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Original Article

Preoperative Graft Volume Assessment with 3D-CT Volumetry in Living-Donor Lobar Lung Transplantations

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To determine the effectiveness of living-donor lobar lung transplantation (LDLLT), it is necessary to predict the recipient's postoperative lung function. Traditionally, Date's formula, also called the segmental ratio, has used the number of lung segments to estimate the forced vital capacity (FVC) of grafts in LDLLT. To provide a more precise estimate of graft FVC, we calculated the volumes of the lower lobe and total lung using three-dimensional computed tomography (3D-CT) and the volume ratio between them. We calculated the volume ratio in 52 donors and tested the difference between the segmental volume ratios with a one-tailed *t*-test. We also calculated the predicted graft FVC in 21 LDLLTs using the segmental ratio pFVC(c) and the volume ratio pFVC(v), and then found the Pearson's correlation coefficients for both pFVC(c) and pFVC(v) with the recipients' actual FVC (rFVC) measured spirometrically 6 months after surgery. Significant differences were found between the segmental ratio and the average volume ratio for both sides (right, $p = 0.03$; left, $p = 0.0003$). Both pFVC(c) and pFVC(v) correlated significantly with rFVC at 6 months after surgery ($p = 0.007$ and 0.006). Both the conventional and the volumetric methods provided FVC predictions that correlated significantly with measured postoperative FVC.

Key words: living-donor lobar lung transplantation, 3D-CT volumetry

Living-donor lobar lung transplantation (LDLLT) is an essential procedure in the treatment of patients with severe lung disease. To assess the appropriateness of LDLLT, it is necessary to predict the recipient's postoperative lung function. This requires correct estimation of the graft function before surgery.

To estimate the graft forced vital capacity (FVC) in LDLLT, Date's formula [1], a calculation based on the number of lung segments, has traditionally been used. The right lower lobe consists of 5 segments, the left lower lobe of 4, and the whole lung of 19; thus, the ratios of the right and left lower lobes to the total lung segments are 5/19 and 4/19, respectively. These are referred to as the segmental ratios.

As a part of preoperative assessment, candidates for lung transplantation are routinely investigated with computed tomography (CT). 3D-CT volumetry has been used widely in prediction of liver function prior to transplantation [2-4]. The use of 3D-CT volume-

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try for preoperative estimation of lung function after LDLLT with a good number of cases has been reported in children [5], but not in adults.

To estimate graft FVC more precisely, we assessed lower lobe and total lung volumes with 3D-CT volumetry and found the volume ratio between them. We then calculated graft FVC using the segmental volume ratios and compared these predictions with the recipients' FVC (rFVC) measured 6 months after surgery.

Materials and Methods

Recipients and donors. Between 1998 and 2009, 50 living-donor lobar lung transplantations (LDLLTs) were performed at Okayama University Hospital. Preoperative chest CT examinations were performed at our hospital in 52 donors (mean age, 37.2 years; age range, 20 to 54 years) for 27 LDLLTs: 25 bilateral LDLLTs (50 donors) and 2 single LDLLTs (2 donors). Volume ratios were calculated for these 52 donors.

In 21 of the 25 bilateral LDLLT cases, FVC was measured in 21 LDLLT recipients 6 months after surgery. One case was excluded because the patient had undergone native lung-sparing lobar transplantation for pulmonary emphysema [6]. Recipients were 4 men and 16 women (mean age, 30.8 years; age range, 8 to 55 years). Diagnoses included primary pulmonary hypertension (n = 8), idiopathic pulmonary fibrosis (n = 5), idiopathic interstitial pneumonia (n = 3), lymphangioleiomyomatosis (n = 2), Langerhans cell histiocytosis (n = 1), and bronchiectasis (n = 1). Fifteen men and 5 women (mean age, 34.9 years) donated their right lower lobes; 3 men and 17 women (mean age 40.7 years) donated their left lower lobes [7].

The institutional ethical committee approved these procedures in October 1997. All patients gave their informed consent.

3D-CT volumetry. CT examinations were performed using 2 MDCT scanners (Aquilion Multi and Aquillion 16; Toshiba Medical, Tokyo, Japan) with the following parameters: FOV, 320 mm; gantry rotation time, 500 ms; helical pitch, 27 mm; effective slice width and increment, 7 or 5 mm (5 mm used only in 3 cases, 6 donors), 120 kV, and 300 effective mAs. CT scan of the chest was performed during a deep inspiration breath hold in the supine position with the arms elevated above the head. The DICOM images were sent to a computer workstation for analysis (AZE Virtual Place Lexus; AZE, Tokyo, Japan).

The total volume of each original image includes the air surrounding the patient, the mediastinum, the chest wall, and part of the upper abdomen, as well as the lung. First, the air density region was selected automatically by the computer. The non-lung air density region (*e.g.*, intestinal gas and trachea) was deselected manually by an experienced radiologist or radiological technologist. A three-dimensional model of the lung was constructed and the total lung volume measured. Then, each side of the lower lung lobe was selected manually and its volume measured.

Graft volume estimation. Date's formula, the conventional method of prediction, uses the segmental ratio to estimate graft FVC according to the following equation:

pFVC(c) = measured FVC of the right donor × 5/19 + measured FVC of the left donor × 4/19

Our volumetric method uses the lung volume ratio to predict the graft FVC with the following equation:

pFVC(v) = measured FVC of the right donor × (graft volume of the right donor/total lung volume of the right donor) + measured FVC of the left donor × (graft volume of the left donor/total lung volume of the left donor)

Recipient functional assessment. Six months after surgery, we performed complete pulmonary function tests, including spirometry, to determine rFVC.

Statistical analysis. We calculated the means and standard deviations (SDs) of measured volume ratios. The difference between the segmental ratio and the average volume ratio was tested with a one-tailed *t*-test. Additionally, we calculated Pearson's correlation coefficient between pFCV (for both pFVC(c) and pFVC(v)) and post-operative FVC. The threshold for significance was set at $p < 0.05$. Stata/SE 10.1 for Windows (STATA Corp., College Station, TX, USA) was used for the data analysis.

Results

Segmental and volume ratios. We calculated lower lobe and total lung volumes on both sides using 3D-CT in 52 donors (25 men and 27 women). The average volume ratio was 0.257 (SD = 0.023) for the right lobe and 0.223 (SD = 0.025) for the left lobe. A one-tailed *t*-test revealed significant differences between the segmental ratio and the average volume ratio for both sides ($p = 0.03$ (right) and 0.0003 (left)) (Table 1).

Graft volume estimation. We calculated pFVC(c) and pFVC(v) for 20 bilateral LDLLTs, and found Pearson's correlation coefficient between each pFCV and rFVC (Fig. 1). A significant correlation with post-operative rFVC was found for both pFVC(c) ($p = 0.007$) and pFVC(v) ($p = 0.006$) (Table 2).

Table 1 Segmental and volume ratios

	SR	VR			*p* value
		Mean	SD	95%CI	
RR	0.263	0.257	0.023	0.250–0.263	0.03*
RL	0.211	0.223	0.025	0.216–0.230	0.0003**

Data were analyzed using a one-tailed *t*-test.
*Alternative hypothesis: mean volume ratio < 5/19.
**Alternative hypothesis: mean volume ratio > 4/19.
SR, segmental ratio; VR, volume ratio; SD, standard deviation; CI, confidence interval; RR, ratio of total to right lower lobe lung; RL, ratio of total to left lower lobe lung.

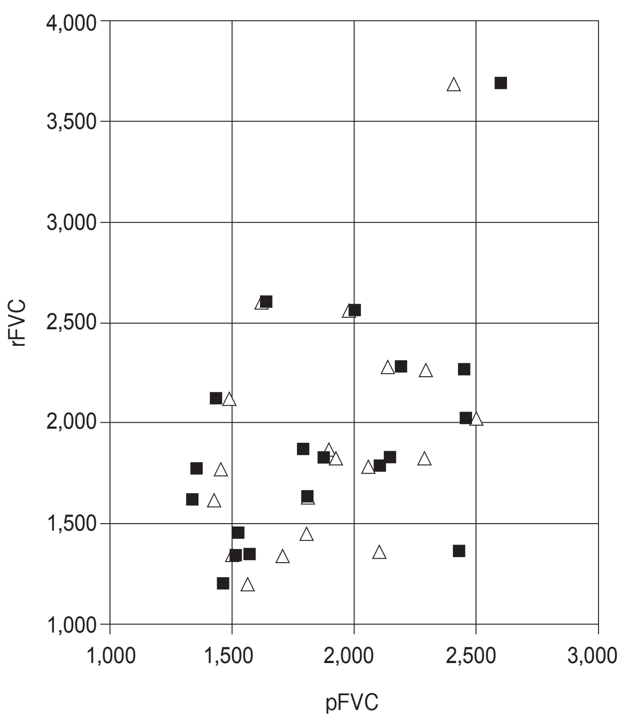

Fig. 1 Association between predicted FVC of the graft (pFVC) and recipients' actual FVC measured 6 months after surgery (rFVC). △ pFVC(c), ■ pFVC(v).

Table 2 Correlation between pFVC and measured rFVC at 6 months

Method	CC	RC	*p* value
Conventional pFVC(c)	0.58	1.03	0.007*
Volumetric pFVC(v)	0.59	0.84	0.006*

*Reached 0.05 significance threshold
CC, vorrelation coefficient; RC, regression coefficient; *p* value, *p* value for regression coefficient.

Discussion

The annual number of lung transplantations in Japan is increasing while the number of cadaveric lung transplantations (CLTs) is decreasing [8, 9]. Due to this trend, LDLLT risk assessment is becoming increasingly important. Precise estimation of graft FVC is necessary to reduce the risk associated with LDLLT, but it is impossible in CLT.

3D-CT volumetry has been used to estimate liver function prior to transplantation, but until now, there have been no reports of its use in predicting lung function after LDLLT. Lung volume assessed using 3D-CT volumetry has been found to correlate well with spirometric measures [10]. In this study, we used lung volume calculated with 3D-CT volumetry to estimate graft FVC. As CT is a routine part of preoperative assessment for LDLLT, this method allows extra procedures and the accompanying X-ray exposure to be avoided.

We hypothesized that the difference between segmental ratio and average volume ratio arose from the disparity in volume of the lung segments. In particular, the comparatively small size of the right S7 leads to the average volume ratio of the right being larger and that of the left smaller than predicted by the respective segmental ratios. There are many factors that may account for this difference, such as ventilation-perfusion inequality [11]. The use of ^{133}Xe gas scanning and ^{99m}Tc macroaggregate perfusion scanning for predicting loss of pulmonary function after pulmonary resection in the treatment of lung cancer has been reported [12–14], but as these scans require transplant candidates to be exposed to extra radiation, it is difficult to justify their use.

In addition to the significant difference seen between segmental ratio and volume ratio, significant correlations were found between both pFVC(c) and pFVC(v) and measured 6-month rFVC. Thus, both the conventional and volumetric methods provide reliable estimates of post-operative lung function. The discrepancy between the 2 results is due to the average of the right-side volume ratio being larger and the left smaller than the corresponding segmental ratios; the sum of both sides results in the correlation found in our study.

The major limitation of our study is the small number of cases used to estimate the correlation between pFVC and rFVC; further accumulation of cases is desirable. Additionally, in some emergency cases, preoperative CT scans were performed at other hospitals. These cases were excluded from this study due to differences in scan parameters, creating the possibility of selection bias.

Within our study, both pFVC(c) and pFVC(v) were found to correlate significantly with measured rFVC at 6 months after surgery. Both methods were found to be reliable, but the volumetric method provides size assessment information that is not possible with the simpler conventional method. Because the size discrepancy between the recipient and lobar graft occasionally results in pleural space problems and poor graft function [7], appropriate size matching between the donor and recipient may reduce the risk of complications. Accurate matching of the graft to the recipient's chest size using 3D-CT volumetry may aid in this goal.

Practically measured, pFVC(c) may more accurately predict the rFVC after LDLLT. Further, matching of the graft size to the recipient's thoracic volume can be accurately estimated using 3D-CT volumetry. 3D-CT volumetry before surgery is recommended even though no significant difference between the abilities of pFVC(c) and pFVC(v) to predict rFVC after LDLLT was seen at the 6-month point.

Conclusions. Segmental volume ratios were found to differ significantly from average measured volume ratios. However, no significant difference was seen between the abilities of conventional method (pFVC(c)) and the volumetric method (pFVC(v)) in their ability to predict rFVC after LDLLT, as both measures were found to correlate significantly with measured rFVC at 6 months after surgery.

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