Objective: To design and test a bench model of an intraluminal optical device capable of accurately measuring airway diameter.

Design: A fresh porcine trachea divided longitudinally and affixed to a linear translation stage was used to simulate 20 tracheal diameters (18.3-30.3 mm). Tungsten-halogen light was dispersed across the luminal surface by a diffraction grating. Determination of the wavelength of diffusely reflected light of peak intensity by spectrograph analysis then allowed for the calculation of an optical distance for each simulated tracheal diameter. The criterion standard was the distance as measured by the micrometer on the translation stage. Intraclass correlation (ICC) and Bland-Altman regression analysis (BARA) were performed between the optical and micrometer measurements.

Subject: Trachea from a newly exsanguinated pig.

Results: The ICC showed high correlation (0.994; 95% confidence interval [CI], 0.986-0.998) \((P < .001)\); BARA showed a small mean difference between the optical and micrometer measurements (0.052 mm; 95% CI, -0.867 to 0.762 mm) and no significant trend in bias for varying diameters \((r = 0.581; 95\% \text{ CI, } 0.187-0.814)\) \((P = .07)\).

Conclusions: The determination of airway diameter by means of the reflection of nonionizing radiation from the luminal surface correlates closely to actual diameter as measured by a micrometer. This bench model may be used to develop a fiberoptic intraluminal probe capable of accurately profiling airway luminal diameter and shape during flexible or rigid bronchoscopy.
herence tomography is limited by its excessive cost. Ultrasoundography has shown poor results in absolute measurements of the airway area. None of these methods have been routinely used outside of a research setting.

Routine objective measurement of the tracheobronchial tree during bronchoscopy is feasible only if the means are quick, reliable, and cost-effective. Herein, we describe the bench model design and ex vivo validation of a novel and inexpensive intraluminal optical probe capable of meeting these criteria. Our design uses the reflection of nonionizing radiation from the luminal surface of the airway as a means to measure proximity.

**METHODS**

**DEFINITION 1: DIFFRACTION AND DIFFRACTION GRATINGS**

Diffraction is the apparent bending of a wave around an obstruction, such as a small slit. A diffraction grating is an array of evenly spaced small slits designed to bend differing wavelengths of light at specific and predictable angles. Longer wavelengths of light are bent at greater angles than are shorter wavelengths. As a result, when collimated white light passes through a diffraction grating, the component wavelengths are separated into a color spectrum similar to that produced by a prism (Figure 1).

**DEFINITION 2: SPECTROMETER**

A spectrometer is an optical instrument for measuring the intensity of a sample of light over some portion of the electromagnetic spectrum. It is used to produce spectrographs, which are plots of light intensity vs wavelength.

**DEFINITION 3: SPECULAR AND DIFFUSE REFLECTION**

There are 2 fundamental types of light reflection, specular and diffuse. Specular reflection occurs for smooth surfaces such as a plane mirror, where the angle of incidence equals the angle of reflection (Figure 2A). Diffuse reflection occurs for rough surfaces and for surfaces that absorb and reemit scattered light, where the reflected light has no directional dependence and is hence reflected in all directions from the surface (Figure 2B). Both types of reflection occur for light incident on the luminal surface of a moist airway. Our design captures the fraction of light reflecting diffusely at an angle perpendicular to the luminal surface to measure proximity.

**MATERIALS AND PROCEDURE**

Institutional guidelines regarding animal experimentation were followed in harvesting a trachea from a newly exsanguinated pig. In this bench model, the porcine trachea was divided longitudinally and mounted on a micrometer-driven linear translation stage (Micrometer Head MHS; Mitutoyo, Kawasaki, Japan) to simulate varying tracheal diameters. A tungsten-halogen light source (LS-1; Ocean Optics, Dunedin, Florida) affixed with a collimating lens was used to pass collimated white light (400-700 nm) through a transmission diffraction grating (HSG-488-LF; Kaiser Optical Systems Inc, Ann Arbor, Michigan) producing a diffraction spectrum on the luminal surface of the porcine trachea. The porcine trachea was positioned at a micrometer-measured distance ($y_1$) from the optical axis (Figure 3A). A pinhole was then positioned in front of a fiberoptic collecting cable at a known fixed distance ($d$) from the diffraction grating along the optical axis (Figure 3D). Only the narrow band of light reflecting diffusely at an angle perpendicular to the luminal surface could pass through the pinhole into the fiberoptic cable (Figure 3B). This light was analyzed by a spectrometer, and the wavelength of peak intensity ($\lambda_1$ peak) of this narrow band was determined (Figure 3C). The angle of diffraction ($\theta_1$) (Figure 3D) of $\lambda_1$ peak was then calculated using a standardized formula for diffraction gratings (Figure 3F, equation 1). A second simple
Collimating lens
Spectrometer

\[ \theta_1 = \sin^{-1} \left( \frac{\lambda_1 \text{peak}}{a} - \sin \theta_i \right) \]
\[ y_1 = d \tan \theta_i \]

\[ \theta_2 = \sin^{-1} \left( \frac{\lambda_2 \text{peak}}{a} - \sin \theta_i \right) \]
\[ y_2 = d \tan \theta_i \]

Figure 3. Tracheal measurement model using diffracted light and porcine trachea. A, White light passed from a tungsten-halogen source is collimated and directed at a diffraction grating to form a spectrum on the luminal surface of the divided trachea. The optical axis, illustrated by the dotted line, connects the diffraction grating with the pinhole. B, Light reflecting directly perpendicular to the surface passes through the fixed pinhole into a collecting optical fiber and on to a spectrometer. C, A computer-generated spectrograph is used to find the reflected wavelength of peak intensity (\(\lambda_1 \text{peak}\)) through the pinhole. D, Geometry illustrating the variable angle of diffraction (\(\theta_1\)) of the (\(\lambda_1 \text{peak}\)), the fixed distance between the pinhole and the point of diffraction (\(d\)), and the variable distance in question from the optical axis to the luminal surface (\(y_1\)). E, The same geometry as in panel D shown from a simplified bird’s-eye view, also demonstrating the fixed angle of incidence (\(\theta_i\)) of the source light on the diffraction grating. F, Equation 1 is the grating equation used to solve for \(\theta_1\) (“\(a\)” is a constant relating to a fixed property of the diffraction grating); equation 2 is a simple trigonometric equation used to solve for \(y_1\) from the geometry problem schematized in panels D and E.

Figure 4. Tracheal measurement model identical to that illustrated in Figure 3 except using greater distance (\(y_2\)). A, White light passed from a tungsten-halogen source is collimated and directed at a diffraction grating to form a spectrum on the luminal surface of the divided trachea. The optical axis, illustrated by the dotted line, connects the diffraction grating with the pinhole. B, Light reflecting directly perpendicular to the surface passes through the fixed pinhole into a collecting optical fiber and on to a spectrometer. C, A computer-generated spectrograph is used to find the reflected wavelength of peak intensity (\(\lambda_2 \text{peak}\)) through the pinhole. D, Geometry illustrating the variable angle of diffraction (\(\theta_2\)) of the wavelength of peak intensity (\(\lambda_2 \text{peak}\)), the fixed distance between the pinhole and the point of diffraction (\(d\)), and the variable distance in question from the optical axis to the luminal surface (\(y_2\)). E, The same geometry as in panel D shown from a simplified bird’s-eye view, also demonstrating the fixed angle of incidence (\(\theta_i\)) of the source light on the diffraction grating. F, Equation 1 is the grating equation used to solve for \(\theta_2\) (“\(a\)” is a constant relating to a fixed property of the diffraction grating); equation 2 is a simple trigonometric equation used to solve for \(y_2\) from the geometry problem schematized in panels D and E.
trigonometric equation (Figure 3F, equation 2) was then used to determine an optically measured value for \( y_2 \) using the known distance \( d \) and the newly calculated angle \( \theta_1 \) (Figure 3E).

The process was then repeated for a larger micrometer-measured distance \( y_1 \) between the luminal surface and the optical axis (Figure 4). As a result of the diffraction spectrum formed on the luminal surface, the wavelength of diffusely reflected light of peak intensity passing through the pinhole was longer for \( y_2 \) than for \( y_1 \). In total, 20 trials were conducted for micrometer-measured criterion distances ranging from 18.288 mm to 30.353 mm in micrometer-driven increments of 0.635 mm. Testing was done in a darkened optics laboratory. The wavelength of peak intensity for each trial was determined by applying Loess regression curves to the spectographs using SPSS software, version 13.0 (SPSS Inc, Chicago, Illinois). The result was then processed through 2 simple equations, the grating equation and a trigonometric identity, to calculate the distance from the luminal surface to the optical axis. This calculation was facilitated by the use of spreadsheet software (Excel 2002; Microsoft Inc, Redmond, Washington).

**STATISTICAL ANALYSIS**

Statistical analysis was done using SPSS 13.0. Loess regression curves were used to calculate a peak for each trial. Correlation between the optical and micrometer distances was evaluated using the intraclass correlation coefficient. The Bland–Altman approach was used to assess agreement between the 2 measures. This method quantifies the difference between 2 methods of measurement of the same quantity. Linear regression of the Bland–Altman plot was done to search for any possible trend in bias, a tendency for the mean difference between the 2 measures to rise or fall with increasing magnitude. For all tests, a \( P < .05 \) was considered significant.

**RESULTS**

Correlation and agreement between the 2 measures were excellent. The intraclass correlation coefficient was 0.994 (95% confidence interval [CI], 0.986-0.998) \( (P < .001) \). The Bland–Altman analysis revealed a mean difference between the optical and micrometer measurements of 0.052 mm (95% CI, −0.867 to 0.762 mm). Linear regression of the Bland–Altman plot demonstrated no statistically significant trend in bias for increasing distances \( (r=0.581, 95\% \text{ CI}, 0.187-0.814) \ (P = .07) \).

**COMMENT**

Our results demonstrate very strong correlation and agreement between the optical and micrometer measurements of the distance from luminal surface to optical axis on an ex vivo porcine trachea. Hence, our bench model has confirmed the validity of distance measurement by means of visible light reflection from luminal surfaces.

Further work should seek to incorporate this technology into an intraluminal probe for in vivo studies. Fortunately, this may prove to be relatively straightforward. Tran et al have recently described and successfully tested an intraluminal probe for optical coherence tomography profiling of the cross-sectional area of a rabbit trachea. Their design consists of a commercially available microlens, microprism, and microelectromechanical system (MEMS) rotary motor, all encapsulated within a 2.4-mm-thick probe head casing attached to flexible cable housing. The MEMS rotary motor allows for 360° cross-sectional airway profiling while the probe and cable housing remain stationary.

With some modifications and the addition of a miniature diffraction grating, this probe could potentially be redesigned to use the significantly less expensive technology we have described herein to profile airway cross-sectional areas. The intraluminal probe would consist of a flexible fiberoptic cable housing tail shielding a bidirectional multimode fiber attached to a shorter, rigid, opaque probe head casing with 2 circumferential transparent sections and a probe head (Figure 6A). A collimating lens, miniature diffraction grating, right-angle prism, and MEMS rotary motor would be housed within the probe head (Figure 6A). Incident light from a tungsten-halogen source passing through the collimating lens and the diffraction grating would exit the probe head from a transparent window forming a diffraction spectrum on the luminal surface (Figure 6B). Reflected light from the surface would reenter the probe through a second narrow transparent window and be directed back into the multimode fiber by the right-angle prism and passed on to a spectrometer (Figure 6B). The MEMS rotary motor would permit 360° radial measurements around the probe to reconstruct a 2-dimensional cross-section of the airway lumen (Figure 6C and D). The sterile flexible housing and probe head could be passed down the airway via a laryngoscope or bronchoscope intraoperatively, while the spectrometer and light source would remain at the head of the bed. Advancing the probe distally through the airway would permit for computer integration of multiple 2-dimensional slices to form a real-time, 3-dimensional luminal reconstruction (Figure 5E and F) within the operating room.
Figure 6. Schematic for intraluminal probe. A, Flexible fiberoptic cable housing shielding a bidirectional multimode fiber connects the probe head to a tungsten-halogen source and a spectrometer. The probe head consists of a collimating lens, miniature diffraction grating, right-angle prism, and microelectromechanical system (MEMS) rotary motor. B, Incident light from a tungsten-halogen source (white arrow) passing through the collimating lens and diffraction grating exits the probe head from a transparent window forming a diffraction spectrum on the luminal surface. Reflected light from the surface reenters the probe through a second narrow transparent window and is directed back into the multimode fiber by the right-angle prism and passed on to a spectrometer (red arrow). C, Cross-section through the airway showing a narrow band of light being reflected back into the probe permitting a single radial measurement at that point. D, 360° Rotation of the MEMS rotary motor allows for multiple radial measurements around the probe head and 2-dimensional profiling of the lumen at that position along the airway. E, Distal advancement of the probe allows for the acquisition of successive 2-dimensional cross-sectional profiles of the airway. F, Real-time, 3-dimensional airway reconstruction is possible by computer integration of these successive 2-dimensional profiles.
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REFERENCES


