Interactions of Regional Respiratory Mechanics and Pulmonary Ventilatory Impairment in Pulmonary Emphysema*

Assessment With Dynamic MRI and Xenon-133 Single-Photon Emission CT

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Study objectives: Dynamic MRI and 133Xe single-photon emission CT (SPECT) were used to directly evaluate the interaction of regional respiratory mechanics and lung ventilatory function in pulmonary emphysema.

Methods: Respiratory diaphragmatic and chest wall (D/CW) motions were analyzed by sequential MRI of fast-gradient echo pulse sequences during two to three respiratory cycles in 28 patients with pulmonary emphysema, including 9 patients undergoing lung volume reduction surgery (LVRS). The extent of air trapping in the regional lung was quantified by the 133Xe retention index (RI) on three-dimensional 133Xe SPECT displays.

Results: By contrast to healthy subjects (n = 6) with regular, synchronous D/CW motions, pulmonary emphysema patients showed reduced, irregular, or asynchronous motions in the hemithorax or location with greater 133Xe retention, with significant decreases in the maximal amplitude of D/CW motions (MADM and MACWM; p < 0.0001 and p < 0.05, respectively). The removal of 133Xe retention sites by LVRS effectively and regionally improved D/CW motions in nine patients, with significant increases in MADM and MACWM (p < 0.01 and p < 0.001, respectively). In a total of 40 studies of the 28 patients including post-LVRS studies, normalized MADM and MACWM correlated with percent predicted FEV1 (r = 0.881, p < 0.0001; and r = 0.906, p < 0.0001, respectively), and also with 133Xe RI in each hemithorax (r = 0.871, p < 0.0001; and r = 0.901, p < 0.0001, respectively.)

Conclusions: This direct comparison of regional respiratory mechanics with lung ventilation demonstrated a close interaction between these impairments in pulmonary emphysema. The present techniques provide additional sensitivity for evaluating pathophysiologic compromises in pulmonary emphysema, and may also be useful for selecting resection targets for LVRS and for monitoring the effects.

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Key words: lung; MRI; pulmonary emphysema; respiratory mechanics; ventilation; xenon-133 single-photon emission CT

Abbreviations: 3D = three-dimensional; D/CW = diaphragm and/or chest wall; LAD = length of apposition of the diaphragm; LVRS = lung volume reduction surgery; MACWM = maximal amplitude of chest wall motion; MADM = maximal amplitude of diaphragmatic motion; PFT = pulmonary function test; RI = retention index; RM = respiratory muscle; TDC = time-distance curve; TE = echo time; TR = repetition time; ∆V = lung volume change per unit of time; V0 = function of the minimal/maximal dimension ratio

The analysis of the interaction between impaired respiratory mechanics and abnormal lung ventilation is fundamental to systematic understanding of pathophysiologic compromises in patients with pulmonary emphysema. In these patients, it can be hypothesized that hyperinflated lungs because of air trapping may regionally impair diaphragm and chest wall (D/CW) motions.1–8 Removal of such lung regions by lung volume reduction surgery (LVRS) may regionally improve respiratory mechanics. However, to date, respiratory mechanics in pulmonary emphysema have been totally and indirectly evaluated using respiratory inductive plethysmography or magnetometer, and interaction with lung ventilatory function has been evaluated by comparisons with overall pulmonary function tests (PFTs).7,8 Fast ac-
quisition techniques for MRI have directly allowed visualization of regional respiratory D/CW motions. Dynamic single-photon emission CT (SPECT) of xenon-133 is also available for accurately assessing the extent and location of air trapping in lung regions without superimposition of lung tissues.13–18 In this study, using these new techniques, the hypothesized regional interaction between regional respiratory mechanics and lung ventilatory function was investigated in patients with pulmonary emphysema, including patients undergoing thoracoscopic LVRS.

**MATERIALS AND METHODS**

The subjects were 28 patients with relatively advanced pulmonary emphysema (26 men; age range, 45 to 78 years). The diagnosis was made on the basis of physical findings, a history of long-term cigarette smoking, PFTs, chest high-resolution CT scans, and radionuclide perfusion scans. Sixteen patients had heterogeneous emphysema with bullae of various sizes on chest CT scan, and the remaining 12 patients had generalized emphysema throughout the lungs without clearly identified bullae. The mean predicted values of FEV₁ (%FEV₁), FVC (%FVC), total lung capacity, and residual volume in these patients were 42.3 ± 12.5%, 60.5 ± 11.6%, 123.1 ± 19.2%, and 164 ± 66.5%, respectively. All the patients showed heterogeneous perfusion on the radionuclide study. Nine of the 28 patients (heterogeneous emphysema with bulla in 5 patients, and generalized noddle emphysema in 4 patients) underwent thoracoscopic LVRS. These patients were reexamined >3 months after surgery to evaluate the treatment effects. These patients were preoperatively dyspneic at rest or during mild exercise [grade 4 in five patients and grade 5 in four patients according to Fletcher’s dyspnea scale22], and the average %FEV₁ and %FVC were 39.5 ± 13.7% and 68.2 ± 6.2%, respectively. Target lung areas for thoracoscopic LVRS were determined from the findings of dynamic 133Xe SPECT, and multiple wedge resections of lung portions with the most extensive 133Xe retention were performed in the more involved hemithorax. For comparison, six nonsmoking healthy volunteers (six men; age range, 28 to 45 years) and five smoking patients (four men; age range, 57 to 71 years) with peripheral lung cancer measuring <30 × 25 mm in diameter were studied. These subjects showed normal PFTs without noticeable emphysematous changes on chest CT scan. After the nature of the procedures had been fully explained, informed consent was obtained from all the participants.

**Dynamic MRI**

Preliminary anatomic imaging of the patient’s thorax in a supine position during steady-state breathing was initially imaged using an MRI instrument (1.5 T; Magnetom Vision; Siemens; Erlangen, Germany) with a phased-array torso coil, using a T₁ sequence (repetition time [TR], 229 ms; echo time [TE], 30 ms; two acquisitions; 256 × 256 pixel matrix; field of view, 450 × 450 mm; 3 mm nongap). Each subject was instructed to breathe regularly and deeply for five to seven cycles from maximal inspiration to maximal expiration (respiratory rates ranging from six to eight cycles per minute). Dynamic MRI was then acquired at a fixed midcoronal plane through the aorta and at two fixed midsagittal planes through the middle of each lung, using a turbo fast low-angle shot sequence (TR/TE=11 ms/4.2 ms; flip angle, 20°; slice thickness, 10 mm; matrix, 100 to 112 × 256) in 13 subjects or a half-Fourier single-shot turbo spine echo sequence (TE/effetive TE=4.2 ms/59 ms; flip angle, 20°; slice thickness, 8 mm; matrix, 128 × 256) in the remaining 11 patients. The field of view for the midsagittal and midsagittal images were 360 to 450 × 450 mm and 300 × 450 mm, respectively. The total acquisition time was 25 to 30 s per each slice plane, producing 20 to 22 sequential images during two to three respiratory cycles.

At an imaging workstation, respiratory D/CW motions were then analyzed by a cine-loop view of the sequential magnetic resonance images, and also by the time-distance curves (TDCs), which documented the changes in vertical dimension from the top of the lung to each hemidiaphragm on a midcoronal plane against time and those of the transversal anteroposterior dimension of the chest wall at two fixed upper and lower thoracic levels (at 10 cm below the lung apex and at 5 cm above the diaphragm in the maximal inspiration, respectively) on midsagittal planes (Fig 1). The maximal and minimal dimensions of D/CW, the minimal/maximal dimension ratios, and the maximal amplitude (the maximal dimension minus the minimal dimension) of diaphragmatic motion (MADM) and chest wall motion (MACWM) were measured on TDCs. The relative degree to which the diaphragm is opposed to the rib cage (ie, the length of apposition of the diaphragm [LAD]) was also measured on maximal expiratory mid-coronal magnetic resonance images.5,10,21 Dynamic MRI acquisition techniques for MRI have directly allowed assessing the extent and location of air trapping in lung regions without superimposition of lung tissues.13–18 In this study, using these new techniques, the hypothesized regional interaction between regional respiratory mechanics and lung ventilatory function was investigated in patients with pulmonary emphysema, including patients undergoing thoracoscopic LVRS.

**Dynamic 133Xe SPECT**

Dynamic 133Xe SPECT was performed using a continuous repetitive rotating acquisition mode with a triple-detector SPECT system (GCA 9,300 A/HG; Toshiba Medical; Tokyo, Japan).14–16 Briefly, after 5 to 6 min of inhalation of 133Xe gas (concentration, 60 to 72 MBq/L), an equilibrium and subsequent 10 to 12 washout images were acquired with an acquisition time of 30 s, at 64 × 64 pixels and an energy window of 80 keV ± 20%. To eliminate the settling time between projections and acquisition of multiple temporal samples of data, each detector was continuously and repeatedly rotated in the clockwise (15 s) and counterclockwise (15 s) directions across the same projection arc. With the use of three detectors, a gantry rotation of 120° around the chest provided projections over a full 360° arc. Averaged projection data at the same angle (per 6°) in both directional rotations was used for reconstructing a single SPECT image; therefore, change of 133Xe activity in the lungs during the 30-s acquisition time was averaged. 133Xe SPECT data were reconstructed into equilibrium and washout images in transaxial planes using a Butterworth prefilter (eighth order; cut-off frequency, 0.5). Downloaded From: http://journal.publications.chestnet.org/pdaccess.ashx?url=/data/journals/chester/21948/ on 06/27/2017
Figure 1. Top: healthy subject’s dynamic magnetic resonance images at midcoronal and right midsagittal planes represent the measurements of the vertical length from the top of the lung to each hemidiaphragm and the transvertical anteroposterior dimension of the upper and lower thoraces. Middle: fusion MRI displays of the maximal inspiration and expiration images showed good respiratory D/CW motions. Bottom: TDCs showed regular sawtooth-like D/CW motions with synchrony (diaphragmatic motion: □, right thorax; ▢, left thorax).
and the five patients with peripheral lung cancer and washout image data (volume of areas with 133Xe retention) to view, and 133Xe retention in the hidden lung was visible when the structures. This 3D display could be freely rotated at any angle of the six healthy subjects without 133Xe retention, because prolonged retention 3 min after washout is considered to sufficiently indicate abnormal ventilation in obstructive diseases. On this display, each of the 3D equilibrium and 3-min washout images kept this color-shading effect, and the overlying 3D equilibrium image was made semitransparent for viewing of 3D 3-min washout image, thereby enabling the viewer to see 133Xe retention located even in the deep lung structures. This 3D display could be freely rotated at any angle of view, and 133Xe retention in the hidden lung was visible when the lungs were overlapped in certain directions. The volumetric extent of 133Xe retention (air trapping) in each lung was quantified by 133Xe retention index (RI), defined as the ratio (as a percent) of the total pixel numbers of the segmented 3-min washout image data (volume of areas with 133Xe retention) to those of equilibrium data (lung volume).

**Image Interpretation and Statistical Analysis**

The magnetic resonance images were independently interpreted by three chest radiology specialists experienced in chest MRI (T.T., H.A., and K.S.), blinded to the information of PFTs and other imaging modalities of the subjects, and the final interpretation was reported after group consensus. Each of the MRI variables was measured by two of the interpreters (T.T. and H.A.), and the average of the two measurements was used when some disparities were noted. The data of MRI variables, 133Xe RI, and PFTs were expressed as mean ± SD. Differences in the means between the groups were assessed using nonparametric analysis of variance (Kruskal-Wallis test). Comparison of the differences in the means before and after surgery was determined using a paired Wilcoxon signed rank test. A p value < 0.05 was regarded as significant. A linear regression analysis was performed to evaluate the correlations of the MRI variables with PFTs and 133Xe RI, using commercially available software (Stat-View 4.02 SE + Graphics; Abacus Concepts; Berkeley, CA). In this analysis, MADM and MACWM were normalized to the minimal dimension to normalize for the differences in height, using the formula (maximal dimension – minimal dimension)/minimal dimension ratios. A p value < 0.05 was considered significant for each correlation coefficient.

**RESULTS**

The six healthy subjects without 133Xe retention and the five patients with peripheral lung cancer and only slight 133Xe retention (133Xe RI, 1.8 ± 1.3%) showed regular, synchronous motions of D/CW; the diaphragm showed upward deflections during expiration and downward deflections during inspiration, and in parallel, the chest wall showed inspiratory expansion and expiratory contraction (Fig 1). On a midsagittal plane, the diaphragm clearly showed a "widening piston" motion with expansion in the anteroposterior dimension with an increase in the radius of the curvature at maximal expiration. The TDCs showed regular D/CW motions with good mobility, appearing as sawtooth peaks and valleys with synchrony between each hemithorax or between upper and lower thoraces (Fig 1). There were no significant right-to-left differences in MADM and LAD, and also no significant upper-to-lower differences in MACWM.

In contrast, all 28 patients with 133Xe retention (133Xe RI, 28.9 ± 17.2%) frequently showed flattening or loss of normal diaphragmatic curvature and reduced, irregular respiratory D/CW motions (Figs 2–5). These abnormalities were always more prominent in the hemithorax with greater 133Xe retention. Chest wall motions were prominently suppressed corresponding to the location with extensive 133Xe retention, often resulting in dissociated motions between the upper and lower chest walls. In some patients with marked 133Xe retention asymmetrically on one side of the hemithorax, mediastinal shifting (n = 2), quick downward deflections of the diaphragm during expiration (n = 3), and asynchronous D/CW motions between the right and left hemithoraces (n = 9) were also noted. TDCs showed irregularly flattened curves, occasionally accompanied by asynchrony in these patients. One of the candidates for LVRS surgery was, therefore, not indicated (Fig 3). As shown in Table 1, the average minimal dimension and minimal/maximal dimension ratios of the hemidiaphragm and chest wall in these 28 patients were significantly greater than those in 6 healthy subjects and 5 patients with lung cancer, although there was no significant difference in the maximal dimension. The MADM, MACWM, and LAD in these 28 patients were significantly less than those in the healthy subjects and patients with lung cancer.

Before LVRS, all nine patients with marked 133Xe retention (133Xe RI, 41.7 ± 14.2%) also showed abnormal D/CW motions in at least one hemithorax. Postoperatively, all these patients showed a higher maximal expiratory position of the diaphragm with more normal configurations and improvements in D/CW motions to various degrees in the hemithorax that was operated on, accompanied by reductions in
Figure 2. Top: chest CT scan from a 79-year-old man with generalized emphysema showed marked emphysematous changes throughout the lungs. Middle: 3D $^{133}$Xe SPECT displays showed greater $^{133}$Xe retention (yellowish colors, arrows) in the left lung than in the right lung. Fusion MRI displays showed reduced D/CW motions especially in the left thorax. Bottom: TDCs showed irregular and markedly reduced D/CW motions, especially in the left thorax. In the right thorax, the chest wall motion was more suppressed in the lower thorax, with relatively greater $^{133}$Xe retention.
133Xe retention (Fig 4, 5). Three of these patients showed improvements in D/CW motions even in the hemithorax that was not operated on (Fig 4). However, two patients showed retardation of the motions in the contralateral hemithorax that was not operated on, with increased 133Xe retention (Fig 5). Including these two patients, three patients still had marked 133Xe retention in the hemithorax that was not operated on, and underwent contralateral LVRS approximately 2 months later. Consequently, all nine patients postoperatively showed improvements in D/CW motions, with significant increases in MADM, MACWM, and LAD compared with preoperation.
Figure 5: A: preoperative chest CT scan from a 69-year-old man who underwent unilateral LVRS twice showed diffuse emphysematous changes in both lungs. B: 3D 133Xe SPECT images showed an increase in 133Xe retention (yellowish color, arrow) in the left lung after the first LVRS for the right lung, but retention was improved after the second LVRS for the left lung. C: fusion MRI displays showed a worsening of the left diaphragmatic motion after the first LVRS, but the motion was improved after the second LVRS. As a result, 133Xe retention and diaphragmatic motions were bilaterally improved compared with preoperative values. D: TDCs showed a worsening of the left diaphragmatic motion after the first unilateral LVRS, but motion was improved after the second LVRS. Note the improvements of bilateral diaphragmatic motions after the second LVRS compared with preoperative values.
The average 133Xe RI was significantly correlated with percent predicted FEV₁, as shown in Table 1. There was a significant rise in percent predicted FEV₁ (52.9 ± 12.0%) and percent predicted FVC (83.5 ± 5.2%; p < 0.01 for both).

Overall, in a total of 40 studies in 28 patients, including 12 post-LVRS studies in 9 patients, a linear regression analysis showed significant correlations between the average maximal diaphragmatic dimension and the percent total lung capacity, between the minimal diaphragmatic dimensions and the percent residual volume, and between the normalized MADM and percent predicted FVC, as shown in Table 1.

### Table 1—Comparisons of Dynamic MRI Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Healthy Subjects (n = 6)</th>
<th>Patients With Peripheral Lung Cancer (n = 5)</th>
<th>Patients With Pulmonary Emphysema (n = 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal dimension of the hemidiaphragm, mm</td>
<td>158.8 ± 17.2</td>
<td>159.1 ± 9.6</td>
<td>211.7 ± 37.8†</td>
</tr>
<tr>
<td>Maximal dimension of the hemidiaphragm, mm</td>
<td>247.5 ± 16.5</td>
<td>249.8 ± 14.8</td>
<td>257.4 ± 23.9</td>
</tr>
<tr>
<td>Minimal to maximal dimension of the hemidiaphragm ratio</td>
<td>0.64 ± 0.07</td>
<td>0.66 ± 0.04</td>
<td>0.78 ± 0.16*</td>
</tr>
<tr>
<td>Minimal dimension of the chest wall, mm</td>
<td>116.0 ± 5.0</td>
<td>118.2 ± 4.8</td>
<td>126.2 ± 11.8†</td>
</tr>
<tr>
<td>Maximal dimension of the chest wall, mm</td>
<td>145.1 ± 8.2</td>
<td>143.7 ± 6.8</td>
<td>139.7 ± 8.9</td>
</tr>
<tr>
<td>Minimal to maximal dimension of the chest wall ratio</td>
<td>0.79 ± 0.03</td>
<td>0.80 ± 0.04</td>
<td>0.89 ± 0.05†</td>
</tr>
<tr>
<td>MADM, mm</td>
<td>82.7 ± 25.0</td>
<td>83.1 ± 21.2</td>
<td>43.5 ± 16.1†</td>
</tr>
<tr>
<td>MACWM, mm</td>
<td>19.0 ± 5.1</td>
<td>18.3 ± 4.8</td>
<td>14.1 ± 7.4*</td>
</tr>
<tr>
<td>LAD, mm</td>
<td>173.9 ± 15.4</td>
<td>168.4 ± 16.1</td>
<td>137.2 ± 28.6†</td>
</tr>
</tbody>
</table>

*p < 0.05.
†p < 0.01.
‡p < 0.0001, compared with the six healthy subjects.

In this study, respiratory D/CW motions were prominently suppressed in the hemithorax or location with greater 133Xe retention. Respiratory D/CW mobility, assessed by the maximal amplitude, was significantly correlated with the extent of 133Xe retention in each hemithorax. Furthermore, the removal of 133Xe retention sites with thoracoscopic LVRS significantly improved respiratory D/CW motions in the surgically treated hemithoraces. These findings indicate a close interaction between regional respiratory mechanics and air trapping in pulmonary emphysema.

Respiratory D/CW motions to generate efficient respiratory intrathoracic pressure are coordinated by respiratory muscles (RMs). The poor or abnormal D/CW motions demonstrated seem to reflect impaired RM function primarily resulting from the abnormal flow-volume performance of the diseased lung. Thoracic hyperinflation because of air trapping results in mechanical disadvantage of the RMs at high volumes or in abnormal thoracic positions. The limited expiratory airflow prolongs expiration and enhances dynamic lung hyperinflation. The prominently suppressed D/CW motions in the hemithorax or location with greater 133Xe retention in our patients indicate that localized lung hyperinflation may induce regionally excessive loads on RMs and impair RM function. Chest wall asynchrony can also be caused by a more generalized fatigue of the RMs, resulting in increased use of accessory muscles (scalenes and sternomastoids) and paradoxical breathing. Shortening of LAD and the loss of the “widening piston” of the diaphragm should diminish the effect of intra-abdominal pressure on the rib cage, thereby placing an additional load on the RMs.

### Discussion

These new techniques enable direct comparisons of regional respiratory mechanics with lung ventilation in patients with pulmonary emphysema. In this study, respiratory D/CW motions were prominently suppressed in the hemithorax or location with greater 133Xe retention. Respiratory D/CW mobility, assessed by the maximal amplitude, was significantly correlated with the extent of 133Xe retention in each hemithorax. Furthermore, the removal of 133Xe retention sites with thoracoscopic LVRS significantly improved respiratory D/CW motions in the surgically treated hemithoraces. These findings indicate a close interaction between regional respiratory mechanics and air trapping in pulmonary emphysema. Respiratory D/CW motions to generate efficient respiratory intrathoracic pressure are coordinated by respiratory muscles (RMs). The poor or abnormal D/CW motions demonstrated seem to reflect impaired RM function primarily resulting from the abnormal flow-volume performance of the diseased lung. Thoracic hyperinflation because of air trapping results in mechanical disadvantage of the RMs at high volumes or in abnormal thoracic positions. The limited expiratory airflow prolongs expiration and enhances dynamic lung hyperinflation. The prominently suppressed D/CW motions in the hemithorax or location with greater 133Xe retention in our patients indicate that localized lung hyperinflation may induce regionally excessive loads on RMs and impair RM function. Chest wall asynchrony can also be caused by a more generalized fatigue of the RMs, resulting in increased use of accessory muscles (scalenes and sternomastoids) and paradoxical breathing. Shortening of LAD and the loss of the “widening piston” of the diaphragm should diminish the effect of intra-abdominal pressure on the rib cage, thereby placing an additional load on the RMs.
Abnormal D/CW motions may conversely influence lung ventilation, because intrapleural pressure changes needed for efficient ventilation are produced by the thoracic pump function operated by well-coordinated D/CW motions. The degree of air trapping is related to the turnover ratios or $\Delta V/V_o$ ratios ($\Delta V$ is the lung volume change per unit time, and $V_o$ is related to a function of the minimal/maximal dimension ratio). The reduced irregular changes of D/CW motions in our patients can be contributing factors to the reduction in $\Delta V$ in the diseased lung. The decreased $\Delta V$ and the increased minimal/maximal dimension ratios ($V_o$) of D/CW should reduce $\Delta V/V_o$ ratios, thereby leading to increases in air trapping. Significant fatigue of expiratory RMs because of chronic excessive recruitment may also impede efficient expiratory airflow from the lung. RM dysfunction can prolong ventilatory turnover and enhance air retention even in the normal lung, as previously reported in some patients with restricted thoracic deformities.

This study indicated that removal of $^{133}$Xe retention sites with successful thoracoscopic LVRS may improve respiratory D/CW motions. LVRS increases outward tension on small airways, thereby reducing intrinsic positive end-expiratory pressure. This reduces trapped gas and allows inspiratory muscles to lengthen, thereby reducing fatigue. Restored D/CW motions, conversely, may show salutary effects on intrathoracic respiratory force generation, leading to better emptying of the remaining lungs and a more precise quantification of D/CW motions. RM dysfunction can prolong ventilatory turnover and enhance air retention even in the normal lung, as previously reported in some patients with restricted thoracic deformities.

Before LVRS, the present techniques effectively showed relative abnormalities in lung ventilation and respiratory mechanics, even in our patients demonstrating generalized emphysema on morphologic chest CT scan. It is often impossible to identify the hemithorax with the worse respiratory function by a simple visual comparison of the lungs when hyperlucency is diffuse. Some patients with large bullae may occasionally show relatively good D/CW motions without significant air trapping, as seen in one of our candidates for LVRS. In thoracoscopic LVRS, it is imperative to preoperatively select the resection targets that can be sacrificed with minimal loss of better functioning lung tissues. The preoperative assessments of regional ventilation and respiratory mechanics with the present techniques will contribute to efficient determination of resection targets. Furthermore, after unilateral LVRS, these modalities may help determine the indication for contralateral LVRS, as shown in several patients.

The present study can be expected to be more specific and comprehensive than studies assessing overall lung function by spirometry or body plethysmography. Ventilatory function is often heterogeneous in the individual hemithorax and can be underestimated by asymmetric forced expiratory flow. The 3D $^{133}$Xe SPECT display allows an overview of extent and locations of air trapping in regional lungs and a more precise quantification as opposed to planar $^{133}$Xe study. Dynamic MRI allows a field of view that can encompass the entire thorax and has an excellent ability to directly visualize regional D/CW motions. Although D/CW motions can be assessed by chest radiographic fluoroscopy, this technique has the obvious advantages of avoiding magnification or parallax distortion and no irradiation. Digital MRI data permit more accurate quantification of D/CW motions. RM function can be indirectly assessed by respiratory inductive plethysmography, magnetometer, or electromyography; these methods often show limitations in accurate assessments because of abnormal abdominal wall motions frequently observed in patients with advanced pulmonary emphysema.

Some correlations between MRI measurements and spirometric data and/or $^{133}$Xe RI in this study indicate that the present MRI technique is acceptable for evaluating ventilatory pump function. However, this technique cannot simultaneously provide multiple sectional planes. Therefore, the analysis of D/CW motions is limited to several selected thoracic planes. The single-plane images do not measure movement of a fixed anatomic point because of respiratory motions. Although the MRI technique provides high-quality images of D/CW motions, each image actually represents the averaged motion of D/CW for approximately 0.8 s. During this acquisition time, these structures might rapidly move more than one third of the maximal amplitude, especially at faster respiratory rates. Therefore, more-advanced MRI techniques, with 3D volumetric acquisition that allows visualization of the overall configurations of D/CW with higher sampling frequencies, are needed for more-accurate analysis. It is also necessary to clarify the alterations in respiratory D/CW motions depending on respiratory pattern or position in a further study.

In conclusion, the present techniques revealed the close interaction between regional respiratory mechanics and air trapping in pulmonary emphysema. This study also indicated that successful removal of the lung areas with air trapping by LVRS can effectively improve regional respiratory mechanics. These techniques will provide additional sensitivity.
for evaluating pathophysiologic compromises in pulmonary emphysema and may also be useful for selecting targets for LVRS resection and for monitoring the postoperative effects.

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