ORIGINAL ARTICLE

Relationship Between Chest Wall Motion and Diaphragmatic Excursion in Healthy Adults in Supine Position

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Background/Purpose: There has been a lack of studies that have used both three-dimensional analysis and imaging tools concurrently to describe lung volume changes and breathing pattern in subjects in the supine position. The purpose of this study was to investigate the correlation between volume changes estimated by optoelectronic plethysmography (OEP) and diaphragmatic excursion (DE) measured by ultrasonography of healthy adults in the supine position.

Methods: Twelve healthy male subjects (age, 25.08 ± 6.35 years) were recruited and asked to perform tidal and deep breathing in the supine position. The volume changes during chest wall motion were quantified from OEP analysis—this was done for the upper thorax (UT), lower thorax (LT), and abdominal (AB) compartment. Lung volume was measured synchronously via the mouth piece of an electrospirometer. The right diaphragmatic movement was measured by ultrasonography.

Results: Linear regression showed that all three compartments (V_{UT}, V_{LT} and V_{AB}) in the inspiratory phase were correlated highly with DE during tidal and deep breathing. However, multiple linear regression analysis showed that the V_{AB} contributed 94–95% of the variance when performing either tidal or deep breathing. A predicted equation for diaphragmatic movement during deep breathing was $DE = 0.052 + 0.294V_{AB}$.

Conclusion: The movement of V_{AB} can be used as an index of DE among the normal population in the supine position. Its application in patients requires further study. [*J Formos Med Assoc* 2009;108(7):577–586]

Key Words: diaphragmatic excursion, optoelectronic plethysmography, thoracic wall, ultrasonography

The spirometer is a simple tool for measuring lung volume, but its validity depends on gas temperature, humidity, viscosity, and density.[1] To eliminate the above problems, external measurement of the chest wall surface motion for lung volume estimation has been suggested as an alternative.[2] Ferrigno et al developed a method of volume estimation by using 3D analysis of chest wall motion with passive markers on the trunk surface (i.e. optoelectronic plethysmography; OEP) in healthy subjects.[3] This method has identified three compartments of the chest wall: the upper thorax (UT), lower thorax (LT), and abdomen (AB). Previous studies with OEP have indicated that the validity and reliability of the volume summation of these three compartments were good, when compared with total lung volume measured by spirometry in the sitting[3,4] and

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supine[5] positions. Measurement of chest wall motion by the motion analysis system has been used in studies of healthy subjects in sitting,[6–9] standing,[4] and prone[5] positions, and with patients in sitting[10–13] and supine[14–17] positions.

The advantages of OEP for lung volume estimation include: (1) obtaining volume measurements with details of three different compartments;[3] (2) investigating the strategy for measuring respiratory performance;[15] and (3) better diagnosis in patient assessment.[1] Nevertheless, simultaneous measurement of chest wall motion by monitoring internal movement of the diaphragm is suggested to complement the indirect method of OEP.

Internal movements of the diaphragm play an important role in respiration. The diaphragmatic excursion (DE) between inspiration and expiration can be determined by ultrasonography (US).[18,19] The relationship between DE measured by US and the inspiratory volume by spirometry is good ($R^2 = 0.96$) in the supine position.[18] The correlation between DE and tidal volume is between 0.976 and 0.995.[19] Recently, Aliverti et al applied the OEP motion analysis system and US to detect chest wall motion and DE concurrently in healthy subjects in a sitting position.[8] This study was the first to demonstrate—by US—a high correlation between diaphragmatic movement and volume change of the abdominal compartment (R^2 changes = 0.89–0.96). However, the relative contributions of DE to the abdominal compartment may differ between subjects in the supine and sitting position.

The contribution of diaphragmatic movement distance between inspiration and expiration in the supine position needs to be determined for patients with respiratory problems, who usually can not stand in an erect position during measurement. The purpose of the present study was to simultaneously investigate the chest wall motion by a motion analysis system and the diaphragmatic movement distance by US in healthy subjects in the supine position. The results of this study may provide normal values for chest wall motion and diaphragmatic movement for patients in the supine position, and evidence of a correlation between the compartments and diaphragmatic movement distance not previously identified. Our hypothesis was that there would be a good correlation between the abdominal compartment and diaphragmatic movement distance obtained simultaneously in healthy subjects in the supine position.

Materials and Methods

Subjects and study design

We recruited 12 subjects in this study. Inclusion criteria were: (1) male; (2) in good health; and (3) aged 18–40 years. Exclusion criteria were: (1) history of chest wall trauma; (2) any respiratory diseases and musculoskeletal problems that interfered with the experimental protocol; (3) history of smoking; and (4) infection during recruitment and measurement. This study was approved by the ethics committee of National Taiwan University Hospital. Before starting the experiment, all subjects understood the procedure and signed a letter of consent. After obtaining baseline data, the subjects were asked to expose their upper trunk and lie on a rigid table with their arms relaxed beside the trunk. After calibration and sticking markers on the anterior and lateral surface of the trunk, the subject was asked to breathe via a mouthpiece to obtain the tidal and deep breathing volumes in the supine position. The chest wall motion, DE and lung volume were measured simultaneously by OEP, US and electrospirometry, respectively.

Measurements

OEP

The placement of marker sets was modified from previous studies of chest wall motion analysis.[3,5] Forty-five passive reflective markers were adhered to the subject's trunk with an anterior four-by-five grid and a symmetric lateral grid (Figure 1). The diameter of the passive markers was 15 mm. An additional wand was placed on the sternum to define a local coordinate system. Each marker was traced in the 3D space by an optoelectronic

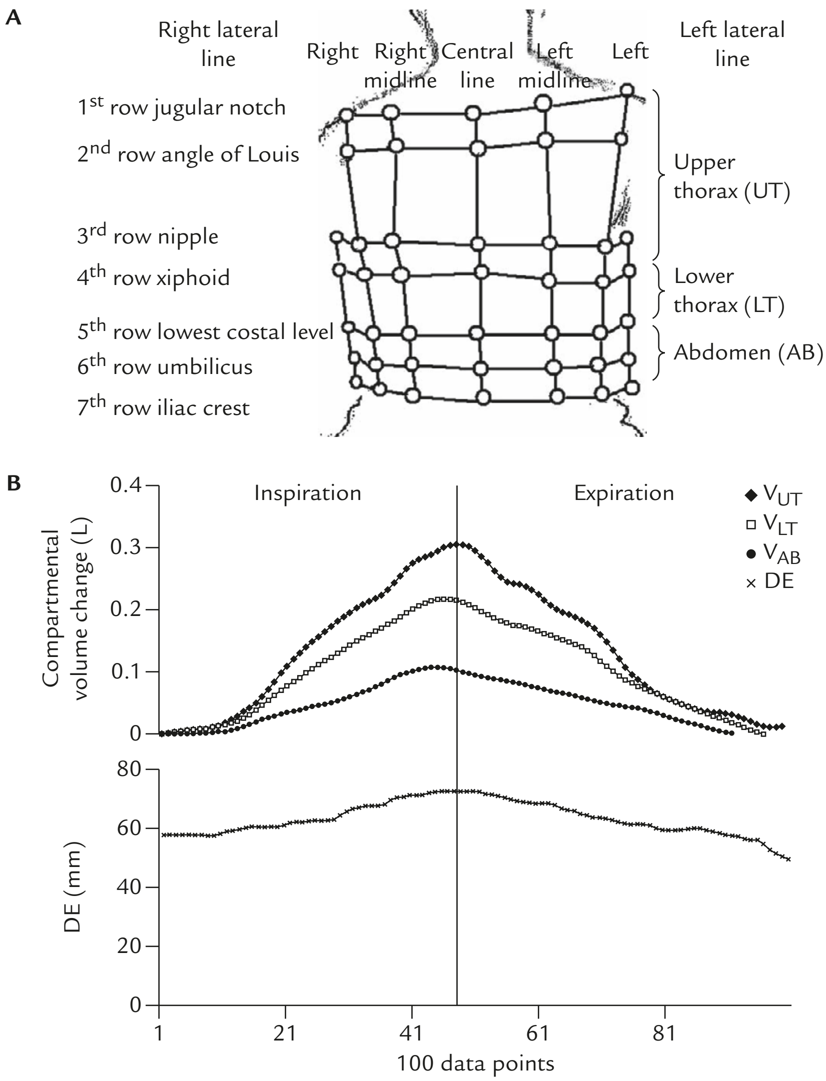

Figure 1. (A) Geometric diagram of chest wall with three-compartment model (upper thorax, lower thorax, and abdomen). (B) An example of breathing cycle for three-compartment volume changes and diaphragmatic excursion (DE).

motion analysis system (Vicon 250; Oxford, UK), which included five high-speed cameras with a sampling rate of 120 Hz. These five cameras were arranged to surround the subject to ensure that every marker was captured by at least two cameras.

In the supine position, the posterior chest wall surface lies on the supporting bed and becomes a hidden part for volume estimation. For the posterior chest wall, a geometric model of volume estimation was used as the reference plane, which corresponded to the horizontal plane of the bed. Computation of the enclosed volume changes was determined with good validity by movement of the markers on the anterior body surface, with a fixed posterior region.[5] According to the methods outlined by Ferrigno and Carnevali,[15] the lung volume was calculated by connecting eight adjacent passive markers to form a six-faced polyhedron that could be further divided into six tetrahedrons with a trigon shape (the formula is shown in the Appendix). Using this method, the whole chest wall could be described by 75 markers split into 209 tetrahedrons.

As shown in Figure 1, we described the chest wall as a three-compartment system, including the UT, LT, and AB. It was assumed that the sum of each compartment equaled the total volume changes in the chest wall: $V_{CW} = V_{UT} + V_{LT} + V_{AB}$, where V_{UT} is the UT volume (mainly reflecting the action of the neck and parasternal muscles and the effect of pleural pressure); V_{LT} is the LT volume (mainly reflecting the action of the diaphragm and the effect of abdominal and pleural pressure); and V_{AB} is the AB volume (mainly reflecting the action of the diaphragm and the effect of the abdominal muscles).[3] The validity of this method in our pilot study compared with spirometry was good (the Pearson correlation coefficient was 0.999, $p < 0.0001$).[20] The validity of this method by using the bed surface as the fixed reference was good.

US

Right-side DE was measured by Sonosite 180 plus US (Bothell, WA, USA) equipped with a curved probe C11 (4–7 MHz). Although both anterior and posterior approaches have been used to detect movements of the right diaphragm, the posterior approach (i.e. scanning the renal area in the prone position) has been reported as uncomfortable, and the anterior approach (i.e. scanning the mid-clavicular intercostal area in the supine position) is currently the most acceptable technique.[21] Hence, the probe for the anterior approach was placed on the 10th intercostal space in the mid-clavicular line, with a slight upward tilt towards the subject's head. The measurement started from the B-mode (depth 10 cm) to view the liver window. This liver window showed a clear margin (high echo zone) between the lung–diaphragm and liver. Next, M-mode was used to measure margin displacements during breathing. Real-time US was synchronized with a Vicon system through a video capture card (UPG301B II; Upmost, Taiwan), and recorded as movie files (AVI format) using the Korean KMPlayer version 2.9.3.1389 at a sampling rate of 30 Hz. A specific program (eclipse, JAVA version 1.5; Sun Microsystems Inc., Santa Clara, CA, USA) was used to digitize the displacement of DE around the apposition zone. Displacement of DE was then calculated by the pixel moving distance between inspiration and expiration. Matlab 7.01 (Mathworks, Boston, MA, USA) was customized to correlate the synchronized chest wall volume changes and DE at 30 Hz. The measurements for DE were used to establish correlations with chest wall movement.

A pilot study was carried out before the present study to ensure the validity of US. The right-side diaphragmatic movement distance in the zone of apposition, which extended from the insertion of the diaphragm to the lower costal margin, was measured by US with a skin probe in five healthy subjects during maximal breathing [i.e. vital capacity (VC)] in the sitting position. The diaphragmatic movement distance (i.e. axial or vertical distance at dome area) measured by fluoroscopy (Medix3000; Hitachi, Japan) during maximal breathing was measured in the sitting position. Figure 2 shows the diaphragmatic movement distance around the zone of apposition measured by US (A), and that around the apex measured by fluoroscopy (B) during inspiration and expiration, respectively. The DE was calculated as the difference between the distances moved during expiration and inspiration with reference to the skin probe (in US) or marker (in fluoroscopy). At the same inspiration volume, DE measured by US and fluoroscopy was 5.38 ± 2.46 cm and 7.34 ± 0.76 cm, respectively. The Pearson correlation coefficient between the US and fluoroscopy measurements was 0.914 ($p = 0.015$), which indicated good validity of US measurements.

Spirometry

A pneumotach (Fleisch no. 2, Lausanne, Switzerland) with a mouthpiece was fixed on a metal stand for the subject to breathe in the supine position. The flow signal from the pneumotach was sent to an electrospirometer (CS6; GM Instruments, Kilwinning, UK) and was integrated into the volume changes. The clamp was clipped to the nose to prevent nasal breathing. When the subject breathed, the electrospirometer collected the lung volume data at the same time as the OEP motion capture or US imaging. The VC (maximal inspiration) was measured in all cases without US imaging, but about 70% of VC (i.e. deep breathing) was measured because the maximal diaphragm movement was out of the range of US imaging.

Statistical analysis

All experimental data were stored using SPSS 11.0 (SPSS Inc., Chicago, IL, USA) and analyzed by Matlab 7.01. Each breathing cycle included

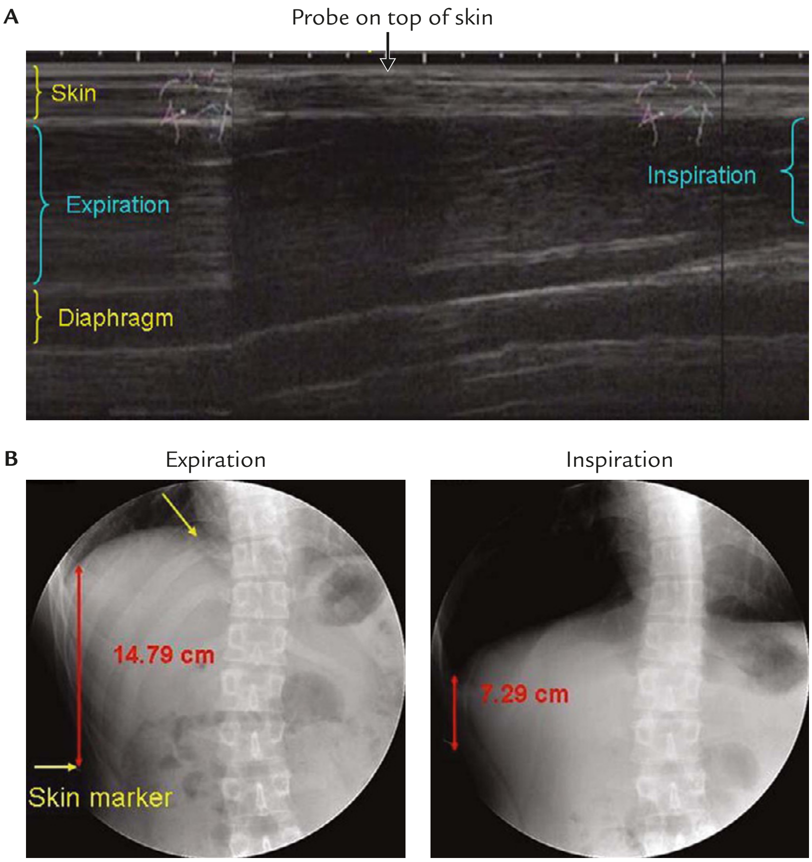

Figure 2. Right side diaphragmatic imaging by (A) ultrasonography in M-mode, and (B) fluoroscopy during expiration and inspiration.

expiration and inspiration phases that were normalized with cycle time to obtain the phase cycle. For the X-Y plot of DE and volume changes, we normalized the changes in DE according to the distance of the rib cage (i.e. between two lateral side markers at the xiphoid level), and inspiratory volume changes according to VC during tidal and deep breathing.

The individual correlation between volume estimation of each compartment (i.e. V_{UT}, V_{LT}, V_{AB}, or V_{CW}) and DE was analyzed by linear regression analysis, but the relative contribution of each compartment to DE was analyzed by multiple linear regression analysis. According to a previous study, we quantified the following regression equation:

$$DE = B_0 + B_1V_{AB} + B_2V_{LT} + B_3V_{UT} \quad (1)$$

where B_0 is the intercept and B_1, B_2 and B_3 are the linear coefficients.[8] Stepwise multiple linear regression with entered method was performed to determine the relative compartmental contribution to DE during quiet and deep breathing. DE and V_{AB} were normalized according to the diameter of the chest wall at the xiphoid, and VC, respectively. The results were express as squared linear regression coefficient (R^2). $R^2 > 0.8$ was considered as a high correlation.

Results

The 12 male subjects were aged 18–40 years (mean, 25.08 ± 6.35 years), with a mean body height of 177.58 ± 5.62 cm and mean body weight of 74.13 ± 9.84 kg. The mean VC and tidal volume (VT) measured by electrospirometry in the subjects in the supine position were 4.55 ± 0.61 L and 0.67 ± 0.29 L, respectively. The mean volume of deep breathing was 3.20 ± 0.70 L (72.59 ± 10.39% of VC). The estimated chest wall volume in the three compartments (V_{UT}, V_{LT} and V_{AB}) and DE during tidal and deep breathing are shown in Table 1.

Table 1. Optoelectronic plethysmography data and diaphragmatic excursion (DE) during tidal and deep breathing ($n = 12$)*

	V_{UT} (L)	V_{LT} (L)	V_{AB} (L)	V_{TOT} (L)	DE (mm)
Tidal breathing	0.23 ± 0.14	0.26 ± 0.10	0.29 ± 0.14	0.78 ± 0.26	16.41 ± 6.46
Deep breathing	1.17 ± 0.37	0.87 ± 0.38	0.85 ± 0.68	2.87 ± 1.23	39.09 ± 18.04

Data presented as mean ± standard deviation. V_{UT} = volume of upper thorax; V_{LT} = volume of lower thorax; V_{AB} = volume of abdomen.

Table 2. Results of multiple linear regression analysis for diaphragmatic excursion (DE)

Condition	Subject	Total R^2	R^2 change		
			V_{AB} (L)	V_{LT} (L)	V_{UT} (L)
Tidal breathing	1	0.972	0.946	0.018	0.008
	2	0.986	0.984	0.001	0.001
	3	0.994	0.992	0.002	0.000
	4	0.964	0.948	0.005	0.011
	5	0.986	0.969	0.005	0.012
	6	0.984	0.879	0.094	0.011
	7	0.896	0.680	0.216	0.000
	8	0.985	0.951	0.017	0.017
	9	0.957	0.948	0.003	0.006
	10	0.99	0.979	0.011	0.000
	11	0.982	0.972	0.009	0.001
	12	0.993	0.977	0.013	0.003
	Mean ± SD	0.97 ± 0.03	0.94 ± 0.09	0.03 ± 0.06	0.01 ± 0.01
Deep breathing	1	0.981	0.965	0.015	0.001
	2	0.986	0.946	0.021	0.019
	3	0.990	0.954	0.035	0.001
	4	0.931	0.920	0.000	0.011
	5	0.996	0.932	0.042	0.022
	6	0.981	0.979	0.002	0.000
	7	0.938	0.931	0.004	0.003
	8	0.992	0.839	0.143	0.010
	9	0.940	0.936	0.000	0.004
	10	0.990	0.990	0.000	0.000
	11	0.951	0.890	0.000	0.061
	12	0.972	0.970	0.001	0.001
	Mean ± SD	0.97 ± 0.02	0.94 ± 0.04	0.02 ± 0.04	0.01 ± 0.02

$DE = B_0 + B_1V_{AB} + B_2V_{LT} + B_3V_{UT}$, where B_0 is the intercept and B_1, B_2 and B_3 are the linear coefficients. V_{UT} = volume of upper thorax; V_{LT} = volume of lower thorax; V_{AB} = volume of abdomen; SD = standard deviation.

Linear regression analysis/multiple linear regression analysis

Linear regression showed that all three compartments (V_{UT}, V_{LT}, V_{AB}) in the inspiratory phase were highly correlated with DE during tidal and deep breathing. The average R^2 for V_{UT}, V_{LT} and V_{AB} with DE was 0.81, 0.91 and 0.94, respectively, during tidal breathing, and 0.93, 0.91 and 0.94 during deep breathing. V_{AB} had the highest correlation with DE.

Multiple linear regression via the entered method was performed for all subjects. Table 2 shows the results during tidal and deep breathing. We found that V_{AB} contributed 94–95% of the

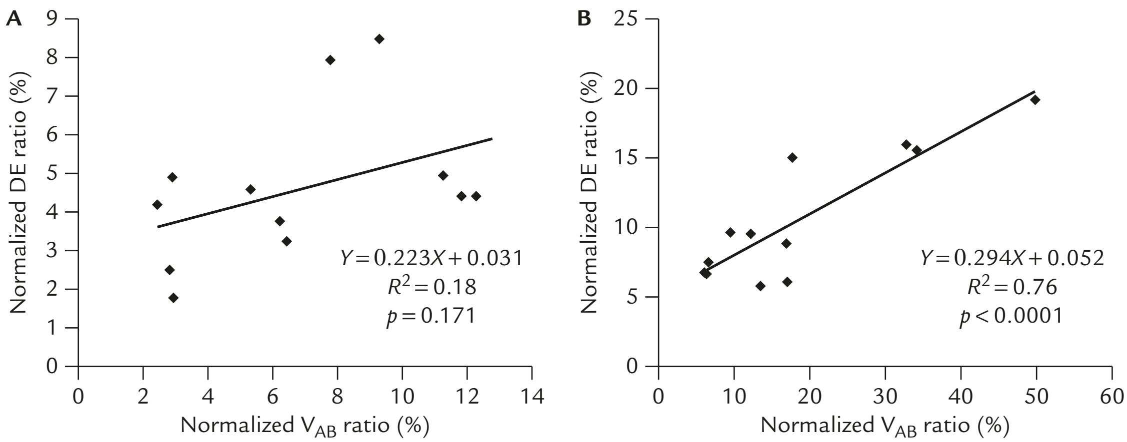

Figure 3. The normalized abdominal compartment (V_{AB})–diaphragmatic excursion (DE) plot with linear regression equation during (A) tidal breathing, and (B) deep breathing ($n = 12$).

variance when performing tidal and deep breathing. However, after adding the other two compartments, the variance improved by only 1–3%.

According to the results of linear regression, collinearity should be considered. After performing collinearity diagnosis, there were collinear relationships among the three compartments. Since V_{AB} is the predictor to generalize a prediction equation, the X-Y plot of V_{AB}–DE, with normalization during tidal and deep breathing, is shown in Figure 3. However, the linear relations achieved statistical significance ($p < 0.0001$) only during deep breathing.

Discussion

The major finding of this study in healthy subjects in the supine position included: (1) all three compartments of chest wall motion were highly correlated with diaphragmatic movement distance in the inspiratory phase during tidal and deep breathing; and (2) the principle predictor of diaphragmatic movement distance was the abdominal compartment of chest wall motion. Similar significant correlations between diaphragmatic movement distance and the abdominal compartment in the sitting position have been reported in healthy volunteers by Aliverti et al.[8] Therefore, changes in the abdominal volume are good predictors of diaphragmatic displacement in the sitting and supine positions in healthy subjects.

Impact of the correlation between the compartments and DE

Based on our linear regression analysis and Aliverti et al's theory,[8] the fixed sequence (i.e. first V_{AB}, then V_{LT}, and V_{UT}) was chosen for multiple regression with the entered method to analyze the contribution of each compartment to DE. The results showed that the abdominal compartment made the greatest contribution to DE during tidal and deep breathing. Adding the other two compartments only increased variance by 1–3%. Our results support Mead and Loring's theory that diaphragmatic movement causes anterior displacement of the abdominal wall.[22] After normalization with volume, the linear relationship between DE and V_{AB} achieved a significant level only during deep breathing. Therefore, the predicted equation is reliable only during deep breathing with large displacement of the diaphragm and abdomen.

Three-compartment model by OEP

According to previous studies, different marker sets were chosen to define the three compartments. The UT compartment (with markers from the clavicular to the xiphoid process level) was the same in the different studies. However, the marker sets chosen for the LC and AB compartments varied greatly.[3,4,6,15] Aliverti et al defined the LT compartment from the xiphoid to the edge of the lower costal margin, and did not include the triangular portion (i.e. the area that contains the stomach).[8] We defined the compartments according to the study by Ferrigno et al;[3] the area between the horizontal planes of the xiphoid and twelfth costal rib was the LT compartment, and the volume below the horizontal plane of the lowest costal rib was the AB compartment. This definition was valid because of the anatomical structure and movement of the chest wall and diaphragm.[1,4]

Spirometry and body plethysmography vs. OEP

In the clinical setting, the common tools traditionally used to measure changes in lung volume are body plethysmography and standard spirometry. Both of these employ basic pieces of equipment to clinically test lung function. Body plethysmography (also known as body box) is favored for measuring the functional residual capacity of the lungs and their total capacity.[23] However, subjects have to sit or stand inside a sealed and restricted chamber. Spirometry is used to measure the volume of air inspired and expired by the lungs through a differential pressure transducer.[10] As a result of its portability and convenience, spirometry is applied preferentially to patients trained in the clinical and home settings, but it cannot estimate the chest wall movement externally.

OEP is a new technique for depicting breathing pattern based on the three-compartment model of chest wall motion. The disadvantages of using OEP are that it usually takes 1 hour for analyzing the motion and it requires sophisticated motion analysis equipment, which may limit its feasibility in clinical practice. However, its advantages are that it assesses mainly the directional changes in the chest wall and can be used to assess the movement pattern externally, as well as lung volume changes in different compartments in patients with lung or respiratory deficits. We suggest the OEP is an appropriate supplementary evaluation tool for supporting clinical diagnosis.

Methodology of US

In our pilot study, we used fluoroscopy to measure axial movement of the right diaphragm (i.e. the difference in vertical distance between the skin-marker horizontal line and diaphragm during inspiration and expiration). We compared it with DE measured by US (i.e. the difference in linear distance between the skin probe and diaphragm during inspiration and expiration) at the same inspired volume (Figure 2). The correlation between axial movement (i.e. vertical displacement) of the diaphragm measured by fluoroscopy and traced excursion (i.e. not exactly vertical displacement) by US was good ($r = 0.914$). Houston et al[18] and Cohen et al[19] detected DE by US and compared it with spirometry, without transforming to axial movements, and showed that the correlation between traced excursion and spirometry was high ($R^2 = 0.89–0.99$). It seems that measurement of untransformed US images provides a convenient analysis of DE, although Aliverti et al's study by US transformed the DE into axial movement.[8]

Study limitations

There were three limitations to the present study. The first concerned OEP assessment in patients. The relationship between DE and chest wall motion may differ in patients with paralyzed diaphragm or abdominal weakness. Furthermore, based on the study by Binazzi et al,[24] the limitations of OEP in measuring the relative change in V_{UT} and V_{LT} might be that it measures changes in the cephalic margin at the zone of apposition of the diaphragm. This limitation is not important because our correlation study with fluoroscopy was good.

The second limitation concerns US measurement. Ideally, US should record left- and right-side DE. In the present study, only the right side was measured. However, measurements on the left side require introduction of gas into the stomach or bowel, and are not performed often in patients. It is not appropriate to fill the stomach with fluid and tilt the subjects in a head-down position.[25] In the current study, we used an anterior approach to detect right-side DE, and the predictive equation from this study can only predict right-side DE. Another issue regarding US was the penetration depth of the probe. The maximal depth for the US probe (model C11) is 100 mm. At this depth, DE was detected around the zone of apposition, and not the dome area. Hence, deep breathing, and not the maximal inspiratory volume, was measured concurrently by chest wall motion analysis and US in the present study. The DE of tidal breathing (16.41 ± 6.46 mm) and deep breathing (39.09 ± 18.04 mm) in our study was similar to that in previous studies (i.e. average DE in tidal breathing of about 13.90 mm and the DE range in deep breathing of 47.00–67.60 mm).[19,21] Further studies are suggested to employ ultrasonographic probes with greater depth of scanning to detect the whole range of DE when performing measurements of VC.

The third limitation was that there were only 12 subjects in the present study. As a result of the small sample size and narrow age range (20–37 years), the correlation between the compartments and DE can be applied only to young and healthy subjects. To minimize this limitation, future studies should recruit a greater number of subjects with a wider age range.

Clinical application

The present study shows that abdominal movement is closely correlated with diaphragmatic movement. When designing a respiratory training program, clinical staff should take into consideration that abdominal movement increases DE. In the clinical setting, visual observation and tape measurement of the waist circumference at the level of the umbilicus may provide information about movement of the AB compartment and the diaphragm, even in the supine position.

Conclusion

In summary, the 3D motion analysis system provides reliable estimation of lung volume changes in the UT, LT, and AB compartments of subjects in the supine position. Furthermore, the AB compartment has a good linear relationship with DE in normal young subjects in the supine position. The motion analysis or real-time US images of DE can be potentially applied to biofeedback training in patients with respiratory deficits, and to evaluate the training effects on respiratory performance. As a result of methodological limitations, the results of the present study cannot be applied to patients with abdominal weakness. Further studies are required with a larger sample size and ultrasonographic probes with a greater depth of scanning to detect the whole range of DE in patients with different diseases.

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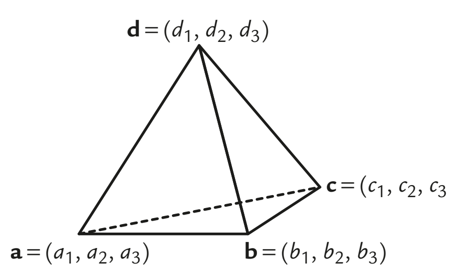
Appendix

For a tetrahedron with vertices $\mathbf{a} = (a_1, a_2, a_3)$, $\mathbf{b} = (b_1, b_2, b_3)$, $\mathbf{c} = (c_1, c_2, c_3)$, and $\mathbf{d} = (d_1, d_2, d_3)$, the volume is $(1/6) \cdot |\det(\mathbf{a} - \mathbf{b}, \mathbf{b} - \mathbf{c}, \mathbf{c} - \mathbf{d})|$, or any other combination of pairs of vertices that form a simply connected graph. This can be rewritten using a dot product and a cross product, yielding det = determinant.



$$V = \frac{|(a - b) \cdot (b - d) \times (c - d)|}{6}$$