

MANAGEMENT OF PULMONARY COMPLICATIONS IN NEUROMUSCULAR DISEASE

Joshua O. Benditt, MD

Normal breathing depends on the function of the ventilatory pump, which consists of the central respiratory control centers, the bony rib cage, diaphragm, and the intercostal and accessory muscles. Normal arterial blood gases and defense of the lung through cough depend on intact muscle function. A wide variety of neuromuscular disorders result in dysfunction of the ventilatory pump that in turn can lead to respiratory failure, pneumonia, and even death. Breathing disorders are recognized as the leading cause of mortality in neuromuscular disease.^{9, 25} Appropriate intervention prevents complications and prolongs life in individuals whose neuromuscular disease affects their respiratory system.

ETIOLOGY OF RESPIRATORY FAILURE IN NEUROMUSCULAR DISEASE

Respiratory failure in neuromuscular diseases results from a number of factors, including: (1) respiratory muscle weakness and fatigue; (2) alteration in respiratory system mechanics; and (3) impairment of the central control of respiration.

From the Department of Medicine, University of Washington Medical Center, Seattle, Washington

Respiratory Muscle Weakness and Fatigue

Respiratory muscle weakness and fatigue are frequent contributors to ventilatory failure in the patient with neuromuscular disease. Respiratory muscle *weakness*, the inability of the respiratory muscles to generate normal levels of pressure and flow during inspiration or expiration, occurs because of lack of appropriate stimulation of muscle fibers, as in spinal cord injury, or intrinsic dysfunction of the fibers themselves, as in the muscular dystrophies. Respiratory muscle *fatigue*, defined as the failure of a muscle to maintain a constant force during repetitive contractions⁵⁵ can occur because of weakness of the respiratory muscles themselves or because of an increase in load. Progressive muscle weakness and fatigue lead to restrictive lung disease and ultimately to hypoventilation, hypercarbia, and respiratory failure. Respiratory muscle fatigue and ventilatory failure usually occur only with significant impairment of respiratory muscle strength, at a level less than 30% of predicted values.¹⁰

Alteration in Respiratory Mechanics

In addition to effects on muscle contraction, neuromuscular disease increases elastic and resistive loads on the respiratory muscles. Both types of loads increase the work of breathing and hasten ventilatory failure. Increases in elastic loads are a consequence of an increase in stiffness of both the lungs⁹ and the chest wall.^{21, 42} Airway secretions and an ineffective cough mechanism for their clearance result in increased airways resistance. Finally, kyphoscoliosis, frequently associated neuromuscular disease processes, can increase the work of breathing. Deformation of the thoracic cage further increases chest wall stiffness and produces mechanical misalignment of the respiratory muscles, thus lessening their ability to operate effectively against the increased elastic and resistive loads.⁹

Impairment of Control of Ventilation

Disorders of central control of respiration frequently are associated with neuromuscular disease processes. Defects in control of respiration may be caused by the disease itself, as in bulbar poliomyelitis, or secondary to hypoxemia and hypercarbia associated with a disease process as it progresses, as in Duchenne muscular dystrophy. The first indicators of disordered respiratory control may occur in association with sleep. Significant nocturnal decreases in partial pressure of oxygen (P_{aO_2}) as well as elevations in arterial partial pressure of carbon dioxide (P_{aCO_2}) have been reported.^{29, 30, 43} These changes are most likely to occur during rapid eye movement sleep when a pattern of rapid shallow breathing develops.^{30, 43} This hypoventilation sometimes is associated

with apneic episodes, leading to further hypercapnia.^{3, 29, 30} Hypercapnia or hypoxemia occurring at night may have a role in reducing daytime central respiratory drive by depressing central drive centers directly and also by increasing the "bicarbonate pool."^{29, 30, 45} This latter effect blunts the stimulus to breathe generated by respiratory acidosis and perpetuates the hypercapnic state.

Presentation of Respiratory Failure

Respiratory failure will present in one of three ways in patients with neuromuscular disease: (1) as acute respiratory failure such as that occurring in high level spinal cord injury; (2) as an acute respiratory decompensation in a chronic disease such as amyotrophic lateral sclerosis (ALS); or (3) as a chronic worsening of a gradually progressive disease such as Duchenne muscular dystrophy (DMD).

Treatment of acute respiratory failure frequently involves endotracheal intubation and positive pressure ventilation in the ICU. Many times tracheostomy tube placement is required. In this situation, unfortunately, there are few choices of methods of ventilation. It is possible, however, to wean a patient from invasive positive pressure ventilation by utilizing a variety of noninvasive ventilatory techniques.⁶ Thus the tracheostomy tube, which some patients find objectionable, is not necessarily permanent.

The insidious onset of respiratory failure in neuromuscular diseases is a common occurrence and provides an opportunity for early intervention with a variety of ventilator options. Noninvasive forms of both positive and negative ventilation as well as the rocking bed and pneumobelt have been used effectively in reversing, at least temporarily, progressive chronic respiratory failure.^{19, 24, 32, 36} Initially, patients may require ventilatory support for only part of the day. In these cases, nocturnal ventilatory support has been shown to be of great value.^{15, 19, 20, 32, 36, 53} Daytime ventilation either full-time or for prescribed periods can be utilized as muscular weakness progresses.

METHODS OF VENTILATORY SUPPORT IN NEUROMUSCULAR DISEASE

Mechanical Ventilation

Artificial ventilation as a means of prolonging human life has been referred to since Biblical times. More recently, but as early as the mid-nineteenth century, ventilation during surgery, including open-chest operations, has been possible. It was not until 1927 and the invention of the motorized iron lung by Drinker¹⁸ that long-term mechanical ventilation became a possibility. Chronic ventilation via a tracheostomy tube became possible in the 1950s with the development of reliable, smaller

positive pressure ventilators. Today a wide variety of devices exist for chronic ventilation of patients with neuromuscular disease as well as other forms of respiratory failure.

DEVICES AVAILABLE FOR MECHANICAL VENTILATION OF NEUROMUSCULAR PATIENTS

- I. NEGATIVE PRESSURE VENTILATORS
 - a. Full body ventilator (tank ventilator or iron lung)
 - b. Raincoat ventilator ("poncho" or "pneumowrap")
 - c. Cuirass ventilator (chest shell)
 - d. Pneumosuit ventilator with leggings
- II. POSITIVE PRESSURE VENTILATORS
 - a. Via tracheostomy
 - b. Noninvasive
 1. Via full face mask
 2. Via nasal mask
 3. Mouthpiece with lipseal
- III. VENTILATORS RESULTING IN PASSIVE MOVEMENT OF THE DIAPHRAGM
 - a. Pneumobelt
 - b. Rocking bed
- IV. PHRENIC NERVE PACING

Negative Pressure Ventilators

Negative pressure ventilators have been used for many years, bringing extensive experience ventilating patients with a wide range of neuromuscular diseases. Negative pressure ventilators function by applying a negative pressure to the surface of the thorax and abdomen, expanding the chest wall and lungs and thus promoting the movement of air into the lungs. Exhalation occurs passively because of the inward elastic recoil of the chest wall and lungs. Because pleural pressure is lowered during inspiration, this type of ventilation more closely mimics spontaneous breathing than does positive pressure ventilation. Full body ventilators such as the iron lung encase the patient's entire body except for the head, which remains outside the device and is sealed at the neck with a rubber or plastic collar. Cyclic negative pressure is created within the tank by a bellows pump connected to an electric motor that can be powered by alternating current or a back-up battery supply. Respiratory rate as well as the volume of each breath can be adjusted. Because of the large size and weight (325 kg)³³ of the iron lung, smaller and lighter devices have been developed. The Portalung is a fiberglass shell that weighs only 1/6 as much as the iron lung and is powered by a separate, large volume negative pressure generator. One drawback to both of these devices, particularly the iron lung, is lack of access to the patient.

In addition, some patients become claustrophobic when these devices are used.

The cuirass or chest shell (Fig. 1) is a device that was developed to overcome the portability and confinement problems of the larger tank ventilators. It consists of a fiberglass shell that fits over the anterior chest and abdomen. This is attached to a negative pressure generator via 2" pressure tubing. Intermittent negative pressure is generated within the shell, resulting in expansion of the chest wall and lungs. Although portable and more convenient than the "full-body" negative pressure ventilators, the cuirass is the least efficient of the negative pressure ventilator devices.¹³ This inefficiency in part may be a consequence of improper fit of the device to the patient's thorax and abdomen, resulting in significant air leaks, which often occur with mass-produced cuirasses. This problem may be circumvented if the cuirass is custom designed and manufactured individually, unfortunately at considerable expense.

The light weight and ease of application are attractive features of this device. Although the cuirass has been used for patients who require 24-hour ventilation, it probably is best reserved for those who require less ventilator assistance.

The pneumowrap negative pressure ventilator⁵² is a poncho-like rubberized garment worn over a shell-like grid placed on the patient's chest. Drawstrings or Velcro attached to the wrist, head, and lower waist openings seal the pneumowrap over the patient. A negative pressure generator attached via 2" tubing to the poncho allows generation of negative pressure around the chest and abdomen. The grid is essential to provide a gas volume around the chest that can be decompressed, causing the thorax to expand. This device does not have to be customized and is relatively inexpensive. Unfortunately, in many patients significant air leaks around the legs can result in inefficient ventilation.³⁵

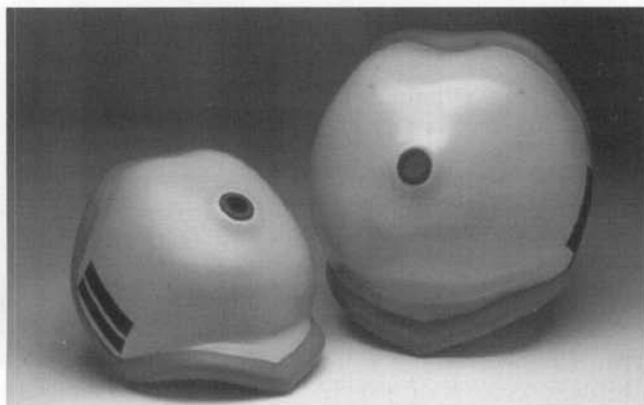


Figure 1. Cuirass or "chest-shell" device for application of negative pressure ventilation. The device (two sizes shown) fits over the anterior thorax and abdomen and is held in place with Velcro straps.

The pneumosuit with leggings is a modification of the pneumowrap that extends the garment over the lower extremities and yields a superior seal for more efficient ventilation. Because it is custom fitted, it is considerably more expensive than the standard pneumowrap device. The cuirass, pneumowrap, and pneumosuit all require negative pressure generators. A number of highly portable generators are available that can control both respiratory rate and inspiratory pressure.

Negative pressure ventilators, especially the more efficient types (iron lung, Portalung) have been used to continuously ventilate patients with little or no vital capacity.⁵³ The utility of negative pressure ventilators is limited because patients must be in the supine position when using them, and obese patients or those with significant kyphoscoliosis will require the use of the iron lung or Portalung because the cuirass and wrap ventilators may not fit adequately. Travel is not possible with the larger devices (iron lung and Portalung). Finally, sleeping with a spouse or significant other is generally not possible with any of the devices.

One potential hazard of negative pressure mechanical ventilation is the development of upper airway obstruction during the negative pressure.^{19, 49} Airway collapse can occur when the negative intratracheal pressure generated by the ventilator is unopposed by upper airway muscle tone. This occurs most frequently in patients with poor control of the upper airway, during periods of poor synchronization of respiratory muscle contraction with the ventilator, and during sleep when upper airway tone is reduced. It has been recommended that patients undergoing nighttime negative pressure ventilation have sleep studies to evaluate possible obstructive events. Patients with poor control of upper airway musculature or obstructive sleep apnea should not be treated with any negative pressure device because this may result in occlusion of the airway and significant risk of hypercapnia and hemoglobin desaturation.¹⁹

Positive Pressure Ventilators

Positive pressure ventilators function by applying positive pressure to the airways, thus promoting the movement of air into the lungs. Exhalation of gases occurs passively with relaxation of the chest wall and lung. Positive pressure ventilation can be delivered to those requiring chronic ventilation in several ways—"invasively" via an indwelling tracheostomy and "noninvasively" via nasal mask, full face mask, or mouthpiece with lip seal.

Invasive positive pressure ventilation utilizing an indwelling tracheostomy has been used successfully in several large series.^{11, 39, 53} The development of convenient, portable positive pressure generators has made this form of ventilation practical even in the home environment. Benefits of this type of ventilator support include complete control of the machine-delivered tidal gas volume and ease of access to the central airways for suctioning of secretions. In addition, treatment during epi-

sodes of acute respiratory failure requires no change in the method of ventilation.

Unfortunately, a number of serious complications from long-term positive pressure ventilation have been cited. Damage to the trachea from the indwelling tube, including tracheal necrosis, stenosis, and hemorrhage, as well as tracheoesophageal fistulae have been reported.⁴ However, the development of low-pressure, high-volume cuffed plastic tracheostomy tubes has lowered the incidence of these complications. Food aspiration and swallowing problems also can occur from interference with the normal swallowing mechanism. An increased risk of airway colonization with bacteria and lower respiratory tract infection also have been noted. The use of a tracheostomy tube requires supplemental humidification, an additional daily respiratory care task. Finally, social interactions and patient psychologic well-being may be impaired by the inability to speak associated with the tracheostomy tube. A number of devices and techniques have been designed to allow speech and communication while the patient is on the ventilator, including one-way valves that allow gas to pass through the vocal cords during exhalation (Passy-Muir valve, Irvine, CA) and the "Trach Talk" tracheostomy tube (Portex, Keene, NH), which has a channel to direct compressed air through the vocal cords. Unfortunately, not all individuals can use these devices.

Noninvasive delivery of positive pressure ventilation was first used during the polio epidemics of the 1950s to allow patients time out of the iron lung. Recently there has been significant renewed interest in this technique. There are currently three ways in which noninvasive positive airway pressure ventilation may be delivered: (1) via mouthpiece with or without a lip-seal; (2) via nasal mask; or (3) via full face mask. Occasionally more than one method may be used in the same patient, for instance with a mouthpiece during the day and a nasal mask at night.

The oral interface was the first type of noninvasive positive pressure ventilation to be utilized. Mouthpiece devices connected by pressure tubing to a positive pressure generator are held between the teeth (Fig. 2A). It has been noted that even while sleeping many patients are able to use this technique, especially when lip seal devices are used.²

In the past decade, nasal interfaces for the delivery of positive pressure ventilation have been developed and used successfully (Fig. 2B). Initially, these nasal masks were designed to deliver continuous positive airway pressure (CPAP) for the treatment of patients with sleep apnea.¹⁷ Currently they are also used to deliver intermittent positive pressure. To deliver the tidal volume most effectively, there should be no leaks around the nasal mask or through the mouth. In patients where leakage around the mask is a problem or facial irritation develops, individually molded custom masks are commercially available. In those where leakage of air out of the mouth occurs, there may be oxyhemoglobin desaturation, elevation of arterial C_{O_2} , and associated symptoms. In this situation, the use of full oral-facial mask interface may be appropriate.² This form of noninvasive delivery of positive pressure ventilation

utilizing custom-designed appliances can eliminate leaks via the mouth and may be more comfortable for some patients.

It has been suggested that the use of noninvasive positive pressure devices be avoided in patients: (1) with coexisting severe lung disease where secretions may be a problem; (2) who are obtunded or uncooperative; (3) when poor oropharyngeal muscle strength is present and secretions cannot be handled effectively; (4) who have uncontrolled seizure disorders; and (5) with orthopedic conditions that interfere with placement of the devices.³

Noninvasive positive pressure ventilation has been used with excellent results in a wide range of patients. Patients who require only nocturnal ventilatory support may be particularly suitable candidates for this form of therapy. In some cases, patients using invasive forms of ventilation have been switched effectively to noninvasive positive pressure ventilation, thus avoiding the problems of tracheostomy.²

NEUROMUSCULAR DISORDERS FOR WHICH MECHANICAL VENTILATION HAS BEEN USED

Central Nervous System

- Central apnea
- Central alveolar hypoventilation

Degenerative Disease

- Spinocerebellar degeneration
- Shy-Drager syndrome

Brain Stem Tumor, Vascular Malformation, Spinal Cord Injury

- Cervical trauma, quadriplegia
- Syringomyelia

Neural or Muscular Disease

- Amyotrophic lateral sclerosis
- Muscular dystrophies
- Spinal muscular atrophy
- Multiple sclerosis
- Poliomyelitis
- Chronic polyneuropathy
- Myopathy

Phrenic Nerve Damage

- Postoperative, traumatic damage
- Idiopathic paralysis of diaphragm

Frequently, the positive pressure generators used to deliver nasal ventilation are the same as those used to deliver positive pressure ventilation with tracheostomy. Another simple and relatively inexpensive device also can be used via the nasal route; it is similar to devices used to deliver continuous positive airway pressure for sleep apnea patients but has been modified so that cyclical positive pressure swings can occur during inspiration independent of the positive pressure set during expiration. Nasal noninvasive positive pressure ventilation

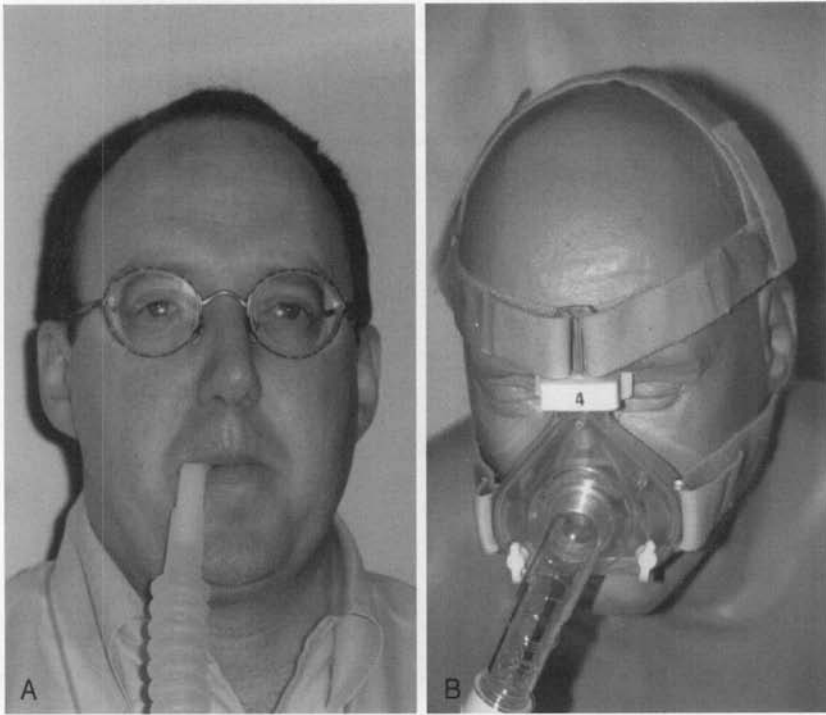


Figure 2. Mouthpiece adaptor (A) for application of positive pressure ventilation. Nasal interface (B) held in place with Velcro straps.

(NIPPV) can be delivered with a number of different types of ventilators, including several machines designed specifically for this.^{54, 57} With these machines, the positive pressure delivered to the patient is high during inspiration and lower during expiration. The positive pressure gradient during inspiration results in delivery of a tidal volume to the patient. Exhalation still occurs passively and is terminated when the airway pressure returns to the lower expiratory level. Since the expiratory pressure is greater than atmospheric, the end-expiratory lung volume is increased. These devices have no back-up alarm; therefore, patients must be able to maintain some spontaneous ventilation.

Ventilators Resulting in Passive Movement of the Diaphragm.

Two types of "ventilators" that result in ventilation by acting on the abdominal contents to move the diaphragm passively are the "pneumobelt" and the rocking bed. The pneumobelt consists of an inflatable rubber bladder encased in a fabric corset that is strapped around the abdomen (Fig. 3). A positive pressure generator attached to the pneumobelt will inflate the device, resulting in compression of abdominal contents, upward displacement of the diaphragm, and forced exhalation. When the bladder deflates, abdominal pressure is lowered and the diaphragm descends, resulting in a spontaneous inhalation of air into the patient's lungs. The patient must be seated at a 30° angle or

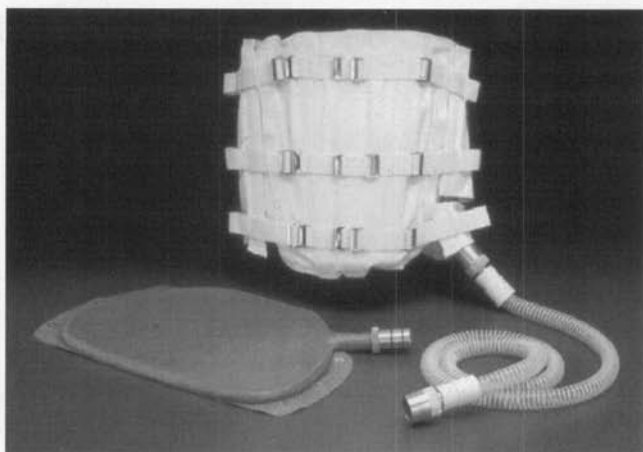


Figure 3. Pneumobelt device showing rubber inner bladder and canvas cover. The device is strapped around the anterior abdominal wall.

greater from the horizontal for the device to function properly.^{1,4} Therefore, daytime use is the most common application, and 24-hour use is not recommended.⁴ The device may not be effective in obese patients, those with significant thoracic deformity, or those with a scaphoid abdomen.³³ Because the ventilator functions during exhalation, a significant benefit for some patients is louder and clearer speech. In addition, the use of the pneumobelt may result in more free time off other forms of ventilation. Some patients may even have had tracheostomies removed and learn to use glossopharyngeal breathing when the pneumobelt is not in use.

Another form of "ventilator" that uses gravitation-induced movement of the abdominal contents and diaphragm to achieve ventilation is the "rocking bed." This device originally was used on patients with poliomyelitis in the early 1950s.⁴⁶ It consists of a motorized bed that moves through an area of about 45° above the horizontal, 12 to 15 times per minute. As the head of the bed tilts downward, gravity forces the abdominal contents and diaphragm upward into the chest, resulting in forced exhalation. As the head of the bed is tilted upward, the diaphragm and abdominal contents shift downward, with resulting inhalation of air. The rocking bed is most appropriate for patients who require ventilator assistance less than 24 hours per day who are able to utilize it at night.

Diaphragm Pacing. Electric stimulation of the diaphragm by pacing with implanted electrodes is a technique available to patients with intact phrenic nerves and diaphragm muscle adequate to sustain ventilation when stimulated. It is used most often in patients with central alveolar hypoventilation and in patients with paralysis of the respiratory muscles secondary to high (C1-C2) cervical cord injuries.²⁶ Diaphragm pacing is not indicated in respiratory muscle dysfunction due to lower motor

neuron lesions involving the phrenic nerve, or from muscular dystrophy involving the diaphragm. Before considering diaphragm pacing, phrenic nerve conduction studies should be performed to assure adequate function.

The diaphragm pacing device itself consists of four parts: one or two phrenic nerve electrodes, a radio frequency receiver attached to the electrodes, an external coil or antenna, and an external radio frequency transmitter that can be programmed with regard to frequency of electrical stimulation and duration of stimulation. The major advantage of this system is the small, lightweight nature of the equipment, which leaves the patient less encumbered compared with standard ventilator techniques. The procedure requires operative implantation of the electrodes and receiver and is relatively expensive, with costs sometimes exceeding \$200,000.² In addition, upper airway obstruction during diaphragm contraction may be encountered, necessitating placement of a tracheostomy, and there is risk of infection of the implanted electrodes.

IMPLEMENTATION OF VENTILATORY SUPPORT MEASURES IN PATIENTS WITH NEUROMUSCULAR DISEASE

When to Initiate Mechanical Ventilation

Disease Characteristics

The point at which long-term mechanical ventilation at home should be implemented has been related to the severity of disease. Baydur⁸ noted two major categories of signs and symptoms that indicated respiratory impairment in their study of patients with DMD. Those consistent with (1) sleep disordered breathing seen as nightmares, morning headaches, and daytime drowsiness and (2) those consistent with respiratory muscle dysfunction, such as exertional dyspnea, orthopnea, generalized fatigue, and paradoxical breathing patterns. When these signs and symptoms are present, disease severity and the need for mechanical ventilation can be assessed further by performing pulmonary function testing. Specifically, the measurement of vital capacity and tests of inspiratory muscle strength (maximal static inspiratory pressure: MIP) have been used most often to aid in determining whether mechanical ventilation should be instituted. Hypercapnia and the need for mechanical ventilation occurred in the study by Baydur when the vital capacity fell to between 500 and 700 mL.⁸ In a study of 53 patients with proximal myopathy by Braun et al,¹⁰ hypercapnia occurred when the MIP was less than 30% of predicted and when vital capacity was less than 55% of predicted. Other authors¹⁵ have noted somewhat lower values for vital capacity measurements in their patients with DMD at the time they required mechanical ventilatory support. Splaingard et al⁵³ in their analysis of 40 patients with a diverse group of neuromuscular disease

noted that all of their patients who required mechanical ventilation had $VC \leq 25\%$ with at least one of the following associated findings: (1) $Pa_{CO_2} > 55$ mm Hg; (2) recurrent atelectasis or pneumonia; (3) moderate dyspnea at rest; or (4) congestive heart failure. Although no clear guidelines have been established for determining the point at which an intervention with mechanical ventilation in patients with gradually worsening neuromuscular disease should occur, the presence of severe restrictive disease ($VC < 45\%$ predicted), respiratory muscle weakness ($MIP < 30\%$ predicted), dyspnea at rest, and hypercapnia would indicate the need for this intervention.

Adjunctive Respiratory Aids for the Patient with Neuromuscular Disease

Mechanical ventilatory support as described above assists the patients' inspiratory muscles to maintain ventilation with normal carbon dioxide levels. However, hypoventilation represents only one of the respiratory problems encountered by patients with neuromuscular disease. *Expiratory muscle function* is also frequently impaired, which leads to problems with effective cough that lead to frequent respiratory infections, pneumonia, and even death. Respiratory infection is one of the leading causes of death for patients with neuromuscular disease. A cough expiratory flow rate of at least 3 L per second has been suggested as the minimum flow rate necessary to produce an effective cough.³ The patient with neuromuscular disease frequently will need assistance to generate these flows.

A number of approaches are available to increase cough expiratory flows in patients with neuromuscular disease. Manually assisted coughing is a method of applying a positive pressure to the abdomen, pleural space, and airway, leading to adequate cough expiratory flow rates. A number of techniques allow an attendant to apply rapid abdominal thrusts that result in effective clearance of secretions.³ Patients can assist the attendant by taking a maximal inspiration before the abdominal thrusts are applied. Glossopharyngeal breathing (GPB or "frog breathing") can be utilized to augment maximal inspiration in patients who cannot generate an adequate inspiratory effort.⁵ Patients with severe obesity or kyphoscoliosis may not tolerate assisted cough techniques and may require additional intervention to maintain airway hygiene and avoid pneumonia. One such method, available for over 40 years but only recently used to any great extent, is the mechanical In-exsufflator MI-E (In-exsufflator, JH Emerson Co, Cambridge MA) (Fig. 4). This device consists of an electric motor that generates positive and negative pressures of up to 50 cm of H_2O to the airways of patients who are unable to cough. The pressure is applied via a facemask connected to the flow generator with flexible pressure tubing. Insufflation is applied to the respiratory system over a 1- to 3-second period by exerting a pressure of between 10 and 50 cm of H_2O . A negative pressure of

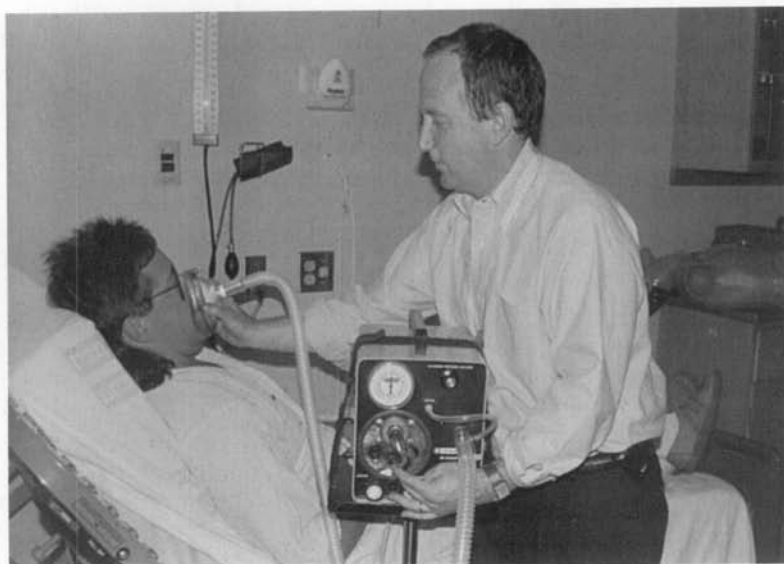


Figure 4. In-sufflator device with full face mask interface. A positive insufflation is followed by a rapid exsufflation (controlled by assistant) resulting in clearance of upper and lower airway secretions.

between 20 and 50 cm H₂O is then rapidly applied to the airway by reversing flow at the generator with a mechanical or electronic switching device. Secretions are suctioned from the airway noninvasively without violation of the airway. Dr. Bach and colleagues are strong proponents of this technique and have published their experience with a large series of ventilated patients who were able to convert from invasive positive pressure ventilation via tracheostomy to noninvasive ventilation in part because of their ability to clear secretions with MI-E.

Other noninvasive mechanical aids include devices that oscillate the chest wall or airway directly.¹²

EFFECTIVENESS OF CHRONIC VENTILATION IN NEUROMUSCULAR DISEASE

Benefits ascribed to the use of chronic mechanical ventilation in neuromuscular patients are numerous and include: reduced Pa_{CO₂} and increased Pa_{O₂}, on-and-off ventilator, decreased symptoms of respiratory failure, improved quality of life, and reduced morbidity and mortality. It has been clear for some time that intermittent ventilation may ameliorate symptoms of respiratory failure, reduce Pa_{CO₂}, increase Pa_{O₂} (even during periods off the ventilator), and prolong survival in patients with neuromuscular disease. Nocturnal ventilation has become a widely accepted clinical practice, providing ventilatory assistance for patients while sleeping and allowing them to breathe on their own during the day.

Curran¹⁵ reported on the initial use of nocturnal negative pressure ventilation in patients with late-stage DMD. In patients who had symptoms of ventilatory failure and $\text{Pa}_{\text{CO}_2} \geq 60$ mm Hg, nocturnal negative pressure ventilation utilizing cuirass or tank ventilators significantly improved arterial Pa_{CO_2} values (60.8 mm Hg pretreatment to 45.5 mm Hg posttreatment) and Pa_{O_2} values (59.3 mm Hg pretreatment and 74.6 mm Hg posttreatment). Since that time, a number of published studies have reported using nocturnal ventilation and have supported these findings.^{19, 20, 24, 32, 53, 57}

The mechanism whereby intermittent nocturnal ventilation results in amelioration of respiratory failure has not been entirely elucidated but probably is multifactorial. During periods of mechanical ventilation there is a significant reduction of diaphragm and accessory muscle EMG activity.^{41, 50} This reduction in EMG activity likely signifies a decrease in work performed and oxygen consumed by the respiratory muscles. Some authors have postulated that nighttime ventilation rests fatigued respiratory muscles, allowing improved daytime function.⁴⁷ The rest provided by this reduction in work load may reverse chronic respiratory muscle fatigue thought to be present in these patients, allowing improved daytime function. In one study²⁹ daytime inspiratory muscle *endurance* was noted to increase from 7.1 ± 3.4 minutes to 14.8 ± 7.6 minutes 3 months after initiation of nighttime ventilation. Results of studies evaluating improvement in muscle *strength* have been mixed, with some authors noting slight improvements and others no improvement.^{19, 50}

A second hypothesis explaining the improvement in daytime respiratory function with nocturnal ventilation is related to reversing the adverse effects of chronic neuromuscular disease on respiratory system mechanics.³⁴ Improvements in lung compliance, increases in resting lung volumes, and a decrease in the work of breathing have been reported^{34, 50} in patients with neuromuscular disease following positive pressure ventilation. If these improvements were sustained throughout the day, they would constitute a reduced load on the respiratory muscles, which would ameliorate chronic fatigue. In addition, increases in end-expiratory lung volumes to more normal ranges would reduce atelectasis and improve oxygenation.

A third explanation involves the reversal of what has been referred to as "central fatigue"⁴⁸ where nighttime hypoventilation and hypoxemia are thought to lead to a blunting of central respiratory drive, resulting in "adaptive" daytime hypoventilation. It has been postulated that nighttime ventilatory intervention results in a "resetting" of central control mechanisms with an increase in chemosensitivity and a reduction of the body bicarbonate pool.²⁹ Increases in Pa_{CO_2} would be met with a more appropriate response in minute ventilation. Data to support this hypothesis are not currently available. It is possible that all three of these mechanisms are involved in the improvement of arterial blood gas values and daytime function noted in patients treated with nocturnal ventilation.

In addition to improvement in arterial blood gases, other measures of physiologic function have been shown to improve with intermittent ventilation. Hoepfner and colleagues³⁴ showed increases in vital capacity, reduction in erythrocytosis, and improvement in right-sided heart failure following nighttime ventilation, with changes maintained over a mean follow-up period of 3.4 years.

For ethical reasons, no randomized-controlled trial evaluating the effect on survival of intervention with mechanical ventilation has been performed in patients with neuromuscular disease. It is clear in most progressive neuromuscular diseases that once an elevation in Pa_{CO_2} and a decrease in Pa_{O_2} is noted, cor pulmonale and death are inevitable within a short time. It is therefore accepted by most authors that mechanical ventilation in the home leads to improved survival in most patients.

The institution of home mechanical ventilation also has enabled patients to improve their quality of life. These patients need not be confined to the home and its nearby environs. It is possible, however, for some patients to lead fully productive lives. Those requiring only nocturnal ventilation can be fully employed or attend school full-time.^{31, 39, 40} For those requiring 24-hour ventilator assistance, portable ventilators adaptable for carrying on specialized wheelchairs are available and may allow access to the community. Many patients receiving nocturnal ventilation will notice a dramatic improvement in daytime alertness and functional activities, and some may become active with minimal assistance.

COSTS OF MECHANICAL VENTILATION IN NEUROMUSCULAR DISEASE

The costs of caring for patients who require prolonged mechanical ventilation can be enormous. This results from the impressive number of technologic devices required to maintain artificial respiration as well as the considerable requirements for attendant care of these patients. Davis et al¹⁶ studied the hospital costs of patients requiring mechanical ventilation for more than 48 hours. In their study, the mean charge for these patients per hospitalization was approximately eight times that for all other hospitalized patients. In patients who are unable to wean from the ventilator and require chronic care, costs can range up to \$66,000 per month.⁷ Because of the high costs of in-hospital management of the chronically ventilated patient and the potential for savings by managing these patients in the home, the federal government has focused some attention on this area.³⁷

It is clear that substantial cost savings can be obtained by moving chronic care into the home. The cost for home mechanical ventilation will vary depending on the type of ventilator required, the number of other respiratory therapy devices required, and the level of assistance for care required. Lafond et al³⁸ estimated the average monthly costs at approximately \$3000 for their series of patients. However, this figure

varies widely.^{7, 51} In a careful estimate of costs for home ventilation versus in-hospital care in London, Creese¹⁴ indicated that savings of approximately 32% could be expected by moving the patient from the hospital to home with 24-hour attendants. In the United States, Bach and colleagues⁷ reported their experience in 20 adult ventilator-assisted individuals who had lived in long-term hospital care settings and subsequently been moved to their homes for chronic care. In-hospital costs averaged \$718.80 per patient day, whereas home care cost on average \$235.13 per day. This decrease of 77% resulted in an annual yearly savings to the health care system of \$176,137 per patient. The American Association for Respiratory Care conducted a 20-state hospital survey in 1980, estimating hospital cost of \$22,569 versus home care costs of \$1766 for chronically ventilated patients.⁵⁶

The most important determinant of cost for home care is the type of attendant engaged in personal care of ventilator-assisted individuals. In the patient with a tracheostomy that requires suction, some states have required the use of licensed nursing at costs of \$29/hour or more.⁷ This increases the cost of home care significantly. A number of groups^{7, 27, 28, 39} have endorsed the use of properly trained nonlicensed attendants in the home care of ventilator assisted individuals. To the extent that family members can be trained to perform patient care activities, costs may be reduced even further. Accordingly, careful training of family members before patient discharge from the acute care setting is important. Family members frequently can provide excellent attendant care, reducing the need for 24-hour care by trained individuals. This can reduce costs to the health care system, although the financial burden in the form of loss of potential wages for family members has not been studied in detail. Once mechanical ventilation is instituted, it has been reported to decrease hospitalization in patients with neuromuscular disease.^{22, 23} Fischer and colleagues²² noted a 73% reduction of hospital days.

A significant financial disincentive to care of ventilated patients in the home is the fact that most insurers will reimburse only 80% of home-care costs.⁴⁴ This places a significant financial burden on even the most affluent families and serves to prevent moving patients into the home in many instances. Sites other than the home may provide less expensive and more independent and comfortable care for patients with long-term ventilation needs. England and France^{27, 28} have significant experience with small chronic care facilities focused on ventilator-assisted individuals. The state organization of regional centers for overseeing the care of home ventilator patients has had a significant positive effect in maintaining appropriate resource utilization. A number of states have established programs for dealing with these.⁷ Given the current need for controlling ever-increasing medical costs it is likely that organization and guidelines will become stronger at the national level in the United States.

SUMMARY

The clinician working with patients with neuromuscular disease should be aware of the effects of muscle weakness on the respiratory system. Symptoms may present insidiously and can result in progressive loss of function, respiratory failure, and even death. A number of techniques, including several forms of mechanical ventilation as well as physical aids to assist airway hygiene, are available and are effective in improving symptoms and survival in appropriately selected patients with neuromuscular disease.

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Address reprint requests to

Joshua O. Benditt, MD
Pulmonary and Critical Care Medicine
University of Washington Medical Center
Box 356522
Seattle, WA 98195-06522