Diaphragm Pacing Stimulation System for Tetraplegia in Individuals Injured During Childhood or Adolescence

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Abstract

Background: Children with cervical spinal cord injury and chronic respiratory insufficiency face the risks and stigma associated with mechanical ventilators. The Diaphragm Pacing Stimulation (DPS) System for electrical activation of the diaphragm is a minimally invasive alternative to mechanical ventilation.

Methods: Review of patients in a prospective Food and Drug Administration trial of the DPS System in individuals who were injured at age 18 years or younger. The procedure involved laparoscopic mapping to locate the diaphragm motor points with electrode implantation. Two weeks after surgery, stimulus/output characteristics of each electrode were determined to obtain an adequate tidal volume for ventilation. A home-based weaning protocol from the ventilator was used.

Results: Of 28 patients implanted with the DPS System, 10 had sustained cervical SCI as children or adolescents. Average age at injury was 13 years (range 1.5 to 17 y). Age at implantation ranged from 18 to 34 years. Length of time from injury to implantation averaged 9.7 years (0.8 to 19 y). All patients tolerated the implantation procedure. Four patients utilize DPS continuously (24/7), 4 patients pace daytime only, and 2 patients are still actively conditioning their diaphragms. Two patients required surgical correction of scoliosis prior to implantation. All patients prefer breathing with the DPS and would recommend it to others; 4 patients specifically identified that attending college or church without a ventilator eases their integration into society.

Conclusions: The results show that the laparoscopic DPS system can be safely implanted in tetraplegics injured as children and used in a home-based environment to wean them off of mechanical ventilation.

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Key Words: Spinal cord injuries, Tetraplegia; Child; Respiratory insufficiency, Mechanical ventilation, Diaphragm pacing

INTRODUCTION

Cervical spinal cord injury (SCI) accounts for 1.5% of SCIs sustained by children; 20% of all SCIs occur in children and adolescents (1). SCI is an overwhelming, devastating experience. The addition of mechanical ventilation adds to the complexity of the care of the individual. For a 15-

year-old who sustains a high SCI and survives the first 24 hours, the need for mechanical ventilation decreases life expectancy by 21 years (2). Positive pressure mechanical ventilation, although life saving, has certain significant negative attributes such as difficulty with speech, reduced mobility, difficulty with transfers, embarrassment due to noise, stigma of tracheostomy and tubes, equipment malfunction, loss of sense of smell, increased respiratory infections leading to decreased survival rates, and increased costs of care (3).

Anderson states that in the field of SCI research, “improvements in respiration and elimination of ventilator dependence are extremely important to the quality of life, and this topic should be at the forefront of research” (4). The present diaphragm pacing stimulation (DPS) system (NeuRx RA/4) was designed after a series of animal and preliminary human investigations at Case Western Reserve University and University Hospitals of Cleveland. The data can be reviewed through previous

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Disclosure: Case Western Reserve University, University Hospitals of Cleveland. Raymond P. Onders, MD, and Anthony Ignagni have the intellectual property of the devices used or equity in Synapse Biomedical, which manufactured the diaphragm pacing technology used in this study. All consents were obtained by individuals without potential conflicts. All data are independent of individuals with potential conflicts.

Figure 1. Mapping instrument being used on the right diaphragm to identify the point where stimulation causes maximal contraction.

publications (5–9). The research team has shown that laparoscopic implantation of a DPS system can strengthen and condition the diaphragm, allowing complete liberation of patients with high SCI from mechanical ventilation (10–12). With a total cumulative active implant time of more than 60 years with the minimally invasive DPS system, we now have the knowledge and experience that may allow expanding the benefits of DPS to the population of children with SCI.

This is a retrospective analysis of patients who sustained cervical SCI as children and were implanted with the DPS system when they were over the age of 18 years. A second goal of this study was to identify unique pacing characteristics shared by this group of patients in developing protocols to begin implanting in patients younger than 18 years of age.

METHODS

Patients who were injured at age 18 years or younger were identified from a prospective database in a Food and Drug Administration– and Institutional Review Board–approved trial of the DPS system at University Hospitals of Cleveland under an investigational device exemption. This study is registered with www.clinicaltrials.gov. The primary inclusion criteria are ventilator-dependent tetraplegia with intact bilateral phrenic nerves. Complete demographic data were gathered, along with implantation results, conditioning processes, and ability to wean from the mechanical ventilators.

The DPS System is a 4-channel percutaneous neuromuscular stimulation system. Intramuscular electrodes are implanted laparoscopically in the diaphragm with leads tunneled subcutaneously to an exit site in the chest. An external stimulator connected to the leads delivers the stimulus pulses and provides respiratory timing. Implantation has become standardized with surgical techniques that can easily be learned by pediatric

Figure 2. The implant instrument houses the electrode in a needle for placement in the diaphragm.

or adult general surgeons; the technique for implantation follows (13).

The initial step in the implementation of the DPS System is the laparoscopic mapping of the diaphragm with a specialized probe that stimulates the diaphragm (Figure 1) (Synapse Biomedical, Oberlin, OH). Prior to implanting an electrode into the diaphragm, the motor point must be identified. The motor point is the location where stimulation will cause maximal contraction of the diaphragm. This is both observed qualitatively with the laparoscope and quantitatively by measuring the strength of the contraction by measuring changes in abdominal pressure.

Once the optimal sites are identified, 2 electrodes are implanted in each diaphragm (Figure 2). The electrode leads are then tunneled to a percutaneous exit site, where they are brought out through the skin. In addition to the stimulating electrodes in the diaphragm, a fifth electrode is implanted in subcutaneous tissue as an anode for a return current pathway. The 5 leads are inserted into a connector block, which is in turn connected to the external stimulator through a patient cable (Figure 3).

The patient/caregiver is able to simply turn the stimulator on and off with the front panel buttons. No other controls are necessary or available to the patient/caregiver. Use and maintenance of the system only require care and cleaning of the percutaneous exit site with an alcohol wipe, changing the connector bandage every few days, changing the battery (after approximately 500 hours of use), and connecting the cable for use.

Characterization of electrodes and system evaluation is done 7 to 10 days post implantation. This recovery period allows the patient to fully recover from the surgery as well as allowing time for the body's reaction to the electrodes to stabilize. Electrode characterization is performed by adjusting individual stimulus parameters (pulse amplitude, width, rate, and frequency) so that a comfortable level of stimulation can be identified for the

Figure 3. The DPS system connects to a patient by percutaneous wires with a cable.

diaphragm conditioning sessions. The DPS will be set to provide a tidal volume that provides 15% above the basal needs (5–7 mL/kg) and that the patient can easily tolerate. The settings will always be below 25 for amplitude <25, frequency <20, and pulse width <200.

A home-based conditioning program is then begun, during which the DPS is turned on and the ventilator is turned off (14). The patient's tidal volume is checked initially with a Wright spirometer and then every 5 minutes. Patients are placed back on the ventilator when they feel uncomfortable or if their tidal volumes start dropping because of diaphragm fatigue. Initially, patients may only tolerate 15 minutes of diaphragm pacing. Due to disuse atrophy and the conversion of muscle fibers to the fast-fatigable type during periods of inactivity, patients who have long-standing and significant respiratory paralysis will require conditioning of the diaphragm muscle in order to sustain ventilation. The diaphragm can recover quite rapidly from training, so patients and their caregivers can repeat sessions every hour. The length of time it takes to sustain greater than 4 continuous hours depends on the amount of time the patient and caregivers devote to this process. Patients communicate weekly the results of their conditioning at home, and the investigators communicate changes that need to be made. With increasing strength of the diaphragm and subsequent increased tidal volumes, the setting of the DPS unit may need to be decreased to maintain appropriate minute ventilation.

RESULTS

Twenty-eight patients with SCI have been implanted to date, including 10 who were less than 18 years of age at the time of injury. Table 1 summarizes the data. Two patients are female and 8 are male. Age at the time of injury ranged from 20 months to 17 years, with an average age of 13 years. Etiologies and levels of injury (C2) are outlined in the table. Age at the time of

implantation ranged from 18 years to 34 years. Length of time from injury to implantation ranged from 9 months to 19 years, with an average of 9.7 years, which is also the length of time spent on mechanical ventilation.

As is usually the case, most of the patients were chronically hyperventilating on their mechanical ventilators. Seven patients had tidal volumes programmed on their ventilators that were 500 to 800 mL in excess of their basal metabolic needs. Three patients had respiratory rates greater than 14 breaths per minute. All patients had minute ventilations exceeding 10 L/min, with 3 patients having minute ventilations of more than 14 L/min. Arterial carbon dioxide levels ranged from 20 to 29 with an average of 23. Only 3 patients had the ability to rescue breathe with glossopharyngeal breathing (frog breathe).

On initial evaluation, 2 of the patients (patients 9 and 10) had significant scoliosis that caused significant decrease in their thoracic space as visualized on chest radiographs. Both of these patients underwent surgical correction after consultation with pediatric orthopedic spinal cord specialists, which delayed implantation of the DPS. Both of these patients are still conditioning and at early evaluation, will require a longer period to reach 4 continuous hours of diaphragm pacing.

All of the patients underwent successful laparoscopic diaphragm pacing implantation with no significant perioperative complications. Average operative time was less than 2.5 hours. All of the patients were discharged the day following implantation. They all underwent outpatient evaluation of the DPS system, and their caregivers were trained in managing the system in weaning the patient off the ventilator at home. All patients were involved in the home-based conditioning program, with the average amount of time required to reach 4 continuous hours of pacing less than 3 weeks for the initial 8 patients. All of the patients who have completed conditioning were able to obtain tidal volumes above their expected basal rate by a significant percentage, as outlined in Table 1. Four patients utilize DPS continuously (24/7), 4 patients pace daytime only, and 2 patients are still actively conditioning their diaphragms.

Patient number 6 had a cardiac pacemaker placed at the time of his SCI because of bradycardia. As a separate clinical study arm of our trial, patients were evaluated intraoperatively and postoperatively to assess for device-to-device interactions. This patient, along with others, showed no interaction between the DPS system and the cardiac pacemaker.

All of the patients have responded to questions concerning the value of diaphragm pacing and how it has changed their lives. All patients preferred breathing with the DPS and would recommend it to others. All patients travel without a ventilator, which simplifies their mobility. One patient was even able to utilize the DPS system on the flight home from Cleveland because it

Table 1. Demographics and Results of DPS in Individuals With Tetraplegia Who Were Injured as Children or Adolescents*

Patient	Circumstances of Injury	Age at Injury (y)	Time From Injury to Implant (y)	Tidal Volume on Ventilator (mL)	DPS Tidal Volume (mL)	% Above Basal Needs	Time Until 4 h Continuous Use (wk)	Current DPS Use
1	Football	17	4	1200	720	56	2.6	Daytime
2	Meningitis	17	7	800	500	26	5.8	Daytime
3	MCA	16	19	1200	800	45	5.9	Full-time
4	Pedestrian-auto	1.5	18	750	650	18	4.9	Daytime
5	Football	17	0.8	1200	850	62	0.1	Full-time
6	Dirt bike	14	4	1000	650	43	0.7	Full-time
7	Soccer goal fell	10	8	900	750	5	1.3	Daytime
8	Wrestling	17	7	900	800	100	0.7	Full-time
9	Bicycle-auto	12	12	900	n/a	n/a	n/a	Conditioning
10	Snowmobile	8	18	1400	n/a	n/a	n/a	Conditioning

*DPS, diaphragm pacing stimulation; MCA, motorcycle accident; n/a, not applicable.

simplified airline transfers. There was no longer a need for an Ambu bag for ventilation during transfers or for someone to manage the ventilator. Patients and caregivers reported fewer secretions and less suctioning. Four patients specifically identified attending college or church without a ventilator as easing their integration into society.

DISCUSSION

This study confirms that the DPS system can be safely implanted up to 19 years post injury in individuals with tetraplegia, allowing them the benefits of natural negative pressure breathing with their own diaphragms. There was no perioperative morbidity, and all tolerated the outpatient surgery. All of the patients were able to return home for the home-based weaning protocol. The results of this study should be used to begin studying implantation into adolescents younger than age 18 years.

Ease of implantation and physiologic breathing are only 2 of the benefits of breathing with DPS. Mechanical ventilation is associated with functional limitations such as decreased mobility. The tubing of the ventilator increases the difficulty of dressing and transferring patients. Mobility is limited to spaces and places that can accommodate a portable, electrically driven mechanical ventilator and suction device. Ventilator-assisted individuals need a caregiver able to use and troubleshoot these devices throughout the day as well as during transport. Several patients who utilize the device feel comfortable enough to travel without attendants.

The need for a reliable source of electricity can limit placement of ventilator-dependent patients and can become a problem during natural disasters such as hurricanes (15). One patient who lost her house in hurricane Rita was able to go to a shelter because she was utilizing the DPS system, while another patient still on a

ventilator was unable to utilize shelters because he was considered too high risk. One of the main benefits patients reported after utilizing the DPS system is that it has eased traveling. It also has decreased the weight of their wheelchairs and simplified transfers.

There are also psychosocial consequences to prolonged mechanical ventilation, with patients feeling more insecure, helpless, and dependent compared to nonventilated patients (16). In addition, mechanical ventilation increases feelings of isolation for both patients and their caregivers (17). Fatigue, depressed mood state, and disruptions of sleep-rest patterns among patients with prolonged mechanical ventilation have been commonly reported (18). All of the patients who received DPS implants stated they would recommend pacing to other patients because of their overall improvement in well being. One of the adult patients had not left her house until after she received the DPS system because she was embarrassed by the ventilator tubes.

Mechanical ventilation also leads to difficulty communicating. Noises from the ventilators can interfere with hearing and concentration. Ventilator use typically results in long pauses between phrases, short phrases, and poor voice quality (19). These changes in voice can make clear communication difficult or stressful. Once DPS system conditioning is complete, patients cap their tracheostomies and talk naturally, once again utilizing their own diaphragms to maintain negative pressure ventilation. Their tone of voice returns to the preinjury tone.

Home-based conditioning and weaning from the ventilator remove any need for hospital stays and have increased patient satisfaction. Because this process enables the patient to integrate immediately back home, family members do not have to take time off from their jobs, and the patient's caregivers can be maintained. A long hospital stay would lead to the potential loss of the

healthcare providers. Once free of the ventilator, patients have stated they are able to find and hire caregivers much more easily because of the inherent fear many people have of ventilators.

Positive pressure mechanical ventilation, although life saving, has certain significant negative attributes such as causing atrophy of the diaphragm muscles, posterior lobe atelectasis and collapse leading to pneumonias, barotrauma from the positive pressure, and impaired hemodynamics from decreasing venous return. Presently, our research team is investigating early institution of the DPS system to allow natural negative pressure ventilation, which ventilates the posterior lobes, thus minimizing atelectasis; improves cardiac function by increasing venous return; and decreases barotrauma for any patient in the intensive care unit on mechanical ventilation (20). Early implantation of the DPS system after SCI could decrease diaphragm muscle atrophy and conversion to a fast-twitch fatigable fiber. Since it is percutaneous, the DPS System could be removed if a patient recovers during the acute phase of a SCI. It may also decrease the period of weaning from a ventilator. Historically, up to 40% of additional ventilated intensive care unit days have been spent trying to liberate patients from the ventilator once they have been on the ventilator for several days. Functional electrical stimulation of the most important muscle of respiration may prove useful in the in the acute management of patients with SCI.

CONCLUSION

The results show the laparoscopic DPS system to be a low-risk and effective system for ventilatory support with home-based weaning from the ventilator for individuals with tetraplegia who were injured as children. The benefits of the DPS System include improved speech patterns, decreased cost of care, increased sense of independence, improved mobility, eliminating inconvenience and stigma associated with ventilators, and the potential for fewer pulmonary complications. Protocols should be developed for developing criteria for implantation of the DPS System in children and studying the effects of implantation soon after injury.

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