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Nozoe, Masafumi

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Regional Chest Wall Volume Changes During Various Breathing Maneuvers in Normal Men

Masafumi NOZOE[1,3], Kyoshi MASE[2] and Akimitsu TSUTOU[3]

[1)] *Department of Rehabilitation, Hyogo College of Medicine Sasayama Medical Center Kurooka 5, Sasayama, Hyogo, 669-2321 Japan*

[2)] *Department of Physical Therapy, Faculty of Nursing and Rehabilitation, Konan Women's University*

[3)] *Division of Preventive Health Sciences, Department of Community Health Sciences, Faculty of Health Sciences, Kobe University Graduate School of Health Sciences*

ABSTRACT. Purpose: The purpose of this study is to investigate the regional chest wall volume changes during various breathing maneuvers in normal men with an optical reflectance system (OR), which tracks reflective markers in three dimensions. Methods: Chest wall volume was measured by the OR system [V_L(CW)], and lung volume was measured by hot wire spirometry [V_L(SP)] in 15 healthy men during quiet breathing (QB), during breathing at a rate of 50 tidal breaths/min paced using a metronome (MT: metronome-paced tachypnea), and during a maximal forced inspiratory and expiratory maneuver (MFIE maneuver). Results: There were few discrepancies between V_L(CW) and V_L(SP) for QB and MT. In the MFIE maneuver, however V_L(CW) was often underestimated compared with V_L(SP), particularly during forced maximal expiration, because of pulmonary rib cage volume changes. Furthermore, the regional chest wall volume changes were affected by breathing maneuver alternation. In the pulmonary and abdominal rib cage, inspiratory reserve volume was larger than expiratory reserve volume, respectively, and in the abdomen, expiratory reserve volume was larger than inspiratory reserve volume. Conclusion: Alternation of breathing maneuvers affects regional chest wall volume changes.

Key words: chest wall volume, breathing maneuver, three-dimensional motion analysis

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In patients with respiratory diseases, such as chronic obstructive pulmonary disease (COPD) patients, lung volume changes are a factor in dyspnea and affect exercise tolerance and ability to perform activities of daily living (ADL)[1,2]. In the clinical setting, we often evaluate the chest wall motion of these patients by palpation or inspection during quiet breathing, breathing training, and exercise because it reflects lung volume changes. Thus, we need to understand the exact regional chest wall volume changes during several breathing maneuvers which have different speed or depth in humans. Many previous studies have tried to measure regional chest wall volume changes[3,4]. Methods have been applied during quiet breathing and exercise, such as magnetometer[3], which measures the change in separation of two points, and respiratory inductive plethysmography (RIP)[4], which calculates the cross-sectional area of the rib cage and abdomen. However, these methods fail to measure the motion of the total chest wall with three degrees of freedom, and they often contain measurement errors obtained during the vital capacity maneuver that arise as a result of postural changes[5,6].

On the other hand, Cala *et al.*[7] first described the method of using an optical reflectance (OR) system for measuring chest wall volume change [V_L(CW)]. The OR method has since been used in several studies[8–12]. It is more accurate than conventional methods of chest wall analysis, such as magnetometer[5] and RIP[6]. Thus, we thought that the OR method would be useful for studying regional chest wall volume changes during several breathing maneuvers in humans. Previous study[7] also reported the accuracy of measuring the total chest wall volume changes during hyperpnea and a slow vital capavcity maneuver by the OR method. However, they did not show the accuracy during forced vital capacity maneuver which we often assess in the

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Correspondence to: Masafumi Nozoe, Department of Rehabilitation, Hyogo College of Medicine Sasayama Medical Center Kurooka 5, Sasayama, Hyogo, 669-2321 Japan
e-mail: sasareha@hyo-med.ac.jp

clinical setting, and the regional chest wall volume changes during various breathing maneuvers.

The purpose of this study was to investigate the regional chest wall volume changes during various breathing maneuvers in normal men by OR, which tracks reflective markers in three dimensions.

Methods

Subjects

We studied 15 healthy men. All subjects were free of cardiopulmonary disorders and had normal lung volumes and forced expiratory volume in 1 second (Table 1). Written informed consent was obtained after a description of the study protocol, which was approved by the appropriate Ethics Committee at Konan Women's University, Japan.

Table 1. Anthropometric and pulmonary function data (n = 15)

	Mean ± SE
Age (years)	26.9 ± 1.3
Height (m)	1.73 ± 0.02
Body mass weight (kg)	65.1 ± 2.3
BMI (kg/m^2)	21.7 ± 0.6
VC (L)	4.24 ± 0.17
%VC (%)	100.0 ± 4.2
FEV_1 (L)	3.50 ± 0.11
%FEV_1 (%)	81.4 ± 2.8
FEV_1/VC (%)	83.3 ± 2.4

BMI: body mass index, VC: vital capacity, %VC: VC % predicted, FEV1: forced expiratory volume in 1 second, %FEV_1: FEV_1 % predicted

Lung volume computed by OR

According to the method described in a previous study by Cala *et al.*[7], we measured changes in chest wall volume using a three-dimensional motion analysis system (Mac 3D System, Motion Analysis Corporation, San Diego, CA, USA). Passive markers made of thin retroreflective film on plastic spheres with diameters of 9 and 7 mm were used. The markers were fixed to the chest wall surface using bi-adhesive hypoallergenic tape. The position of each marker was also determined as described in a previous study[7]; 42 were anterior, 34 were posterior, and 10 were lateral (Fig. 1). To prevent errors in measurement when markers were in close proximity to one another, markers with a diameter of 7 mm were used.

The subjects stood with their arms down at the sides avoiding lateral markers were hidden. Eight video cameras (Eagle, Motion Analysis Corporation) were positioned such that four were 2–4 m in front of the subject, with the other four behind the subject, and two pairs of cameras were arranged vertically. The shutter speed of each camera was set to 0.002 sec.

The coordinate data of all reflective markers were sampled at 100 Hz using analysis software (EVaRT5.04, Motion Analysis Corporation) and the system had an accuracy of ~0.2 mm in each spatial coordinate. Chest wall volume was then calculated using the following method (Fig. 2).

First, the midpoint of each horizontal line was calculated and defined as a vertex, and the three markers adjoining

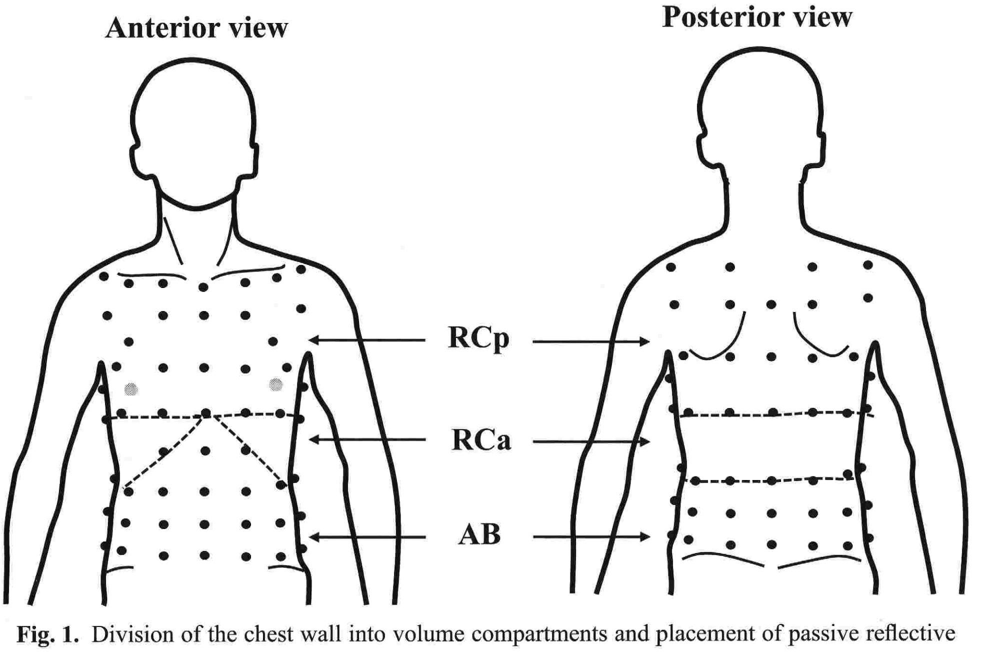

Fig. 1. Division of the chest wall into volume compartments and placement of passive reflective markers on the chest wall: 42 anterior, 34 posterior, and 10 lateral markers between the clavicles and anterior superior iliac crest for erect subjects. RCp, pulmonary rib cage; RCa, abdominal rib cage; AB, abdomen.

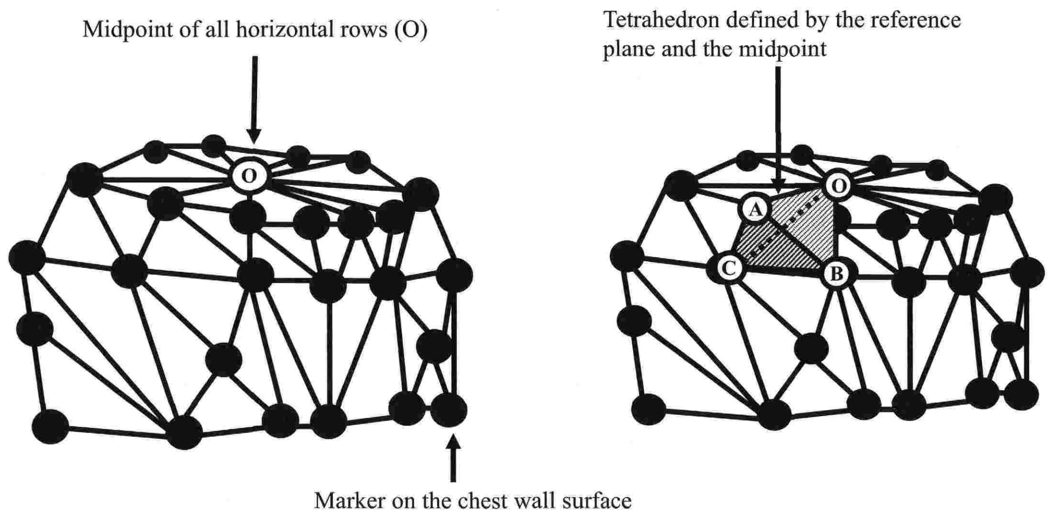

Fig. 2. Diagram of volume computation. Every set of three adjacent markers placed on the skin surface is used as a reference plane. The volume of the tetrahedron defined by the reference plane and the midpoint is then computed. Each frame contains 219 tetrahedrons, the volumes of which are summed to obtain the chest wall volume.

this point on the body surface were defined as the base of a tetrahedron. Each tetrahedron was defined as one unit, and 219 tetrahedrons were constructed for each chest wall.

The volume of each tetrahedron was calculated using position vectors as the four marker coordinates. The three adjoining markers on the body surface were defined as A, B, and C, and the midpoint of each horizontal line was defined as O. The coordinates A, B, C, and O were defined as (ax, ay, az), (bx, by, bz), (cx, cy, cz), and (ox, oy, oz), respectively, and the position vectors were defined as $\overrightarrow{OA}$ = (ax−ox, ay−oy, az−oz), $\overrightarrow{OB}$ = (bx−ox, by−oy, bz−oz), and $\overrightarrow{OC}$ = (cx−ox, cy−oy, cz−oz). The volume (V) of the tetrahedron OABC was then calculated as V = 1/6 [(ax−ox) × (by−oy) × (cz−oz) + (ay−oy) × (bz−oz) × (cx−ox) + (az−oz) × (bx−ox) × (cy−oy) − (ax−ox) × (bz−oz) × (cy−oy) − (ay−oy) × (bx−ox) × (cz−oz) − (az−oz) × (by−oy) × (cx−ox)]. Chest wall volume was computed by summing the total volume of the tetrahedrons.

Lung volume obtained by spirometry (SP)

Air flow was measured using hot wire spirometry connected to face mask (AE300-s, Minato Medical Science, Tokyo, Japan), with the flow signal integrated to give volume. The volume data were analyzed by software (EVaRT5.04) synchronized with the automatic motion analyzer and digitally recorded at 100 Hz. Assessment of lung volume changes using flow-sensing devices such as spirometry is prone to base-line "drift" that occurs in the signal because of electrical changes over time. This drift was corrected prior to analysis by performing paired-inspiratory capacity (IC) maneuvers at the beginning and end of the recording period, based on the method reported by Johnson *et al.*[13]. Assuming that maximal inhalation volume is equal during both maneuvers, the peak can be aligned by performing interpolated volume correction between the two points. The difference between paired-ICs was divided by time to calculate the change in volume caused by drift for 0.01 sec; the change due to drift was then subtracted from the measured volume change.

Protocol

Spirometry measurements were obtained for each subject under the following three breathing conditions: 1) quiet breathing (QB: 1 min); 2) metronome-paced tachypnea[14] (MT: 50 breaths/min, 30 sec) to assess the regional chest wall volume changes during breathing speed was increased without changing depth (rapid shallow breathing); and 3) the maximal forced inspiratory and expiratory maneuver (MFIE maneuver: maximal forced inspiration from residual volume to total lung capacity, and maximal forced expiration from total lung capacity to residual volume) to assess the regional chest wall volume changes during breathing speed and depth were increased. In MT, we coached subjects to avoid increasing tidal volume compared to QB. No constraints were given to the movement during all breathing maneuvers. Each subject performed three MFIE maneuvers; data from the maneuver with the highest forced expiratory volume were used for analysis.

Data analysis

First of all, V_L(CW) and lung volumes by hot wire spirometry [V_L(SP)] were compared according to methods described by Cala *et al.*[7] and Kenyon *et al.*[11]. Specifically, lung volume was computed by assuming that end expiratory V_L(SP) was equal to V_L(CW) when the residual volume calculated from spirometry was 0 L[11]. Regression analysis was performed between V_L(CW) and V_L(SP) for all breathing maneuvers in all subjects, and the coefficient, intercept,

Table 2. Linear regression parameters of OR measurements of chest wall volume changes with respect to volume changes measured by SP during three breathing maneuvers (n = 15)

	Slope	Intercept (L)	r^2	Coeff. of Variation
QB	1.01 ± 0.01	-0.01 ± 0.03	0.99 ± 0.01	1.7 ± 0.2
MT	1.00 ± 0.01	0.01 ± 0.02	0.99 ± 0.01	1.9 ± 0.3
MFIE maneuver	1.01 ± 0.01	-0.05 ± 0.02	0.99 ± 0.01	9.1 ± 1.2*†

mean ± SE *: $p < 0.01$ vs. QB, †: $p < 0.01$ vs. MT

OR: optical reflectance system, SP: spirometry, QB: quiet breathing, MT: metronome-paced tachypnea, MFIE: maximal forced inspiratory and expiratory, Coeff.: coefficient.

coefficient of determination, and coefficient of variation of residual error were computed. Comparisons of the coefficients of variation among the three breathing maneuvers were performed using the paired *t*-test, for which Bonferroni-type adjustment was carried out.

For all measurements, total and regional chest wall (CW, chest wall; RCp, pulmonary rib cage; RCa, abdominal rib cage; AB, abdomen) (Fig. 1)[11] volume changes and V_L(SP) during tidal inspiration and expiration were computed for all breathing maneuvers. Then, the tidal inspiratory volume percentage contribution to total chest wall inspiratory volume of the different compartments (% tidal volume) was calculated for all measurements. Finally, inspiratory and expiratory reserve volumes (IRV, ERV, respectively) in total and regional chest wall compartments were computed from the measurements of QB and the MFIE maneuver to assess the compartmental reserve volume characteristics (IRV: the difference of chest wall volumes at the end of inspiration during the MFIE maneuver and QB, ERV: the difference of chest wall volumes at the end of expiration during the MFIE maneuver and QB). Comparisons of inspiratory and expiratory tidal volume measured by OR and SP, regional chest wall volume changes, and IRV and ERV in total and in regional chest wall compartments were performed using the paired *t*-test. Comparisons of % tidal volume were performed using two-way ANOVA, with Bonferroni methods on a post hoc basis. The level of significance was set at $p < 0.05$. All statistical procedures were performed using SPSS 12.0J for Windows statistical software (SPSS Inc., Chicago, IL, USA).

Results

Comparison between V_L(CW) and V_L(SP)

Table 2 shows the results of regression analysis between V_L(CW) and V_L(SP) for QB, MT, and the MFIE maneuver; representative data are also shown in Fig. 3. The coefficients of variation of residual error from regression of V_L(CW) vs. V_L(SP) during QB and MT were very low and significantly lower than for the MFIE maneuver ($p < 0.01$). For the MFIE maneuver, the maximal difference between V_L(CW) and V_L(SP) occurred during maximal expiration in all subjects, and V_L(CW) was often underestimated compared with V_L(SP). The maximal discrepancy between V_L(CW) and V_L(SP) was 0.48 ± 0.24 L in the MFIE maneuver, but -0.01 ± 0.05 L and -0.03 ± 0.07 L, respectively, in QB and MT.

Table 3 shows the tidal inspiratory and expiratory volumes measured by OR and SP during three breathing maneuvers. There were no significant differences between V_L(OR) and V_L(SP) during QB, MT, and inspiration for the MFIE menauver. However, during expiration for the MFIE maneuver, there was a significant discrepancy between V_L(OR) and V_L(SP).

Regional chest wall volume changes during three different breathing maneuvers

Table 4 shows the tidal inspiratory and expiratory volumes in the regional chest wall compartments during all maneuvers. There were no significant differences between the volume of inspiration and expiration in all compartments during QB and MT. However, during the MFIE maneuver, there was a significant discrepancy between CW and RCp.

Table 5 shows the tidal inspiratory volume percentage contribution to total chest wall inspiratory volume of the different compartments. Alternation of breathing maneuvers affected regional chest wall volume changes ($p < 0.01$; ANOVA), and the MFIE maneuver had higher RCp and RCa contributions than other breathing maneuvers, but a lower AB contribution. There were no significant compartmental contribution differences between QB and MT.

Static chest wall volumes

Table 6 shows IRV and ERV in total and regional chest wall volume. From comparisons between IRV and ERV in total and in each compartment, there was no significant difference between IRV and ERV in CW. However IRV was higher than ERV in RCp and RCa, respectively, while IRV was lower than ERV in AB.

Discussion

The regional chest wall volume changes during QB,

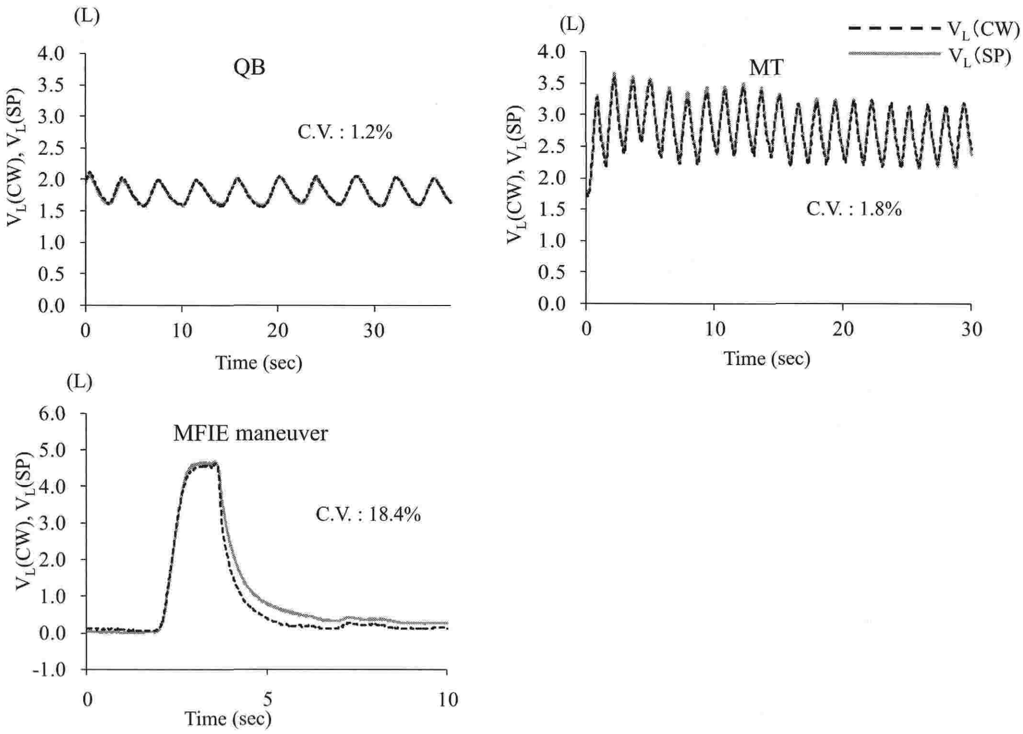

Fig. 3. Representative examples of QB, MT, and the MFM. The dashed line indicates the estimated changes in volume by OR (V_L(CW)), and the solid line is spirometry (V_L(SP)). In QB and MT, V_L(CW) and V_L(SP) have similar changes. However in the MFIE maneuver, V_L(CW) is underestimated compared with V_L(SP) particularly during maximal forced expiratory phase.

QB: quiet breathing, MT: metronome-paced tachypnea, MFIE: maximal forced inspiratory and expiratory, C.V.: coefficient of variation, OR: optical reflectance system, CW: chest wall, SP: spirometry.

Table 3. Tidal inspiratory and expiratory volumes measured by OR and SP during three breathing maneuvers. (n = 15)

	inspiration		expiration	
	V_L(CW)	V_L(SP)	V_L(CW)	V_L(SP)
QB (L)	0.52 ± 0.04	0.52 ± 0.04	0.51 ± 0.04	0.51 ± 0.04
MT (L)	0.54 ± 0.03	0.54 ± 0.03	0.54 ± 0.03	0.54 ± 0.03
MFIE maneuver (L)	4.09 ± 0.16	4.00 ± 0.16	4.24 ± 0.14	4.02 ± 0.16*

mean ± SE *: $p<0.05$ vs. V_L(CW)

OR: optical reflectance system, SP: spirometry, V_L(CW): chest wall volume measured by optical reflectance system, V_L(SP): lung volume measured by hot wire spirometry, QB: quiet breathing, MT: metronome-paced tachypnea, MFIE: maximal forced inspiratory and expiratory.

Table 4. Tidal inspiratory and expiratory volumes in total and regional chest wall during three breathing maneuvers. (n = 15)

	QB		MT		MFIE maneuver	
	inspiration	expiration	inspiration	expiration	inspiration	expiration
CW (L)	0.52 ± 0.04	0.51 ± 0.04	0.54 ± 0.03	0.54 ± 0.03	4.09 ± 0.16	4.24 ± 0.14*
RCp (L)	0.15 ± 0.02	0.15 ± 0.02	0.19 ± 0.02	0.18 ± 0.02	1.66 ± 0.06	1.78 ± 0.08*
RCa (L)	0.12 ± 0.01	0.12 ± 0.01	0.15 ± 0.02	0.15 ± 0.02	1.29 ± 0.08	1.30 ± 0.08
AB (L)	0.24 ± 0.03	0.24 ± 0.03	0.21 ± 0.02	0.21 ± 0.02	1.14 ± 0.09	1.17 ± 0.08

mean ± SE *: $p < 0.01$ vs. MFIE maneuver during inspiration

QB: quiet breathing, MT: metronome-paced tachypnea, MFIE: maximal forced inspiratory and expiratory, CW: chest wall, RCp: pulmonary rib cage, Rca: abdominal rib cage, AB: abdomen.

Table 5. Tidal inspiratory volume distribution in the three different chest wall compartments during three breathing maneuvers. (n = 15)

	QB	MT	MFIE maneuver
RCp (%)	29.1 ± 2.2	33.0 ± 2.7	40.9 ± 1.3*†
RCa (%)	24.2 ±1.9	26.6 ± 1.9	31.0 ± 1.2*†
AB (%)	46.7 ± 3.4	40.3 ± 4.0	27.7 ± 1.5*†

mean ± SE *: $p < 0.01$ vs. QB, †: $p < 0.01$ vs. MT

QB: quiet breathing, MT: metronome-paced tachypnea, MFIE: maximal forced inspiratory and expiratory, CW: chest wall, RCp: pulmonary rib cage, Rca: abdominal rib cage, AB: abdomen.

Table 6. Inspiratory and expiratory reserve volume in total and in regional chest wall compartments. (n = 15)

	IRV	ERV
CW (L)	1.91 ± 0.09	1.81 ± 0.09
RCp (L)	0.96 ± 0.06	0.69 ± 0.05*
RCa (L)	0.76 ± 0.05	0.43 ± 0.05*
AB (L)	0.24 ± 0.06	0.70 ± 0.03*

mean ± SE *: $p < 0.01$ vs. IRV

IRV: inspiratory reseve volume, ERV: expiratory reserve voleum, CW: chest wall, RCp: pulmonary rib cage, Rca: abdominal rib cage, AB: abdomen.

MT, and the MFIE maneuver were studied in healthy men by OR. For the MFIE maneuver, the coefficient of variation of residual error from regression of V_L(CW) vs. V_L(SP) was significantly higher than for the two maneuvers, and V_L(CW) was often underestimated, particularly during forced maximal expiration. The regional chest wall volume changes were affected by breathing maneuver alternation, particularly in the MFIE maneuver.

Comparison between V_L(SP) and V_L(CW)

A recent study proposed that two factors induce the difference between V_L(SP) and V_L(CW): underestimation of V_L(CW) by gas compression effects when air is compressed by increasing pleural pressure[15]; and overestimation of V_L(CW) during inspiration and underestimation of V_L(CW) during expiration because of the movement of blood from the thorax to the extremities[15]. The relationships between these factors were also investigated in this earlier study. The change of chest wall volume (ΔVcw) was equal to the sum of lung volume change (ΔV_L) and blood shift of venous return (VB) ($\Delta Vcw = \Delta V_L + VB$). ΔV_L was taken as the sum of the volume of gas exhaled at the mouth (ΔVm) and the volume of gas compression (ΔVc) ($\Delta V_L = \Delta Vm + \Delta Vc$). Therefore, $\Delta Vcw = \Delta Vm + \Delta Vc + VB$. This relationship shows that there are many factors other than change in lung volume that affect volume change in the chest wall. Nevertheless, the present results showed a very small discrepancy during QB and MT. We concluded that the discrepancy was small for these two maneuvers because there was negligible gas compression or blood shift in venous return.

In contrast, there was a high degree of discrepancy between V_L(SP) and V_L(CW) in the MFIE maneuver. During forced maximal expiration in particular, underestimation of V_L(CW) was marked, and tidal expiratory volume in CW increased more than inspiratory volume because of RCp volume changes. Blood shift from the extremities to the thorax generally increases during inspiration and decreases during expiration[16]. Gas compression, however, is observed in forced maximal expiration[17,18]. Therefore, we consider that the main factor inducing the difference between V_L(SP) and V_L(CW) during forced maximal expiration was compression of gas in the lung, and these effects could be seen in RCp volume changes. We also considered that high pleural pressure during maximal expiration could decrease the RCp volume even without V_L(SP) changes.

Regional chest wall volume changes during three different breathing maneuvers

The MFIE maneuver has higher RCp and RCa contributions than other breathing maneuvers, but QB and MT have a higher AB contribution than the MFIE maneuver. In the previous study, humans performed static inspiration mainly with their intercostals and accessory muscles[19]. Thus, the present subjects tended to have higher RCp and RCa contributions during the MFIE maneuver, including maximal inspiration. No significant difference between QB and MT compartmental contributions was seen, but a previous study showed that rapid breathing was accomplished mostly through rib cage displacement[20]. The difference compared to our results was probably due to the difference in measuring methods, because the previous study used a magnetometer. From the present results measured by the OR system, rapid shallow breathing during normal conditions affects only breathing speed but not chest wall volume contribution.

Static chest wall volumes

From the results of the chest wall reserve volumes, IRV was higher than ERV in RCp and RCa, respectively. On the other hand, IRV was lower than ERV in AB. These findings were explainable by the mechanical characteristics of the rib cage and abdomen[21,22]. Konno and Mead showed that, although rib cage compliance changes little with increasing volume, abdominal compliance decreases markedly as its volume increases[21]. Thus, RCp and RCa have a tendency to increase the volume, but AB have a tendency to decrease the volume. This is the reason for our results that IRV was higher in RCp and RCa, and the ERV was higher in AB.

Limitations of the study

The present study showed the regional chest wall volume changes during various breathing maneuvers in normal men, but not in women or obese subjects. Bellemare *et al.*[23] reported that females have smaller radial rib cage dimensions in relationship to height than male and a greater inclination of the ribs. In obese subjects, diaphragm motion and chest wall size and shape were different from normal men[24]. Therefore regional chest wall volume changes in these subjects may be different from the present subjects. These considerations indicate that our results can been applied to normal men, but not to other subjects.

Conclusion

We measured regional chest wall volume changes during QB, MT, and the MFIE maneuver using a three-dimensional motion analyzer in normal men. In the MFIE maneuver, $V_L(CW)$ was often underestimated, particularly during forced maximal expiration, because of RCp volume changes. The regional chest wall volume changes were affected by breathing maneuver alternation. In the rib cage, IRV was larger than ERV, respectively, and in the abdomen, ERV was larger than IRV.

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