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Variability in Diaphragm Motion During Normal Breathing, Assessed With B-Mode Ultrasound

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Abstract

STUDY DESIGN—Clinical measurement, cross-sectional.

OBJECTIVES—To establish a set of normal values for diaphragm thickening with tidal breathing in healthy subjects.

BACKGROUND—Normal values for diaphragm contractility, as imaged sonographically, have not been described, despite the known role of the diaphragm in contributing to spinal stability. If the normal range of diaphragm contractility can be defined in a reliable manner, ultrasound has the potential to be used clinically and in research as a biofeedback tool to enhance diaphragm activation/contractility.

METHODS—B-mode ultrasound was performed on 150 healthy subjects to visualize and measure hemi-diaphragm thickness on each side at resting inspiration and expiration. Primary outcome measures were hemi-diaphragm thickness and thickening ratio, stratified for age, gender, and body mass index. Interrater and intrarater reliability were also measured.

RESULTS—Normal thickness of the diaphragm at rest ranged from 0.12 to 1.18 cm, with slightly greater thickness in men but no effect of age. Average ± SD change in thickness from resting expiration to resting inspiration was 20.0% ± 15.5% on the right and 23.5% ± 24.4% on the left; however, almost one third of healthy subjects had no to minimal diaphragm thickening with tidal breathing.

CONCLUSION—There is wide variability in the degree of diaphragm contractility during quiet breathing. B-mode ultrasound appears to be a reliable means of determining the contractility of the diaphragm, an important muscle in spinal stability. Further studies are needed to validate this imaging modality as a clinical tool in the neuromuscular re-education of the diaphragm to improve spinal stability in both healthy subjects and in patients with low back pain.

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Keywords

B-mode ultrasound; diaphragm; low back pain

The diaphragm is well known for its role as the principal muscle of respiration. The dome-shaped musculotendinous structure contracts during inspiration, flattening the pleural cavity and expanding the lungs. When diaphragm function is impaired, accessory muscles must assume this role but are much less efficient, resulting in shortness of breath with exertion in patients with diaphragm dysfunction. In the case of bilateral dysfunction, as in phrenic neuropathy or spinal cord injury at the level of C3 or above, patients have severe dyspnea and often require artificial ventilation to breathe, particularly when supine.

In addition to the diaphragm's well-known role in respiration, this muscle also contributes to the mechanical stabilization of the spine, functioning as the superior stabilizing structure of the "abdominal canister."[12,13,16] Contraction of the diaphragm increases intra-abdominal pressure, working synergistically with the pelvic floor and abdominal muscles to increase spinal stiffness and stability.[14,17] Hodges et al[15] showed that even isolated contraction of the diaphragm (via phrenic nerve stimulation) without concurrent contraction of abdominal or back extensor muscles increases intra-abdominal pressure and thereby augments spinal stability. The diaphragm may also increase spinal stability directly via the attachment of its crurae to the lumbar vertebrae.[25]

Previous studies have shown that, compared to healthy subjects, patients with chronic low back pain and sacroiliac joint pain have abnormal diaphragm movement and/or position during tidal breathing with postural tasks.[20,22] Kolář et al[20] found that patients with low back pain had less motion (excursion) of the diaphragm with dynamic loading of the limbs during normal breathing. Furthermore, O'Sullivan et al[22] found that patients with sacroiliac joint pain had decreased diaphragmatic excursion, in addition to increased pelvic floor descent, when compared with pain-free patients.

Despite the importance of the diaphragm for respiration and spinal stability, knowledge of variability in diaphragm motion during quiet breathing is still limited. Various methods of assessing diaphragm kinetics include fluoroscopy,[2,6] electromyography,[13,17,18] dynamic magnetic resonance imaging,[20] and high-resolution ultrasound. The latter has the advantage of portability, relatively low cost, and minimal contraindications. Although ultrasound has been available as a tool to assess diaphragm movement for many years, there has been limited use to date. With the increasing availability of high-resolution, portable, lower-cost machines, real-time ultrasound visualization of the diaphragm could be easily performed in an outpatient setting.[4]

Most ultrasound studies of the diaphragm have used M-mode, which allows for evaluation of diaphragm motion and excursion.[1,5,9–11,19,21,28] B-mode ultrasound provides a 2-dimensional image of the muscle, rather than the 1-dimensional waveform produced with M-mode, allowing evaluation of muscle thickness and the degree of contractility. The latter is determined by the thickening ratio (thickness of the muscle at maximal inspiration compared to thickness of the muscle at end expiration). Evaluation of muscle thickness at end expiration also allows the examiner to identify the presence of atrophy. Given the ease of visualization of changes in muscle thickness, this method of imaging has the potential to be used as a biofeedback tool for patients, similar to the current use of high-resolution ultrasound in the neuromuscular re-education of the transversus abdominis muscle.[23] Previous studies have used M-mode ultrasound to quantify diaphragm displacement during tidal breathing,[3,19] but diaphragm thickness and contractility during quiet breathing have not been systematically quantified to date.

The aim of this study was to establish a range of normal values for diaphragm thickening in healthy subjects during quiet breathing, with the ultimate goal of introducing this imaging technique as a diagnostic and educational tool in clinical practice, given that future studies confirm its reliability and validity in both healthy subjects and patients with low back pain. Because the diaphragm is an essential respiratory muscle as well as an important contributor to core stability, objective measurement of diaphragm thickening has the potential to aid in the identification of dysfunction in patients with conditions such as low back pain or pelvic floor disorders.

METHODS

The study was approved by the Mayo Clinic Institutional Review Board. Healthy subjects were recruited from a tertiary-referral electromyography laboratory, after giving verbal consent and signing the Health Insurance Portability and Accountability Act of 1996 authorization. A minimum of 10 subjects per gender were recruited for each decade, from ages 20 to 29 years up to 70 to 79 years, with a final group aged 80 years and older. This was determined prospectively; therefore, subjects were actively recruited based on their age and gender. Subjects were excluded if they had any history of dyspnea or generalized neuromuscular disease, such as peripheral neuropathy, myopathy, motor neuron disease, or central nervous system disease Basic demographic data, including body mass index (BMI), were collected.

B-mode ultrasound imaging of the diaphragm was then conducted with the subjects positioned supine, using a previously described technique.[4] A high-resolution portable ultrasound machine (LOGIQ e; GE Healthcare, Waukesha, WI) was used, with a 7- to 13-MHz linear-array transducer placed transversely over the lowest intercostal space that allowed good visualization of the diaphragm without lung encroachment during tidal breathing (FIGURE 1). The diaphragm was identified by its typical 3-layered appearance and location deep to the intercostal muscle layer and ribs. Three images were captured at the end of quiet expiration (FIGURE 2A) and 3 more were taken at the end of quiet inspiration (FIGURE 2B). The thickness of the diaphragm muscle was measured by placing electronic calipers just inside the 2 hyperechoic fascial lines outlining the diaphragm where the lines were most parallel. The 3 measurements for each position were averaged to give a thickness at the resting end expiration (T^{exp}) and a thickness at the resting end inspiration (T^{insp}). A thickening ratio was then derived by dividing T^{insp} by T^{exp}.

Measurements were obtained by 1 of 2 examiners who were working in the Mayo Clinic electromyography lab at the time of subject recruitment. The senior author (A.J.B.) had several years of experience with imaging both normal and abnormal diaphragms and trained the other examiner for several weeks before image acquisition began. Reliability of the measurement technique was assessed by determining intrarater reliability. Intrarater reliability was obtained with intraclass correlation coefficient model 3,3 ($ICC_{3,3}$) by having the same examiner obtain separate sets of images and measurements from the same subject on 2 separate days. The intercostal space used for the measurements was documented, and this was the only information available to the examiner at the time of repeat testing to ensure blinding to the diaphragm thickness and contractility measures.

Interrater reliability was obtained using $ICC_{2,3}$ by having the 2 examiners obtain images and measurements from the same subject at 2 different times, usually on different days, sometimes weeks apart. The examiner independently determined which intercostal space to measure. On each occasion, electronic calipers were placed and measurements obtained in real time during image acquisition by the examiner performing the exam.

Statistical Analysis

Data analysis was performed using JMP Version 9 software (SAS Institute Inc, Cary, NC). The Wilcoxon rank-sum test or chi-square test was used to compare baseline demographic data by gender. To measure the difference between sides in resting thickness and in thickening ratio between subjects, for the entire group and when stratified for age and gender, the Wilcoxon signed-rank test was used. *P* values less than .05 were considered statistically significant. MedCalc for Windows Version 12.1.3.0 (MedCalc Software bvba, Ostend, Belgium) was used to calculate ICC measurements for the analysis of the intrarater and interrater reliability data. Minimum detectable difference for follow-up clinical trials with a similar sample size and 80% power, using a 2-tailed *t* test and $P<.05$, was also calculated.

RESULTS

A total of 150 healthy subjects were recruited, ranging in age from 20 to 83 years (mean ± SD, 50.6 ± 17.8 years) and BMI from 16.1 to 51.2 kg/m^2 (mean ± SD, 27.9 ± 5.3 kg/m^2). Mean age and mean BMI for men were 51.3 ± 18.2 years and 27.9 ± 4.7 kg/m^2, respectively, and those for women were 51.3 ± 18.0 years and 26.6 ± 6.8 kg/m^2, respectively. Diaphragm thickness and thickening ratio data are presented in the TABLE. Diaphragm thickness ranged from 0.12 to 1.18 cm, with mean resting thickness slightly higher in men. For the group as a whole, the difference between T^{insp} and T^{exp} was significantly different ($P<.0001$), although mean difference was only 0.06 cm (95% confidence interval [CI]: 0.05, 0.06) on the right and 0.07 cm (95% CI: 0.06, 0.08) on the left, indicating that the diaphragm typically thickens to some extent with tidal breathing in healthy subjects. However, 29% of hemi-diaphragms increased in thickness by less than 10% with tidal breathing, and there were 3 subjects who did not use 1 hemi-diaphragm at all during tidal breathing. There was no significant difference in thickening ratio between sides, with a correlation coefficient of 0.96. Furthermore, there was no significant difference in the thickening ratio between men and women or between individuals 50 years of age or greater compared to those below 50 years of age, with the exception of men aged 50 years or older, in whom the left thickened more than the right (mean thickening ratio = 1.28 versus 1.17, $P = .02$).

Interrater and intrarater reliability were evaluated and found to be very high. Mean interrater reliability ICCs for the 12 subjects tested by 2 different examiners were 0.97 (95% CI: 0.91, 0.99) for T^{insp} and 0.98 (95% CI: 0.94, 0.99) for T^{exp}. Mean intrarater reliability ICCs for the 10 subjects tested on 2 different days by the same examiner were 0.94 (95% CI: 0.79, 0.98) for T^{insp} and 0.98 (95% CI: 0.94, 0.99) for T^{exp}.

Based on our findings, the minimum detectable difference for follow-up clinical trials with a similar sample size and 80% power, using a 2-tailed *t* test and $P<.05$, would be 0.07 cm for diaphragm thickness and 0.08 for diaphragm thickening ratio.

DISCUSSION

This study establishes the normal range of diaphragm thickening in healthy subjects during quiet breathing. Furthermore, it surveys a larger patient population to confirm previous resting values obtained with B-mode ultrasound by Enright et al[8] in a smaller population. Thus, the present study provides a wide database of healthy controls for future use in the evaluation of diaphragm dysfunction. The rates of interrater and intrarater reliability in this study were very high (all reliability values ranged between 0.94 and 0.98), implying that B-mode ultrasound is a reliable technique for assessing diaphragm thickening with tidal breathing.

The present study found that most people use their diaphragm during quiet breathing, and there is no significant difference between sides or across age groups (with the exception of older men, in whom the left side thickens more than the right). However, there is also a fairly large subset of people who either do not use their diaphragm at all or contract it minimally during quiet breathing. These baseline values are of importance in the context of rehabilitation of patients with back pain. There is evidence in the literature that the diaphragm contributes to spinal stability, and previous studies have established a link between diaphragm dysfunction and low back pain and sacroiliac pain.[20,22] Although those studies have employed other imaging methods, such as dynamic magnetic resonance imaging or M-mode sonography, B-mode sonography has the advantage of assessing both anatomical structure and function of the muscle.

This study lays the groundwork for follow-up studies using B-mode ultrasound to compare activation and contraction of the diaphragm in patients with low back pain to healthy controls, and to promote the development of rehabilitation strategies to normalize or enhance diaphragm activation as a component of improved core stability. Ultrasound imaging has been used as biofeedback for other muscles that contribute to spine stability, including the transversus abdominis,[23] lumbar multifidus,[27] and pelvic floor.[7]

Richardson et al[23] first proposed the use of ultrasound as a biofeedback tool for neuromuscular re-education of the transversus abdominis muscle in patients with low back pain. The abdominal-hollowing exercise has been shown to facilitate co-activation of the transversus abdominis and lumbar multifidus, thereby increasing stiffness of the joints in the lumbopelvic region.[23,24] Emphasis is placed on muscle synergy and motor control training. When utilizing ultrasound imaging, correct muscle activation during abdominal hollowing is assessed according to 2 criteria: (1) a 2-fold increase in the transversus abdominis muscle thickness during abdominal hollowing compared to at rest, with relatively little change in muscle thickness of the internal and external obliques[26]; and (2) tension of the anterior abdominal fascia with shortening of the transversus abdominis, observed by lateral motion of the midline attachment of the transversus abdominis, as described by Richardson et al[23] and Teyhen et al.[26] Once a correct technique is achieved, the patient may be progressed to tasks that load the spine, such as arm or leg lifts. Patients may also be progressed through exercises in various positions, from supine to sitting to standing. Ultrasound is used to monitor the transversus abdominis and trunk muscle activity during all phases of progression to provide feedback to patients.

In the same way that ultrasound has been used for training the transversus abdominis, lumbar multifidus, and pelvic floor muscles, it may be a useful clinical tool for training individuals to engage the diaphragm to enhance spinal stability. However, further studies are needed to determine whether this imaging modality is sensitive enough to change in thickening to be clinically useful. If proven so, B-mode ultrasound would be particularly useful for such therapy purposes due to its ability to provide real-time feedback, qualitatively and/or quantitatively, to both therapists and patients.

The main limitation to this study is its relatively limited reliability data. We evaluated intratester reliability for a single examiner in 10 subjects and found this to be very high; however, we do not know if that would apply to other examiners, particularly those who have limited experience with ultrasound imaging. We also only evaluated interrater reliability between 2 different examiners in 12 subjects. In order to robustly support the use of this modality in clinical practice, a study focusing purely on intratester and intertester reliability may be needed. In addition, this is a pilot study determining normal values for diaphragm contractility; however, we do not know whether this imaging modality is sensitive enough to detect subtle differences in diaphragm contractility that would translate into clinically effective changes in dynamic muscle stabilization. Further studies are needed to determine the clinical utility of diaphragm ultrasound in the rehabilitation setting.

CONCLUSION

This study provides a set of normal values for diaphragm thickening during tidal breathing. Due to the role of the diaphragm as a contributor to spinal stabilization, evaluation of diaphragm thickening and comparison to this set of normal values will allow clinicians to determine baseline diaphragmatic function in patients with conditions such as chronic low back pain. Furthermore, visualization of diaphragm thickening with B-mode ultrasound may serve as an effective biofeedback tool for training the diaphragm and enhancing its contribution to spinal stability.

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References

1. Ayoub J, Cohendy R, Dauzat M, et al. Non-invasive quantification of diaphragm kinetics using M-mode sonography. Can J Anaesth. 1997; 44:739–744. http://dx.doi.org/10.1007/BF03013389. [PubMed: 9232305]
2. Ayoub J, Metge L, Dauzat M, et al. Diaphragm kinetics coupled with spirometry. M-mode ultrasonographic and fluoroscopic study preliminary results. J Radiol. 1997; 78:563–568. [PubMed: 9537172]
3. Blaney F, English CS, Sawyer T. Sonographic measurement of diaphragmatic displacement during tidal breathing manoeuvres – a reliability study. Aust J Physiother. 1999; 45:41–43. [PubMed: 11676752]
4. Boon AJ, Alsharif KI, Harper CM, Smith J. Ultrasound-guided needle EMG of the diaphragm: technique description and case report. Muscle Nerve. 2008; 38:1623–1626. http://dx.doi.org/10.1002/mus.21187. [PubMed: 19016552]
5. Cohen E, Mier A, Heywood P, Murphy K, Boultbee J, Guz A. Excursion-volume relation of the right hemidiaphragm measured by ultrasonography and respiratory airflow measurements. Thorax. 1994; 49:885–889. [PubMed: 7940428]
6. de Toledo JS, Munoz R, Landsittel D, et al. Diagnosis of abnormal diaphragm motion after cardiothoracic surgery: ultrasound performed by a cardiac intensivist vs. fluoroscopy. Congenit Heart Dis. 2010; 5:565–572. http://dx.doi.org/10.1111/j.1747-0803.2010.00431.x. [PubMed: 21106016]
7. Dietz HP. Ultrasound imaging of the pelvic floor. Part I: two-dimensional aspects. Ultrasound Obstet Gynecol. 2004; 23:80–92. http://dx.doi.org/10.1002/uog.939. [PubMed: 14971006]
8. Enright SJ, Unnithan VB, Heward C, Withnall L, Davies DH. Effect of high-intensity inspiratory muscle training on lung volumes, diaphragm thickness, and exercise capacity in subjects who are healthy. Phys Ther. 2006; 86:345–354. [PubMed: 16506871]
9. Epelman M, Navarro OM, Daneman A, Miller SF. M-mode sonography of diaphragmatic motion: description of technique and experience in 278 pediatric patients. Pediatr Radiol. 2005; 35:661–667. http://dx.doi.org/10.1007/s00247-005-1433-7. [PubMed: 15776227]
10. Gerscovich EO, Cronan M, McGahan JP, Jain K, Jones CD, McDonald C. Ultrasonographic evaluation of diaphragmatic motion. J Ultrasound Med. 2001; 20:597–604. [PubMed: 11400933]
11. Haber K, Asher M, Freimanis AK. Echographic evaluation of diaphragmatic motion in intra-abdominal diseases. Radiology. 1975; 114:141–144. http://dx.doi.org/10.1148/114.1.141. [PubMed: 1208854]
12. Hodges PW. Is there a role for transversus abdominis in lumbo-pelvic stability? Man Ther. 1999; 4:74–86. http://dx.doi.org/10.1054/ math.1999.0169. [PubMed: 10509061]
13. Hodges PW, Butler JE, McKenzie DK, Gandevia SC. Contraction of the human diaphragm during rapid postural adjustments. J Physiol. 1997; 505(pt 2):539–548. [PubMed: 9423192]
14. Hodges PW, Cresswell AG, Daggfeldt K, Thorstensson A. In vivo measurement of the effect of intra-abdominal pressure on the human spine. J Biomech. 2001; 34:347–353. [PubMed: 11182126]
15. Hodges PW, Eriksson AE, Shirley D, Gandevia SC. Intra-abdominal pressure increases stiffness of the lumbar spine. J Biomech. 2005; 38:1873–1880. http://dx.doi.org/10.1016/j.jbiomech.2004.08.016. [PubMed: 16023475]
16. Hodges PW, Gandevia SC. Activation of the human diaphragm during a repetitive postural task. J Physiol. 2000; 522(pt 1):165–175. [PubMed: 10618161]
17. Hodges PW, Gandevia SC. Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. J Appl Physiol (1985). 2000; 89:967–976. [PubMed: 10956340]
18. Hodges PW, Heijnen I, Gandevia SC. Postural activity of the diaphragm is reduced in humans when respiratory demand increases. J Physiol. 2001; 537:999–1008. [PubMed: 11744772]

19. Houston JG, Morris AD, Howie CA, Reid JL, McMillan N. Technical report: quantitative assessment of diaphragmatic movement—a reproducible method using ultrasound. Clin Radiol. 1992; 46:405–407. [PubMed: 1493655]
20. Kolář P, Šulc J, Kynčl M, et al. Postural function of the diaphragm in persons with and without chronic low back pain. J Orthop Sports Phys Ther. 2012; 42:352–362. http://dx.doi.org/10.2519/jospt.2012.3830. [PubMed: 22236541]
21. McCauley RG, Labib KB. Diaphragmatic paralysis evaluated by phrenic nerve stimulation during fluoroscopy or real-time ultrasound. Radiology. 1984; 153:33–36. http://dx.doi.org/10.1148/radiology.153.1.6473801. [PubMed: 6473801]
22. O'Sullivan PB, Beales DJ, Beetham JA, et al. Altered motor control strategies in subjects with sacroiliac joint pain during the active straight-legraise test. Spine (Phila Pa 1976). 2002; 27:E1–E8. [PubMed: 11805650]
23. Richardson, C.; Hodges, P.; Hides, J. Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain. 2nd ed.. Edinburgh, UK: Churchill Livingstone; 2004.
24. Richardson CA, Snijders CJ, Hides JA, Damen L, Pas MS, Storm J. The relation between the transversus abdominis muscles, sacroiliac joint mechanics, and low back pain. Spine (Phila Pa 1976). 2002; 27:399–405. [PubMed: 11840107]
25. Shirley D, Hodges PW, Eriksson AE, Gandevia SC. Spinal stiffness changes throughout the respiratory cycle. J Appl Physio (1985). 2003; 95:1467–1475. http://dx.doi.org/10.1152/japplphysiol.00939.2002.
26. Teyhen DS, Miltenberger CE, Deiters HM, et al. The use of ultrasound imaging of the abdominal drawing-in maneuver in subjects with low back pain. J Orthop Sports Phys Ther. 2005; 35:346–355. http://dx.doi.org/10.2519/jospt.2005.35.6.346. [PubMed: 16001906]
27. Van K, Hides JA, Richardson CA. The use of real-time ultrasound imaging for biofeedback of lumbar multifidus muscle contraction in healthy subjects. J Orthop Sports Phys Ther. 2006; 36:920–925. http://dx.doi.org/10.2519/jospt.2006.2304. [PubMed: 17193869]
28. Wait JL, Nahormek PA, Yost WT, Rochester DP. Diaphragmatic thickness-lung volume relationship in vivo. J Appl Physio (1985). 1989; 67:1560–1568.

KEY POINTS

FINDINGS: There is wide variability in diaphragm contractility during quiet breathing in healthy subjects, as assessed with B-mode ultrasound. In some healthy subjects, there is no contraction of the diaphragm with quiet breathing, but on average the diaphragm will thicken by about 20%. Test-retest reliability is high for ultrasound measurements of diaphragm thickness during the breathing cycle.

IMPLICATIONS: The present study confirms the reliability of B-mode ultrasound to assess the degree of diaphragm thickening with quiet breathing, although further studies are necessary to confirm its potential use as a biofeedback tool in clinical practice.

CAUTION: Some degree of variability has to be expected in values obtained from B-mode ultrasound in clinical practice, depending on the skill of the examiner and various patient factors.

FIGURE 1.

The ultrasound transducer is placed transversely over the lowest intercostal space that allows for good visualization of the diaphragm without lung encroachment during tidal breathing.

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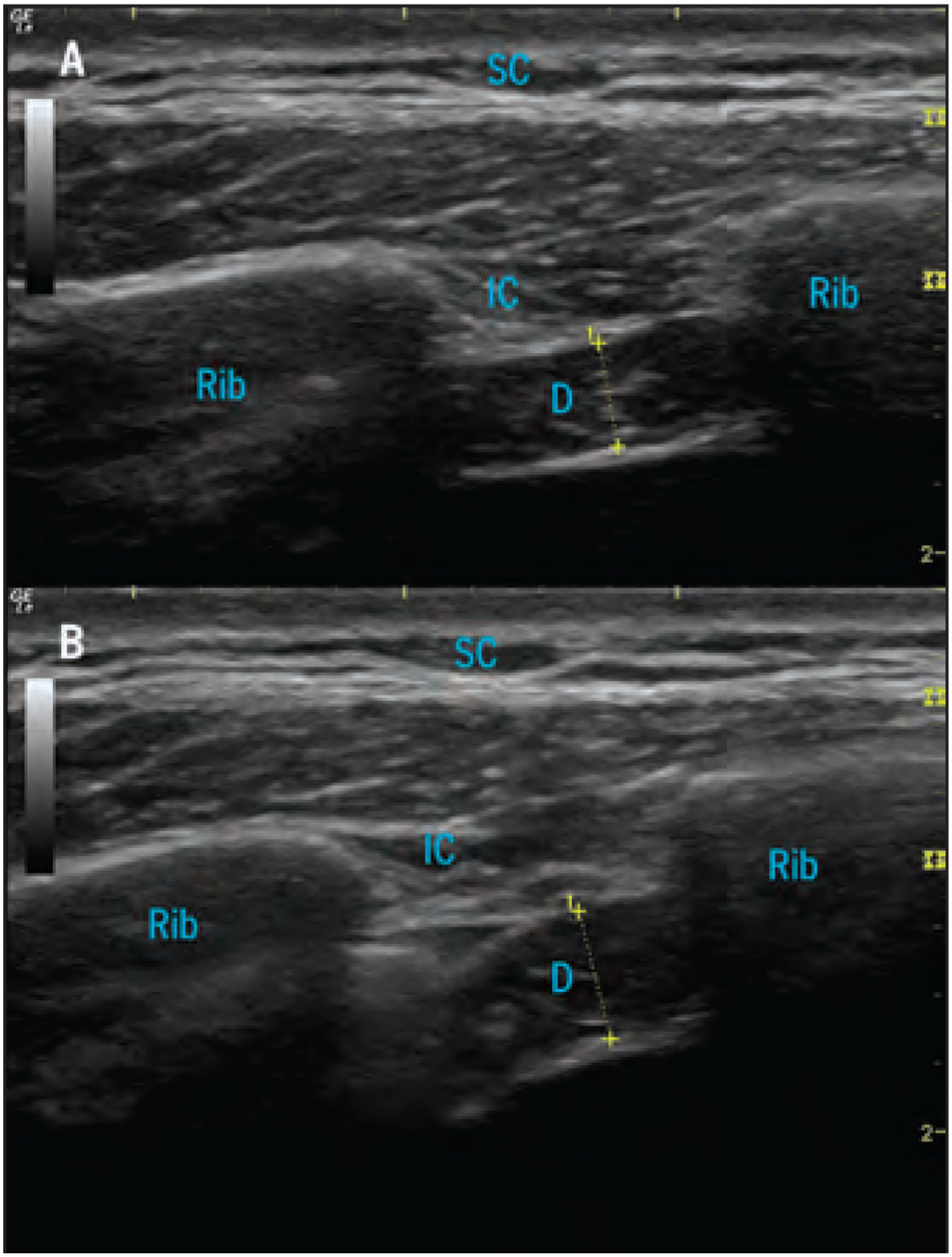

FIGURE 2.

(A) Ultrasound identification of the diaphragm at the end of quiet expiration, deep to the intercostal muscle layer and ribs; T^{exp} = 0.39 cm. (B) Ultrasound identification of the diaphragm at the end of quiet inspiration, deep to the intercostal muscle layer and ribs; T^{insp} = 0.49 cm. Abbreviations: D, diaphragm; IC, intercostal muscle; SC, subcutaneous tissue; T^{exp}, thickness at resting end expiration; T^{insp}, thickness at resting end inspiration.

TABLE

Hemi-Diaphragm Thickness at End of Quiet Inspiration and End of Quiet Expiration and Hemi-Diaphragm Thickening Ratio

Parameter/Side	n	Mean ± SD (Range)	95% CI	*P* Value	Mean Difference (95% CI)
T^{insp*} right, cm	150	0.37 ± 0.14 (0.15–0.81)	0.35, 0.40	<.0001	0.06 (0.05, 0.06)
$T^{exp\dagger}$ right, cm	150	0.32 ± 0.13 (0.13–0.76)	0.30, 0.34		
T^{insp*} left, cm	150	0.40 ± 0.20 (0.12–1.30)	0.37, 0.44	<.0001	0.07 (0.06, 0.08)
$T^{exp\dagger}$ left, cm	150	0.34 ± 0.18 (0.12–1.18)	0.31, 0.38		
$T^{insp*}/T^{exp\dagger}$ ratio, right	150	1.20 ± 0.15 (1.00–2.04)	1.18, 1.23	.1	0.16 (0.13, 0.20)
$T^{insp*}/T^{exp\dagger}$ ratio, left	150	1.23 ± 0.24 (1.00–2.70)	1.20, 1.27		

Abbreviations: CI, confidence interval; T^{exp}, thickness at resting end expiration; T^{insp}, thickness at resting end inspiration.

* Hemi-diaphragm thickness on B-mode ultrasound at end of quiet inspiration.

† Hemi-diaphragm thickness on B-mode ultrasound at end of quiet expiration.