A dynamic analysis of chest wall motions with MRI in healthy young subjects*

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Objective: The objective of this study was to analyse respiratory-related motion of the chest wall with non-invasive method.

Methodology: Using magnetic resonance image (MRI), 30 sequential images (scanning time, 0.4 s per image) on sagittal, axial and coronal planes were obtained in nine healthy young subjects during quiet breathing (QB) and maximal deep breathing (MDB). The coronal planes were obtained in five of nine subjects during MDB. Ventilation was simultaneously measured with pneumotachometer.

Results: There was a linear correlation between instantaneous lung volume and lung cross-sectional area. Motion of the diaphragm and rib cage was also linearly related to instantaneous lung volume. The exception was lower anteroposterior (AP) diameter of the rib cage. The contribution of individual part of the chest wall motion to a unit lung volume change was assessed by slope (S) of the linear regression line. The S at the anterior diaphragm was significantly smaller than those at middle and posterior parts during MDB. The S of middle and posterior diaphragmatic motion was approximately five times that of AP motion of upper rib cage. The S of AP motion of upper rib cage was twice that of transverse motion during either QB or MDB.

Conclusion: We concluded that dynamic MRI study with concurrent ventilation measurement is a simple and reliable method for evaluation of local chest wall motion, and that neither diaphragm nor rib cage works as a single functional unit during active ventilation.

Key words: diaphragmatic motion, non-invasive analysis, pneumotachometer, pulmonary mechanics.

INTRODUCTION

Non-invasive measurement of chest wall motion includes the magnetometer, inductive plethysmography, fluoroscopy, computed tomography, and optical reflection. However, most of these methods have disadvantages such as radiation exposure, inability to obtain information about the diaphragmatic contour or the necessity of a special system. Magnetic resonance imaging (MRI) can overcome these disadvantages, although it requires a prolonged period to acquire individual images and it generates a strong electromagnetic field. The former problem has restricted MRI studies to quasi-static analysis and the latter has hindered simultaneous use of electronic instruments. Because recent advances in MRI technology, such as the fast-spin echo method, have shortened image acquisition time, we planned a dynamic analysis of chest wall motion by MRI. To match each MRI image to instantaneous lung volume, we simultaneously recorded subjects’ respiratory flow by insulating a pneumotachograph from the electromagnetic field. In this study we tested whether MRI with simultaneous recording of respiratory flow could be applicable to a dynamic analysis of chest wall motion, and investigated how the chest wall changes during breathing in healthy young subjects.
MATERIALS AND METHODS

The subjects were nine male healthy volunteers. They joined the study after a full explanation of the research objectives and the recording procedure, but none were informed about the expected results of the study. The ethics committee of Tokai University School of Medicine approved the objective and procedure of the study. Each subject lay supine in an MRI instrument (Gyroscan ACS NT15; Philips Medical Systems, Best, The Netherlands) wearing an air-tight face mask for nasal continuous positive airway pressure ventilation (CPAP). The mask was connected to a Fleisch pneumotachograph (TV112T; Nihon Kohden Tokyo, Japan, Tokyo, Japan) whose stainless steel shell was replaced by a Teflon one. The pressure transducer for the pneumotachograph (TP602T; Nihon Kohden) was stored in a box composed of 1 mm thick steel plate and 1 mm thick copper plate to insulate it from the strong electromagnetic field of the MRI. The box was fixed on the floor approximately 1 m from the MRI scanner. An electronic system (AR601G, AQ601G; Nihon Kohden) transformed the signals from the pneumotachograph to respiratory flow and volume signals. The respiratory volume output was calibrated by a 2 L syringe while the pneumotachograph was in its final position. We confirmed the reproducibility and linearity of the volume signals by blowing 0.5, 1.0, 1.5, and 2.0 L of air through the pneumotachograph.

The MRI was operated by fast-spin echo mode T1 (repetition time of 400 ms, echo time of 60 ms, 73 x 256 phase-encoding steps, flip angle of 90°, and thickness of 12 mm). The time to scan one slice was 0.4 s. Thirty sequential sagittal images at the right mid-clavicular line were obtained during quiet breathing and during maximal deep breathing. During maximal deep breathing we simply asked the subjects to breathe as deeply as possible. Then, 30 sequential axial images at the tracheal bifurcation level were obtained during quiet breathing and during maximal deep breathing. In five of them, coronal images at the tracheal bifurcation level were also obtained during maximal deep breathing. As shown by example pictures in Fig. 1, the MRI provided good resolution of the thoracic images. The MRI scanner generated sounds which were augmented during each of the image acquisitions. We recorded these sounds on a chart recorder simultaneously with respiratory volume, and thus matched each MRI image to the instantaneous respiratory volume.

Each MRI image was transferred to a personal computer. Using software (NIH-image, ftp://zippy.nih.gov/pub/nih-image/), the inner contour of the thoracic wall in each image was automatically detected. All of the following parameters were determined by the software. In the sagittal images (Fig. 2a), the area within the thoracic margin was automatically measured. We drew a line tangent to the lung apex and perpendicular to the MRI platform. The distances from this line to the diaphragm at the anterior chest wall margin, at the tracheal bifurcation level, and at the posterior chest wall margin were measured as the parameters of diaphragmatic motion. Thoracic anteroposterior (AP) diameters at the level of third spine and at the tracheal bifurcation, and at the boundary of the anterior rib cage were also measured. In the axial images (Fig. 2b), the cross-sectional area of the thorax, the anteroposterior diameter at the right mid-clavicular line, and transverse diameter at the tracheal bifurcation were measured. In the coronal images (Fig. 2c), a line tangent to the thoracic apex and parallel to the MRI platform was drawn. The distances from this line to the diaphragm at the right lateral chest wall margin, at right mid-clavicular line, and at the mediastinal margin were measured. Thoracic transverse diameters at the level of the tracheal bifurcation and at the level of costophrenic angle were also measured.

Figure 1 Examples of sagittal, axial and coronal magnetic resonance images at end-inspiratory levels of deep breathing.
Since it took 0.4 s to scan one MRI image, the exact lung volume corresponding to each of the images was not able to be determined. We measured the instantaneous lung volumes with three timings, at the onset, at the middle, and at the end of each scan, and matched them to MRI images. We found that lung volume at the end of each scan frequently missed the exact end-expiratory levels. In contrast, the measured chest wall dimension in MRI images were only slightly changed (<5%) by measuring lung volume either at the onset or middle of each scan duration. Thus, we assumed that the lung volumes corresponding to each MRI images were those at the middle of each scan.

All distances were measured as the number of pixels and converted to cm. One pixel represented approximately 0.08 cm. The processed data were expressed as mean ± SD. Statistical analysis was performed using a one-way ANOVA. Values of P < 0.05 were considered significant.

RESULTS

The mean age of the subjects was 28.6 ± 3.2 years old and mean height was 171.6 ± 5.8 cm. The mean FVC and FEV₁ were 4.62 ± 0.36 L and 3.68 ± 0.31 L, and were within the predicted normal range. For all subjects, images for two or three breaths were recorded during quiet breathing, and images for 1.5 or two breaths were recorded during maximal deep breathing.

Table 1  Mean (SD) tidal volume (L) during magnetic resonance image acquisition

<table>
<thead>
<tr>
<th>Healthy subjects</th>
<th>Sagittal</th>
<th>Axial</th>
<th>Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet breathing</td>
<td>0.70 (0.20)</td>
<td>0.68 (0.15)</td>
<td>0.74 (0.05)</td>
</tr>
<tr>
<td>Maximal deep breathing</td>
<td>2.04 (0.49)*</td>
<td>2.18 (0.67)*</td>
<td>2.19 (0.91)*</td>
</tr>
</tbody>
</table>

* P<0.05 compared with quiet breathing.

Ventilation during image acquisition

Table 1 shows the mean tidal volumes during each of the image acquisitions. The mean tidal volumes during quiet breathing were between 0.68 and 0.74 L and were not significantly different to each other. The mean tidal volumes during maximal deep breathing were approximately three times that of quiet breathing. They were significantly larger than the corresponding tidal volumes during quiet breathing. The differences of mean tidal volumes during maximal deep breathing in each of image acquisitions were not significantly different to each other.

Linearity of chest wall motions

Figure 3 shows the diaphragmatic motions (i.e. distances from the thoracic apex to the diaphragm), at the anterior chest wall margin and at the posterior chest wall margin, and lung volume changes during quiet breathing in a representative subject. In 12 s of sagittal images obtained with each 0.4 s interval, lung vol; ○, ANT; △, PST.
dimensions change linearly with changes in lung volume. Figure 4 shows a cross-sectional lung area and each of the distances measured on the sagittal image plotted against the corresponding lung volumes during maximal deep breathing from the same subject as in Fig. 3. All measured parameters correlated well with the instantaneous lung volumes. There also was a linear correlation between these parameters and lung volume during quiet breathing on sagittal images, and during quiet and maximal deep breathings in axial and coronal images. Thus, we assessed respiratory changes in these parameters by the slope (S), y-axis intercept (C), correlation coefficient (R), and the P value of the linear regression. If R at any part of the chest wall is high, the S of the corresponding part of the chest wall represents the contribution of its motion to a unit change in lung volume. If R of the regression lines are high, we are able to compare the contribution of different parts and different planes of the chest wall motion to the change in lung volume by using S. The C represents the cross-sectional area or the distance at end-expiration. If the P value of the regression line was less than 0.05 the relationship was regarded as sufficiently linear.

**Instantaneous lung volume and cross-sectional lung area**

Figure 5 shows the mean values and SD of R, S, and C of the linear regressions of cross-sectional lung area versus instantaneous lung volume. Cross-sectional lung area on coronal images were not obtained because respiratory motions of heart and large vessels were not negligible in these images (see Fig. 1). The mean R at either sagittal or axial image were extremely high (> 0.80) during either maximal deep or quiet breathing, suggesting that changes in cross-sectional lung area were linearly related to lung volume changes. The P values of each parameter were all less than 0.05.

The S of maximal deep breathing were not significantly different from those during quiet breathing in either of the images. The S of sagittal image were tended to be higher than those in axial image, but these differences were not significant.

At either of the images, C of maximal deep breathing were not significantly different from those of quiet breathing, suggesting that end-expiratory cross-sectional lung area did not increase in maximal breathing. The C during quiet breathing were not different from those during maximal deep breathing.

![Figure 4](image1.png)

*Figure 4* The parameters measured from the sagittal images during maximal deep breathing are plotted against corresponding lung volumes. The volume 0 represents that at end expiration. Linear regression lines are drawn for each of the parameters: ▲, APlw; ●, APsg; ○, ANT; □, CNT; △, PST; ■, ARA. ARA, cross-sectional lung area; abbreviation of the other parameters are the same as in Figure 2.

![Figure 5](image2.png)

*Figure 5* Mean values and SD of correlation coefficient (R), slope (S) and y-axis intercept (C) of the linear regressions cross-sectional lung area is lung volume. □, maximal deep breathing (MDB); ●, quiet breathing (QB).
Instantaneous lung volume and
diaphragmatic motions

Figure 6 shows R, S, and C of the linear regressions at each of the diaphragmatic motions. The distance between the lung apex and the diaphragm measured at the central diaphragm in sagittal image (CNT) was almost the same as that measured at middle diaphragm in coronal image (MID). Thus, although the original images were different, the corresponding R, S and C in the two images were almost the same. The P values of each regression were all less than 0.05.

The mean R at each portion of the diaphragm were extremely high (>0.80) during either maximal or quiet breathing, suggesting that diaphragmatic motion was linearly related to lung volume changes. The S of the anterior part of the diaphragm (ANT) was significantly lower than that of posterior part (PST) during maximal deep breathing. The S obtained from the lateral (LAT), middle (MID) and inner (IN) parts of the diaphragm in coronal image were almost the same, suggesting that the diaphragm moved evenly in coronal image. The S of any part of the diaphragm during quiet breathing tended to be greater than those during maximal deep breathing but the differences were not significant.

The C fairly depicted the shape of diaphragm contour at end expiration. The C during quiet breathing were not different from those during maximal deep breathing.

Instantaneous lung volume and
rib cage motions

Figure 7 shows R, S, and C of the linear regressions of the chest wall motions at each portion of the rib cage. As similar to the diaphragm, sagittal AP diameter and axial AP diameter (i.e. APsg and APax), and axial transverse diameter and coronal transverse diameter (i.e. TRax and TRcr) measured almost the same portions of the rib cage. It was again seen that R, S and C of rib cage motions at the corresponding portions were almost the same values.

The mean R at each portion of rib cage except at lower rib cage (APlw) were high during either maximal deep (>0.70) or quiet breathing (>0.60). The P value at APlw was also higher than 0.05 in four of nine subjects during quiet breathing while it was higher than 0.05 (i.e. 0.11) only in one subject during maximal deep breathing. The S of APlw was not compared to S at the other part of rib cage because the R and P value of this portion were not sufficient. In other parts of the rib cage, the P value was higher than 0.05 only for lower transverse diameter (TRlw) (i.e. P=0.10 in one subject). The S of upper rib cage AP motion (APsg and APax) was approximately twice that of lower rib cage AP motion (APlw) during maximal deep breathing.
of transverse motion (TRax and TRcr), but difference was not significant. The S of the middle and posterior part of the diaphragm were approximately five times those of the upper rib cage motion, and the differences were significant.

The C during quiet breathing were not different from those during maximal deep breathing.

DISCUSSION

The major findings in this study were that there was a linear correlation between lung volume change and chest wall motion as well as cross-sectional lung area, and that neither rib cage nor diaphragm moved as one functional unit during breathing.

Method

Magnetic resonance imaging (MRI) is a non-invasive method for the analysis of chest wall motion and configuration. However, MRI has several disadvantages for physiological analysis. One of them is its long scanning time. In one report, it was assumed that according to Nyquist's theory, 1.2 s MRI scanning time was short enough to represent the diaphragmatic motion. However, this assumption is not satisfactory because diaphragmatic respiratory displacement is not sinusoidal. Another disadvantage of MRI studies is the lack of information of ventilation. We found that a pneumotachograph can function well during MRI with proper electromagnetic shielding. Owing to the non-invasiveness and speed of our MRI instrument we almost continuously depicted motion of the chest wall in association with instantaneous lung volumes.

We measured the R, S and C of AP diameter and transverse diameters at the upper rib cage on two independent planes. In either AP (i.e. APsg and APax) or transverse (i.e. TRax and TRcr) diameter, the corresponding R, S and C were found to be almost the same. This finding shows reproducibility of this analysis.

The contribution of individual parts of the chest wall motions to lung volume changes was assessed using the variables of the linear regression lines. Although the trajectories of the chest wall motion during inspiration and expiration are theoretically different, the linear relationship between chest wall motion and lung volume change has been shown in several studies. The high R of the regression line suggested that hysteresis of the chest wall motion might be overlooked. We have shown that most portions of the chest wall moved linearly with instantaneous lung volume. However, the contribution (i.e. S) of individual parts of the chest wall to lung volume changes was quite different. The diaphragm contributed approximately five times and the AP diameter two times of the transverse diameter of the rib cage to lung volume change. This may be a mechanism for why the cross-sectional lung area in transverse and sagittal images also has a linear correlation with lung volume changes. Although we did not examine mediastinal configuration in this study, changes in mediastinal structure can also contribute to the linear correlation between cross-sectional area and lung volume.

Chest wall motions

The advantage of this analysis compared with some other non-invasive methods may be the depiction of the chest wall contour. Due to this advantage we analysed the motion of the individual part of the chest wall. In the sagittal image, the contribution (i.e. S) of anterior diaphragmatic motion to ventilation was lower than those of central and posterior parts of the diaphragm. A similar observation has been reported in semistatic vital capacity manoeuvres by Verschakelen et al. who analysed diaphragmatic motion in upright subjects using fluoroscopy. In our study, the lateral, middle and inner parts of the diaphragm moved almost in parallel in the coronal image. Gauthier et al. also reported a piston motion of the diaphragm in a static MRI study. Although inspiratory and expiratory muscles might have been recruited in dynamic breathing, our findings suggested that the motion of the diaphragm was qualitatively an extension of the static condition. This study, furthermore, suggested that the diaphragm did not uniformly move during breathing; the diaphragm does not act as a single functional unit during active breathing.

In the sagittal plane, the contribution of the diaphragm to the lung volume changes estimated by S was almost five times larger than that of the upper rib cage. This value is larger than those measured with a magnetometer which approximated 3.1 times (see figs 11, 14, 16 in Konno & Mead). Since our study estimated the value at a specific plane, where the diaphragmatic contribution to lung volume change is greatest, our results may be larger than the overall contribution of the diaphragm.

The upper rib cage moved in proportion to lung volume change and the slope of linear regression during quiet breathing was almost the same as that during maximal breathing. In contrast, the lower rib cage anteroposterior motion was poorly synchronized with lung volume changes during quiet breathing and it became more linear to lung volume change during maximal deep breathing. This finding suggested that the rib cage is also not a single functional unit.

Since our subject was in the supine posture, his posterior rib cage was fixed to the MRI platform. Thus, the poor synchronization of low AP diameter indicates a poorly synchronized motion of an anterior rib cage. It should be noted that the anterior lower rib cage is a boundary to the anterior diaphragm which is also a poorly synchronized part of the diaphragm. In animal studies it has been reported that the force generated by diaphragmatic contraction is transformed to chest wall expansion at the lower rib cage. Presumably, the ‘recruited’ motion of the lower rib cage may compete with the diaphragmatic contraction during maximal deep breathing. This speculation
is supported by another report describing that sternum becomes convex during inspiration in severe emphysema.\textsuperscript{11}

In conclusion, a dynamic MRI study with concurrent ventilation measurement is a simple and reliable method for evaluation of local chest wall motion. Neither diaphragm nor rib cage work as a single functional unit for active ventilation. The boundary between the anterior diaphragm and lower rib cage possibly has some functional significance for rib cage and diaphragm motions.

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REFERENCES