fibers so that they approximate fatigue-resistant type I fibers.

COMPLICATIONS AND PACING FAILURE

Poor result are related to poor selection of patients, complications related to implantation, or inappropriate pacing schedule, inadequate follow-up, lack of patient or family support, progression of or complications due to the underlying cause of hypoventilation, equipment problems, and unilateral rather than bilateral pacing or no supplementary ventilatory support.[43] External component failure such as the antenna or transmitter implies little morbidity in properly monitored patient. On the other hand, failure of implanted components such as receiver failure or wire breakage requires surgical intervention.

Pacing failure is present when there is a fall in tidal volume and oxygen saturation or an increase in Pa_{CO2}. Symptoms of malfunction varied from absent diaphragm movement to intermittent function to pain at the receiver site or ipsilateral shoulder. Intermittent function was typically due to receiver unit dysfunction or breakage of electrode wire insulation. Pacemaker evaluation includes a chest radiograph to rule out wire breakage or electrode malposition. A receiver is placed over the implanted receiver to synchronize the oscilloscope sweep with the pacemaker output. Surface electrodes are positioned at the costal margin to record the pacemaker stimulus pulse and the diaphragmatic action potential.

The mean time to failure for an internal component (Avery Laboratory), based on the study by Weese-Mayer et al[44] of 33 phrenic pacing patients, was 56.3 months. Receiver failure constituted the majority of complications. The internal components problems were classified into 4 categories: receiver failure, electrode wire or insulation breakage, infection, or mechanical nerve injury.

ADVANTAGES AND CAVEATS

In the Fodstad series, from a total of 40 implanted DP and a mean follow-up time of 62 months (range 2 months to 13 years), 19 patients were entirely independent of a conventional respirator. Full-time continuous bilateral pacing for several years has been demonstrated with advantages of increased independence and productivity, fewer tracheal tube complications, and improved phonation.[3,4,9,47] DP achieves adequate ventilation without any equipment placed in the airway. Simplified nursing care, periodic closure of the tracheostomy stoma, and restoration of the patient's olfactory sense are other important advantages of DP over constant positive-pressure ventilation.

In contrast to noninvasive ventilatory support, DP necessitates surgery, usually a thoracotomy, with the small but recognizable morbidity and mortality. The specialized skills required of both physicians and surgeons, and the prolonged period of diaphragmatic conditioning (in quadriplegic patients) all act as deterrents,[3] even when DP represents a good therapeutic option. The high cost of pacing devices, $50,000 to $80,000, must be compared with the savings in health, supervisory, and institutional care cost. Increases in productivity must also be considered.[32] The risk-benefit assessment should be individualized in carefully selected patients using the previous described criteria.

The long-term results of DP demonstrate its usefulness when applied in the correct circumstances. Patients who would otherwise be hospitalized and confined to mechanical ventilation have greater autonomy, with pacing and psychologic benefit. With proper supportive care, select individuals who use DP for full- or part-time ventilatory support carry out productive lives that include attending college full time, full-time employment, travel, and other leisure activities. Children are able to play sports and perform other activities for which they previously had inadequate ventilatory capacity.[9] DP is also advantageous over mechanical ventilation because it more closely mimics physiologic negative-pressure ventilation. This poses less barotrauma danger to the lung and may decrease pulmonary vascular resistance and increase systemic blood flow.[43] Patient morbidity from mechanical ventilation failure, malfunction, or accidental disconnection from the ventilator in an unattended patient is also eliminated.

FOLLOW-UP

Unlike cardiac pacemakers, which are largely maintenance free, phrenic pacemakers require vigilance and a thorough understanding of the pacing device, its limitations, and the associated caveats to avert potential complications.[3] Pulse oximetry with an alarm and memory capacity is necessary. Some patients, such as those with CHS, may not sense asphyxia, and other patients, such as those with quadriplegia, may not be able to respond to it. The general recommendations[32] are summarized in Table 2. Experienced physicians should inspect equipment function at least annually. However, initially more frequent visits are needed. Close follow-up is very important because of rate of DP failure and need for adjustments. As expected, the recommendations will depend on the disease. Fluoro and ultrasound movement does not necessarily translate into proper gas exchange, so O_2 and CO_2 monitoring on the pacer should be assessed. Patients with high cervical cord abnormalities should not be tested on and off the pacer.

POTENTIAL AVENUES FOR FUTURE RESEARCH EFFORTS

Regarding the great plasticity in the innervation ratio under physiologic conditions, there is investigative interest in producing continuous phrenic nerve stimulation by modifying the electrical parameters used in a totally implantable stimulator to make pacemakers sensitive to position of the body or level of activity, allowing DP to simulate natural ventilation quite closely.[32] Incoordination among the contracting diaphragm (obstructive apnea and paradoxical thorax's movement), phonation and swallowing problems could

TABLE 2. Annual Systematic Follow-up

Test	Look for/Measurement
General physical examination	Inspection of the implantation site, neurological examination, test for any suspected infection, neuropathy or myopathy
Chest radiography	Pulmonary and equipment status. Adequacy of electrode wire length in growing children.
Electrophysiological studies	Phrenic nerve latency and threshold activation.
Fluoroscopy or ultrasound	Diaphragmatic movements in response to pacing.
Pulmonary function test	Seated and supine positions
	Under paced and unpaced conditions
Sleep studies	Full polysomnography
	Transient turn-off of the DP
Need for the tracheostomy	Temporarily plugged.
Arterial blood gases	At the end of the night, while the patient is still in bed.
CO_2 monitoring	End tidal CO_2
	Transcutaneous device
	Intra-arterial electrode

be overcome by using specific triggers in "demand" diaphragm pacers, avoiding tracheotomy.[48] Finally, the long-term effects of the DP on structure and function of the diaphragm have not been well characterized.

Ongoing research in the field of DP includes refinements in electrode placement, direct muscular diaphragm activation using the laparoscopic placement,[49] continued testing of totally implantable devices, combined phrenic and intercostals pacers,[9] miniaturization of implanted equipment, and making external equipment more automated and more user friendly.[41]

CONCLUSIONS

DP offers important advantages to a highly selected group of patients with ventilatory insufficiency and intact lower motor-neuron innervation of the diaphragm. It is simple to use for patients; however, long-term tracheotomy is usually required, and prolonged conditioning time is required in quadriplegic patients. The equipment is costly, and backup ventilator support is mandatory in quadriplegic patients.

Problems encountered by patients in the course of DP can be minimized by well-instructed home caregivers and by systematic medical follow-up. Although a few patients derive considerable benefit from DP, many patients with respiratory paralysis are better treated by less invasive means such as nasal bilevel positive airway pressure or intermittent positive-pressure ventilation.[32] Among the important benefits of pacing in quadriplegics with paralysis or respiratory muscles are the social and psychologic advantages of not being dependent on a mechanical ventilator.[47]

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