Quantification of the impact of segmentectomy on pulmonary function by perfusion single-photon-emission computed tomography and multidetector computed tomography

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Objective: The impact of segmentectomy for preservation of pulmonary function was quantified by using a co-registered perfusion single-photon-emission computed tomography and multidetector computed tomography (SPECT/CT).

Methods: Pulmonary function tests and perfusion SPECT/CT were conducted before and after segmentectomy in 56 patients. Actual values of forced expiratory volume in 1 second (FEV₁) after segmentectomy were compared with the FEV₁ after virtual lobectomy, which was calculated by SPECT/CT. The preoperative and postoperative FEV₁ of each lobe that had undergone segmentectomy was measured by SPECT/CT.

Results: The mean percent of FEV₁ preserved after segmentectomy was significantly higher than the value after virtual lobectomy (88% ± 9% vs 77% ± 7%; $P < .001$). Whereas the mean value of the preoperative FEV₁ of each lobe that was undergoing segmentectomy was 0.51 ± 0.21 L, segmentectomy could preserve 41% ± 24% of it. The FEV₁ of each lobe after the resection of more than three segments ($n = 4$) was preserved in 17% ± 12% of the preoperative values, which was significantly less than 49% ± 23% and 35% ± 22% after the resection of one ($n = 29$) and two ($n = 23$) segments ($P = .02$ and $.08$, respectively). The FEV₁ of the left upper lobe after the upper division segmentectomy ($n = 8$) was preserved in 21% ± 11% of the preoperative values, which was significantly less than 35% ± 12% after the lingular segmentectomy ($n = 7$) ($P = .03$).

Conclusion: Segmentectomy can preserve the pulmonary function more significantly than lobectomy, except for the resection of more than three segments or the left upper division segmentectomy.

Several recent studies of segmentectomy for lung cancer suggest that segmentectomy can produce cure rates equivalent to those obtained after lobectomy in patients with T1 N0 non-small cell lung cancer (NSCLC).¹⁻⁵ However, controversies for preservation of pulmonary function remain because of the strong impact from the results of only one randomized controlled trial by the Lung Cancer Study Group in 1995, which showed little advantage in postoperative pulmonary function after segmentectomy.⁶ Although the previous reports compared the data of postoperative pulmonary function testing between lobectomy and segmentectomy,⁶⁻⁹ the pulmonary function of each lobe that had been subjected to segmentectomy has not been examined.

The recent development of a co-registered single-photon-emission computed tomography (SPECT) and computed tomography (CT) imaging (SPECT/CT) can show the

anatomy of the lung on perfusion SPECT images, enabling the measurement of pulmonary function of each lobe.¹⁰ Therefore, the preservation of pulmonary function of each lobe after segmentectomy would be measurable by the perfusion SPECT/CT. Since April 2005, we have conducted a prospective study of segmentectomy for C-T1 N0 M0 NSCLC.¹¹ To evaluate the usefulness of segmentectomy for preservation of postoperative pulmonary function in the present study, we compared pulmonary function between segmentectomy and virtual lobectomy and also used a perfusion SPECT/CT to measure the preserved pulmonary function of each lobe that had undergone segmentectomy.

PATIENTS AND METHODS

Eligibility

The study for examining perfusion scintigraphy with SPECT/CT in patients undergoing major lung resection was approved by the Ethics Committee of Kumamoto University Hospital in April 2005. Informed consent was obtained from all patients after the costs and benefits of the study had been discussed.

Patients

Between August 2005 and June 2007, 96 patients had undergone segmentectomy for NSCLC ($n = 85$), metastatic lung cancer ($n = 9$), and other diseases ($n = 2$). Of the 96 patients, 15 were excluded because they had undergone additional resections for other lesions. Twenty-five patients were also excluded because perfusion SPECT/CT was not conducted both before and after segmentectomy. As a result, 56 patients were enrolled in

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Abbreviations and Acronyms

CT	= computed tomography
DICOM	= Digital Imaging and Communications in Medicine
FEV ₁	= forced expiratory volume in 1 second
LUL	= left upper lobe
NSCLC	= non-small cell lung cancer
RI	= radioisotope
RLL	= right lower lobe
RUL	= right upper lobe
SPECT	= single-photon-emission computed tomography

the present study; they were examined with pulmonary function tests and perfusion SPECT/CT before and after segmentectomy (Table 1). One segment was resected in 29 patients, two segments in 23 patients, three segments in 2 patients, and four segments in 2 patients, with a mean number of 1.6 ± 0.7 segments per patient. Table 2 shows the sites of segmentectomy in each lobe.

Pulmonary Function Tests

Vital capacity, forced vital capacity, and forced expiratory volume in 1 second (FEV₁) were measured with the patient in a seated position using a dry rolling-seal spirometer (CHESTAC-9800DN; CHEST Inc, Tokyo, Japan) according to American Thoracic Society standards.¹²

SPECT/CT

Lung perfusion scintigraphy images were obtained by a SPECT/CT system. This system was composed of a commercially available gantry-free SPECT with dual-head detectors (Skylight; ADAC Laboratories, Milpitas, Calif) and an 8-multidetector-row CT scanner (Light-Speed Ultra Instrument; General Electric, Milwaukee, Wis). The two instruments were juxtaposed so that the CT table carrying the patient could be moved directly into the SPECT scanner before CT scanning. As a result, each patient was identically positioned for SPECT and CT imaging.

Each 185 MBq of ^{99m}Tc-macroaggregated human serum albumin (Daiichi Radioisotope Laboratories, Ltd, Tokyo, Japan) was administered intravenously with the patient first in the supine then in the prone position to make the albumin distribute uniformly.

SPECT data acquisition was performed with a vertex ultra-high resolution parallel-hole collimator. A 360-SPECT scan was acquired and was followed by CT scanning. Reconstructive CT images were processed into Digital Imaging and Communications in Medicine (DICOM) data and then transferred to Pegasys (ADAC Laboratories, Milpitas, Calif), which is a workstation for SPECT processing. One lumen of a 3-way stopcock (inner diameter 4 mm, length 10 mm) containing an aqueous solution of 99m technetium pertechnetate (^{99m}TcO₄⁻) and a contrast medium was used as an external fiducial marker. To obtain a precise record of both images, we fixed external fiducial markers to the common platform for SPECT and CT imaging. The two scans were performed sequentially. The SPECT images were manually fused with the CT images by aligning the external fiducial markers of the two images on the workstation. Transaxial, coronal, and sagittal sections of SPECT and CT images were manually fused with each other to obtain the best matching images on a workstation (AZE Virtual Place; AZE Co Ltd, Tokyo, Japan).

Postoperative SPECT/CT was conducted with the pulmonary function test more than 6 months after surgery (median 12 months; range 6–24 months).

TABLE 1. Patients' characteristics

Mean age (y) (range)	70 ± 9 (32–82)
Sex	
Male	25
Female	31
Mean FEV ₁ (L)	2.2 ± 0.6
Mean FEV ₁ /FVC (%)	74 ± 9
Mean FVC (L)	3.0 ± 0.8
Mean %FVC (%)	109 ± 14
Lobe undergoing segmentectomy	
Right upper lobe	9
Right lower lobe	16
Left upper lobe	22
Left lower lobe	9
No. of resected segments	
1	29
2	23
3	2
4	2
Mean tumor size (cm) (range)	1.8 ± 0.7 (0.8–4.4)
0–2	33
2–3	21
>3	2

FEV₁, Forced expiratory volume in 1 second; FVC, forced vital capacity.

Measurement of FEV₁ After Virtual Lobectomy

The postoperative FEV₁ after virtual lobectomy was predicted by SPECT/CT. The objective lobe was traced on the CT image with a region of interest, making the SPECT image after lobectomy (Figure 1). FEV₁ after virtual lobectomy was predicted according to the following formula:

FEV₁ after virtual lobectomy = Preoperative FEV₁ × (RI counts of the whole lung after virtual lobectomy/RI counts of the whole lung before surgery), where RI is radioisotope.

TABLE 2. Sites of segmentectomy

Segment	No. of patients	Segment	No. of patients
RUL (n = 9)		LUL (n = 22)	
S1	1	S1+2	3
S2	3	S3	3
S3	4	S1+2, 3	8
S3, 2a	1	S4, 5	7
		S3, 1+2a	1
RLL (n = 16)		LLL (n = 9)	
S6	6	S6	2
S7, 8	1	S8	1
S8	3	S8, 9	3
S9	1	S9, 10	2
S9, 10	1	S8, 9, 10	1
S7, 8, 9, 10	2		
S10	1		
S6, 9, 10	1		
Total	25		31

RUL, Right upper lobe; RLL, right lower lobe; LUL, left upper lobe, LLL, left lower lobe; S, segment. Right upper lobe: S1, apical; S2, anterior; S3, posterior. Right lower lobe: S6, apical; S7, medial; S8, anterior; S9, lateral; S10, posterior. Left upper lobe: S1+2, apical posterior; S3, apical anterior; S4, superior lingular; S5, inferior lingular. Left lower lobe: S6, apical; S8, anterior; S9, lateral; S10, posterior.

FIGURE 1. Virtual lobectomy of the left lower lobe on single-photon-emission computed tomography (SPECT) in a patient. A, Axial. B, Coronal. C, Sagittal. D, Three-dimensional imaging.

Measurement of Pulmonary Function of Each Lobe

Images of the lobe before segmentectomy and of the remaining lobe after segmentectomy were traced on the CT image with region of interest, of which RI was counted on the SPECT image (Figure 2). The FEV₁ of the objective lobe before and after segmentectomy was measured from the preoperative or postoperative SPECT/CT according to the following formula:

FEV₁ of the lobe before or after segmentectomy = Preoperative or postoperative FEV₁ × (RI counts of the lobe/RI counts of the whole lung).

Statistical Analysis

The paired *t* test was used to compare the pulmonary function before and after virtual lobectomy by using SPSS software (SPSS, Inc, Chicago, Ill). The Student *t* test was used to compare the FEV₁ of the remaining lobe among the number of resected segments and the sites of the lobe. All values in the text and table are given as mean ± SD.

RESULTS

There were no postoperative major complications after segmentectomy in any of the patients. Figure 3 shows the actual values of FEV₁ before and after segmentectomy and the predicted values after virtual lobectomy. The mean values of FEV₁ before and after segmentectomy were 2.2 ± 0.6 and 1.9 ± 0.5 L, respectively, of which mean percent of FEV₁ preserved was 88% ± 9%. The

mean value of the predicted FEV₁ after virtual lobectomy was 1.6 ± 0.4 L, of which mean percent of FEV₁ preserved was 77% ± 7%. The postoperative FEV₁ after segmentectomy was significantly higher than that after virtual lobectomy (*P* < .001).

Figure 4 shows the FEV₁ of each lobe that had undergone segmentectomy before and after surgery. The mean values of FEV₁ of each lobe before and after segmentectomy were 0.51 ± 0.21 and 0.21 ± 0.15 L, respectively. The segmentectomy preserved 41% ± 24% of the preoperative FEV₁ of each lobe.

Table 3 shows the FEV₁ of each lobe before and after segmentectomy according to the number of resected segments. Whereas the resections of one and two segments preserved 49% ± 23% and 35% ± 22% of preoperative FEV₁ of each lobe, respectively, that of three or four segments preserved only 17% ± 12%. The mean percent of the preserved FEV₁ with the resections of one and two segments was higher than that with the resection of three or four segments (*P* = .02 and .08, respectively), whereas there was no significant difference between the resection of one and two segments.

FIGURE 2. A, Coronal image of CT before surgery, showing a lung cancer in the anterior segment of the left lower lobe. B, Coronal image of the perfusion SPECT/CT of the left lower lobe before segmentectomy. C, Coronal image of the perfusion SPECT/CT of the remaining left lower lobe after segmentectomy.

FIGURE 3. Measured forced expiratory volume in 1 second (FEV_1) before and after segmentectomy and predicted value after virtual lobectomy.

FIGURE 4. Forced expiratory volume in 1 second (FEV_1) of each lobe before and after segmentectomy measured by perfusion SPECT/CT.

TABLE 3. Forced expiratory volume in 1 second of the lobe before and after segmentectomy

No. of resected segments	No. of patients	Mean FEV ₁ of the lobe (L)		After/before (%)
		Before	After	
1	29	0.52 ± 0.21	0.25 ± 0.15	49 ± 23
2	23	0.54 ± 0.21	0.19 ± 0.13	35 ± 22
3 or 4	4	0.32 ± 0.15	0.06 ± 0.06	17 ± 12

FEV₁, Forced expiratory volume in 1 second.

Table 4 shows the FEV₁ of the left upper lobe (LUL) before and after segmentectomy in 8 patients who had undergone upper division segmentectomy (the resection of apical posterior and apical anterior segments) and 7 patients who had undergone lingular segmentectomy (the resection of superior lingular and inferior lingular segments). The mean percent of FEV₁ of the LUL after the upper division segmentectomy was 21% ± 11% of the preoperative value, which was significantly lower than 35% ± 12% after the lingular segmentectomy ($P = .03$). There was no difference in the mean percent of FEV₁ of the remaining lobe between the upper division segmentectomy and resections of more than three segments ($P = .54$).

Table 5 shows the FEV₁ of the lobe that had undergone segmentectomy before and after segmentectomy in each lobe. Although there was no significant difference in the number of resected segments among each lobe, the mean percent of FEV₁ after segmentectomy in the right lower lobe (RLL) was 61% ± 30% of the preoperative value, which was significantly higher than 34% ± 13% and 32% ± 14% in the right upper lobe (RUL) and LUL ($P = .02$ and $.001$, respectively).

Table 6 lists 11 patients who had less than 0.10 L of FEV₁ in the remaining lobe. Of these, 3 patients (Nos. 8, 10, and 11) had undergone basal segmentectomy, and another 3 patients (Nos. 5, 6, and 7) had undergone the left upper division segmentectomy.

DISCUSSION

The present study clarified the following points: (1) virtual lobectomy showed significant decrease of FEV₁ com-

TABLE 4. Forced expiratory volume in 1 second of the left upper lobe before and after upper division segmentectomy or lingular segmentectomy

Site of segmentectomy	No. of patients	Mean FEV ₁ of LUL (L)		Before/after (%)
		Before	After	
Upper division	8	0.63 ± 0.21	0.14 ± 0.11	21 ± 11
Lingular	7	0.56 ± 0.22	0.21 ± 0.11	35 ± 12

FEV₁, Forced expiratory volume in 1 second; LUL, left upper lobe. Upper division: apical posterior (S1+2) and apical anterior (S3). Lingular: superior lingular (S4) and inferior lingular (S5).**TABLE 5. Forced expiratory volume in 1 second of the object lobe before and after segmentectomy**

Lobe	No. of patients	No. of resected segments	Mean FEV ₁ of the lobe (L)		After/before (%)
			Before	After	
RUL	9	1.1 ± 0.2	0.54 ± 0.16	0.18 ± 0.09	34 ± 13
RLL	16	1.6 ± 1.1	0.49 ± 0.22	0.30 ± 0.19	61 ± 30
LUL	22	1.7 ± 0.5	0.61 ± 0.19	0.20 ± 0.11	32 ± 14
LLL	9	1.9 ± 0.6	0.28 ± 0.09	0.11 ± 0.08	38 ± 20

FEV₁, Forced expiratory volume in 1 second; LUL, left upper lobe; LLL, left lower lobe; RUL, right upper lobe; RLL, right lower lobe.

pared with segmentectomy; (2) the FEV₁ of each lobe after segmentectomy remained 0.21 L in the mean value, which could contribute to the preservation of postoperative pulmonary function; (3) although segmentectomy with the resection of one or two segments could preserve FEV₁ of each lobe absolutely, the resection of more than three segments could not; and (4) although the lingular segmentectomy could preserve FEV₁ of the LUL absolutely, the upper division segmentectomy could not.

FEV₁ values after virtual lobectomy in the present study were calculated by perfusion SPECT/CT but were not actual values. However, Ohno and associates¹⁰ showed highly significant correlation of pulmonary function after lobectomy between the actual value and the value calculated by perfusion SPECT/CT. Because the perfusion SPECT/CT can count the RI of each lobe accurately, we believe that it can predict postoperative pulmonary function after lobectomy with significant accuracy. However, even by using SPECT/CT, postoperative pulmonary function after segmentectomy might be hard to predict, because CT cannot clearly identify the border of the segments within a lobe.

TABLE 6. Characteristics of patients with less than 0.10 L of forced expiratory volume in 1 second in the remaining lobe

Case	Sex	Age (y)	Lobe	Resected segments	FEV ₁ of the lobe (L)	
					Before	After
1	F	81	LLL	S8	0.10	0.03
2	F	75	LUL	S4, 5	0.19	0.05
3	F	59	LLL	S9, 10	0.34	0.05
4	M	69	LLL	S9, 10	0.19	0.05
5	M	80	LUL	S1+2, 3	0.49	0.06
6	F	70	LUL	S1+2, 3	0.27	0.06
7	M	70	LUL	S1+2, 3	0.82	0.07
8	F	81	LLL	S8, 9, 10	0.24	0.03
9	M	64	RUL	S3	0.50	0.03
10	F	80	RLL	S7, 8, 9, 10	0.15	0.01
11	F	70	RLL	S7, 8, 9, 10	0.45	0.07

S, Segment; LUL, left upper lobe; LLL, left lower lobe; RUL, right upper lobe; RLL, right lower lobe. Right upper lobe: S1, apical; S2, anterior; S3, posterior. Right lower lobe: S6, apical; S7, medial; S8, anterior; S9, lateral; S10, posterior. Left upper lobe: S1+2, apical posterior; S3, apical anterior; S4, superior lingular; S5, inferior lingular. Left lower lobe: S6, apical; S8, anterior; S9, lateral; S10, posterior.

The present study shows that although the segmentectomy with the resection of one or two segments could preserve FEV₁ of the remaining lobe absolutely, that with the resection of more than three segments could preserve only 0.06 L of the mean FEV₁ in the remaining lobe. In addition, all 3 patients who had undergone basal segmentectomy, that is, the resection of more than three segments, had less than 0.10 L of FEV₁ in the remaining lower lobe. Therefore, the resection of more than three segments or basal segmentectomy should be indicated only for patients with critical pulmonary function.

The present study showed that the left upper division segmentectomy resulted in significantly lower FEV₁ of the remaining LUL than the lingular segmentectomy. In addition, 3 of the 8 patients who had undergone upper division segmentectomy had FEV₁ less than 0.10 L in their remaining LUL. We suspect that the reasons for this outcome were as follows: (1) the upper division segment is usually larger than the lingular segment, because the former had 6 subsegments and the latter had only 4; and (2) the upper division segmentectomy could cause the significant decrease of the FEV₁ of the lingular segment, probably because of the excessive upward bending and rotation of the lingular bronchus, similar to the occurrence of right middle lobe syndrome after right upper lobectomy.^{13,14}

Our results showed that the FEV₁ of the remaining lobe was significantly higher in RLL than in RUL and LUL, which could be caused by the following reasons: (1) the RUL has only three segments, whereas the RLL has five, which could result in a higher FEV₁ of the remaining lobe in the segmentectomy of the latter; and (2) both of the apical posterior segment (S1+2) and apical anterior segment (S3) in the LUL are usually larger than each segment of the RLL, which could result in a higher FEV₁ of the remaining lobe in the segmentectomy of the latter.

We conclude that segmentectomy can preserve postoperative pulmonary function absolutely compared with lobectomy, except for the resection of more than three segments or the left upper division segmentectomy. Throughout the world, several randomized trials of lobectomy versus

segmentectomy in patients with small peripheral stage IA NSCLC are about to commence or are ongoing. From our data, we recommend that the patients requiring the resection of more than three segments or the left upper division segmentectomy should be excluded or examined separately for the examination of postoperative pulmonary function in these studies.

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