Airway Luminal Diameter and Shape Measurement by Means of an Intraluminal Fiberoptic Probe

A Bench Model

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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% 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.


The ability to conduct routine real-time objective measurements of airway size and shape in the operating room during bronchoscopy remains elusive to the otolaryngologist. The only widely practiced means of objective airway sizing involves stepwise inserting increasingly larger endotracheal tubes while monitoring for leaks using positive pressure. Although simple and reproducible, this method is problematic in that it may cause trauma to the soft tissues lining the airway. Furthermore, this method provides no information about the status of the airway distal to the narrowest point. Currently, subjective approximations of airway dimensions by means of direct visualization or video imaging often guide the bronchoscopic assessment and management of challenging tracheobronchial abnormalities, including hypoplastic airways, stenoses, and malacias. An accurate and real-time method to quantify the severity of airway collapse during bronchoscopy would facilitate the immediate evaluation of airway interventions and comparisons between patients. It could also be used as an adjunct to preoperative assessment of tracheobronchial lesions by computed tomography scanning in assessing the anatomic location, profile, and status of the airway distal to the lesion.

Several noncontact technologies, which range from computer analysis of videobronchoscopy, optical coherence tomography by use of intraluminal probes, and ultrasonography, that may potentially be used in the operating room have been used to measure airway dimensions with varying success. Videobronchoscopy continues to be limited by difficulties in calculating the effects of distance on magnification and by various types of optical distortions. Optical co-
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
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 (λ₁ peak) through the pinhole. D. Geometry illustrating the variable angle of diffraction (θ₁) of the (λ₁ 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 (y₁). E. The same geometry as in panel D shown from a simplified bird's-eye view, also demonstrating the fixed angle of incidence (θ₁) of the source light on the diffraction grating. F. Equation 1 is the grating equation used to solve for θ₁ ("a" is a constant relating to a fixed property of the diffraction grating); equation 2 is a simple trigonometric equation used to solve for y₁ 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 (y₂). 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 (λ₂ peak) through the pinhole. D. Geometry illustrating the variable angle of diffraction (θ₂) of the wavelength of peak intensity (λ₂ 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 (y₂). E. The same geometry as in panel D shown from a simplified bird's-eye view, also demonstrating the fixed angle of incidence (θ₁) of the source light on the diffraction grating. F. Equation 1 is the grating equation used to solve for θ₂ ("a" is a constant relating to a fixed property of the diffraction grating); equation 2 is a simple trigonometric equation used to solve for y₂ 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 $y_2$ between the luminal surface and the
optical axis (Figure 4). As a result of the diffraction spectrumbased on the luminal surface, the wavelength of dif-
fusely 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 spectrographs 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.14 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.15 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% CI, 0.187–
0.814) ($P = .07$).

Our results demonstrate very strong correlation and
agreement between the optical and micrometer mea-
surements 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 tech-
ology into an intraluminal probe for in vivo studies.
Fortunately, this may prove to be relatively straightforward.
Tran et al12 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
designed to use the significantly less expensive
stationary. With some modifications and the addition of a mini-
ature diffraction grating, this probe could eventually
be redesigned to use the significantly less expensive
techology 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 cir-
cumferential 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 spec-
trometer (Figure 6B). The MEMS rotary motor would
permit 360° radial measurements around the probe to
reconstruct a 2-dimensional cross-section of the air-
way lumen (Figure 6C and D). The sterile flexible
housing and probe head could be passed down the air-
way via a laryngoscope or bronchoscope intraopera-
tively, 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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Author Contributions: Dr Jowett had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Jowett, Weersink, Zhang, Campisi, and Forte. Acquisition of data: Jowett and Zhang. Analysis and interpretation of data: Jowett and Weersink. Drafting of the manuscript: Jowett and Campisi. Critical revision of the manuscript for important intellectual content: Jowett, Weersink, Zhang, Campisi, and Forte. Statistical analysis: Jowett. Obtained funding: Jowett. Administrative, technical, and material support: Zhang and Campisi. Study supervision: Campisi and Forte.
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