Semi-Automatic Measurement of the Airway Dimension by Computed Tomography Using the Full-With-Half-Maximum Method: a Study of the Measurement Accuracy according to the Orientation of an Artificial Airway

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Objective: To develop an algorithm to measure the dimensions of an airway oriented obliquely on a volumetric CT, as well as assess the effect of the imaging parameters on the correct measurement of the airway dimension.

Materials and Methods: An airway phantom with 11 poly-acryl tubes of various lumen diameters and wall thicknesses was scanned using a 16-MDCT (multidetector CT) at various tilt angles (0, 30, 45, and 60°). The CT images were reconstructed at various reconstruction kernels and thicknesses. The axis of each airway was determined using the 3D thinning algorithm, with images perpendicular to the axis being reconstructed. The luminal radius and wall thickness was measured by the full-width-half-maximum method. The influence of the CT parameters (the size of the airways, obliquity on the radius and wall thickness) was assessed by comparing the actual dimension of each tube with the estimated values.

Results: The 3D thinning algorithm correctly determined the axis of the oblique airway in all tubes (mean error: 0.91 ± 0.82°). A sharper reconstruction kernel, thicker image thickness and larger tilt angle of the airway axis resulted in a significant decrease of the measured wall thickness and an increase of the measured luminal radius. Use of a standard kernel and a 0.75-mm slice thickness resulted in the most accurate measurement of airway dimension, which was independent of obliquity.

Conclusion: The airway obliquity and imaging parameters have a strong influence on the accuracy of the airway wall measurement. For the accurate measurement of airway thickness, the CT images should be reconstructed with a standard kernel and a 0.75 mm slice thickness.

Index terms:
Airway dimension measurement
Obliquity effect
FWHM (Full Width at Half Maximum)
CT imaging parameters, phantom study.

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The recent development of multi-detector computed tomography (MDCT) scanners allow for the exact quantification of peripheral airway geometry, which in turn provide important information for evaluating regional airway physiology and structure. In particular, the elucidation of bronchial tree dimensions can be used to evaluate and track the development of diseases affecting the airways, such as asthma and chronic obstructive lung diseases, as well as to determine the efficacy of new therapeutic approaches (1, 2). To date, such studies have for the most part, been limited the assessment of airway dimensions into the airways perpendicular to their local long axis in order to avoid the overestimation of pleural wall thickness or luminal diameters associated with the oblique sectioning of a tubular structure (3−7). It is especially important to accurately measure an oblique airway, since most peripheral airways are tilted in the axial section. Only a few researchers have measured the airway as a result of this airway obliquity. Saba et al. studied oblique airway measurements using a physical phantom and an elliptical fitting (8). However, this method assumed that the airway lumen is circular.

In addition, there is a large estimation error in the tilt angle in the case of a small airway, due to the partial volume effect. For a virtual bronchoscopy, several studies have addressed the detection of the airway center line (9, 10). However, these studies do not focus on the accurate measurement of the tilted airway dimension to the axial scan plane, but rather on the accurate path generation of the camera.

The aim of this study was to develop an algorithm which accurately measures the dimensions of an obliquely oriented airway to an axial scanning plane assessed by volumetric CT, and to evaluate the degree of influence on the measurement accuracy of the obliquity of an airway and the interacting factors including, which include the CT imaging parameters and airway sizes, using the full width at half maximum (FWHM) method. In addition, we attempted to create a clinically viable recommendation for oblique airway measurement using the FWHM method.

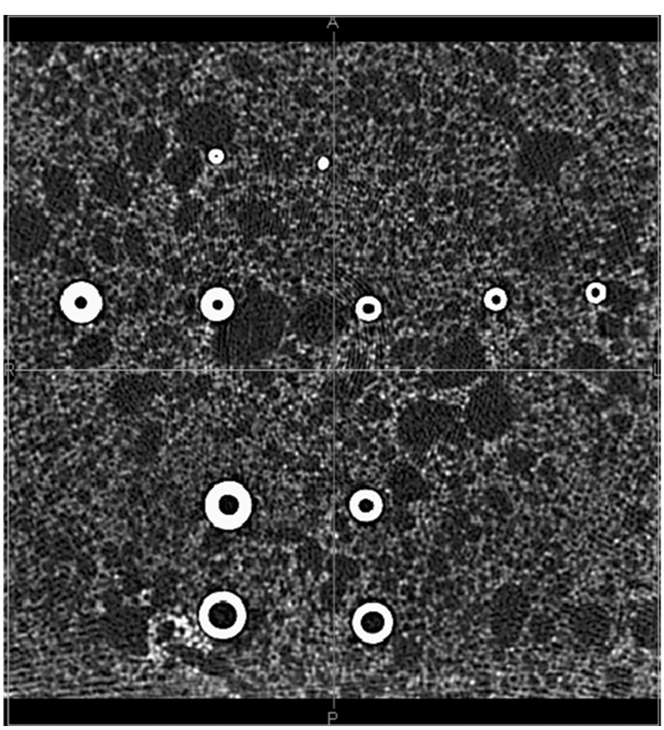
MATERIALS AND METHODS

Airway Phantom and Measurement

A phantom was composed of eleven poly-acryl tubes which simulated airways of various inner diameters and wall thicknesses, ranging from 1.26 to 8.46 mm and from 0.45 to 3.08 mm, respectively. The details of the airway phantom design and measurement have been described in our previous report (11).

CT Scan and Data Storage

The phantom was scanned at various tilt angles (i.e., 0, 30, 45, and 60°), to the axial plane on a 16-multi-detector-row CT scanner (Siemens Sensation 16, Siemens Medical Solutions, Erlangen, Germany). The CT scan parameters included a 16 × 0.75 mm collimator with 100 effective mAs, a pitch of 1.0 and 120 kVp, a 512 × 512 matrix setting, and a 360-mm field of view (FOV). The CT images were reconstructed using every combination of the following parameters: five different reconstruction kernels (B10f, B30f, B50f, B70f and B80f); tilt angles (0, 30, 45, and 60°) to the axial plane; and slice thicknesses (0.75, 1, and 2 mm) (Fig. 1). A reconstruction kernel of B10f corresponds to a soft reconstruction kernel, as opposed to B50f, which is standard, and B80f, which is a sharp reconstruction kernel. The resulting 2D image data were stored in the Digital Imaging and Communications in Medicine (DICOM)



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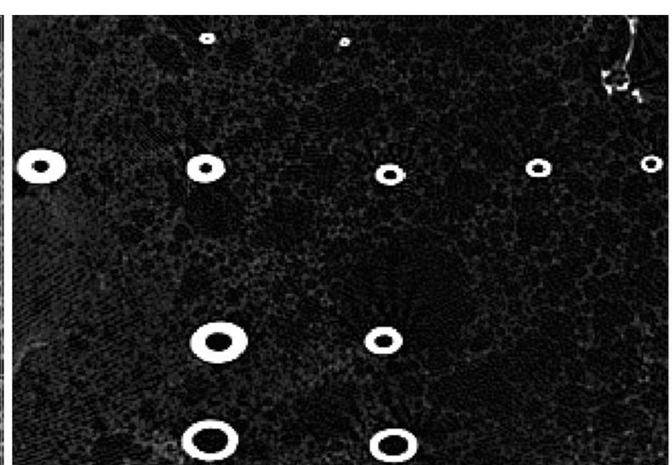

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Fig. 1. CT images of poly-acryl airway phantom.
A. CT image of phantom without tilt angle.
B. CT image of phantom tilted at 45° to scan plane. These images were taken with 360-mm reconstruction field of view, B50f reconstruction kernel, and 0.75-mm slice thickness. Note tube shape distortion to ovoid at tilted orientations.

format.

Data Processing and Analysis Procedure

In-house software was developed at the Asan Medical Center to accurately measure airway wall thickness and luminal radius. Figure 2 shows the schematic diagram of the data processing and analysis. In addition to the data process steps described in our previous report, we added two steps for axis determination of an oblique airway and for image reconstruction perpendicular to the axis (Fig. 2).

Estimation of the Medial Axis of Oblique Airways

The medial axis of oblique airways was estimated using a 3D distance map. A 3D distance map is the simplest and the most convenient way to represent and store the set of points furthest from the airway boundary. Moreover, a 3D distance map is a three-dimensional array where the x, y, and z distance information corresponds to the rows, columns, and depths, respectively. An example this is CT volume data and the corresponding distance from the boundary (distance values) are stored in the array's elements (pixels). The 3D distance map is like a grey scale

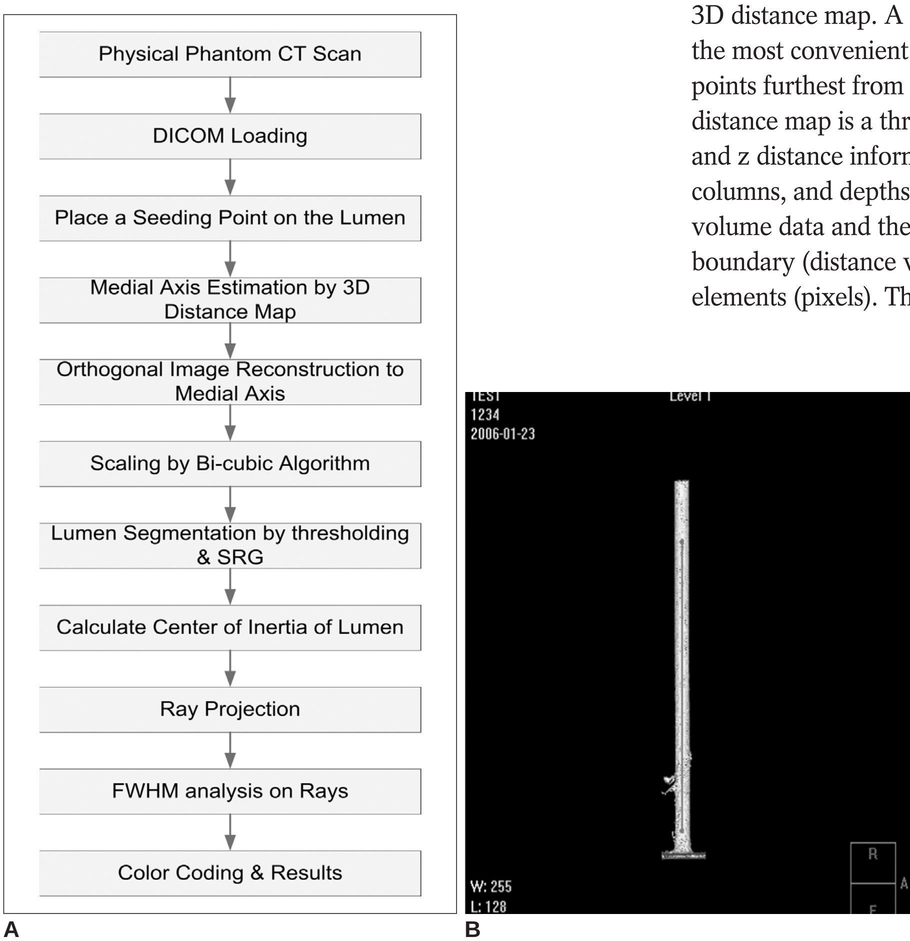

Fig. 2. Software design and representative images for measurement of oblique airway.
A. Schematic work flow diagram for measurement of oblique airway.
B. Medial axis estimation of artificial airway tilted at 45° to scan plane. Line represents estimated medial axis on volume rendering images.
C. Original axial slice of artificial airway tilted at 45° to scan plane.
D. Reconstructed image orthogonal to axis of artificial airway.

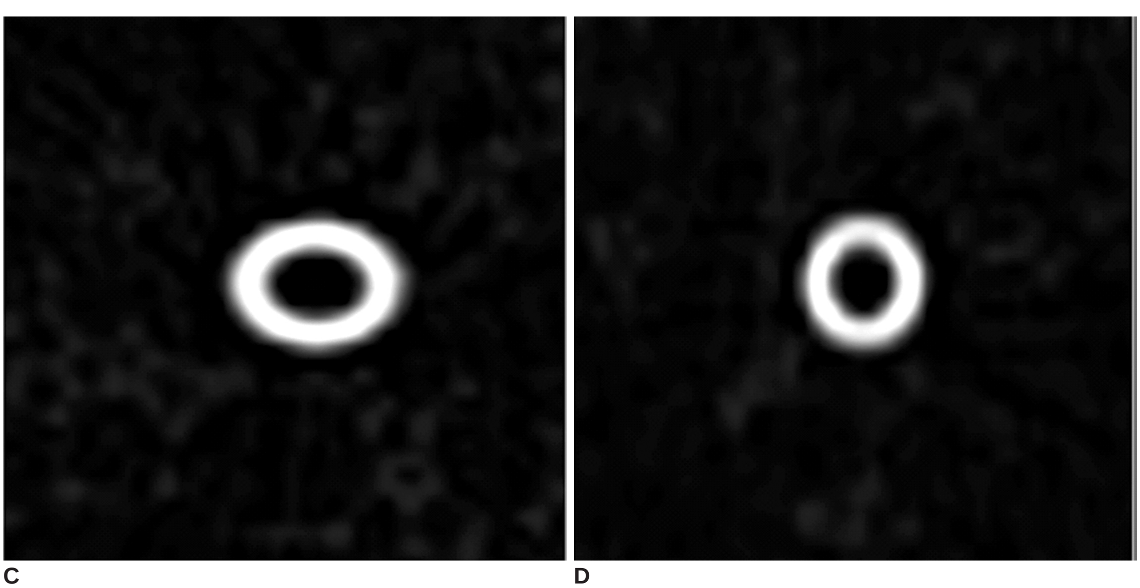

image except that the distance information (float - 32 bytes) replaces the intensity information. In addition, after generating a 3D distance map, the centroid of the upper and lower slices along the medial axis of the oblique airway was re-calculated to obtain a more accurate estimated axis of the airway.

Measurements and Statistics

After image reconstruction of every combination of tilt angle and reconstruction parameters (axis, wall thickness, and luminal radius) of each artificial airway, the CT images were measured using the in-house software. Each measurement was performed ten times at different medial axes, and the average numbers were used for statistical analysis.

To assess the effectiveness of axis determination, the actual angle of each tube, and the estimated angle of the CT images of the physical phantom were compared using a Student's *t*-test. To determine the effects of the orientation of the airway, the actual and measured dimension of each tube from the various oblique CT scans were compared using a repeated ANOVA test. The accuracy of the actual and estimated measurements was evaluated using the Bland-Altman method. The paired *t*-test was used to determine the possible presence of a significant difference between each set of measurements and the reference of the actual dimension. A *p* value less than 0.05 was considered a statistically significant difference. The *t*-test for single means was performed using StatisticaTM 7.0 (StatSoft, Tulsa, OK).

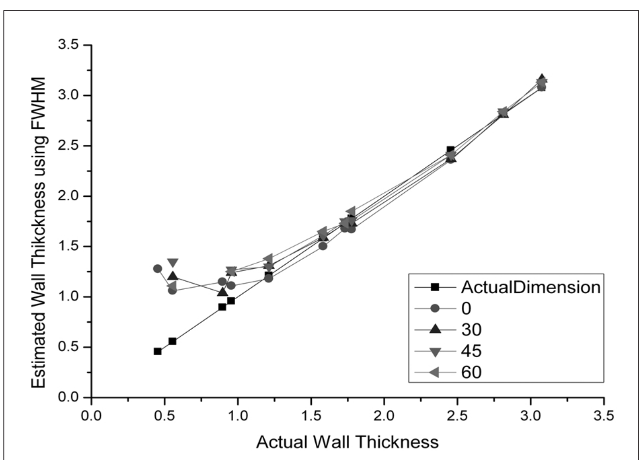

Fig. 3. Effect of tilt angle and its influence on accuracy of airway wall measurement. All images were reconstructed with 0.75-mm slice thickness, standard reconstruction kernel (B50f), and 360-mm field of view. No significant difference in accuracy of airway wall measurements was observed at four different tilt angles. Airway thicknesses are overestimated for all images if airway thickness is smaller than 1 mm.

RESULTS

Axis Estimation

The axis estimation method using a 3D thinning algorithm was evaluated on CT scans at various tilt angles (0, 30, 45, and 60°), a 0.75 mm slice thickness, and a standard reconstruction kernel (B50f). All eleven poly-acryl tubes were evaluated and compared. The mean error and standard deviation (SD) of each tilt angle were 0.0 ± 0.0° at 0°, 30.51 ± 1.57° at 30°, 44.97 ± 1.10° at 45°, and 59.91 ± 0.96° at a 60° tilt angle. The overall absolute error of the medial axis estimation were 0.0 ± 0.0° at 0°, 1.35 ± 0.85° at 30°, 0.62 ± 0.88° at 45°, and 0.74 ± 0.56° at

Table 1. Agreement between Estimated and Actual Airway Orientation

Tilt Angles		Difference between Estimated and Actual Angle $\lvert A_{est} - A_{act} \rvert$		
		Mean (°)	SD (°)	P †
Tilt Angles	0°	0	0	–*
	30°	1.35	0.85	0.306
	45°	0.623	0.88	0.979
	60°	0.74	0.56	0.763

Note.—SD = standard deviation, A_{est} = estimated angle, A_{act} = actual angle, * *t*-test for simple samples could not evaluate due to no variance.
† *t*-test for single samples. *P* value less than 0.0125 (i.e., Bonferroni adjustment of significance level [alpha = 0.05]) was considered to be statistically significant.
All images were scanned using following parameters: B50f reconstruction kernel, slice thickness of 0.75 mm and field of view, 36 cm.

Table 2. Agreement between Estimated Measurement of Airway Wall Thickness and Actual Dimension at Different Tilt Angles

Tilt Angles		Difference between Estimated Measurement and Actual Dimension $M_{act} - M_{est}$			
		Mean (mm)	SD (mm)	95% Limits of Agreement (mm)*	P †
Tilt angles	0°	–0.03	0.19	–0.41 to 0.35	0.623
	30°	–0.11	0.23	–0.56 to 0.34	0.191
	45°	–0.13	0.26	–0.66 to 0.38	0.154
	60°	–0.13	0.19	–0.50 to 0.24	0.067

Note.—SD = standard deviation, M_{ast} = actual measurement, M_{est} = estimated measurement, * Bland-Altman method.
† Paired *t*-test. *P* value less than 0.0124 (i.e., Bonferroni adjustment and significance level [alpha = 0.05]) was considered to be statistically significant.
All images were scanned using following parameters: reconstruction kernel, B50f; slice thickness, 0.75 mm; field of view, 360 mm.

a 60° tilt angle. The estimated tilt angles were not significantly different from the actual tilt angles (*t*-test for single samples) (Table 1).

Airway Wall Thickness

Effects of Obliquity and Estimated Wall Thickness

Figure 3 shows the actual and estimated wall thicknesses of the airway at the four measured tilt angles. We found no statistically significant difference among the four tilt angles with 0.75 mm slice thickness, a standard reconstruction kernel (B50f), and an FOV of 360 mm, although general increases in measurement error increased as the tilt angle increased from 0° to 60° (Table 2). If the wall thickness of the airway is less than 1 mm and therefore be within the magnitude of a single pixel, a rapidly increasing amount of errors was observed in the airway wall measurement. The small airway with less than a 1-mm wall thickness (1st and 2nd airways) were excluded in all of the statistical tests performed to determine the degree of error.

Effects of Obliquity and Slice Thickness

As the image thickness increased and a larger tilt angle of airway axis was used, the estimated wall thickness became smaller than the actual wall thickness (Fig. 4). There was an internal interaction between the slice thickness image parameters and the obliquity of the airway on the measurement accuracy which demonstrated a statistically significant difference among the tilt angles ($p < 0.001$). The measurement of the CT image with a thickness of 0.75-mm resulted in the most accurate and independent measurement of the obliquity of an airway, which was not statistically different from the actual wall thickness.

Effects of Obliquity and the Reconstruction Kernel

Figure 5 shows the interaction of airway obliquity and the reconstruction kernel on the measurement of airway wall thickness. When a sharper reconstruction kernel was used and the airway was tilted at a larger angle, the estimated wall thickness became smaller than the actual wall thickness (Fig. 5). Moreover, a significant internal interaction ($p < 0.001$) was observed between the reconstruction kernel and the obliquity of an airway at the different tilt angles. Measurement of the CT images reconstructed by a standard kernel (B50f) resulted in the most accurate measurement, measuring of the obliquity of an airway. With these imaging parameters, there was no significant difference between was observed between the estimated measurement of the airway wall thickness at all tilt angles.

Luminal Radius

Effects of Obliquity and Estimated Luminal Radius

No statistical significant was found in the measurement of the difference between the measured luminal radii and actual radii among the four tilt angles when using a slice thickness of 0.75 mm, standard reconstruction kernel (B50f); and FOV at 360 mm, although there were general increases in measurement error as the tilt angle increased from 0° to 60° (Table 3).

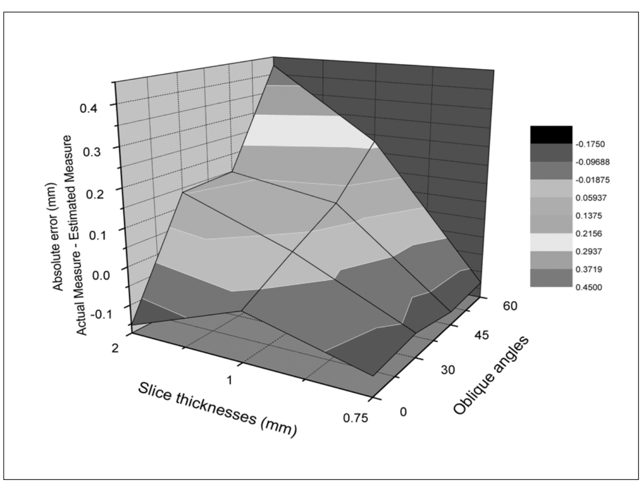

Fig. 4. Interaction of obliquity and slice thickness in measurement of wall thickness. As image thickness increases and larger tilt angle of airway axis is used, estimated wall thickness becomes smaller than actual wall thickness. 0.75-mm wall thickness provided highest quality CT image which in turn results in most accurate measurement, independent of obliquity of airway. Images were reconstructed via standard reconstruction kernel (B50f).

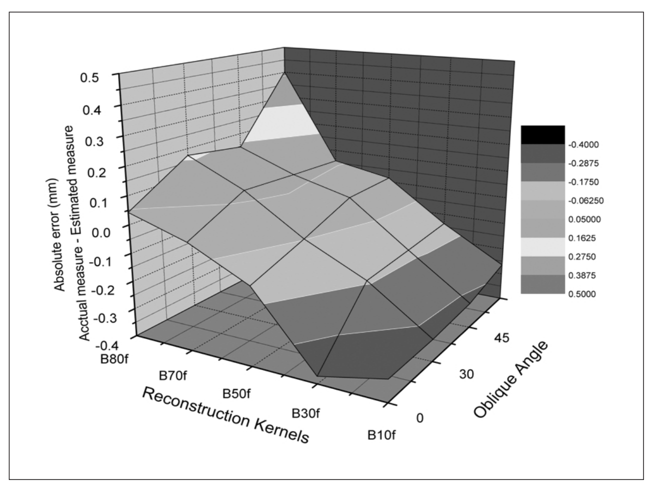

Fig. 5. Interaction of obliquity and reconstruction kernel on measurement of wall thickness. Images were reconstructed with 0.75 mm wall thickness. When sharper reconstruction kernel is used and airway is tilted to larger angle, estimated wall thickness becomes smaller than actual wall thickness. Hence, measurement of reconstructed CT images using standard kernel (B50f) results in most accurate measurement, independent of obliquity of airway.

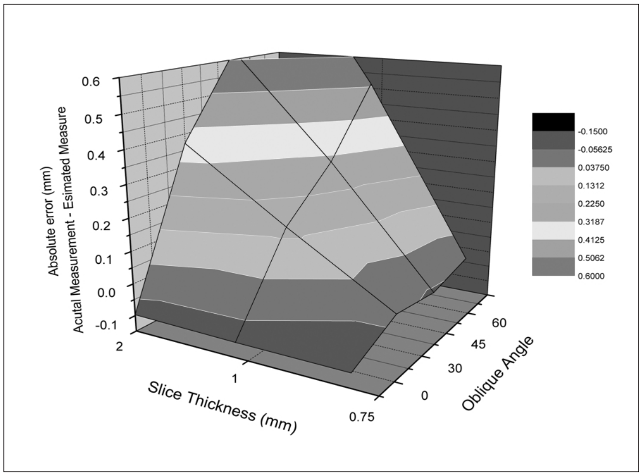

Fig. 6. Interaction of obliquity and slice thickness on measurement of luminal radius. As image thickness increases and larger tilt angle of airway axis is used, estimated luminal radius becomes smaller than actual luminal radius. Measurement on CT image with 0.75-mm thickness results in most accurate measurement, independent of obliquity of airway. Images were reconstructed using standard reconstruction kernel (B50f).

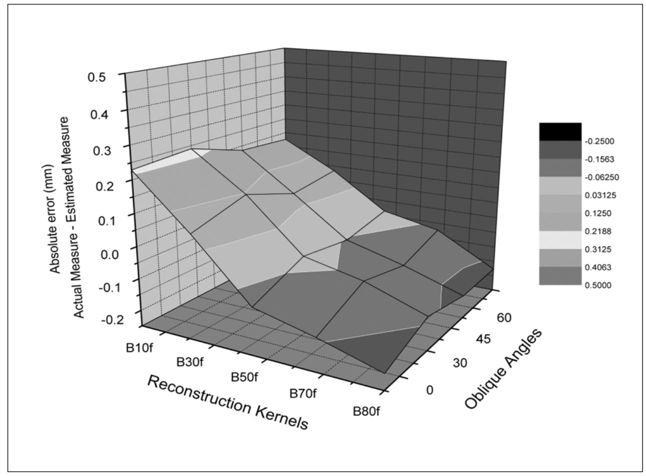

Fig. 7. Interaction of obliquity and reconstruction kernel in accurate measurement of luminal radius. Images were reconstructed at 0.75 mm wall thickness. When sharper reconstruction kernel is used and airway is tilted to larger angle, estimated radius becomes smaller than actual luminal radius. Hence, measurement of reconstructed CT images, using standard kernel (B50f) results in most accurate measurement, independent of obliquity of airway.

Table 3. Agreement between Estimated Measurement of Luminal Radius and Actual Dimension at Tilt Angles

Tilt Angles		Difference between Estimated Measurement and Actual Dimension M_{act} - M_{est}			
		Mean (mm)	SD (mm)	95% Limits of Agreement (mm)*	$P^{\dagger}$
Tilt angles	0°	−0.08	0.08	−0.24 to 0.08	0.016
	30°	−0.04	0.14	−0.32 to 0.24	0.419
	45°	−0.06	0.08	−0.23 to 0.10	0.047
	60°	−0.04	0.10	−0.24 to 0.17	0.322

Note.—SD = standard deviation, M_{ast} = actual measurement, M_{est} = estimated measurement, * Bland-Altman method.
† Paired *t*-test. *P* value less than 0.0124 (i.e. Bonferroni adjustment of significance level [alpha = 0.05]) was considered to be statistically significant.
All images were scanned using following parameters: reconstruction kernel, B50f; slice thickness, 0.75 mm; field of view, 360 mm.

Effects of Obliquity and Slice Thickness

As the image thickness increased and a larger tilt angle of airway axis was used, the estimated radius became smaller than the actual radius (Fig. 6). A statistically significant internal interaction between the slice thickness image parameters and the obliquity of the airway on the measurement accuracy was observed at the different tilt angles ($p < 0.001$). The measurement on the CT image at a 0.75-mm thickness resulted in the most accurate measurement, independent of the obliquity of an airway, which was not significantly different from the actual luminal radius.

Effects of Obliquity and Reconstruction Kernel

Figure 7 shows the interaction between the airway obliquity and the reconstruction kernel in the measurement of the airway luminal radius. When a sharper reconstruction kernel was used and the airway was tilted to a larger angle, the estimated radius became smaller than the actual radius (Fig. 5). A statistically significant internal interaction between the reconstruction kernel and the obliquity of an airway was observed at the different the tilt angles ($p < 0.001$). The measurement of the luminal radius was independent of the airway obliquity. The standard kernel (B50f) yielded the most accurate results.

DISCUSSION

To accurately measure the airway dimension when the airway is oriented obliquely, it is essential to generate an image perpendicular to the airway axis. Our phantom study has shown that accurate axis determination of an obliquely oriented airway is possible using the proposed algorithm at a 60° tilt angle.

This study also demonstrated that there exists a complex interaction between the airway obliquity and the various CT scan parameters in the determination of airway measurement accuracy. Slice thickness and reconstruction kernel factors interacted significantly with tilt angles. In our study, the decrease in accuracy of measurement was proportional to the increase in slice thickness in the measurements of airway wall thickness and luminal radius. This result is expected when considering the partial volume effect. At a 0.75-mm slice thickness, the accuracy of measurement is guaranteed at tilt angles of 0 to 60 degrees. As the FOV of this study is 360 mm, the Z-axis resolution of 0.75 mm results in an approximately isocubic voxel resolution. In the case of a reconstruction kernel, the standard kernel (B50f) offered the best accuracy. By combining a 0.75-mm thickness and a standard reconstruction kernel, we were able to reliably measure the dimension of the tubes regardless of their oblique orientation. Similar to the results of the previous study, the CT scans with various tilt angles also showed that there is a threshold which rapidly increases the error of the airway wall measurement when using the FWHM method with a wall thickness less than 1 mm. This result suggests that with current commercial instruments, it is possible to correctly measure the dimension of airways located obliquely to the image plane when the images are reconstructed at a sub-millimeter slice thickness and a standard reconstruction kernel, although a clear limitation exists in the measurement of airways smaller than 1 mm in wall thickness.

Future studies should evaluate the measures necessary for the clinical application of the correct airway wall measurement at airway wall thicknesses below 1 mm. Even though the measurement using the FWHM method with a wall thickness less than 1 mm was not correct, the magnitude of the CT profile is proportional to wall thicknesses below 1 mm. Consequently, a modified FWHM may need to be developed.

In conclusion, we verified that the accurate determination of the airway axis located in the oblique direction on a volumetric CT is feasible using the proposed algorithm. There are strong significant interactions in the measurement accuracy between airway obliquity and the CT parameters. For a clinically acceptable measurement of airway thickness without considering obliquity, we recommend obtaining CT images at a sub-millimeter slice thickness and a standard reconstruction kernel.

Acknowledgments

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