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Morphological and functional reserves of the right middle lobe: radiological analysis of changes after right lower lobectomy in healthy individuals

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Word count

2912
Abbreviations

CT = computed tomography

RU lobe = right upper lobe

RM lobe = right middle lobe

RL lobe = right lower lobe

RL lobectomy = right lower lobectomy

ELV = effective lung volume

LAA = low attenuation area

FVC = forced vital capacity

FEV₁ = forced expiratory volume in one second

DLCO = diffusing capacity of lung for carbon monoxide
Central Picture Legend

The middle lobe shows expansion and functional compensation after right lower lobectomy.
Central Message

The right middle lobe contributes largely to expansion and functional compensation after right lower lobectomy with preservation of its structural complexity.
Expansion and functional compensation of the remaining lung after pulmonary resection are heterogeneous. Following right lower lobectomy, the right middle lobe demonstrates morphological and functional reserves, despite its small size. Better understanding of such heterogeneous changes would lead to an improvement of methods to predict postoperative function.
Abstract

Objectives

Remaining lung tissue after pulmonary resection can expand without decline in structural complexity and compensate for functional loss, showing morphological and functional reserves. However, the distribution of these reserves is unknown. This study examined the heterogeneity of morphological and functional reserves of the remaining lung tissue.

Methods

We retrospectively analyzed 53 donors who underwent right lower lobectomy for living-donor lobar lung transplantation. We examined morphometric changes in computed tomography images from 3 to 12 months after lobectomy. We assessed lung volume and structural complexity expressed as the fractal dimension. We also assessed effective lung volume (the volume of the lung with intermediate density) and volumetric fluctuation during respiration. Changes were compared between the right upper lobe, middle lobe, and left lung.

Results

The expansion of lung tissue was greater in the middle lobe (130.9 ± 19.7%) than in the upper lobe (109.7 ± 9.2%, P < 0.001). The fractal dimension declined in the upper lobe.
(P < 0.001) but was maintained in the middle lobe (P = 0.39). The increase in effective
lung volume was larger in the middle lobe (97.2 ± 73.5 ml) than in the upper lobe (62.7 ±
87.1 ml, P < 0.001) but not significantly different from that of the left lung (55.8 ±
186.3 ml, P = 0.052). A similar pattern was seen in respiratory fluctuation.

Conclusions

Morphological and functional changes in lung tissue remaining after pulmonary
resection were heterogeneous. The right middle lobe demonstrated morphological and
functional reserves after right lower lobectomy.
Graphical abstract legend

Among heterogeneous changes in the remaining lung tissue after right lower lobectomy, the RM lobe demonstrates great morphological and functional reserves, compared to the RU lobe.

CT, computed tomography; RU lobe, right upper lobe; RM lobe, right middle lobe.
Pulmonary resection is a widely utilized therapeutic option for lung diseases\(^1\). Expansion of the remaining lung tissue is a major compensatory response after resection\(^2,3\). However, postoperative changes in the pulmonary microstructure have not been fully elucidated. Our group previously reported that the structural complexity of the ipsilateral remaining lung was preserved after lower lobectomy despite the increase in volume\(^4\), which suggests a “morphological reserve” of the remaining lung tissue.

Patients who undergo pulmonary resection gradually recover pulmonary function\(^5,6\). Function after anatomical resection was reported to exceed predicted values\(^5,7\), which are calculated on the assumption that the function of the remaining lungs does not change between before and after resection. These findings suggest that the remaining lungs could also have functional reserves.

Remaining lung tissue expanded heterogeneously after resection in animal models\(^8\). Based on this finding, morphological reserves in the remaining lung tissue may be distributed heterogeneously. Moreover, because pulmonary function is associated with lung volume\(^9,10\), functional reserves may also be heterogeneous. However, interlobar heterogeneity in morphological and functional reserves has not been studied in previous studies, including those from our group\(^4,6\).

In this study, we hypothesized that morphological and functional reserves are
heterogeneous in the remaining lung tissue. We retrospectively analyzed computed tomography (CT) images of the remaining lung tissue after right lower lobectomy (RL lobectomy) in healthy adults who donated their lobes in living-donor lobar lung transplantation.

Methods

This retrospective observational study was conducted in a single center. The Ethics Committee of Kyoto University Hospital approved the protocol. The need for written informed consent was waived because of the retrospective nature of this study. We searched the institutional database at Kyoto University Hospital for donors who underwent RL lobectomy for living-donor lobar lung transplantation between January 2011 and December 2017. The donor selection criteria are listed in Table 1. Patients with chronic obstructive lung disease were not included in donors. We mainly analyzed regional changes in CT morphometrics from 3 to 12 months after RL lobectomy.

CT acquisition

CT images were obtained during deep inspiratory and expiratory breath-holding using multidetector CT scanners before and 3 and 12 months after lobectomy. We used three
scanners (Toshiba Medical Systems, Tochigi, Japan): Aquilion 64 from January 2011 to January 2016, Aquilion ONE from August 2015 to January 2019, and Aquilion PRIME from February 2016 to April 2018. The scanning parameters were the same throughout the study period: 0.5-mm collimation, field of view of 320–381 mm, a gantry rotation time of 500 ms, and automatic exposure control at 120 kVp. No intravenous contrast medium was administered. Images with a slice thickness of 1 mm were reconstructed using a standard lung algorithm (FC51).

**Three-dimensional CT volumetry**

CT data were imported into a workstation SYNAPSE VINCENT (FUJIFILM Medical, Tokyo, Japan) for segmentation and three-dimensional CT volumetry. The airway and thoracic cage were removed from images. Areas less than -250 Hounsfield Units (HU) were extracted as lung fields. Interlobar lines were drawn semi-automatically. All lines were checked in multiplanar reconstruction images and manually corrected paying careful attention to interlobar fissures (even when they were incomplete) and peripheral bronchi and vessels. Volumes of the right upper (RU), right middle (RM), and right lower (RL) lobe and the left lung were measured automatically. The diaphragmatic surface of the lung was evaluated using three-dimensional reconstructed images,
regardless of whether there was intervening pleural effusion.

Effective lung volume (ELV) was defined as volume of the lung area with a CT density of -950 to -600 HU on inspiratory CT. To assess respiratory fluctuation in lung volume, the difference in CT volumes between deep inspiration and expiration was calculated.

**Fractal analysis**

Postoperative inspiratory CT images were analyzed using custom-made software. We calculated the D value of each lung region in a fractal analysis of the low attenuation area (LAA) cluster. The D value reflects the fractal dimension of the terminal air space geometry, indicating the structural complexity of the lung. As previously reported, the cumulative frequency distribution of the LAA cluster Y, which is the number of clusters larger than the size of a given cluster X, follows a power law of \( Y = K \times X^{-D} \), where K is a constant. The exponent, D, can be calculated as the slope of the straight line on log-log plots in a linear regression. In this study, D was calculated for each axial image. The average of all these values were used to calculate D for a region. We determined the threshold of LAA as the 25th percentile of a histogram of CT densities in the lung field. This D value, referred to as D’25, was reported to be robust against
changes in the lung volume and to have the potential to detect structural changes in patients with chronic obstructive pulmonary disease more sensitively than the conventional D value and fraction of LAA\textsuperscript{13}.

Prediction of postoperative pulmonary function

Pulmonary function tests, including forced vital capacity (FVC), forced expiratory volume in one second (FEV\textsubscript{1}), and diffusing capacity of lung for carbon monoxide (DL\textsubscript{CO}), were performed before and 3 and 12 months after lobectomy. We predicted postoperative FVC, FEV\textsubscript{1}, and DL\textsubscript{CO} using two methods. In the segment counting method, predicted values (FVC, FEV\textsubscript{1}, and DL\textsubscript{CO}) were calculated using the following equation: predicted value = preoperative value × 14/19. In the CT volumetric method, which is a modified version of a previously described method\textsuperscript{7}, predicted values were calculated using the following equation: predicted value = preoperative value × (1 - [ELV in RL lobe]/[ELV in whole lungs]).

Statistical analysis

Statistical analysis was performed using JMP® Pro 14.0.0 software (SAS Institute Inc., Cary, NC). Expansion of the lung is expressed as a ratio of lung volume. Changes in
D′25, ELV, and respiratory fluctuation are expressed as differences. Continuous variables are expressed as mean ± standard deviation. Comparisons of continuous variables were analyzed using a paired t-test. Differences were considered significant at values of $P < 0.05$.

**Results**

Seventy-five donors underwent RL lobectomy during the study period. Among them, 12 donors lacked CT images following the appropriate protocol. Donors with air in the pleural space ($n = 9$) and ground glass opacity in the lung area ($n = 1$) on CT images obtained 3 months after lobectomy were excluded. Therefore, postoperative changes in 53 donors were analyzed. Preoperative characteristics of the donors are shown in Table 2.

Postoperative complications occurred in nine donors, including pneumothorax ($n = 3$), pleural effusion ($n = 3$), hemothorax ($n = 1$), chylothorax ($n = 1$), and a residual foreign body that required re-thoracotomy ($n = 1$). These complications resolved within 3 months of lobectomy. No donors required thoracentesis due to pleural effusion from 3 to 12 months after lobectomy.
Postoperative pulmonary function

Predicted and postoperatively measured functions are described in Table 3. FVC, FEV₁, and DL_CO at 12 months were significantly greater than those at 3 months after lobectomy (P < 0.001) and those predicted using the two methods (P < 0.001).

Gross change in the right lung

Change in a representative case is shown in Figure 1. Before resection, the RM lobe lay in the ventral portion of the lower hemithorax, with little or no contact with the diaphragm. After RL lobectomy, the remaining right lung deformed and expanded to compensate for the loss of the RL lobe. The RM lobe occupied most or all of the diaphragmatic surface of the remaining right lung.

Changes in CT morphometrics from 3 to 12 months after lobectomy

Morphometric data from CT images are shown in Table 4. Expiratory CT before and three months after lobectomy was not obtained in one donor. Lung volume, ELV, and respiratory fluctuation increased from 3 to 12 months after lobectomy in the RU lobe, RM lobe, and left lung. D′25 decreased significantly in the RU lobe but was maintained in the RM lobe.
Changes in the morphometrics from 3 to 12 months after lobectomy were compared between regions and are shown in Figure 2. Expansion was greater in the RM lobe (130.9 ± 19.7%) than in the RU lobe (109.7 ± 9.2%) (P < 0.001) (Figure 2A). The decline in D′25 was greater in the RU lobe (-0.08 ± 0.11) than in the RM lobe (-0.02 ± 0.15) (P < 0.001) (Figure 2B). The increase in ELV was greater in the RM lobe (97.2 ± 73.5 ml) than in the RU lobe (62.7 ± 87.1 ml) (P < 0.001). There was no significant difference in changes in ELV between the RM lobe and left lung (55.8 ± 186.3 ml) (P = 0.052) (Figure 2C). The increase in respiratory fluctuation was greater in the RM lobe (148.2 ± 107.2 ml) than in the RU lobe (95.2 ± 144.2 ml) (P < 0.001). There was no significant difference in change in respiratory fluctuation between the RM lobe and left lung (105.5 ± 331.6 ml) (P = 0.27) (Figure 2D).

**Volumetric changes from before to 12 months after lobectomy**

Changes in volume, ELV, and respiratory fluctuation from before to 12 months after lobectomy showed similar tendencies as those observed from 3 to 12 months after lobectomy (Table 4). Expansion of the RM lobe (192.6 ± 48.3%) was significantly greater than that of the RU lobe (138.5 ± 21.2%) (P < 0.001). The increase in ELV was greater in the RM lobe (252.1 ± 108.7 ml) than in the RU lobe (191.2 ± 104.6 ml) and
left lung (121.2 ± 179.1 ml) (P < 0.001). The increase in respiratory fluctuation was
greater in the RM lobe (291.5 ± 145.7 ml) than in the RU lobe (166.1 ± 182.5 ml) (P <
0.001) but was not significantly different from that in the left lung (319.3 ± 392.7 ml) (P
= 0.58).

Discussion

In this study, we radiologically analyzed regional changes in remaining lung tissue
after RL lobectomy in healthy adults. Regarding heterogeneous changes in the
remaining lung tissue, the RM lobe demonstrated great morphological and functional
reserves. These specific features of the RM lobe have not been previously reported.
The RM lobe demonstrated morphological reserves after RL lobectomy. The RM lobe
greatly expanded without a significant decline in structural complexity, unlike the RU
lobe. We previously reported that the structural complexity of the ipsilateral remaining
lung was maintained in donors after right or left lower lobectomy\(^4\). The present study,
focusing on RL lobectomy cases, revealed that a large part of the morphological
reserves of the remaining right lung was derived from the RM lobe, although the size of
the RM lobe was small preoperatively.
The RM lobe also demonstrated great functional reserves. Pulmonary function tests
revealed that remaining lung tissue compensated for the functional loss of the RL lobe. Among regions of the remaining lungs, gains in ELV and respiratory fluctuation were greater in the RM lobe than in the RU lobe and not significantly inferior to those in the left lung. These results strongly suggest that the RM lobe contributed largely to the postoperative functional compensation.

Reserves of the RM lobe could be associated with its position relative to the diaphragm. Preoperatively, the RM lobe had limited or no contact with the diaphragm. Inflation and ventilation of the RM lobe were modest, compared to those of the RU and RL lobes. After RL lobectomy, however, the RM lobe obtained broader contact with the diaphragm and showed greater amplification of inflation and ventilation than the RU lobe. A similar heterogeneity was found in previous studies$^8,1^4$. In the first study using four-dimensional CT in healthy adults, the lower lobes contributed to ventilation more than the upper and middle lobes$^1^4$. The authors attributed the heterogeneity to the motion of the diaphragm, which is the predominant driver of lung inflation. In the other study focusing on changes after resection in a canine model, the expansion after extensive pulmonary resection was larger in the lobe next to the diaphragm than that in the other lobes$^8$. These two studies highlight the effect of the diaphragm on heterogeneity in preoperative and postoperative behavior of the lung. Based on these
studies, our results can be interpreted as follows: preoperatively, the RL lobe could interfere with inflation and ventilation of the RM lobe by limiting its contact with the diaphragm; removal of the RL lobe could facilitate access of the RM lobe to the diaphragm, enhancing inflation and ventilation of the RM lobe. Although the mechanisms of acquiring and utilizing the reserve are of great interest, they are beyond the scope of this study. Postoperative unfolding of alveolar septa\textsuperscript{8} could be associated with the reserve. Other processes, such as the new growth of alveolar tissue, which was observed after pneumonectomy\textsuperscript{15}, might be also involved. Further studies would be required to assess this issue.

When evaluating the heterogeneity of postoperative changes, there are two advantages in focusing on donors who underwent RL lobectomy. First, all subjects were healthy adults with no visible abnormalities on CT. Lung cancer is the most common disease that requires pulmonary resection\textsuperscript{1}. However, emphysema and/or pulmonary fibrosis are sometimes seen in patients with lung cancer, making these individuals poor candidates for assessing the effects of resection on lung tissue. Second, the minor fissure in the right lung, even if incomplete, helps define the interlobar line to separate the RU and RM lobes. Left lower lobectomy has also been performed in donors; however, this does not allow the evaluation of the heterogeneity of changes in our methods owing to
difficulty in the division of the left upper lobe into the upper division and lingula because the fissure between these two regions is usually absent\textsuperscript{16}.

Our findings obtained from living donors could help predict postoperative behavior of the lungs in other situations. In the field of cadaveric transplantation, bilateral lung transplantation, in which the RL lobe is not utilized due to lung injury, may induce similar changes in the recipient. A more common example is RL lobectomy for lung cancer in patients without pulmonary comorbidities. We estimate that this population accounts for a certain proportion of surgical patients, considering that the frequency of never smokers in patients undergoing resection for lung cancer is increasing\textsuperscript{17,18}. On the other hand, it is unknown whether lungs in patients with emphysema or pulmonary fibrosis experience similar changes after lobectomy. Further studies are warranted to assess this issue.

The heterogeneity in changes may have an effect on the prediction of postoperative pulmonary function. As our data demonstrated, postoperative pulmonary function often exceeds predicted values\textsuperscript{5,7}. One reason for this discrepancy is that the remaining lung tissue compensates for functional loss. The site of resection could influence postoperative functional compensation\textsuperscript{19}. Heterogeneous change, which we found in this study, may also influence the extent of compensation. Further exploration of the
heterogeneity would provide us better knowledge on postoperative changes, leading to the development of more accurate prediction of postoperative function.

This study has limitations. First, this is a retrospective study with relatively small number of cases. Second, the use of multiple CT scanners may have influenced the results. We additionally examined 32 cases in which the same CT scanner was used at 3 and 12 months after lobectomy. Donor characteristics were almost the same as those of the entire cohort (Supplementary table 1). The results were similar to those obtained from the analysis of 53 cases, except that the CT volumes of the left lung did not increase (Supplementary table 2). Prospective studies are required to exclude the potential effects of using multiple scanners on the results. Third, neither changes immediately after lobectomy nor those in long-term were investigated. We did not compare structural complexity between before and after lobectomy because deformations immediately after RL lobectomy in the remaining lobes, especially in the RM lobe, were so large that they could affect the results of the fractal analysis even without structural alterations. More sophisticated methods are required to assess regional changes in the structural complexity between before and after resection.

Regarding long-term changes, because the postoperative follow-up of donors is usually terminated at 1 year after donation, we could not analyze changes over a longer period.
Fourth, postoperative pleural effusion and shift in pulmonary perfusion may have influenced the results. Although the pleural effusion was too small to require thoracentesis, it may have influenced the postoperative changes in the lung, for example, by inducing microatelectasis. Resection can alter pulmonary perfusion by decreasing the vascular bed volume and migration of the lung, modifying regional CT densities. Although these two events occur immediately after resection, the changes in CT morphometrics between 3 and 12 months after lobectomy may have been influenced by a shift in perfusion. In the histogram of CT densities in the lung field, pixels were frequently distributed near the -950 to -600 HU range. Therefore, the ELV, which is the volume of the lung area with a CT density in the abovementioned range, may have been influenced by the change in CT densities because of the shift in perfusion. However, the lung volume, calculated as a volume less than -250 HU, would be less susceptible because few pixels had CT densities near -250 HU. In the fractal analysis, the effect of perfusion on D′25 would be minimal because the threshold density of LAA for D′25 is not fixed (for example, at -950 HU), but it reflects the distribution of CT densities in the region. Fifth, the accuracy of interlobar lines were not tested.

In conclusion, this study revealed that changes in the remaining lung tissue after RL lobectomy were heterogeneous and that the RM lobe demonstrated morphological and
341 functional reserves.


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Figure legends

FIGURE 1. Three-dimensional reconstructed images showing postoperative gross change. The left lung is removed in the right lateral views. After right lower lobectomy, the right middle lobe greatly expanded and extended its diaphragmatic surface area. Yellow, right upper lobe; blue, right middle lobe; green, right lower lobe; red, left lung.

FIGURE 2. Comparison of morphometric changes from 3 to 12 months after lobectomy between regions. A, expansion was greater in the RM lobe (130.9 ± 19.7%) than in the RU lobe (109.7 ± 9.2%) (P < 0.001, n = 53). B, the decline in structural complexity, expressed as D’25, was greater in the RU lobe (-0.08 ± 0.11) than in the RM lobe (-0.02 ± 0.15) (P < 0.001, n = 53). C, the increase in ELV was greater in the RM lobe (97.2 ± 73.5 ml) than in the RU lobe (62.7 ± 87.1 ml) (P < 0.001, n = 53). D, the increase in respiratory fluctuation was greater in the RM lobe (148.2 ± 107.2 ml) than in the RU lobe (95.2 ± 144.2 ml) (P < 0.001, n = 52). ELV, effective lung volume; RU lobe, right upper lobe; RM lobe, right middle lobe.
Table 1. Criteria for selection of donors in living-donor lobar lung transplantation

<table>
<thead>
<tr>
<th>Criteria</th>
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<tbody>
<tr>
<td>Age ≥ 20 and ≤ 60 years</td>
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<tr>
<td>Relatives within the third degree or a spouse of the recipient</td>
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<tr>
<td>ABO blood type identical or compatible to the recipient</td>
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<td>No major medical history or active medical problems</td>
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<td>No recent viral infections</td>
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<tr>
<td>Non-smoker (current smoker at the offer for donation is required never to smoke after then)</td>
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<tr>
<td>No major abnormalities of the lung on the graft side on CT</td>
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<tr>
<td>FVC and FEV₁ ≥ 85% of predicted values</td>
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<tr>
<td>Partial pressure of arterial oxygen ≥ 80 Torr</td>
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<tr>
<td>No history of thoracic operations on the graft side</td>
</tr>
<tr>
<td>No abnormalities on the electrocardiogram or echocardiogram</td>
</tr>
<tr>
<td>Satisfactory psychosocial evaluation</td>
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<td>Voluntary donation</td>
</tr>
</tbody>
</table>

CT, computed tomography; FVC, forced vital capacity; FEV₁, forced expiratory volume in one second.
<table>
<thead>
<tr>
<th>Table 2. Preoperative characteristics of donors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Sex (male), n (%)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Body mass index (kg/m^2)</td>
</tr>
<tr>
<td>Smoking history (never/ex/current)</td>
</tr>
<tr>
<td>Smoking pack-years of ever smoker</td>
</tr>
<tr>
<td>Pulmonary function test</td>
</tr>
<tr>
<td>FVC (% predicted)</td>
</tr>
<tr>
<td>FEV\textsubscript{1} (% predicted)</td>
</tr>
<tr>
<td>FEV\textsubscript{1}/FVC (%)</td>
</tr>
<tr>
<td>DL\textsubscript{CO} (% predicted)</td>
</tr>
</tbody>
</table>

FVC, forced vital capacity; FEV\textsubscript{1}, forced expiratory volume in one second; DL\textsubscript{CO}, diffusing capacity of lung for carbon monoxide.
Table 3. Postoperative pulmonary function

<table>
<thead>
<tr>
<th></th>
<th>Predicted value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Segment counting</td>
<td>CT Volumetry</td>
</tr>
<tr>
<td></td>
<td>3 months</td>
<td>12 months</td>
</tr>
<tr>
<td>FVC (L)</td>
<td>3.03 ± 0.54</td>
<td>3.02 ± 0.54</td>
</tr>
<tr>
<td>FEV&lt;sub&gt;1&lt;/sub&gt; (L)</td>
<td>2.50 ± 0.45</td>
<td>2.49 ± 0.45</td>
</tr>
<tr>
<td>DL&lt;sub&gt;CO&lt;/sub&gt;</td>
<td>19.09 ± 3.80</td>
<td>19.04 ± 3.85</td>
</tr>
<tr>
<td>(ml/min/mmHg)</td>
<td></td>
<td>4.58</td>
</tr>
</tbody>
</table>

* P<0.001 compared with predicted values and with the measured value at 3 months after lobectomy. FVC, forced vital capacity; FEV<sub>1</sub>, forced expiratory volume in one second; DL<sub>CO</sub>, diffusing capacity of lung for carbon monoxide; CT, computed tomography.
Table 4. Changes in CT morphometrics

<table>
<thead>
<tr>
<th></th>
<th>Before lobectomy</th>
<th>After lobectomy</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lobectomy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3 months&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12 months&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Lung volume</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe (ml)</td>
<td>881.8 ± 203.2</td>
<td>1107.4 ± 263.8</td>
<td>1213.2 ± 299.1</td>
</tr>
<tr>
<td>RM lobe (ml)</td>
<td>441.4 ± 103.7</td>
<td>635.0 ± 141.8</td>
<td>824.4 ± 199.7</td>
</tr>
<tr>
<td>RL lobe (ml)</td>
<td>1295.2 ± 273.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left lung (ml)</td>
<td>2300.8 ± 450.3</td>
<td>2454.5 ± 447.9</td>
<td>2530.5 ± 453.1</td>
</tr>
<tr>
<td><strong>D'25</strong></td>
<td></td>
<td></td>
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<tr>
<td>RU lobe</td>
<td>2.15 ± 0.15</td>
<td>2.07 ± 0.18</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RM lobe</td>
<td>2.10 ± 0.18</td>
<td>2.08 ± 0.22</td>
<td>0.39</td>
</tr>
<tr>
<td>Left lung</td>
<td>2.12 ± 0.18</td>
<td>2.10 ± 0.19</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>ELV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe (ml)</td>
<td>662.6 ± 162.4</td>
<td>791.1 ± 188.6</td>
<td>853.8 ± 206.0</td>
</tr>
<tr>
<td>RM lobe (ml)</td>
<td>310.6 ± 76.7</td>
<td>465.5 ± 102.1</td>
<td>562.7 ± 129.9</td>
</tr>
<tr>
<td>RL lobe (ml)</td>
<td>966.3 ± 176.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left lung (ml)</td>
<td>1708.8 ± 311.4</td>
<td>1774.1 ± 316.6</td>
<td>1829.9 ± 301.4</td>
</tr>
<tr>
<td><strong>Respiratory fluctuation</strong></td>
<td></td>
<td></td>
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33
<table>
<thead>
<tr>
<th>Lobe</th>
<th>Volume (ml)</th>
<th>Difference</th>
<th>p-value 1</th>
<th>p-value 2</th>
</tr>
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<tbody>
<tr>
<td>RU lobe</td>
<td>347.8 ± 168.7</td>
<td>432.3 ± 223.7</td>
<td>524.9 ± 256.3</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RM lobe</td>
<td>144.7 ± 67.7</td>
<td>289.4 ± 121.7</td>
<td>439.2 ± 166.9</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RL lobe</td>
<td>652.0 ± 249.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left lung</td>
<td>1055.9 ± 410.1</td>
<td>1288.5 ± 462.8</td>
<td>1388.7 ± 437.6</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

CT computed tomography; ELV, effective lung volume; RU lobe, right upper lobe; RM lobe, right middle lobe; RL lobe, right lower lobe.
Video legends

Short video describing the radiological methods of this study.
Supplementary table 1. Preoperative characteristics of donors undergoing CT with the same scanner

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39 ± 11</td>
</tr>
<tr>
<td>Sex (male), n (%)</td>
<td>24 (75)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>167.7 ± 7.7</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>23.5 ± 2.8</td>
</tr>
<tr>
<td>Smoking history (never/ex/current)</td>
<td>16/16/0</td>
</tr>
<tr>
<td>Smoking pack-years of ever smoker</td>
<td>12 ± 7</td>
</tr>
<tr>
<td>Pulmonary function test</td>
<td></td>
</tr>
<tr>
<td>FVC (% predicted)</td>
<td>104.3 ± 13.7</td>
</tr>
<tr>
<td>FEV₁ (% predicted)</td>
<td>99.4 ± 10.1</td>
</tr>
<tr>
<td>FEV₁/FVC (%)</td>
<td>83.8 ± 6.0</td>
</tr>
<tr>
<td>DL₉₀ (% predicted)</td>
<td>92.8 ± 12.2</td>
</tr>
</tbody>
</table>

FVC, forced vital capacity; FEV₁, forced expiratory volume in one second; DL₉₀, diffusing capacity of lung for carbon monoxide.
Supplementary table 2. Morphometric changes in donors undergoing CT using the same scanner

<table>
<thead>
<tr>
<th></th>
<th>3 months</th>
<th>12 months</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lung volume</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe (ml)</td>
<td>1127.6 ± 290.4</td>
<td>1211.3 ± 326.0</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RM lobe (ml)</td>
<td>646.6 ± 153.1</td>
<td>824.4 ± 206.9</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Left lung (ml)</td>
<td>2511.5 ± 463.5</td>
<td>2521.0 ± 450.4</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>D’25</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe</td>
<td>2.18 ± 0.17</td>
<td>2.11 ± 0.18</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RM lobe</td>
<td>2.15 ± 0.19</td>
<td>2.15 ± 0.24</td>
<td>0.95</td>
</tr>
<tr>
<td>Left lung</td>
<td>2.18 ± 0.16</td>
<td>2.16 ± 0.19</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>ELV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe (ml)</td>
<td>776.9 ± 198.3</td>
<td>802.6 ± 197.3</td>
<td>0.049</td>
</tr>
<tr>
<td>RM lobe (ml)</td>
<td>460.6 ± 113.1</td>
<td>530.3 ± 123.5</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Left lung (ml)</td>
<td>1763.0 ± 309.3</td>
<td>1738.9 ± 261.7</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>Respiratory fluctuation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU lobe (ml)</td>
<td>465.6 ± 243.6</td>
<td>525.7 ± 281.5</td>
<td>0.020</td>
</tr>
<tr>
<td>RM lobe (ml)</td>
<td>301.7 ± 118.6</td>
<td>434.0 ± 160.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Left lung (ml)</td>
<td>1353.4 ± 453.8</td>
<td>1380.0 ± 443.3</td>
<td>0.62</td>
</tr>
</tbody>
</table>

CT computed tomography; ELV, effective lung volume; RU lobe, right upper lobe; RM lobe, right middle lobe.

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Central picture
Figure 1

Anterior view

Right lateral view

Before lobectomy 3 months 12 months after lobectomy
Figure 2

A

B

C

D

RU lobe  RM lobe  Left lung

RU lobe  RM lobe  Left lung

RU lobe  RM lobe  Left lung

RU lobe  RM lobe  Left lung

Expansion (%)

Change in D'25

Change in ELV (ml)

Change in respiratory fluctuation (ml)

P<0.001  P<0.001

P<0.001  P=0.86

P<0.001  P=0.052

P<0.001  P=0.27

0  50  100  150  200

0  0.2  0.4  0.6  0.8

-600  0  200  400  600

-1000  0  500  1000

0  500  1000  1500

0  500  1000  1500
Graphical abstract

Donors of right lower lobe for living-donor lobar lung transplantation (N = 53)

Changes in CT in the remaining lung

CT volumetry
- Expansion
- Functional compensation

Fractal analysis
- Decline in structural complexity

RU lobe < RM lobe
RU lobe > RM lobe

The RM lobe had great morphological and functional reserves.