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# Neuromuscular Ultrasound for Evaluation of the Diaphragm

**Aarti Sarwal, MD [Assistant Professor]**,
Neurology and Critical Care, Wake Forest School of Medicine

**Francis O. Walker, MD [Professor]**, and
Neurology, Wake Forest School of Medicine

**Michael S. Cartwright, MD, MS [Associate Professor]**
Neurology, Wake Forest School of Medicine

## Abstract

Neuromuscular clinicians are often asked to evaluate the diaphragm for diagnostic and prognostic purposes. Traditionally, this evaluation is accomplished through history, physical exam, fluoroscopic sniff test, nerve conduction studies, and electromyography (EMG). Nerve conduction studies and EMG in this setting are challenging, uncomfortable, and can cause serious complications such as pneumothorax. Neuromuscular ultrasound has emerged as a non-invasive technique that can be used in the structural and functional assessment of the diaphragm. This article reviews different techniques for assessing the diaphragm using neuromuscular ultrasound and the application of these techniques to enhance diagnosis and prognosis by neuromuscular clinicians.

### Keywords

diaphragm; ultrasound; electromyography; nerve conduction studies; phrenic nerve injury; respiratory failure

## INTRODUCTION

The diaphragm is the major respiratory muscle used for quiet breathing. Dysfunction can be caused by conditions that directly involve the diaphragm, such as trauma, cardiothoracic surgery, adjacent thoracic or abdominal pathology (e.g. basal pulmonary atelectasis, pneumonia, or tumors), upper abdominal masses, extensive pleural or abdominal fluid, and muscular dystrophies.[1] Diaphragm movement can also be affected by central nervous system diseases, phrenic nerve involvement as it travels in the neck and chest, motor neuron disease, and diseases of the neuromuscular junction.[1, 2] Diaphragm dysfunction caused by hypothermia, traction, or cauterizing or severing of the phrenic nerve[3] are potential factors in the etiology of postoperative pulmonary complications[4–7] and may lead to prolonged mechanical ventilation and failed extubation.

Diaphragm paralysis is under-diagnosed because of its varied and often non-specific presentation. Clinical findings include unexplained dyspnea, especially in the supine position, difficulty weaning from oxygen or mechanical ventilation, diaphragm elevation on chest radiographs, unexplained respiratory distress, asymmetric breathing pattern, paradoxical movement of the epigastrium, recurrent pneumonia, or recurrent unilateral lung

Correspondence to: Aarti Sarwal, MD, Wake Forest University School of Medicine, Reynolds M, Medical Center Blvd, Winston Salem, NC 27157, asarwal@wakehealth.edu.

collapse. Early diagnosis is important, because diaphragmatic paralysis may be amenable to therapeutic strategies and may require adapted and prolonged ventilatory support. Therefore, the need for assessment of diaphragm function arises in many clinical situations.

Different structural and functional techniques are available for evaluating the diaphragm. Each technique has its strengths and weaknesses. Chest radiographs may reveal diaphragm elevation on the side of diaphragm weakness but are relatively insensitive and poor predictors of normal motion.[6, 7] Fluoroscopy[8] assesses excursion of individual domes and shift of the mediastinum via the sniff test of Hitzenburger.[9] Paradoxical motion of the diaphragm is indicative of unilateral paralysis, but apparently normal descent of the hemi-diaphragms may be seen during inspiration in the setting of bilateral paralysis due to compensatory respiratory strategies.[10–12] Fluoroscopy requires patients to breathe spontaneously while they are disconnected from any source of positive pressure ventilation in order to assess diaphragm motion. In addition, it involves significant radiation exposure and the need to transport the patient to the fluoroscopy unit, making it less ideal for critically ill patients.[13] Computed tomography has been used to assess diaphragm structure but dynamic imaging is limited.[14] Dynamic magnetic resonance imaging has evolved with new techniques for quantitative evaluation of excursion, synchronicity and velocity of diaphragm motion,[8, 15] but drawbacks include operator dependence, limited availability, high costs, and the need for patient transport.

Non-imaging diagnostic tests are also available for diaphragm evaluation. Pulmonary function tests can help diagnose diaphragm weakness, but their accuracy and reproducibility are limited by dependence on lung volumes, patient effort, and the wide degree of variability within the normal range.[11, 13] Spirometry itself may alter diaphragm kinetics, making it less ideal.[16] Measurement of trans-diaphragmatic pressure using esophageal or gastric transducers during maximal inspiratory effort or during phrenic nerve stimulation[17] can be used in the diagnosis of bilateral diaphragm paralysis.[13, 18] However, it is invasive, time consuming, and is not useful in diagnosing unilateral weakness. [13] Phrenic nerve conduction studies assess neural continuity and can be coupled with electromyography (EMG). [19] Diaphragm EMG can detect evidence of denervation and differentiate between neuropathic and myopathic causes of paralysis with high sensitivity and specificity, and it can be performed in patients on full ventilator support.[3, 20, 21] However, it is uncomfortable, can be technically challenging to perform and interpret, and carries the risk of pneumothorax. [7]

Neuromuscular ultrasound is an evolving technique that is now being used to image the diaphragm in normal and pathological conditions given recent advances that allow high resolution images. First described by Cohen et al in 1969, [22, 23] it is now being more commonly used, especially in children, for the evaluation of diaphragm structure and function.[6, 8] Ultrasonography is portable, ubiquitous in medical facilities, has no risk of ionizing radiation, and allows visualization of structures below and above the diaphragm. It carries the advantage of assessing both the structural and functional components of the diaphragm at the bedside. Ultrasound has been shown to be similar in accuracy to most other imaging modalities for diaphragm assessment.[1, 3, 5, 10, 14, 24–27] This paper will review the techniques and measurements that have been proposed for ultrasonographic assessment of the diaphragm and their use to enhance diagnosis and prognosis by neuromuscular clinicians.

## ULTRASONOGRAPHIC APPEARANCE OF THE DIAPHRAGM

The diaphragm is composed of 4 components: the transverse septum (which is anterior and becomes the central tendon of the diaphragm), pleuroperitoneal folds, esophageal mesentery, and muscular body wall laterally (Figure 1). With ultrasound, the diaphragm is typically

identified by its deep location, curved geometry, and muscular echotexture. Longitudinally, muscles have a mixed echogenic appearance, consisting of hypoechoic (dark) muscle fibers separated by hyperechoic (bright) fibroadipose septae (perimysium). Transversely, the mixed echogenicity pattern of muscle produces a "starry night" appearance.[28] The diaphragm can be seen as 2 echogenic layers[29] of peritoneum and pleura sandwiching a more hypoechoic line of the muscle itself (Figure 2). [13, 18, 30, 31] It thickens during inspiration, unless it is severely atrophic. An atrophic diaphragm will appear as a very thin strip deep to the intercostal muscles, and it may not move with inspiration. Some authors have described visualizing 5 layers of the diaphragm – 2 outer bright parallel layers of the parietal pleura and peritoneum with an irregular bright layer due to connective tissue and vessels within the echo poor diaphragm muscle layer. [32] Thickness and echogenicity of the diaphragm can be assessed using B mode ultrasound, which is also known as real-time imaging. M mode ultrasound, which displays a single beam of a B-Mode image on the *y* axis as it changes over time on the *x* axis[33], evaluates a specific site over time and can assess excursion (including side-to-side variability), velocity, and response to phrenic nerve stimulation.

Ultrasound focuses mainly on the posterior and lateral parts of the diaphragm, which are the muscular crural components innervated by the phrenic nerve, rather than the anterior central tendon seen in fluoroscopy, which moves 40% less with respiration. [12] The diaphragm is usually higher in children, young adults, and obese individuals, and its position and motion depend on the position of the subject [1, 34]

It is important for the sonographer to be aware of diaphragmatic anomalies and adjacent thoraco-abdominal structures such as diaphragm slips (strips of muscle protruding from the inferior surface of the diaphragm), scalloping, eventration (usually located in the anterior aspect of right hemidiaphragm), inversion due to fluids or mass in the chest, hypertrophic crus, masses affecting the diaphragm, and pleural or peritoneal effusions.[35] These can significantly affect diaphragmatic visualization and excursion studies.

## TECHNIQUES

Patients are typically examined during spontaneous respiration to help identify the moving diaphragm. Diaphragm position and motion depend on the position of the subject during the study. The supine position is preferred, because there is less overall variability, less side-to-side variability, and greater reproducibility.[1, 15] Diaphragm excursion is known to be greater in the supine position for the same volume inspired than in the sitting or standing positions, because the abdominal viscera more easily move the diaphragm in this position and the relationship between inspired volume and diaphragm movement has been shown to correlate better in the supine than the sitting position.[1, 2, 12, 36] The supine position also exaggerates any paradoxical movement and limits any compensatory active expiration by the anterior abdominal wall which may mask paralysis.[12] Patients can be examined in quiet respiration and during deep breathing or sniff maneuver.

The right diaphragm can be visualized through the liver window. Visualization of the left diaphragm is more difficult because of the smaller window of the spleen but can be facilitated by a more coronal approach and by paralleling the ribs. Pathologic conditions such as splenomegaly, hepatomegaly with a large left lobe, or the presence of a left upper quadrant mass may make evaluation of the left diaphragm easier.[1] To allow reproducible images of the diaphragm for quantitative analysis it is important to have complete visualization of both the pleural and peritoneal membranes at all times while imaging the diaphragm for thickness measurements. This extrapolates to an angle of incidence of the ultrasound beam relatively close to 90 degrees to the cross section of the diaphragm and

measures thickness accurately.[37] The approaches and planes that have been used to visualize the diaphragm are described below, followed by detailed descriptions of parameters that can be studied using these approaches. Thickness assessment of the diaphragm at the zone of apposition requires a higher frequency transducer[32, 37] to provide good spatial resolution, while excursion measurements can be done with a lower frequency transducer,[38] especially when the deeper posterior dome of diaphragm is visualized.

### Intercostal View

To obtain an intercostal view, a higher frequency linear array transducer (7 to 18 MHz) is placed at the anterior axillary line, with the transducer positioned to obtain a sagittal image at the intercostal space between the 7$^{th}$ and 8$^{th}$, or 8$^{th}$ and 9$^{th}$ ribs (Figure 2). An image spanning 2 ribs, with the intercostal space between the ribs, is ideal (Figure 2). In this view, the zone of apposition is assessed for measurements such as diaphragm thickness and echogenicity. Excursion of the diaphragm can be measured but is challenging and difficult to reproduce (specific measurement techniques are discussed below). Since this approach limits the visualization of the diaphragm to the zone of apposition, the image can be obscured with deep inspiration when the lung displaces downwards.

### Anterior Subcostal View

The anterior subcostal view is the preferred method for evaluating diaphragm excursion. It requires a lower frequency, ideally curvilinear, transducer (2 to 6 MHz) placed between the mid-clavicular and anterior axillary lines, in the anterior subcostal region (Figure 3). The transducer is directed medially, cranially, and dorsally, so that the ultrasound beam reaches the posterior third of the right diaphragm approximately 5 cm lateral to the inferior vena cava foramen. B mode is used to visualize the diaphragm moving towards or away from the transducer. Imaging is then changed to M mode with the line of sight positioned in order to obtain maximum excursion (Figure 3). [8, 6, 16, 39] Amplitude of excursion can be measured on M mode, and diaphragm velocity can be calculated (Figure 3). Either dome of the diaphragm can be evaluated using the liver and spleen window.

### Posterior Subcostal View

The posterior subcostal view is performed similar to the anterior subcostal view, with a low frequency curvilinear transducer placed in the posterior subcostal region, and the individual domes can be assessed in sagittal planes on either side (Figure 4).[7] Images obtained are similar to those of the anterior subcostal view, and diaphragm excursion can be measured. This view requires patients to be seated, which may not be practical in critically ill or mechanically ventilated patients and is not a commonly used technique.

### Subxiphoid View

The subxiphoid view provides another option for measuring excursion, and it is particularly useful in children. A low frequency curvilinear transducer (2 to 6 MHz) is placed below the xiphoid in a transverse orientation, angled upwards towards the posterior leaflets of the diaphragm (Figure 5).[40, 41] Using the B mode, portions of both domes can be seen together on an oblique transverse view obtained at the midline, and a qualitative comparison of their excursion can be done in real time (Figure 5). [8] For quantitative side-to-side variability, excursion amplitude can be measured on each side using M mode directed sequentially at either dome. Since the line of sight needs to be directed towards only one dome at a time when using the M mode, simultaneous measurements cannot be made, although both domes can be visualized at the same time.

## MEASUREMENTS

Several different diaphragm measurements have been described with neuromuscular ultrasound, and some of these measurements are obtained from still images on B mode and others from tracings acquired with M mode. These measurements are likely to prove important in the quantitative assessment of the diaphragm eventually, but so far most of these have only been studied in a few individuals and infrequently in patients with neuromuscular or pulmonary disorders. The validity and reliability of ultrasound techniques to study the diaphragm for systematic quantitative assessment has not been studied either. With these limitations in mind, measurements reported in the literature are described in detail below.

### Diaphragm Thickness

Two-dimensional B-mode ultrasound can be used to measure diaphragm thickness at the zone of apposition (Figure 2) during inspiration or expiration using the intercostal approach. Thickness measured by ultrasound has been shown to correlate with direct diaphragm thickness measurements on a cadaver.[37] The average thickness of the diaphragm is 0.22–0.28 cm in healthy volunteers[37] and 0.13–0.19 cm in a paralyzed diaphragm. A diaphragm thickness less than 0.2 cm, measured at the end of expiration, has been proposed as the cut-off to define diaphragm atrophy.[11, 18] It is important to define the intercostal space where the thickness of the diaphragm is measured as it varies, with the more inferior portions of the diaphragm being thicker than more superior portions.

### Change in Thickness

Muscle fibers shorten with contraction and cause muscle thickening. Increase in diaphragmatic thickness during inspiration has been used as an indirect measurement of muscle fiber contraction. [18, 37] A chronically paralyzed diaphragm is thin, atrophic, and does not thicken during inspiration. [18] The measurement of thickness alone may miss an acutely paralyzed diaphragm with normal thickness and could incorrectly identify atrophy in a low weight individual with a healthy, yet thin, diaphgram.[13] Therefore, the degree of diaphragm thickening has been proposed to be more sensitive than measurement of thickness alone.[13] Several measurements of diaphragm thickening have been proposed, with the general formula being: *(thickness at end-inspiration – thickness at end-expiration)/thickness at end-expiration.* A change in diaphragm thickness of 28–96% has been reported in healthy volunteers, with a change of −35 % to 5% in those with a paralyzed diaphragm.[18] A lack of change in thickness has been correlated with invasive measurements of transdiaphragmatic pressure and has proven to be sensitive and specific in the diagnosis of diaphragm paralysis. [18] Diaphragm thickening of less than 20% is proposed to be consistent with paralysis.[13]

### Diaphragm Excursion

The M mode records the successive positions of a structure on a time scale and thereby allows the quantification of motion. Early studies measured craniocaudal excursion of the diaphragm relative to the renal pelvis or the portal vein.[41] More recently, studies have shown feasibility of directly measuring the amplitude of excursion of the diaphragm on the vertical axis of the M Mode ultrasound tracing from the baseline to the point of maximum inspiration (Figure 3). Using M mode, the diaphragm is seen as a single thick echogenic line, and its movements with respiration can be plotted against a time curve (Figure 3D). [1, 42] The direction of movement of the diaphragm towards or away from the transducer on ultrasound tracing can be correlated to the phases of the respiratory cycle in order to determine the direction of motion of each hemi-diaphragm.[6] Paradoxical motion is considered when the diaphragm moves away from the transducer during inspiration (Figure

6). Measurement of the amplitude of excursion can be used to compare movement of the two hemi-diaphragms and for follow-up of diaphragmatic function (Figure 3D). [6, 19] The normal range of motion from the resting expiratory position to full inspiration in adults has been reported in the range of 1.9 to 9 cm, with higher values reported in deep breathing or sniff.[2, 26, 38, 43–46] Diaphragmatic paralysis is indicated by the absence of excursion with quiet and deep breathing and with absence of movement or paradoxical motion upon sniffing (Figure 6) [3, 39] . Diaphragm weakness is indicated by less than normal amplitude of excursion on deep breathing with or without paradoxical motion on sniffing. [39], [41]

In a study comparing pre-operative and post- operative excursion in adult patients, diaphragmatic inspiratory amplitude of less than 2.41 cm was shown to correlate with a 50% decrease of vital capacity from the baseline.[4] Excursion greater than 2.5 cm in adults has been proposed as a cut off for excluding severe diaphragm dysfunction.[17] Most values obtained with ultrasonography are consistent with studies done using fluoroscopy[9] and MRI. [15] Note should be made that for all the maneuvers studied, diaphragm excursion has been shown to be greater in men than in women.[1, 2, 26, 43] Corrections for age, weight, and height have been published but are not uniform across different laboratories.[1, 2, 26, 43] Though excursion measurement can be difficult because it is critical to keep the transducer in the same position during all phases of respiration, this represents one of the most clinically useful markers of diaphragm function.

### Side-to-side Variation

Excursion of the diaphragm with maximum inspiration in healthy, standing patients is usually asymmetrical, with greater excursion on the left side.[9, 12, 15, 26, 36] A normal range of side-to-side variability as defined by the right-to-left ratio of maximal excursion has been shown to be 0.5 to 2.5 in quiet and 0.5 to 1.6 during deep breathing,[2, 12] which indicates that the normal difference in excursion between the hemi-diaphragms should be less than 50%. [39] The range of motion of the diaphragm is also shown to be greater posteriorly than anteriorly and greater laterally than medially.[1]

### Diaphragmatic Velocity

Respiratory muscle strength can also be assessed by the sniff test, where the velocity of muscle contraction correlates with muscle strength. The maximal sniff involves a short, sharp inspiratory effort through the nose and is a reproducible and quantitative assessment of diaphragm strength. The velocity of diaphragm movement during the sniff maneuver has been shown to increase almost 7-fold from 1.52 cm/s during quiet breathing to 10.4 cm/s during sniff. [38, 46] Calculation of diaphragm velocity is captured with M mode and is demonstrated in Figure 3.

## CLINICAL APPLICATIONS

Neuromuscular ultrasound of the diaphragm is an evolving diagnostic modality with several techniques and measurements that can be employed for structural and functional assessment of the diaphragm. This section discuss the clinical scenarios in which neuromuscular ultrasound can be helpful.

### Identification of Diaphragm Paralysis

Direct visualization of the diaphragm can provide a portable, non invasive bedside method for detection of unilateral or bilateral paralysis in patients with the clinical suspicion of diaphragm dysfunction.[10, 38] For example, this approach is particularly useful in children with respiratory failure following cardiothoracic surgery, where prompt recognition of abnormal diaphragm motion can direct patient care in the immediate postoperative period

(Figure 6). Procedures such as plication can facilitate weaning from mechanical ventilation, thus minimizing the risk for potential ventilator-associated pneumonia and decreasing intensive care unit and hospital length of stay.[3, 11]

## Identification of the Etiology of Diaphragm Paralysis

Direct visualization of the diaphragm can identify intrinsic or extrinsic pathology such as diaphragm eventration, hernias, pleural fluid, subphrenic abscess, hepatic abscess, metastatic disease, thoracic masses or rupture causing diaphragm paralysis.[1, 35]. Ultrasound to diagnose traumatic diaphragm rupture has been proposed as an extension of the "Focused Abdominal Sonography for Trauma" (FAST) examination.[47] When a neurological cause of diaphragm weakness is suspected, such as motor neuron disease, phrenic nerve stimulation can be used to distinguish central nervous system pathology from lower motor neuron disease (phrenic neuropathy). In central pathology, phrenic nerve stimulation will result in normal diaphragm motion detected by ultrasound, whereas in the latter, no movement will be seen despite nerve stimulation. By distinguishing between central and lower motor neuron etiologies, decisions regarding therapeutic options such as diaphragm pacing can be made.[48] Finally, resting diaphragm muscle thickness has been shown to be increased in patients with Duchenne muscular dystrophy below the age of 12. This is thought to be analogous to the pseudohypertrophy seen in other limb muscle groups and can be used to predict respiratory failure.[31]

## Prognosis after Diaphragm Paralysis

In patients with serial ultrasound measurements after diaphragm paralysis, an increase in thickness of the diaphragm during inspiration, which probably correlates with re-innervation, has been associated with improvement in inspiratory function and increases in vital capacity over time.[13]

## Selecting patients for Surgical Plication

Phrenic nerve injury during cardiothoracic surgery is usually a neurotmesis-type injury from partial or complete transection of the phrenic nerve during harvesting of the left side internal mammary artery. Alternatively, thermal injury may occur during cardiac hypothermia, precipitating axonotmesis because it is more likely that the nerve sheath will remain intact[49]. Authors in the cardiothoracic surgery literature have proposed use of ultrasound of the diaphragm to help chose the optimum candidates for early plication[50]. In general, plication is reserved for patients who have paradoxical motion, where mediastinal shifts cause dyspnea[51, 52]. Respiratory symptoms in the presence of an immobile diaphragm are not observed to be amenable to surgical fixation of the diaphragm[50]. Figure 6 illustrates an immobile diaphragm and a diaphragm with paradoxical motion on sniffing. This has led to a hypothesis that post-operative diaphragm weakness with paradoxical motion probably indicates a more severe phrenic nerve injury and more complete denervation. It would be expected that more severe injury would cause delayed recovery with prolongation of ventilatory support and hospitalization, and such patients should be plicated early. Immobility of the diaphragm is thought to represent incomplete denervation with some residual tone left in the innervated part of the diaphragm . This has been clinically proposed to reflect incomplete phrenic nerve injury in acute post-operative diaphragm palsy. The observation that patients with unilateral diaphragm palsy who have chronic dyspnea respond better to plication than patients with acute dyspnea from acute weakness of the diaphragm may be concurrent with this hypothesis[53, 54]. Future studies that correlate ultrasound features of paradoxical motion versus immobility with pulmonary function testing and success at plication are needed for corroboration.

### Adjusting Diaphragmatic Pacemakers

Patients with persistent diaphragm paralysis may benefit from implanted diaphragmatic pacemakers. Pacemakers allow patients to become independent from mechanically assisted ventilation. The output of the pacemaker needs to be regulated, depending on the degree of diaphragm response. The optimal response varies with patient characteristics such as age and body habitus. Ultrasonography is an excellent tool for providing a quantitative evaluation of diaphragm excursion[1] while the pacemaker output is adjusted in real time.[38]

### Assessment of Weaning Failure

A prevalent clinical problem in critically ill adult patients is failure to wean from mechanical ventilation. Mechanical ventilation is associated with decreased muscle weight and alterations in contractile properties of the diaphragm within 48 hours of intubation.[55, 56] This has led to suspicion that diaphragm dysfunction may contribute to weaning failure, even in patients with no obvious reason to suspect phrenic nerve or diaphragm pathology. Recently, decreased diaphragm excursion on M-mode ultrasound has been shown to predict weaning failure equal to the rapid shallow breathing index (a volumetric index of respiration) during spontaneous breathing trials.[19] The cutoff of diaphragm excursion for predicting weaning failure is 1.4 cm for the right hemi-diaphragm and 1.2 cm for the left hemi-diaphragm, and less excursion is consistent with a greater chance of weaning failure.[19]

### Understanding Respiratory Dysfunction after Acute Stroke

Dynamic studies of diaphragm motion may help understand pathogenesis of respiratory failure after central nervous system disease. Hemiplegic patients immediately after stroke have been found to have unilateral or bilateral reduced diaphragm motion during deep breathing that has not been seen on quiet breathing.[44, 57] This finding may contribute to prolonged mechanical ventilation after stroke[57] and can be used for triage decisions on weaning from mechanical ventilation in these difficult patients.

### Peri-operative Marker of Pulmonary Function

Postoperative changes in pulmonary function are an important cause of decreased functional status after thoraco-abdominal surgeries and correlate with pulmonary complications like pneumonia and atelectasis. Spirometry itself may not be practical in such patients. M mode ultrasonography of diaphragm motion has been proposed as a clinical tool to predict peri-operative changes in pulmonary function[4] and to assess strategies to improve it. Diaphragm position and function have been shown to be significantly altered in patients with chronic heart failure[58] and after cholecystectomy. [5] Improvement in diaphragm function has been shown in patients with ischemic heart disease after inspiratory muscle training.[59] Coached diaphragmatic breathing has been suggested to enhance diaphragm excursion, and it may provide more effective prophylactic treatment against the pulmonary complications of surgery.[60]

### Guidance for Needle EMG

Electromyographic examination of the diaphragm can be challenging due to the risk of injury to the lung, liver, spleen, and colon. Ultrasound provides excellent direct and real-time visualization of soft tissue, anatomic landmarks, fascial planes, and neurovascular structures. It thereby enhances safety by avoiding accidental needle puncture of vital organs, and it also increases the diagnostic utility of the needle examination [28] Confirmation of needle placement within the diaphragm by direct visualization is particularly helpful in patients with a paralyzed or severely atrophic diaphragm, where the normal sound of motor unit potential firing cannot be relied on to confirm appropriate placement. In high-risk patients such as those on anticoagulants or with bleeding disorders, hematoma formation can

be visualized immediately, allowing the examiner to terminate the examination or to intervene promptly if clinically indicated. When using ultrasound for EMG needle placement into the diaphragm, 2 methods can be used. First, ultrasound can be used to measure the depth of the diaphragm and to look for any anomalies. The transducer is then removed, and the EMG needle inserted. The second technique that can be used is to keep the transducer in place, and use it to directly guide needle placement in real time. With this technique, the transducer is placed at the anterior axillary line and rotated so that it is parallel to the intercostal space, typically between the 8$^{th}$ and 9$^{th}$ ribs. The needle is then inserted medial or lateral to the transducer and advanced in-plane with the transducer. This allows visualization of the entire needle, and it can be seen entering the diaphragm (Figure 7). [28]

## LIMITATIONS

Overall, ultrasound is a clinically valuable diagnostic modality, because it is radiation-free, portable, and relatively inexpensive, but it does have some potential limitations. Ultrasound imaging has been traditionally criticized for being operator dependent. Recent studies have addressed the intra and inter-observer reliability specifically in diaphragm assessment, and high correlation coefficients between and within observers have been demonstrated by several studies.[2, 3, 12, 19, 27, 36–38, 61] Non-visualization of a hemi-diaphragm has been reported in the past, with an incidence of failure to visualize between 28–63%, but more recently it has been described as low as 0.71% using a subcostal approach and correct positioning.[1, 2, 6, 46] Downward excursion of the lung and the smaller window of the spleen on the left are 2 potential impediments to successful visualization. A pitfall found on ultrasonography in patients with large pleural effusions is the presence of paradoxical diaphragmatic motion when the patients are examined in the standing position, which typically suggests paralysis. This finding has been reported to revert to normal motion in the supine position, hence favoring ultrasound evaluations in the supine position.[62] Paradoxical movements of an unparalyzed diaphragm have also been reported to occur in hydrothorax, negative pressure pneumothorax, lung fibrosis, atelectasis, and subphrenic abscess. [9]

The measurement of excursion depends on maximal voluntary inspiratory effort. This limits the interpretation and generalization of cut-off values of excursion amplitudes in heterogeneous populations. [27], [17] It has also been argued that density of the muscle may change during contraction, changing the speed of sound through the muscle and producing an error in the measured thickness at peak inspiration.[37] This effect has been shown to be negligible.[63, 64]

Another limitation to the widespread use of ultrasound for diaphragm assessment is a lack of reference values for diaphragm parameters in patients with pulmonary or neuromuscular disease, because they have different ranges of lung volumes for quiet breathing, deep breathing or sniff maneuvers (Figure 6). Only limited studies have evaluated diaphragmatic parameters using ultrasound in patients with lung disease[65] . The relationship between inspired lung volume and diaphragm excursion has been found to be linear in healthy controls by many authors[12, 36, 37, 44] but other studies specifically in patients with lung disease have reported poor correlation[7, 66], [46] This discordance across different studies may be explained by several factors that can alter the contribution of the diaphragm during inspiration relative to other inspiratory muscles.[10]. Depending on body position, weight, height, underlying lung disease or physical condition of the subject, the upper rib cage and neck muscles have been shown to make a greater contribution to inspired volume in certain subjects.[37] Ultrasound parameters of thickness and excursion can also vary depending on the initial point of measurement being end expiration[13, 26, 37] or beginning of inspiration.[43]

Hence, when normative data is collected, simultaneous spirometric measurements should be performed. [2, 4]

## FUTURE DIRECTIONS

Imaging protocols should be developed and validated to standardize the ultrasonographic assessment of the diaphragm, and these protocols should include information for both intercostal and subcostal views.[43] Further studies establishing reference values are needed for diaphragm thickness, excursion amplitude, and velocity that take into account the phase of the respiratory cycle. Ventilator weaning protocols that involve diaphragmatic parameters to predict success at extubation can be developed and tested. Finally, ultrasound of the diaphragm in a wide variety of neuromuscular diseases, including motor neuron disease, muscular dystrophy, and polyneuropathy, may help predict and elaborate the natural history of respiratory failure in these conditions.

## CONCLUSION

In summary, ultrasonography is a promising technique for the evaluation of the structure and dynamic function of the diaphragm. It is accurate, reproducible, and relatively easy to learn. The modality is portable, which is very important for critically ill patients on mechanical ventilation, and uses no ionizing radiation. Many clinical groups[6, 8] have reported ultrasonography as the modality of choice for evaluation of diaphragm paralysis, especially in neonatal, pediatric, and critically ill patients.

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## Abbreviations

| | |
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| **EMG** | electromyography |
| **MHz** | Mega Hertz |

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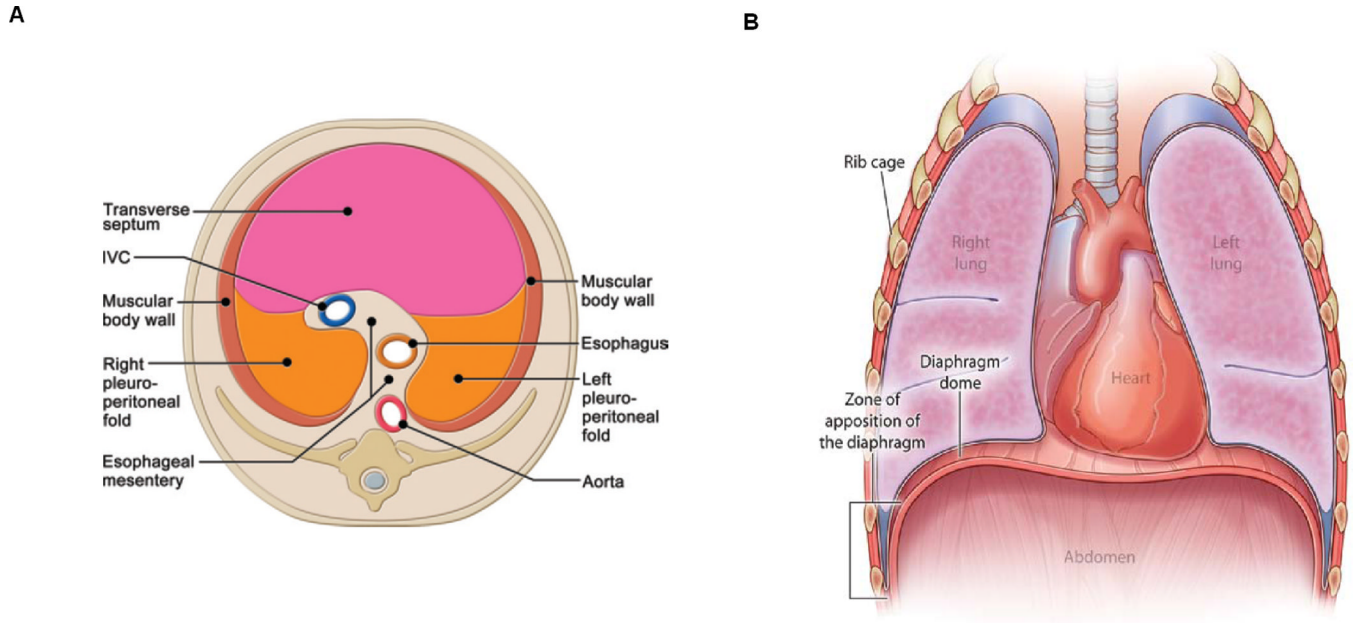


**Figure 1.**

Image A is a schematic of the diaphragm with a view from below, and it shows that the diaphragm develops by fusion of 4 structures: the paired pleuroperitoneal folds, esophageal mesentery, transverse septum, and muscular body wall. The transverse septum, which is anterior, becomes the central tendon of the diaphragm. In image B the cylindrical region of the diaphragm that touches the lower rib cage is referred to as the zone of apposition. IVC = inferior vena cava. Reprinted with permission.[11, 41]

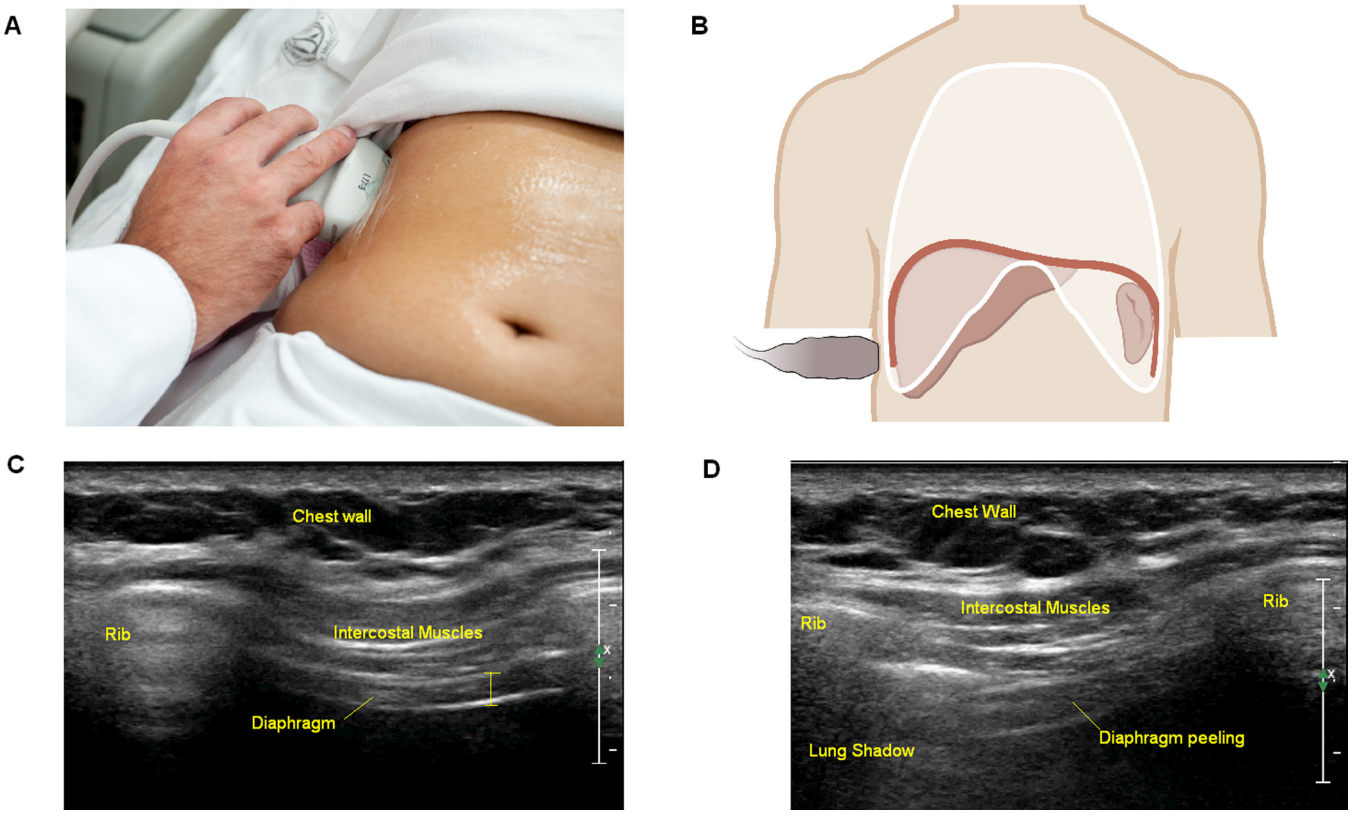


**Figure 2.**

Image A demonstrates transducer placement for an intercostal view, with the transducer positioned on the 9$^{th}$ intercostal space in the anterior axillary line. Image B demonstrates diaphragm visualization at the zone of apposition using this approach. Image C shows the corresponding B mode ultrasonography image, with the left side of the image being cranial. In image D the patient is inspiring and the diaphragm is seen “peeling away” from the chest wall. The downward displacement of the lung can also be appreciated.

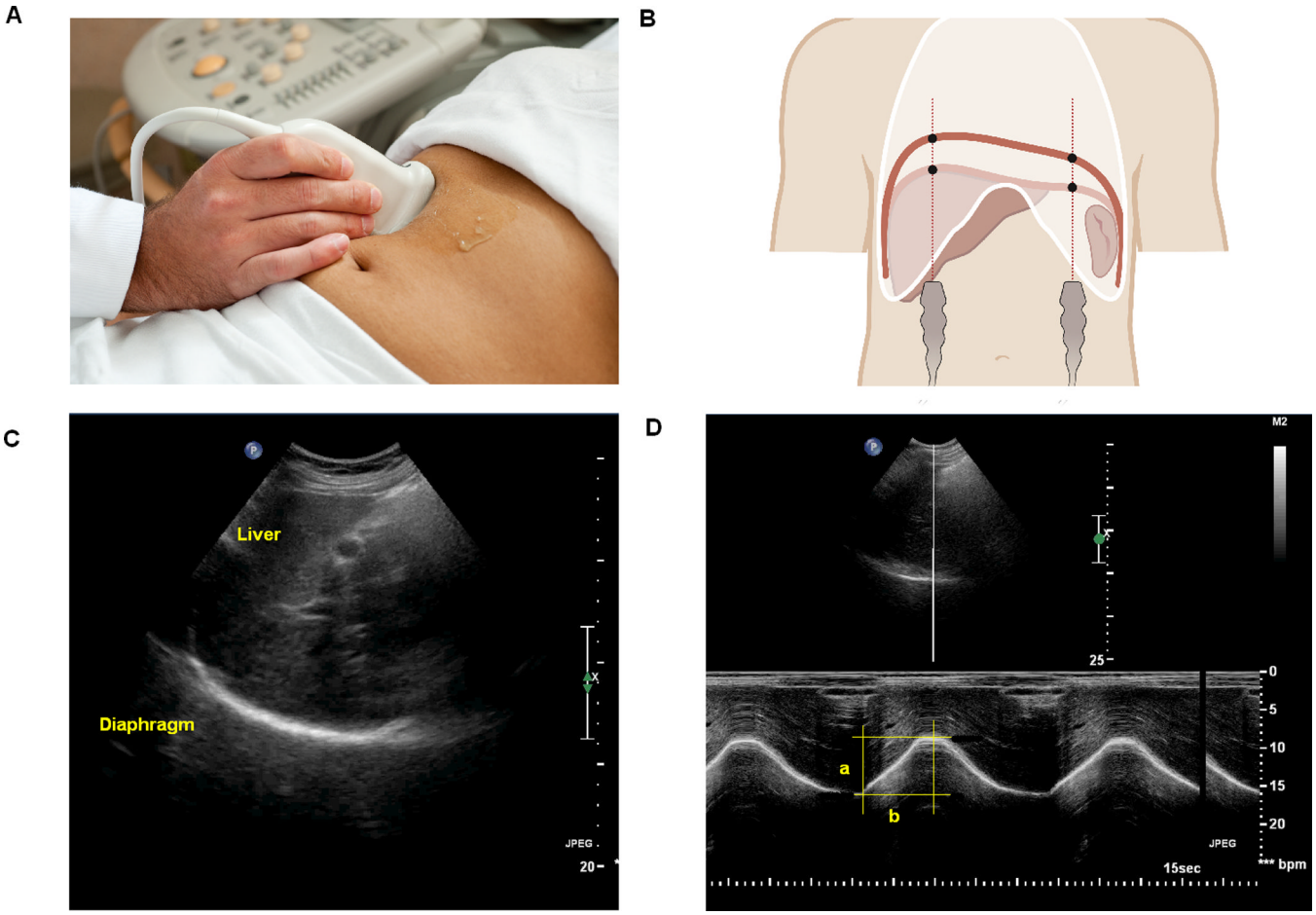


**Figure 3.**

Image A demonstrates a curvilinear transducer placement for the anterior subcostal view, with the transducer positioned below the costal margin in the mid-clavicular line. Image B shows the ultrasound beam and the path it travels to image the diaphragm. Image C is a B mode view of the diaphragm with the anterior subcostal approach. Image D is an M mode view of diaphragm motion with an anterior subcostal view. “a” represents the amplitude of excursion during deep breathing and “b” represents the time frame used for diaphragm contraction, which is used to calculate velocity of movement. Velocity = “a” cm / “b” seconds

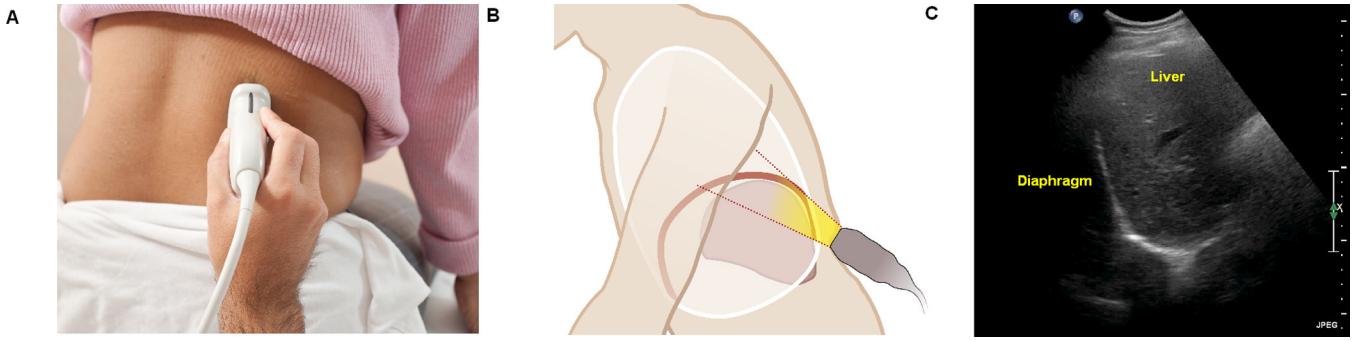


**Figure 4.**
Image A shows the posterior subcostal view with the curvilinear transducer placed posteriorly at the mid-scapular line. Image B shows the ultrasound beam and the path it travels to image the diaphragm. Image C is a B-mode image of the diaphragm obtained with this view.

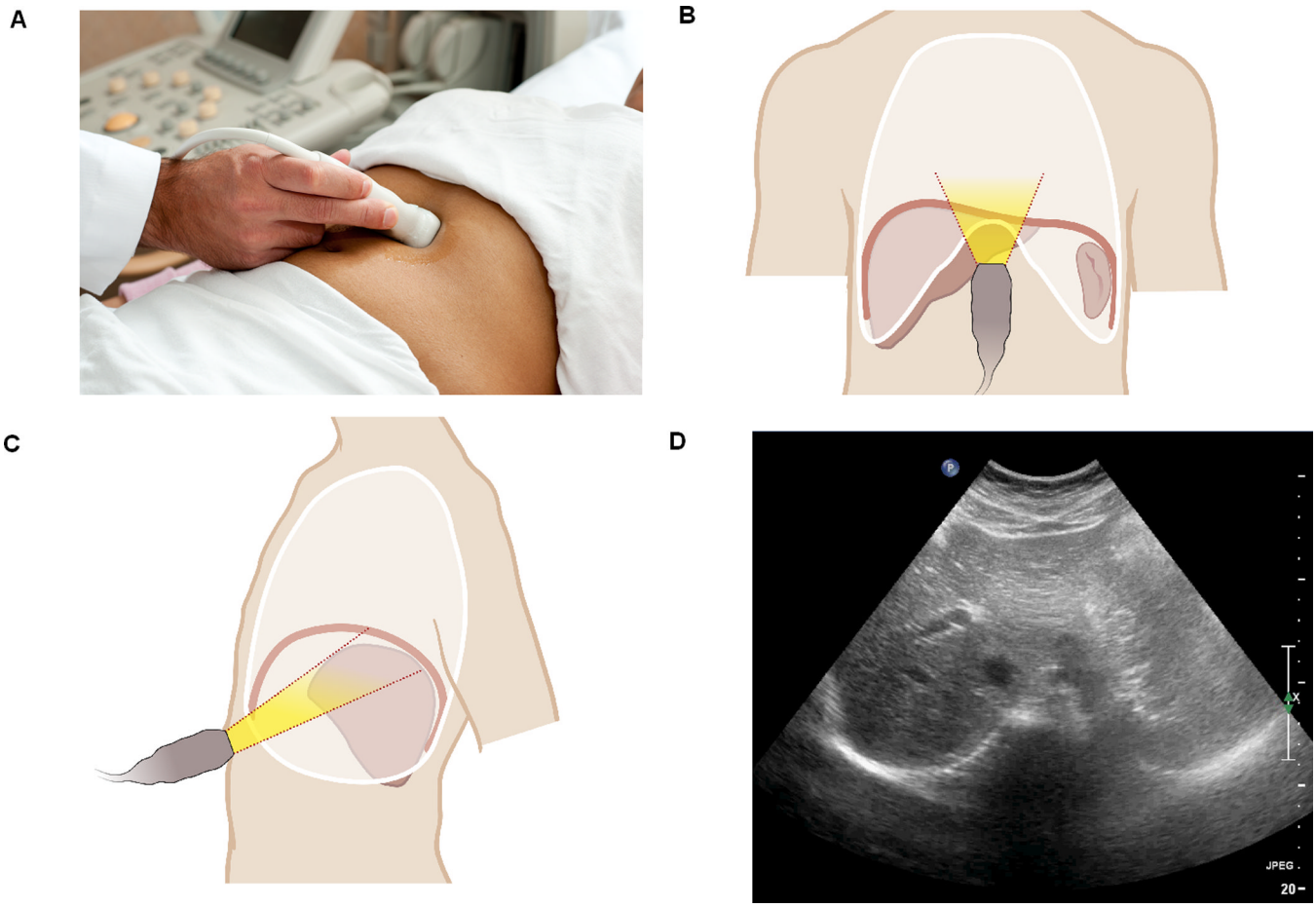


**Figure 5.**
Image A demonstrates the transducer position for the subxiphoid view, with the transducer placed below the xiphoid in the midline and aiming cranially. Images B and C are schematics that show the path of the ultrasound beam in this approach. Image D shows both hemi-diaphragms viewed simultaneously using the subxiphoid view.

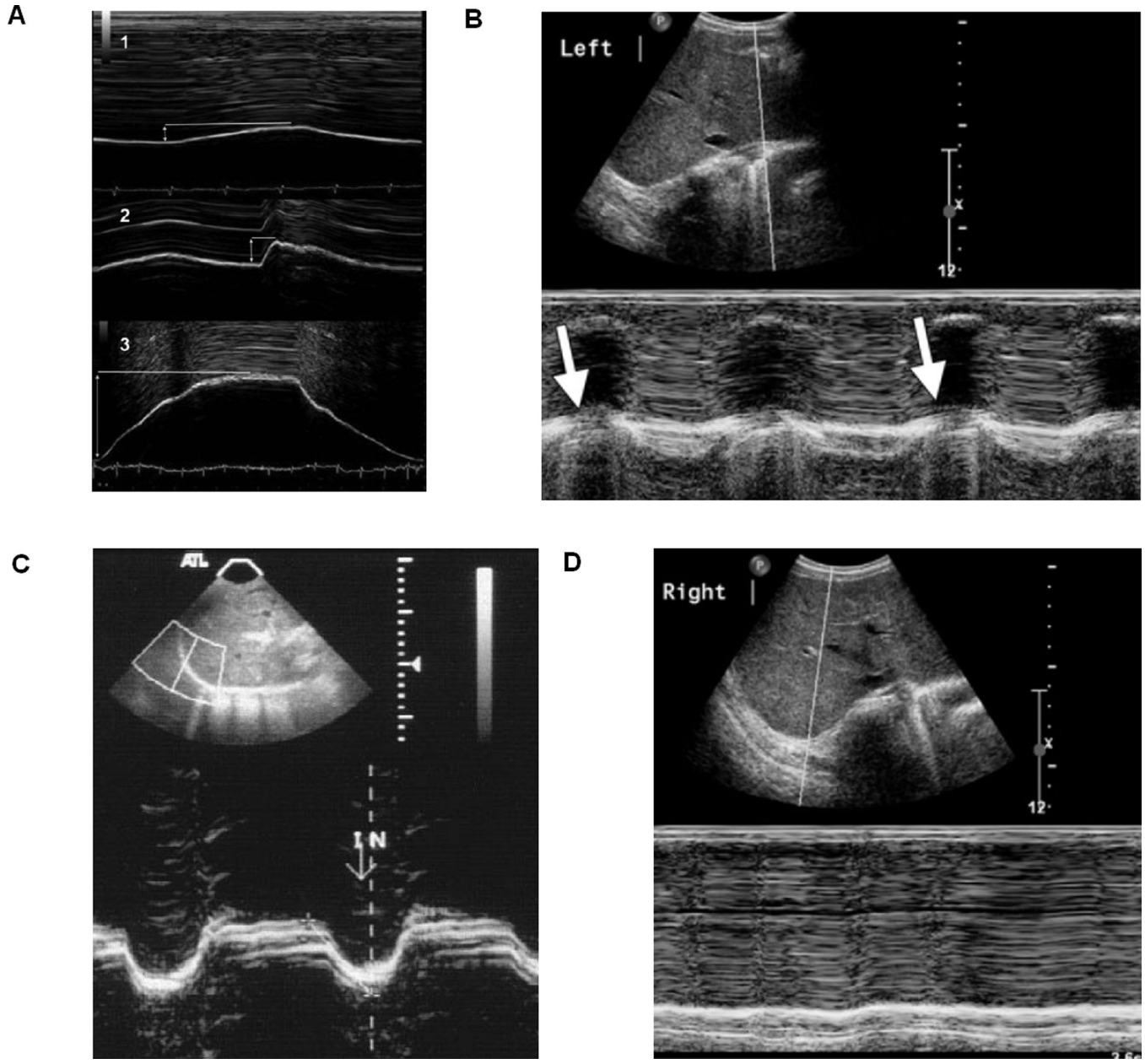


**Figure 6.**

This figure demonstrates normal and abnormal diaphragm movement. In image A, the top M-mode tracing shows normal quiet breathing (1), the middle tracing normal sniffing(2), and the bottom tracing normal deep breathing(3). Image B shows normal diaphragm movement in the anterior subcostal approach, with a typical M-mode tracing showing the diaphragm moving closer to the transducer with inspiration. Image C shows paradoxical movement, with the diaphragm moving slightly away from the transducer during inspiration. Image D shows a lack of movement of the diaphragm during deep breathing. Reprinted with permission.[1, 2, 41]

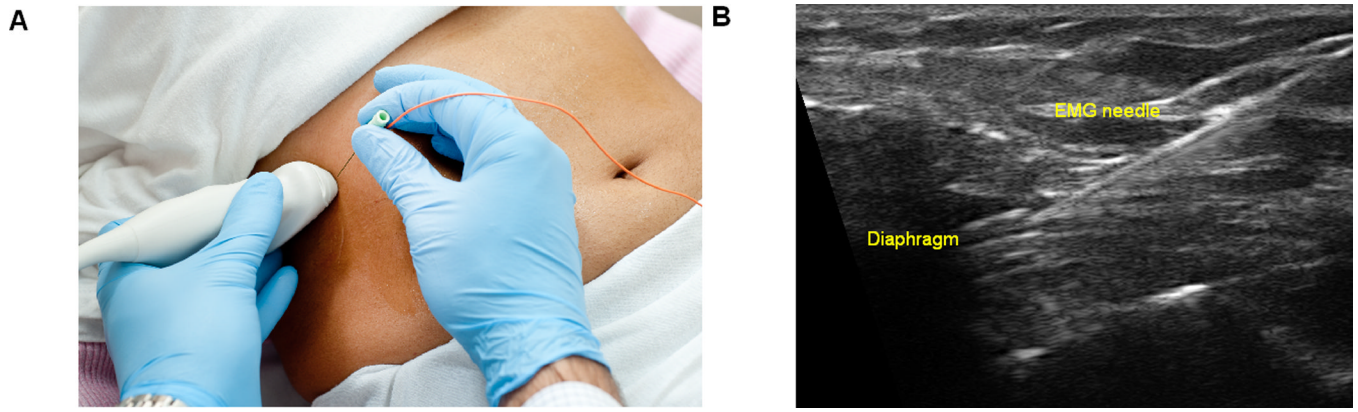


**Figure 7.**
Image A shows the transducer placement used to guide the needle into the diaphragm during real-time placement of an EMG electrode. Image B shows the needle entering into the diaphragm at the zone of apposition. The needle can also be brought in from a lateral to medial approach, using an "in-line" approach beneath and parallel to the long axis of the transducer