Preoperative (3-dimensional) computed tomography lung reconstruction before anatomic segmentectomy or lobectomy for stage I non–small cell lung cancer

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ABSTRACT

Objectives: Accurate cancer localization and negative resection margins are necessary for successful segmentectomy. In this study, we evaluate a newly developed software package that permits automated segmentation of the pulmonary parenchyma, allowing 3-dimensional assessment of tumor size, location, and estimates of surgical margins.

Methods: A pilot study using a newly developed 3-dimensional computed tomography analytic software package was performed to retrospectively evaluate preoperative computed tomography images of patients who underwent segmentectomy (n = 36) or lobectomy (n = 15) for stage 1 non–small cell lung cancer. The software accomplishes an automated reconstruction of anatomic pulmonary segments of the lung based on bronchial arborization. Estimates of anticipated surgical margins and pulmonary segmental volume were made on the basis of 3-dimensional reconstruction.

Results: Autosegmentation was achieved in 72.7% (32/44) of preoperative computed tomography images with slice thicknesses of 3 mm or less. Reasons for segmentation failure included local severe emphysema or pneumonitis, and lower computed tomography resolution. Tumor segmental localization was achieved in all autosegmented studies. The 3-dimensional computed tomography analysis provided a positive predictive value of 87% in predicting a marginal clearance greater than 1 cm and a 75% positive predictive value in predicting a margin to tumor diameter ratio greater than 1 in relation to the surgical pathology assessment.

Conclusions: This preoperative 3-dimensional computed tomography analysis of segmental anatomy can confirm the tumor location within an anatomic segment and aid in predicting surgical margins. This 3-dimensional computed tomography information may assist in the preoperative assessment regarding the suitability of segmentectomy for peripheral lung cancers. (*J Thorac Cardiovasc Surg* 2015;150:523-8)

Automated 3D rendering of pulmonary segmental anatomy.

Central Message

A novel 3D CT software package provides automated lung segmentation, tumor localization, and estimated margins of surgical resection.

Perspective

Preoperative 3D CT analysis can assist surgeons in patients in whom tumors encroach on segmental boundaries, in patients in whom tumors may be neither visible nor palpable intraoperatively (eg, ground glass opacities), and in patients for whom surgeons are deciding on whether to perform segmentectomy versus lobectomy on the basis of tumor size, location, and anticipated surgical margins.

See Editorial Commentary page 529.

Although lobectomy remains the established standard in the management of clinical stage I non–small cell lung cancer (NSCLC), numerous recent studies have suggested that

anatomic segmentectomy might afford similar locoregional and distant control when compared with lobectomy in this setting.^{1,2} Small, peripheral tumors that are confined to discrete segmental boundaries represent the ideal candidates for segmental resection when acceptable surgical margins can be obtained.^{3,4} Establishing a computed tomography (CT) analytic program capable of accurately mapping out tumor segmental location and its spatial relationship within the boundaries of the lung parenchyma would be valuable in enhancing preoperative planning. This CT analytic approach has proven to be effective in other surgical disciplines, as in the case of parenchymal-sparing hepatic resection.^{5,6}

In this study, we evaluated the feasibility of a newly developed analytic software package to evaluate tumor

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Abbreviations and Acronyms

CT	= computed tomography
NSCLC	= non-small cell lung cancer
3D	= 3-dimensional

segmental location, to provide accurate 3-dimensional (3D) estimates of lung and tumor volumes, and to estimate margins of resection in a cohort of patients undergoing segmentectomy or lobectomy for clinical stage I NSCLC.

MATERIALS AND METHODS**Patient Population**

A retrospective pilot study was conducted on patients undergoing lobectomy or segmentectomy for clinical stage I NSCLC. A cohort of potential candidates with a tumor size less than 2 cm and a preoperative forced expiratory volume in 1 second greater than 60% were identified in the Lung Cancer Database of the Department of Cardiothoracic Surgery at the University of Pittsburgh Medical Center. Institutional review board approval was obtained, and informed consent was waived because of the retrospective nature of the study. Patient and tumor characteristics are delineated in Table 1.

Surgical Technique

Anatomic segmentectomy and lobectomy were performed as described previously.² Anatomic segmentectomy was accomplished by individual isolation and division of the targeted segmental bronchial and vascular structures, and complete excision of the corresponding segmental pedicle. Once the segmental pedicle has been divided, we develop the intersegmental plane near the pedicle with electrocautery to permit adequate separation of the pedicle from the neighboring segment(s). The plane of division at this level can be identified by the intersegmental vein. Once the segmental pedicle is adequately mobilized, test inflation of the ipsilateral lung is performed to aid in establishing the parenchymal line of demarcation. We then perform an extended segmentectomy using a stapled approach to complete the parenchymal transection. This staple line is carried into the adjacent segmental tissue to ensure complete segmental excision. Lobectomy was also accomplished using similar techniques of individual isolation and division of the corresponding bronchovascular contributions to the lobe. Systematic hilar and mediastinal nodal sampling was then performed. A majority of the resections were accomplished using the video-assisted thoracoscopic surgery approach: segmentectomy (81%) and lobectomy (60%).

Computed Tomography Imaging and Analysis

Preoperative CT scans obtained within 6 weeks of the surgical procedure were identified from the electronic medical record. The preoperative CT scan data were obtained in the form of Digital Imaging and Communication in Medicine files and de-identified before being provided to the investigators for analysis. A total of 51 scans (segmentectomy = 36, lobectomy = 15) were obtained and uploaded into a 3D CT imaging software package developed in the Department of Radiology at the University of Pittsburgh Medical Center. Although the program used in this analysis is not currently commercially available as of yet, there are several programs in the market that have similar capabilities that have been studied in the literature (Velocity AI, Varian Medical Systems, Palo Alto, Calif; Apollo, Vida Diagnostics, Inc, Coralville, Iowa). However, none of the commercially available programs currently have the capability to autosegment the lungs, as is possible in this software package.

Study Parameters and Statistical Analysis

Study parameters included patient demographics, autosegmentation of lung parenchyma (Figure 1, A), tumor characteristics (eg, diameter, volume, lobar and segmental location, and histology), CT image characteristics, predicted total volume of both the left and right lungs, and the closest anticipated distances from the tumor to the parenchyma margin of the 3D CT reconstructed pulmonary segment. Autosegmentation is achieved on the basis of the intrinsic bronchial arborization within the parenchyma of the lung using differential geometric algorithms programed into our CT imaging software package (Figure 1, B).⁷⁻¹⁰ Margin to tumor diameter ratio was calculated from these measurements performed with the functions provided by the 3D CT imaging software package and compared with the margins of resection actually recorded from the surgical specimen in the anatomic pathology laboratory. Sensitivity, specificity, and positive and negative predictive values were all calculated for the program's ability to predict a calculated margin to tumor diameter ratio greater than 1 and a marginal clearance greater than 1 cm with the 3D CT rendering of the pulmonary segmental boundaries. In an additional subset of 11 patients who underwent lobectomy, a simulated segmentectomy was performed to assess the potential adequacy of surgical margins had anatomic segmentectomy been performed rather than lobectomy. Margins were recorded as if these 11 cases would have undergone a segmentectomy rather than lobectomy. 3D renderings of lung volume were also obtained from the program. The average computer time to complete the segmentation, evaluate marginal status, and perform lung volumetric analysis was approximately 15 to 20 minutes.

RESULTS**Segmentation of Computed Tomography Images**

Of the 51 scans analyzed, 33 (65%) (21/36 in the segmentectomy group, 12/15 in the lobectomy group) of the successfully uploaded CT scans were segmented by the program (Figure 1, A and B). A total of 73% (32/44) of scans with a slice thickness less than 3 mm were successfully segmented by the program (segmentectomy, 21/31 [68%]; lobectomy, 11/13 [85%]). Reasons reported for segmentation failure include the use of whole body scans instead of a dedicated chest CT, poorly visualized fissures, and poor airway visualization due to the quality of the CT images or the parenchymal distortion (eg, pneumonitis/fibrosis).

Tumor Assessment and Margin Analysis

3D CT reconstruction allowed for accurate segmental location of the tumor in all cases in which the program was able to segment the lung (33/33) (Figure 2, A and B). Tumor diameter was measured in 51 of 51 successfully uploaded cases with an average predicted tumor size of 3.0 cm. The average tumor volume was 7.9 cm³. The predicted parenchymal margin of resection was calculated using the 3D CT software in the same 33 patients (segmentectomy and lobectomy) (Figure 2, C and D). The average predicted margin of resection was 2.0 cm in the segmentectomy group and 2.7 cm in the lobectomy group. There were no statistically significant differences between the predicted values and the actual margin of resection for the segmentectomy group ($P = .781$) or lobectomy group ($P = .681$) (Table 2). Sensitivity and positive predictive values were 77% and 87%, respectively, and specificity

TABLE 1. Patient and tumor characteristics

Variable	Segmentectomy	Lobectomy
Age, mean (range), y	70 (42-83)	66 (44-74)
Gender		
Male	19 (53%)	13 (87%)
Female	17 (47%)	2 (13%)
Histology (%)		
Adenocarcinoma	22 (61%)	8 (53%)
Squamous cell carcinoma	13 (36%)	6 (40%)
Other	1 (3%)	1 (7%)
Tumor size (cm)	1.8	2.1
Tumor location		
RUL	8	8
RML	2	1
RLL	8	3
LUL	11	1
LLL	7	2
Approach (%)		
VATS	29 (81%)	9 (60%)
Open	7 (19%)	6 (40%)

LLL, Left lower lobe; LUL, left upper lobe; RLL, right lower lobe; RML, right middle lobe; RUL, right upper lobe; VATS, video-assisted thoracoscopic surgery.

and negative predictive value were 40% and 25%, respectively, when using our program as a screening tool to detect marginal clearance greater than 1 cm (Table 3).

There was no statistically significant difference between the predicted and the actual surgical margin to tumor

diameter ratio for the segmentectomy cohort ($P = .187$) or lobectomy cohort ($P = .588$). The 3D CT software program predicted a margin to tumor diameter ratio less than 1 in 11 of 13 (5/6 in segmentectomy group, 6/7 in lobectomy group) when compared with the pathologic evaluation of the resected specimen. The specificity and positive predictive value in using the predicted calculated margin to tumor ratio greater than 1 were both 75%. Sensitivity and negative predictive value were found to be lower at 47% each (Table 3).

Preoperative Planning

Among the patients undergoing lobectomy, we analyzed the predicted surgical margins that would potentially have been obtained if segmentectomy, rather than lobectomy, had been performed. The average surgical margin was calculated to be 0.8 cm (median, 0.5 cm). Average margin to tumor diameter ratio was only 0.9 cm (median, 0.1 cm). Of note, 91% (10/11) of these simulated segmentectomy margin to tumor diameter ratios were calculated to be less than 1, suggesting that segmentectomy might not have been able to obtain an adequate margin in these cases.

Volumetric Assessment

Volumetric measurements of the lungs were performed on all 51 analyzable scans. An estimate of bilateral lung volumes was successfully obtained in 51 of 51 (100%) of the scans that were uploaded and analyzed (Table 2). Average lung volume was 5055 mL in all analyzed scans (4861 mL in the segmentectomy group, 5519 mL in the lobectomy group).

DISCUSSION

CT imaging represents the cornerstone of the preoperative assessment of the patient with lung cancer. This modality provides critical information regarding tumor size and location in the context of the patients underlying anatomy. Surgeons routinely use this information to generate a “mental model” of characteristics to assess the resectability of the lung nodule, as well as foresee any possible technical difficulties when performing the planned procedure.¹¹ A logical next step in the preoperative assessment of solitary lung nodules or known lung cancers would be the implementation of 3D analysis to more accurately delineate the segmental anatomic relationships of the tumor, tumor volumes, and an estimate of the surgical margins in reference to the extent of surgical resection being planned. Such 3D CT imaging programs have been used in other surgical arenas to determine the extent of resection needed to adequately clear the target lesion, most notably in hepatic surgery.

Song and colleagues¹² reported their experience with a preoperative planning software package to accurately segment the liver parenchyma, visualize pertinent

FIGURE 1. A, Three-dimensional rendering of the bronchial airways with color-coded segmental branches. B, Lung parenchyma divided into anatomic segments based on the labeled airways. Note the detail in the segmental boundaries.

GTS

FIGURE 2. A, Lung parenchyma is divided into lobes and made transparent to visualize the relationship between the tumor (highlighted in red) and the lobar divisions and airways. Note the detail in the contouring of the tumor surface. B, 3D rendering demonstrates how this tumor crosses segmental boundaries. C and D, The program is able to provide specific 3D measurements of anticipated surgical margins. Shown are views of a 3D measured distance (white line) between a tumor (red) and the anticipated point of bronchial division (purple).

intrahepatic vasculature, and characterize the tumor's relationship to vital intrahepatic structures. These authors found this preoperative 3D CT useful in preoperative

treatment planning. Yamanaka and associates¹³ in 2007 compared data provided by a 3D CT analytic program with the traditional planimetry method (values estimated on the basis of manually traced boundaries on CT images with an electronic cursor) used by other hepatic surgeons to assess the volume of hepatic tissue resected in a cohort of 113 patients undergoing hepatic resection for hepatocellular carcinoma. The authors found a stronger positive correlation between the simulated predicted liver resection volumes and the actual weight of resected specimens ($r = 0.96$, $P < .0001$) than the values calculated through

TABLE 2. Lung parenchyma and tumor analysis

Margin	Segmentectomy		Lobectomy	
	Predicted	Actual	Predicted	Actual
Mean distance to the nearest bronchial division (cm)	8.72	Not recorded	8.18	Not recorded
Mean distance to the nearest parenchymal staple line (cm)	2.0	2.1 $P = .781$	2.7	2.4 $P = .681$
Mean margin: tumor diameter ratio	1.0	1.5 $P = .187$	1.7	1.3 $P = .568$
Mean maximal diameter (cm)	2.4	1.8	4.3	2.1
Volume (cm ³)	5.2	Not recorded	14.3	Not recorded
Mean right lung volume (mL)		2616		2882
Mean left lung volume (mL)		2245		2637
Total lung volume (mL)		4861		5519

TABLE 3. Statistical margin analysis

Statistical variable	Value
Marginal clearance >1 cm	
Sensitivity	77
Specificity	40
Positive predictive value	87
Negative predictive value	25
Margin: tumor diameter ratio >1	
Sensitivity	47
Specificity	75
Positive predictive value	75
Negative predictive value	47

planimetry ($r = 0.74$, $P < .05$).¹³ The difference between predicted and actual margins was only 1.6 ± 2.6 mm. Such estimates of surgical margin are not easily obtainable through standard hepatic planimetric assessment. These investigators were also able to perform hepatectomy simulations with the 3D hepatic reconstruction based on estimates of volume of resection.

There is little published experience with the use of 3D CT pulmonary parenchymal reconstruction as a preoperative aid in evaluating potential surgical strategies for the small peripheral lung cancer. Some preliminary work has been done with 3D CT reconstruction of the pulmonary vasculature.¹⁴⁻¹⁶ In the current investigation, we were able to demonstrate that a 3D CT analytic software program is able to successfully and automatically contour the lung lobar and segmental anatomy using the lobar and segmental bronchial anatomy as a primary guide. Localization of lung tumors to their anatomic segment of involvement was successful in 100% of cases. Pulmonary volumetric information also can be obtained with the use of these CT analytic tools, which may have clinical importance. Total lung volumes, as well as individual lobar and segmental volumes, can be quantitated. These lung volume estimates will need to be explored in future studies in the context of preoperative and postoperative pulmonary function testing.

The use of this 3D CT reconstruction was also successful in predicting the adequacy of the surgical resection margin as a function of margin to tumor diameter ratio greater than 1 in 75% of cases evaluated. The low negative predictive value in this study (25%-47%) (Table 3) may be, in part, a reflection of measures taken during the time of surgery to obtain an adequate margin. Specifically, the use of an extended segmentectomy approach could result in a larger final parenchymal margin than that calculated by purely anatomic segmental boundaries during analysis of preoperative CT imaging.

3D CT rendering of the pulmonary bronchovascular anatomy may enhance the delineation of anatomic variants that might come into play during anatomic dissection, tumor and lung volumetric assessments, and the precise localization of the lung tumor. This information will also be valuable in the sequential CT surveillance of suspicious lung lesions. Such data may be especially useful in cases in which tumors encroach on segmental boundaries, tumors may be neither visible nor palpable intraoperatively (eg, ground-glass opacities), and surgeons are deciding on whether to perform segmentectomy versus lobectomy on the basis of tumor size, location, and anticipated surgical margins. The high positive predictive value in our analysis suggests that final margins are likely to be satisfactory after segmentectomy when a preoperative estimated margin greater than 1 cm or a margin to tumor diameter ratio greater than 1 is anticipated.

Study Limitations

There are a number of limitations regarding the utility of this 3D CT imaging analysis program. Given the retrospective nature of this study, the analysis of the results can be inherently influenced by selection bias. Patients in this study were selected for each procedure before performing the 3D analysis. Therefore, patients chosen for segmentectomy in this study likely represent those most fit to undergo this procedure on the basis of favorable patient and tumor characteristics. Interpretation of these results may not necessarily be generalizable to more complex clinical scenarios, and prospective studies will be necessary to validate these findings and to delineate the merits of this technology. The quality and resolution of CT scans vary from hospital to hospital. When only CT scans that had slices less than 3 mm in thickness were analyzed, successful autosegmentation rates increased from 65% to 73%. We have observed that complete pulmonary segmental analysis and volumetric assessment can be obtained in nearly all cases when CT scan slices of 1.25 mm or less are used in the absence of important pulmonary parenchymal distortion by bullous emphysema or important local lung infiltrate/consolidation. This observation also has been reported in the setting of hepatic and pulmonary reconstruction, where the typical slice thickness achieved by their CT scanners was 1.25 and 0.5 mm.¹²⁻¹⁷

CONCLUSIONS

The use of a CT imaging analysis program in a highly selected group of patients with suitable anatomic characteristics seems to provide thoracic surgeons with tools that can be helpful in the preoperative assessment of a patient undergoing anatomic lung resection. This pilot study examined the feasibility of a 3D CT imaging analytic package to segment lungs, compute accurate 3D margin measurements, and effectively identify tumor characteristics such as size and segmental location. Application of such a program in a prospective analysis could further delineate the merits of this analytic software package in treatment planning and surgical decision-making in the management of the small, peripheral lung cancer.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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Key Words: computed tomography, lung cancer, lung reconstruction, segmentectomy

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