Respiratory Muscle Evaluation of the Patient with Neuromuscular Disease

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ABSTRACT

This review presents clinically relevant issues regarding the assessment of respiratory muscles in individuals with neuromuscular disorders, and discusses the advantages and disadvantages of methods generally available to the clinician. Vital capacity (VC) and total lung capacity (TLC) are routinely measured in pulmonary function laboratories and are typically reduced in the context of severe respiratory muscle weakness, but the sensitivity and specificity of these measures are limited. Better measures of respiratory muscle weakness are maximal static inspiratory and expiratory pressures (PI max and PE max). PI max is reduced even with mild or moderate degrees of inspiratory muscle weakness, but low values also may be related to submaximal effort. To circumvent this problem, pressures can be measured using simpler maneuvers such as a maximal sniff. Specific tests of diaphragm function such as measurements of maximal transdiaphragmatic pressure are invasive and not routinely available to the clinician. Recently, noninvasive methods that specifically assess diaphragm function, such as diaphragm ultrasound of the zone of apposition and magnetic or electrophrenic nerve stimulation, have shown promise as new techniques for clinical use.

KEYWORDS: Respiratory muscles, lung volumes, diaphragm ultrasound, phrenic nerve stimulation

Objectives: Upon completion of this article, the reader should be able to: (1) identify the tests commonly used to assess respiratory muscle function; (2) recognize the limitations of these tests; and (3) be familiar with techniques that specifically assess diaphragm function.

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Respiratory muscle dysfunction in patients with neuromuscular disease is manifested in a variety of ways. The pathology of neuromuscular disease can interfere with the function of the central nervous system, spinal cord, peripheral nerves, neuromuscular junction, and muscles. Typical methods for assessing peripheral skeletal muscle, such as electromyography, are difficult to use or interpret for assessing respiratory muscles. Therefore, evaluating the respiratory pump in patients with neuromuscular diseases can be a challenge. We review recent advances in monitoring and assessing the respiratory muscles that may facilitate the respiratory evaluation of these individuals.

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HISTORY AND PHYSICAL EXAM

As with the evaluation of any organ system, history and physical examination are important starting points. Generalized muscle weakness triggers the suspicion of neuromuscular disease as the cause of respiratory symptomatology. Alternatively, respiratory failure can be the sole presenting manifestation of neuromuscular disease.[1,2] Symptoms due to respiratory muscle weakness include dyspnea, most often with exertion.[3,4] However, with severe limb muscle weakness, the patient's ability to exert may be insufficient to elicit dyspnea.[5,6] As the disease progresses, though, dyspnea can occur at rest, a sign that respiratory failure may be imminent. Dyspnea with supination, bending, or immersion in water (i.e., entering a swimming pool) is suggestive of diaphragmatic weakness.[4,7] Respiratory muscle weakness can also be exacerbated by muscle relaxants, corticosteroids, and aminoglycoside antibiotics,[8–10] so a medication history should also be included in the interview.

Involvement of the upper airway musculature may produce further symptoms, such as difficulties with speech or swallowing. Consequently, aspiration associated with dysphonia is a common complication of neuromuscular disease.[2,11–13] Also, because upper airway muscle weakness contributes to airway obstruction during sleep, symptoms due to sleep apnea, such as excessive daytime sleepiness and morning headache, are common. This weakness also predisposes to sleep-related breathing disorders during use of negative-pressure body ventilators.[14] Bulbar muscle weakness combined with weakness of the expiratory muscle adversely affects cough.[15] The inability to generate high intrathoracic pressures, dynamically compress the airways, and close the glottis impairs cough efficacy. Peak expiratory flows can be so diminished that these individuals cannot adequately clear airway debris.

The physical examination of the respiratory system may be normal during the initial stages of neuromuscular disease. As the disease progresses, tachypnea at rest may be an early manifestation, associated with a decrease in tidal volume. This rapid shallow breathing pattern has the advantage of lowering the elastic work per breath but has the disadvantage of increasing dead space ventilation (increasing the dead space to tidal volume [VD:VT] ratio). It is thought that an imbalance between the strength and load placed on the inspiratory muscles triggers the signal for the integrated response that brings about rapid shallow breathing.[16,17]

Accessory respiratory muscle recruitment may be apparent in patients with neuromuscular weakness. The sternocleidomastoids, scalenes, external intercostals, and parasternal muscles can be readily assessed visually and by palpation. Further insight regarding respiratory muscle weakness can be obtained by palpating the abdominal muscles. Normally, the expiratory muscles are relaxed during quiet breathing, but they may be recruited to compensate for diaphragm weakness.[18–20] Active expiration allows these individuals to exhale below functional residual capacity (FRC). When the abdominal muscles are relaxed at the end of expiration, the passive forces of the respiratory system will assist inspiration.

Rib cage and abdominal motion can easily be assessed at the bedside. Normally, the abdomen and rib cage expand synchronously during inspiration. When an individual adopts the supine position, abdominal compliance is increased and there is greater expansion of the anterior abdominal wall during inspiration. With inspiratory and expiratory muscle weakness, this pattern of motion is altered. Diaphragm weakness may cause the abdomen to move inward as the rib cage expands during inspiration (Fig. 1), whereas this pattern may be reversed with weakness of the inspiratory rib cage muscles.[7] Occasionally, these two patterns of paradoxical rib cage or abdomen motion may be seen at different times in the same individual, a phenomenon known as respiratory alternans. This is thought to represent a breath-

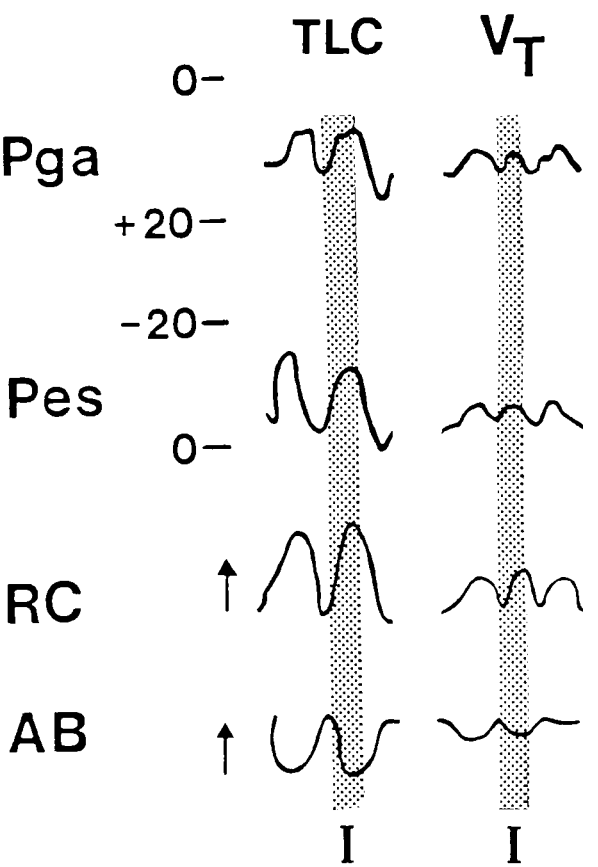

Figure 1 Changes in esophageal pressure (Pes), gastric pressure (Pga), and anteroposterior dimensions of the rib cage (RC) and abdomen (AB) during breaths to total lung capacity (TLC) and tidal breathing in an individual with bilateral diaphragm paralysis. There is no change in transdiaphragmatic pressure (Pdi) during these maneuvers and paradoxical inward motion of the abdomen during inspiration.

ing strategy that alternates the respiratory load between the diaphragm and the inspiratory muscles of the rib cage, thereby averting fatigue of either set of inspiratory muscles.

Chest wall motion can also be assessed using devices that sense changes in rib cage or abdomen dimensions. Magnetometers measure changes in rib cage and abdomen diameters, whereas the respiratory impedance plethysmograph measures changes in rib cage and abdomen cross-sectional areas. Magnetometry assesses respiratory excursions at the body surface by using pairs of electromagnetic coils, one that transmits and the other that receives an electromagnetic signal.[21] Respiratory inductance plethysmography assesses respiratory excursions by measuring changes in the electrical impedance of belts placed around the rib cage and abdomen. Both techniques will detect paradoxical motion of the rib cage and abdomen and asynchronous motion that may not be noted during the physical exam. These techniques are noninvasive and can be easily applied to patients with respiratory muscle weakness. One advantage of magnetometry over respiratory inductance plethsmography is that the axial motion of the chest wall can also be assessed.[22,23]

GLOBAL ASSESSMENT OF RESPIRATORY MUSCLE FUNCTION

Gas Exchange and Acid–Base Status

With mild to moderate respiratory muscle weakness, ventilatory drive is increased, leading to hyperventilation, a normal or elevated pH, and a reduced arterial tension of carbon dioxide (pCO_2).[24] The arterial tension of oxygen (pO_2) and the alveolar–arterial oxygen tension gradient ($pA–aO_2$) should be normal, providing there is no concomitant alveolar-filling process (i.e., aspiration). As respiratory muscles further weaken, pCO_2 increases. However, the degree of chronic hypercapnia may be greater than would be expected from measures of muscle weakness alone.[24,25] This suggests that factors other than muscle weakness contribute to the CO_2 retention. Among these, alterations in the control of breathing may be compounded by blunting of hypercapnic and hypoxic ventilatory drives. Other factors include mechanical ones such as atelectasis and abnormalities in the chest wall that reduce compliance and increase the elastic load presented to the respiratory muscles.[26] In patients with neuromuscular disease, dynamic elastance (a parameter that reflects elastic load of the lung per unit of maximal inspiratory muscle strength) has been suggested to be the strongest predictor of CO_2 retention.[27] Lanini and collaborators suggest that increased elastic load in the setting of muscle weakness modulates the central respiratory output and contributes to rapid shallow breathing.[17]

An assessment of gas exchange is an important part of the respiratory evaluation in neuromuscular disease. Hypoxemia occurs in advanced disease and is usually multifactorial. First, alveolar hypoventilation increases the pCO_2 and thereby reduces the pO_2. Concomitant processes can increase the $pA–aO_2$ gradient, such as airway obstruction (retained secretions, mucous plugs) or involvement of the pulmonary parenchyma (pneumonia, atelectasis). Ventilation and oxygenation can be further compromised during sleep. Rapid eye movement–associated respiratory muscle weakness and obstructive sleep apnea contribute to hypoxemia and hypercapnia,[28] so sleep monitoring using oximetry or polysomnography becomes important as respiratory muscle dysfunction progresses (see articles by Piper and Bach).

Lung Volumes and Expiratory Flow Rates

Measurements of total lung capacity (TLC) and vital capcity (VC) provide a global assessment of respiratory muscle function because they rely on the integrated function of the respiratory pump (muscles and nerves) with that of the chest wall bellows (airways, lung parenchyma, rib cage, and abdomen) (Table 1). Diseases of the nerves and muscles alter respiratory pump function by limiting the ability to lower intrathoracic pressure and inflate the lung. Accordingly, pulmonary function tests in patients with neuromuscular disease are characterized by a pattern of restriction. TLC and VC are reduced,[25,28,29] whereas FRC[26,30] may be normal or decreased. Residual volume (RV), on the other hand, is increased when expiratory muscle weakness is severe.[25,31] Lung volumes are usually measured using standard methods, but techniques such as three-dimensional reconstruction of the thorax using computed tomography or magnetic resonance imaging can also be used, and

Table 1 Respiratory Muscle Assessment

Chest wall motion
Magnetometers
Respiratory inductive plethysmography
Global respiratory muscle strength
Lung volumes
Upright and supine vital capacity
Maximal static inspiratory and expiratory pressures at the airway opening
Maximal sniff nasal or esophageal pressures
Diaphragm strength
Maximal transdiaphragmatic pressure (Mueller or combined maneuver)
Maximal sniff transdiaphragmatic pressure
Twitch Pdi (magnetic or electric phrenic nerve stimulation)
Diaphragm thickness (ultrasound)

correspond well with plethysmographic measures of lung volumes.[32]

Forced expiratory flow rates are reduced in patients with neuromuscular weakness. The forced expiratory volume in 1 second (FEV_1) is generally reduced in proportion to the reduction in the forced vital capacity (FVC) such that their ratio is preserved. A reduction in this ratio suggests an independent obstructive process. A 12-second maximum voluntary ventilation maneuver (MVV) provides another means of evaluating the integrative function of the inspiratory pump and chest wall bellows. The MVV is usually low in neuromuscular disease, reflecting weakness, poor coordination, or reduced endurance of the respiratory muscles.[30]

The fall in VC between the upright and supine positions has been used to assess diaphragm weakness and is a more sensitive indicator of respiratory muscle weakness than upright measures of VC and TLC. Normally, there is less than a 10% drop in VC when changing from the upright to the supine position. With bilateral diaphragm paralysis, VC may be reduced by more than 30% in the supine position. The utility of this measurement in detecting diaphragm weakness was recently studied in a group of patients with neuromuscular weakness.[33] Individuals with the most pronounced diaphragm dysfunction had the greatest change in supine VC. However, there were individuals without diaphragm weakness who had similar changes in VC (Fig. 2).

The advantage of measuring lung volumes is that they are noninvasive and readily available for the clinician. However, the strength of the respiratory muscles must be severely impaired (reduced by as much as 50%) before any significant reduction in lung volumes is appreciated.[25] Thus VC and TLC are insensitive measures of respiratory muscle weakness and, for this reason, maximum inspiratory and expiratory pressures are often used to assess respiratory muscle strength.

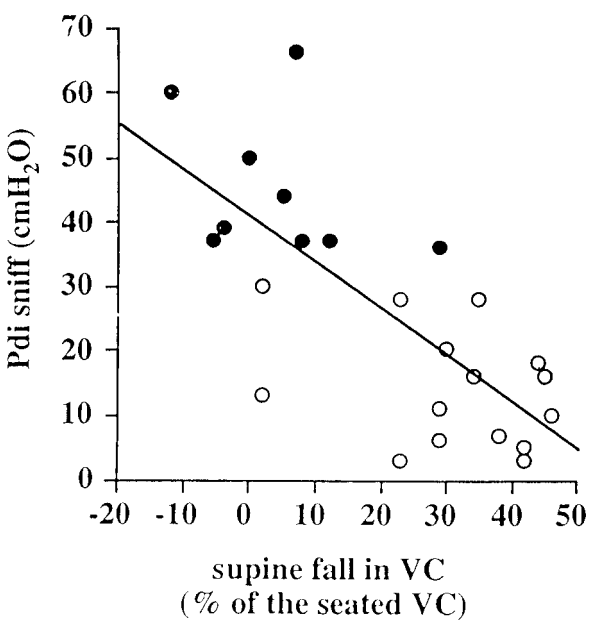

Figure 2 The supine fall in vital capacity (VC) is related to the degree of respiratory muscle weakness as assessed by changes in transdiaphragmatic pressure during a maximal sniff maneuver (Pdi sniff). Most of the individuals with severe diaphragm dysfunction (negative Pga during the maneuver; open symbols) had a greater than 30% reduction in VC in the supine position. (From Fromageot et al.[33])

Maximal Inspiratory and Expiratory Pressures

Measurements of maximal inspiratory and expiratory pressures may be helpful in the evaluation of the patient with neuromuscular disease. Maximal inspiratory pressure (PI max) is measured at the airway opening during a maximal, static inspiratory effort (Muller maneuver) initiated at either FRC or RV. In general, greater inspiratory pressures are obtained when the maneuver is performed at lower lung volumes (Fig. 3). The advantage of measuring PI max during maneuvers initiated from FRC rather than RV is that only the force of the inspiratory muscles is assessed, and not the negative recoil pressure of the respiratory system. In patients with neuromuscular weakness, the recoil pressure of the respiratory system at RV may be a substantial fraction of PI max. The type of mouthpiece used may also affect the value of PI max. Greater pressures are typically obtained when using a phlange- rather than a tube-style mouthpiece.

Maximal expiratory pressures (PE max) are measured at the airway opening during a maximal, static expiratory effort (Valsalva maneuver). In contrast to the inspiratory muscles, the expiratory muscles are stronger at high lung volumes (see Fig. 3). PE max is measured at either FRC or TLC. The advantage of measuring PE max during efforts initiated from TLC is that the expiratory muscles are at their optimal length to generate maximal force. The type of mouthpiece used also affects the value of PE max. Greater pressures are typically obtained when using a tube or mask that covers the mouth rather than a phlange-style mouthpiece. Generalized neuromuscular weakness reduces both PI max and PE max, whereas isolated involvement of the diaphragm, such as with idiopathic diaphragm paralysis or the early stages of amyotrophic lateral sclerosis, may reduce only PI max.

Normal values of PI max and PE max have large ranges,[34,35] depending on gender and to some extent on age. PI max and PE max are lower in females and are relatively constant with age until the seventh decade, when normal values for both decline. The variability in these values in healthy individuals may be related to factors such as lung volume, type of mouthpiece, variable effort, and learning.[36] Values of PI max and PE max are reduced in patients with advanced neuromuscular disease. However, other factors such as submaximal effort or air leaks around the mouthpiece be considered as possible explanations for low values, especially in indi-

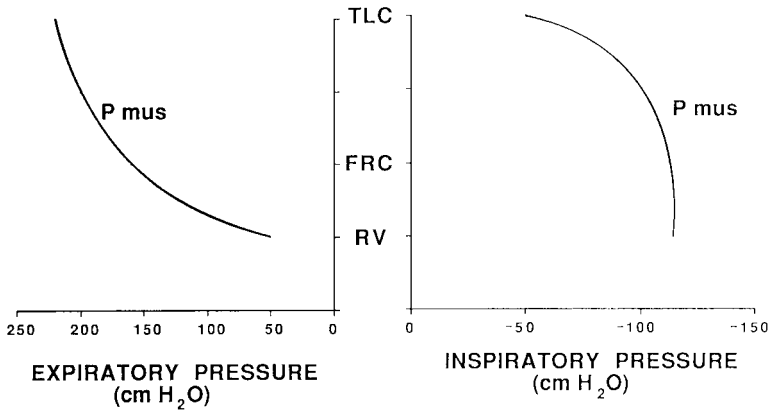

Figure 3 The relationship between lung volume and maximal static expiratory (PE max) and inspiratory (PI max) pressures. The expiratory muscles are strongest at high lung volumes, whereas the inspiratory muscles are strongest at low lung volumes.

viduals with orofacial muscle weakness. For these reasons, simplified maneuvers or measures that require no subject effort have been proposed as alternate means of measuring inspiratory muscle strength.

Maximal Sniff Pressures

To reduce the variability of the maneuvers required to measure PI max, investigators have measured respiratory pressures during maximal sniff maneuvers. The sniff maneuver is easily performed and does not require the use of a mouthpiece. The maximal sniff is initiated from FRC, and either transdiaphragmatic, esophageal, or nasal pressures can be measured during the maneuver. Nasal inspiratory pressures are measured by occluding one nostril with a special nasal plug fitted around a catheter.[37] Because there is considerable air flow through the nares and airways during this maneuver, the pressure applied by the respiratory muscles will be dissipated across these structures. Thus measurements of transdiaphragmatic (Pdi) or esophageal pressures (Pes) should be greater in magnitude than measurements of nasal pressure (Pn). However, Pn is often measured rather than Pdi and Pes, because it is much less invasive. In normals, transdiaphragmatic (Pdi) and nasal pressures developed during a sniff have consistently higher mean values, narrower ranges, and significantly less variability than the maximal pressures developed during a Muller maneuver.[38]

Maximal sniff maneuvers have been used to assess respiratory muscle strength in individuals with neuromuscular disease.[39,40] Populations studied include those with amyotrophic lateral sclerosis, Duchenne muscular dystrophy, Becker muscular dystrophy, and spinal muscular atrophy.[39–41] These studies suggest that the sniff test (1) is a more reliable means of assessing respiratory strength than the Muller maneuver in patients with inspiratory muscle weakness, and (2) maximal sniff pressures, whether measured at the nose, esophagus, or across the diaphragm, are generally greater than those measured during maximal static inspiratory efforts (Fig. 4).[40,42–44] However, measurements of Pn sniff are a test of global respiratory muscle function and do not give specific information regarding diaphragm strength.

SPECIFIC ASSESSMENT OF DIAPHRAGM FUNCTION

Maximal Transdiaphragmatic Pressure

Diaphragm contraction lowers intrathoracic pressure while increasing intra-abdominal pressure. Pressure developed specifically by the diaphragm can be measured as the difference between abdominal pressure, as assessed with a gastric catheter (Pga), and the pleural pressure, as assessed with an esophageal catheter (Pes). Transdiaphragmatic pressure (Pdi) is then calculated as Pdi = Pga − Pes.

The change in transdiaphragmatic pressure during normal quiet inspiration is about 10 cm H_2O (Pes = −5 cm H_2O and Pga = +5 cm H_2O). With inhalation to TLC, Pdi is typically greater than 30 cm H_2O and may increase to values greater than150 cm H_2O during maximal inspiratory efforts (i.e., Muller maneuver).[45] The coefficient of variation for Pdi during maximal Mueller efforts is large, whereas the variability of Pdi during a sniff maneuver is less and the magnitude of Pdi greater.[38] However, the greatest values of Pdi max are not obtained during Muller maneuvers or sniffs but rather during a more complex maneuver where the individual attempts to lower Pes by contracting the diaphragm while raising Pga by contracting the abdominal muscles (combined maneuver). Values of Pdi max during maximal combined maneuvers may be 60% greater than those obtained during maximal sniffs or Muller efforts.[46]

Although measurements of Pdi have the advantage of specifically assessing diaphragm function, disadvantages of measuring Pdi are numerous. First, it requires placement of esophageal and gastric catheters that may be uncomfortable or even hazardous in pa-

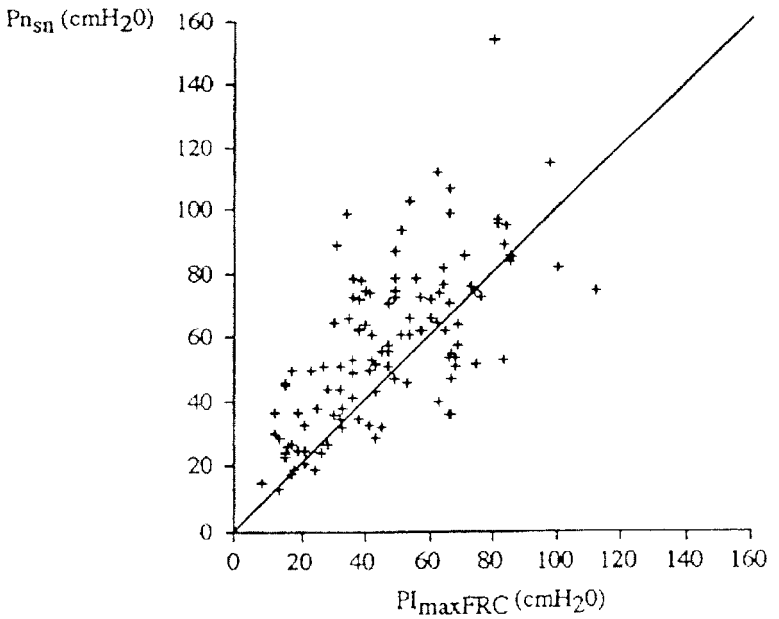

Figure 4 The relationship between maximal pressures during a Muller effort (PI max) and maximal sniff pressures (Pn sn) in individuals with varied forms of neuromuscular weakness. Pressures measured during the sniff maneuver were generally greater than those measured during a Muller maneuver. (From Stefanutti et al.[40])

tients with swallowing impairment. Second, in patients with diaphragm paralysis or profound respiratory muscle weakness, proper placement of the gastric catheter may be difficult because the changes in Pga and Pes may parallel one another. Finally, the maneuver needed to generate Pdi max is complex and difficult to perform.

Phrenic Nerve Stimulation

The phrenic nerve arises from C3–C5 to innervate the diaphragm and is accessible to direct stimulation as it traverses the neck. The nerve can be stimulated transcutaneously either by electric[47]or magnetic[48] impulses. The electric technique selectively stimulates the phrenic nerve and activates the diaphragm. In contrast, the magnetic technique is nonselective, not only stimulating the phrenic nerve but also the cervical nerve roots that, in turn, activate the muscles of the rib cage.

Measuring phrenic nerve conduction time assesses the integrity of the phrenic nerve, whereas measuring Pdi following phrenic nerve stimulation assesses the mechanical output of the diaphragm. Phrenic nerve conduction time is the time from the onset of the stimulus to the onset of the diaphragm action potential. This is usually measured using a surface electromyogram placed on the lower rib cage. A conduction time less than 9 msec is considered normal. Diaphragm mechanical output is measured as the magnitude of twitch Pdi. In normals, Pdi following bilateral electric phrenic nerve stimulation is generally between 25 and 35 cm H_2O.[49–51] Values are lower with unilateral stimulation and greater with magnetic stimulation. The greater values with magnetic stimulation reflect activation of the inspiratory muscles of the rib cage. These muscles may directly increase Pdi by lowering Pes or indirectly by decreasing chest wall compliance.

A major advantage of phrenic nerve stimulation to assess diaphragm function is that it requires no patient effort. This feature makes it especially attractive for patients with neuromuscular disease. Twitch Pdi has been successfully and reproducibly measured in various neuromuscular disorders using either electric or magnetic stimulation. However, a drawback of the techniques is that the magnitude of twitch Pdi depends on the impedance of the abdomen and rib cage. Patients with neuromuscular disorders who are limited in activity may have a large abdominal girth that increases impedance and thereby raises Pdi. Another disadvantage is that the "contraction history" of the diaphragm must be considered. Twitch potentiation is the phenomenon whereby twitch pressures are increased if there has been a preceding maximal contraction of the diaphragm. Individuals with neuromuscular disorders may have a high degree of diaphragm activity at baseline and this may predispose to twitch potentiation. Furthermore, the technology is not readily available to most clinicians.

Imaging the Diaphragm Dome

The chest radiograph is noninvasive and allows for visualization of the diaphragm dome but provides little information regarding diaphragm function. Although elevation of the hemidiaphragms may be appreciated on the radiograph, additional testing is needed to deter-

mine if the diaphragm is paralyzed and to exclude other pathologies that can result in an elevated diaphragm. The utility of the chest radiograph in patients with neuromuscular weakness, then, lies in detecting other pulmonary pathologies as a cause of respiratory symptoms.

Diaphragm fluoroscopy is a more useful means of assessing diaphragm function than chest radiography. Fluoroscopy yields a real-time examination of diaphragm dome motion, best appreciated by using a lateral projection so both hemidiaphragms can be studied simultaneously. A paralyzed hemidiaphragm will move paradoxically cephalad during inspiration.[52] However, the degree of diaphragm dome excursion during quiet breathing may provide insufficient evidence of diaphragm dysfunction. Therefore, the test is usually performed with the individual taking deep breaths to near TLC and exhaling to RV, or during sniff maneuvers to more fully activate the diaphragm and exaggerate its motion.

The disadvantages of fluoroscopy include the exposure of patients to ionizing radiation, and its poor sensitivity and specificity. A false negative result (descent of a paralyzed diaphragm during inspiration) can occur by contracting the abdominal muscles during exhalation and relaxing them at the beginning of inspiration. This breathing strategy may be employed by patients with neuromuscular disease to passively assist inspiration.[7] A false positive result occurs when there is paradoxical cephalad motion of the anterior portion of a normally functioning diaphragm during inspiration. By using ultrasound to evaluate diaphragm dome motion, exposure to ionizing radiation can be averted.[53] However this technique has the same limitations as fluoroscopy in interpreting diaphragm motion.

Imaging the Diaphragm Zone of Apposition

Ultrasound can be used to evaluate the diaphragm in the zone of apposition to the rib cage rather than assessing motion of the dome. With this approach, the contraction of the diaphragm muscle itself can be visualized. The zone of apposition is the area of the chest wall where the abdominal contents abut the lower rib cage. On the right side, the diaphragm is sandwiched between the lower rib cage and the liver. This provides an ideal area for visualizing the pleura, diaphragm muscle, and peritoneum (Fig. 5). Once visualized, diaphragm thickness (tdi) at end-expiration can be measured along with the change in tdi during inspiration. Changes in tdi during inspiration are proportional to diaphragm shortening in adults and infants,[54,55] whereas tdi measured at end-expiration is proportional to diaphragm strength.[56]

The technique is performed by imaging the diaphragm with a 7 to 10 MHz ultrasound transducer placed over the lower rib cage between the seventh and ninth intercostal spaces in the midaxillary line. A linear array transducer allows for more accurate measurement of tdi. High-frequency sound waves emitted from an ultrasound transmitter penetrate body tissues and are reflected back by structures in relation to their acoustic impedance.[57] The information is then displayed as a two-dimensional image (cross-sectional view of the structure) with the brightness of the image representing differences in acoustical impedance, which allows for differentiation between structures. The diaphragm muscle in the zone of apposition is represented as a nonechogenic central structure bordered by two echogenic lines, the peritoneal and diaphragmatic pleurae.[58] This approach has been successfully applied in neonates, children, and adults.[54–56,59]

Advantages of ultrasound are that it is a portable, noninvasive means of evaluating the diaphragm that can be performed without the use of a mouthpiece and requires minimal subject cooperation. These features make it particularly attractive in evaluating diaphragm function in individuals with neuromuscular weakness. Of particular importance in these individuals is the ability of ultrasound to distinguish between a functioning and a nonfunctioning diaphragm. With diaphragm paralysis, tdi is less than 2 mm and the diaphragm does not thicken during inspiration (Fig. 6).[60]

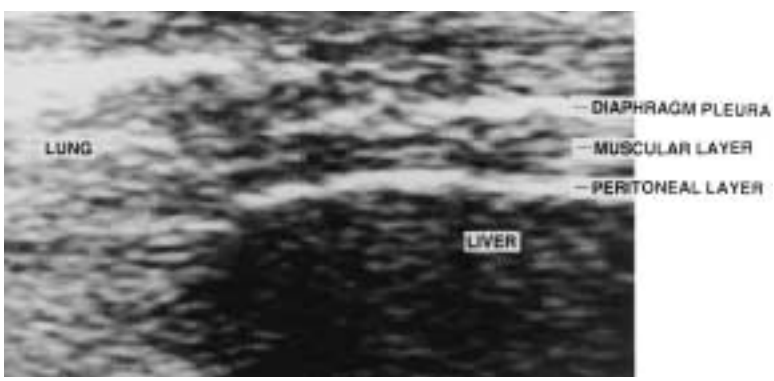

Figure 5 Ultrasound image of the diaphragm in the zone of apposition in a healthy individual. The diaphragm is identified as the structure bounded by the pleura and peritoneum.

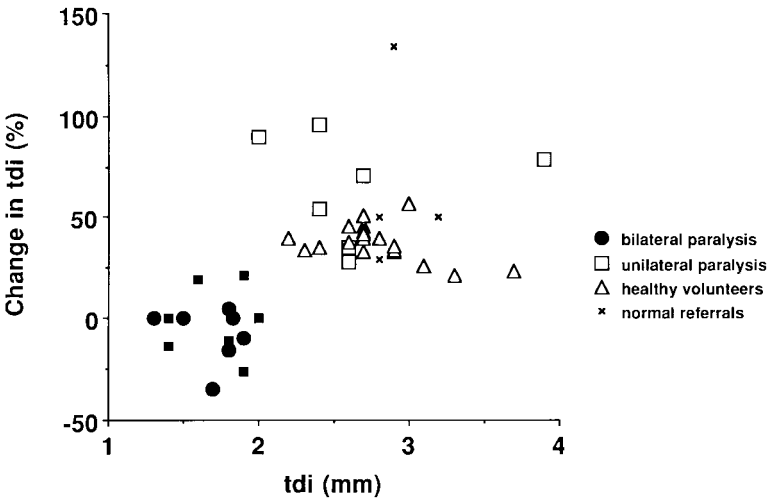

Figure 6 Diaphragm thickness and the change in diaphragm thickness during inspiration is depicted for individuals with bilateral diaphragm paralysis (BDP), unilateral diaphragm paralysis, and healthy individuals. With BDP, the diaphragm is thin (< 2.0 mm) and does not thicken during inspiration (tdi < 5%). (From Gottesman and McCool,[60] with permission.)

SUMMARY AND CONCLUSIONS

The clinician has access to a number of tools to assess diaphragm function in patients with neuromuscular disorders. Attention to the detailed history and physical exam that focuses on inspection and palpation of the respiratory muscles and motion of the chest wall will provide the first clues that respiratory muscle weakness is present. This can be followed by tests of global respiratory muscle assessment such as measurements of TLC, VC, PI max, PE max, and nasal sniff pressures. These tests are often nonspecific but are readily available and provide further documentation that the respiratory muscles are impaired. Specific tests of diaphragm function such as transdiaphragmatic manometry can be utilized but may be limited in that this is invasive and uncomfortable. Finally, newer techniques such as magnetic stimulation of the phrenic nerves and ultrasound of the diaphragm in the zone of apposition may become available as their utility is demonstrated in varied neuromuscular disorders.

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