Published in final edited form as:

Int J Pediatr Otorhinolaryngol. 2016 December ; 91: 108–112. doi:10.1016/j.ijporl.2016.10.004.

Objective characterization of airway dimensions using image processing

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Abstract

Objectives—With the evolution of medical and surgical management for pediatric airway disorders, the development of easily translated techniques of measuring airway dimensions can improve the quantification of outcomes of these interventions. We have developed a technique that improves the ability to characterize endoscopic airway dimensions using common bronchoscopic equipment and an open-source image-processing platform.

Methods—We validated our technique of Endoscopic Airway Measurement (EAM) using optical instruments in simulation tracheas. We then evaluated EAM in a large animal model (*Ovis aries*, $n = 5$), comparing tracheal dimensions obtained with EAM to measurements obtained via 3-D fluoroscopic reconstruction. The animal then underwent resection of the measured segment, and direct measurement of this segment was performed and compared to radiographic measurements and those obtained using EAM.

Results—The simulation tracheas had a direct measurement of 13.6, 18.5, and 24.2 mm in diameter. The mean difference of diameter in simulation tracheas between direct measurements and measurements obtained using EAM was 0.70 ± 0.57 mm. The excised ovine tracheas had an average diameter of 18.54 ± 0.68 mm. The percent difference in diameter obtained from EAM and from 3-D fluoroscopic reconstruction when compared to measurement of the excised tracheal segment was $4.98 \pm 2.43\%$ and $10.74 \pm 4.07\%$ respectively. Comparison of these three

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measurements (EAM, measurement of resected trachea, 3-D fluoroscopic reconstruction) with repeated measures ANOVA demonstrated no statistical significance.

Conclusions—Endoscopic airway measurement (EAM) provides equivalent measurements of the airway with the improved versatility of measuring non-circular and multi-level dimensions. Using optical bronchoscopic instruments and open-source image-processing software, our data supports preclinical and clinical translation of an accessible technique to provide objective quantification of airway diameter.

Keywords

Airway reconstruction; Quantitative endoscopy; Airway management; Airway stenosis; Image processing

1. Introduction

Laryngotracheal stenosis is a common complication of critically ill children, affecting 1–2% of patients in the neonatal intensive care unit and up to 11% of pediatric patients requiring mechanical ventilation [1,2]. As an adjunct to clinical metrics, the quantification of airway narrowing plays a vital role in directing surveillance, medical interventions and surgical management. Subjective assessment of airway stenosis has been shown to result in misclassification, even with experienced practitioners [3]. In order to critically assess and manage laryngotracheal stenosis, objective characterization is necessary. The most commonly used method of objective measurement is approximation of the inner airway diameter with the known outer diameter of endotracheal tubes as proposed by Myer et al., classifying airway size into four grades in relation to age appropriate norms [4]. The simplicity and reliability of the Cotton-Myer system has made it the gold standard for airway sizing and the associated classification of grading will undoubtedly continue to be useful in the characterization of airway stenosis.

Although endotracheal tube approximation is the preferred technique for airway sizing, it has some limitations. First, sizing with a circular instrument such as an endotracheal tube is most accurate when approximating a circular structure; regions of stenosis are commonly irregular in shape and not adequately measured with circular endotracheal tubes. Additionally, there are clinical scenarios that preclude approximation of the airway with an endotracheal tube including patients with a difficult airway, distal stenosis, or multilevel lesions. The aim of our study is to describe and validate a method for airway measurement integrating commonly available optical instruments used in pediatric airway evaluation and an open-source image-processing platform using both *ex-vivo* and ovine models. Our hypothesis is that our method of endoscopic airway measurement (EAM) is as effective as radiographic techniques for measuring airway dimensions.

2. Materials and methods

2.1. Technique for endoscopic airway measurement (EAM)

An endoscope with an associated optical instrument is selected. Once the optical instrument is secured to the endoscope, a calibration image is captured using a ruler in contact with the

end of the optical instrument. Endoscopic images are then captured with attention directed to maintaining the tip of the optical instrument at the level of interest in the center of the airway lumen. Images are adequate if the captured image includes the entire lumen of the airway at the level of the end of the optical instrument.

The calibration image and endoscopic image are then uploaded into Image J (v 1.49, NIH, Bethesda, MD, USA). The calibration image is used to set a distance to pixel ratio using the ruler in the image as reference. This ratio is then applied to the endoscopic image since the distance to pixel ratio will be the same for all images captured with the same camera and same resolution at the same distance from the end of the lens. The optical instrument guarantees this relationship as it provides a fixed distance from the end of the telescope. Once the scale is set, the airway lumen to be measured is outlined with Image J using the freehand drawing tool. The airway dimensions are then calculated using Image J.

2.2. Ex-vivo model

Polyvinyl chloride (PVC) conduits (internal diameter of 13.6 mm, 18.5 mm, and 24.2 mm) were used as *ex-vivo* tracheal models. An optical forceps (spoon-shaped, round) (10350L) was mounted on a 5.5 mm diameter/50 cm length Hopkins® Straight Forward Telescope 0° (10320 AA) (Storz, Tuttlingen, Germany) and used to obtain images with a Storz telepack X (Tuttlingen, Germany) (Fig. 1, c and d). The spoon-shaped optical forceps head served as a calibration instrument and images were obtained using a ruler placed at the end of the forceps (Fig. 1a and b). Measurements taken with EAM were compared to measurements obtained with an electronic digital caliper (accuracy 0.001 inch, repeatability 0.0005 inch) (iGAGING, San Clemente, California).

2.3. Ovine model

The use of juvenile sheep in this study was approved and overseen by the Institutional Animal Care and Use Committee (IACUC Protocol #AR13-00071) to ensure humane treatment and the respect for animal rights. Anesthetic induction of the sheep was performed using either ketamine and diazepam or propofol. Following endotracheal intubation, the animals were maintained under general anesthesia using propofol and/or isoflurane. After initial preparation, the Hopkins rod telescope with optical forceps was inserted into the airway and images of the planned tracheal resection segment were digitally captured using the Storz telepack system. Calibration images were obtained as described in Section 2.1 (Fig. 1e and f). Three-dimension rotational fluoroscopy was performed (Infinix, Toshiba, Japan) and analyzed using Vitrea® Enterprise Suite Imaging Software (Vital, Minnetonka, MN, USA; Fig. 1g and h). The animals then underwent tracheal resection of a 3 cm segment with orthotopic implantation of a tissue-engineered tracheal graft. Images of both the proximal and distal ends of the resected segment were obtained for measurement of the excised tracheal segment in addition to direct measurement with the electronic digital caliper.

2.4. Bronchoscopic image analysis

Two images of the trachea were measured using EAM. The airway circumference at the level of the end of the instrument was traced using Image J as described in Section 2.1 and used to calculate a luminal area and diameter.

2.5. Fluoroscopic image analysis

After processing, the axial images of the 3-D reconstruction were reviewed and 4 images at the level of the proximal and distal anastomosis were selected, corresponding to the proximal C2 and mid C3 vertebral bodies. Vitrea (Vital Images, Inc, Minnetonka, MN, USA) was used to measure the circumference and diameter of the internal lumen of the trachea at these levels (Fig. 1g and h).

2.6. Data analysis

The Biostatistics Core at The Nationwide Children's Hospital Research Institute analyzed the data.

2.6.1. Ex-vivo analysis—The average diameter of the bronchoscopic images was calculated using the area obtained via Image J measurements. The difference between the direct measurements and EAM was computed for each tube and for the data set as a whole. The percent difference between the two methods was also calculated.

2.6.2. Ovine model—An average value for diameter and area was obtained for each animal using EAM, caliper measurements of resected native trachea, and 3-D fluoroscopic images. The two images selected for each method were averaged and the difference between the bronchoscopic and resected segment measurements was calculated. The average difference and standard deviation for all animals ($n = 5$) was then obtained. A similar comparison was then performed between the measurement of excised trachea and 3-D fluoroscopic images as well as EAM and 3-D fluoroscopic images.

2.6.3. Biostatistics—Because different measurements on the same animal were correlated, a repeated measures ANOVA was used to evaluate for statistical significance.

3. Results

3.1. Ex-vivo model

The mean diameter of the 13.6 mm tube was 14.0 ± 1.1 mm. The mean diameter for the 18.5 mm tube was 18.7 ± 1.2 mm. The mean diameter for the 24.2 mm tube was 22.7 ± 0.8 mm. The absolute difference between the bronchoscopic and caliper measurements was 0.4 mm, 0.2 mm, and 1.5 mm respectively resulting in a percent difference of area of 2.9, 1.1, and 6.2% respectively (Table 1).

3.2. Ovine model

The measurements obtained from EAM, resected tracheal segment, and 3-D fluoroscopic measurements are listed in Table 2.

3.2.1. EAM versus resected tracheal segment measurements—The average difference in area was $26.4 \pm 12.4 \text{ mm}^2$, while the average difference in diameter was $0.93 \pm 0.46 \text{ mm}$. This resulted in percent difference in area of $9.77 \pm 4.52\%$ (Table 3).

3.2.2. EAM versus 3-D fluoroscopic measurements—The average difference in area was $53.9 \pm 18.3 \text{ mm}^2$ and the mean difference in diameter was $1.97 \pm 0.67 \text{ mm}$. The percent difference in area between these two techniques was $24.4 \pm 9.90\%$ (Table 3).

3.2.3. 3-D fluoroscopic measurements versus resected tracheal segment measurements—The average difference in the area was $55.18 \pm 21.0 \text{ mm}^2$ and the mean difference in diameter was $2.0 \pm 0.76 \text{ mm}$, resulting in a percent difference in area between these two techniques of $20.3 \pm 7.14\%$ (Table 3).

3.2.4. Comparison of all measurements—When all three methods were compared using a repeated measures ANOVA, there were no significant differences in area ($p = 0.0935$) or diameter ($p = 0.1345$).

4. Discussion

With the evolution of endoscopic techniques, application of biomaterials, and novel pharmacotherapies for the management of pediatric aerodigestive disorders, accurate objective characterization provides a valuable metric to compliment clinical outcomes. This pilot study was born of necessity while evaluating stenosis in tissue engineered tracheal replacement: we developed a large animal model of orthotopic tracheal replacement and characterization of graft dimension in response to endoscopic interventions was a main outcome metric. The method that we present has proven to be a valuable way of precisely quantifying airway dimensions during surveillance bronchoscopy given that we are frequently faced with a non-circular airway with multi-level stenoses. We performed this pilot study to validate our endoscopic measurements. We demonstrate that quantitative endoscopic airway assessment can be performed when a calibration tool is integrated with free image processing software. Comparison between radiographic techniques and EAM demonstrated no significant difference between the two techniques. We propose that with the addition of a calibration image and an image at the level of pathology, this will generate a reference point that can be used for prospective or retrospective data collection. With that in mind, this technique can be useful not only in pre-clinical large animal models, but in the clinical setting as well. Our data demonstrate that these methods could allow for more rigorous evaluation and description of outcomes in aerodigestive research.

Applying a scale at a set focal distance from an endoscope to measure an area of stenosis was first introduced in an ex-vivo model in 1992 [5]. This technique required manually tracing the outline of the airway lumen on a calibrated grid to measure the area of stenosis. It was found to be reproducible between observers, but found to be less accurate as the airway dimension of the model increased. Other studies have proposed novel equipment or programming to improve the accuracy of endoscopic airway measurement. Adaptation of these techniques has been poor, related to hurdles in medical equipment development, acquisition of new instruments, or complexity of methods [6–11]. One advantage of our

proposed method when compared to the more complex methods reported in the literature is the use of both a standard bronchoscopic attachment and a free, widely available measurement program (Image J), allowing the technique to be readily applied at any center without additional expenses. While the comparison of airway measurement to images obtained from 3D rotational fluoroscopy did result in a 24% difference between techniques, this difference was not significant. This difference may be for several reasons, including a difference in temporal and spatial resolution between multi-slice computed tomography and 3-D rotational fluoroscopy. Additionally, 3-D fluoroscopic measurements represent an average of the anastomotic regions, which may not exactly correlate to the bronchoscopic images. Furthermore, airway dimensions may change with ventilatory changes in the animal during radiographic image acquisition.

One limitation of this study is that we measured native trachea as opposed to an area of stenosis. The measurement of native trachea is subjectively more difficult than measurement of a stenosis or anastomosis as there is not as clear of a delineation of what is to be measured in a native trachea. The difference between these measurements will likely improve with a pathologic specimen. We did not include pathological areas of tracheal stenosis in this study as our control was the resected native trachea and imaging, which was only available using native trachea. Future studies will be aimed at confirming the accuracy of this technique with pathology, as well as with translation to clinical use.

Another limitation is that we were unable to compare our measurements to the current standard of approximation of airway size with an endotracheal tube due to the size and length of a sheep's trachea. There is currently no normative data to allow comparison, and standard size endotracheal tubes (sized up to size 11 are available for veterinary use at our facility) are not large enough to occlude the subglottis as is required for Cotton-Myer leak testing. Future work will focus on validating this system when compared to the Cotton-Myer grading scale in the clinical setting. We anticipate that our method will be able to use the Cotton-Myer grading scale to classify airway stenosis by comparing the measurements taken endoscopically with image processing to the known outer diameters of the endotracheal tubes specified in the Cotton-Myer grading scale. One final limitation is that since our measurements are based upon endoscopic images that we capture along with image processing software, there is a dependence upon the reliability of the images and software being used. However, this program is widely used within the scientific community because of its reliability and accuracy. Capturing of appropriate images and use of the program would likely require a small amount of education for those unfamiliar with the software.

Through this study we have developed an innovative technique for precise objective airway sizing integrating endoscopic optical equipment available at any tertiary pediatric hospital and open-source image processing software. While this method is not intended to clinically replace endotracheal tube approximation under most circumstances, this technique potentially addresses some specific shortcomings of endotracheal tube approximation including irregularly shaped, non-circular stenosis, airways with multilevel or distal lesions, and difficult airway cases without the need for additional costly devices or programming..

This technique will be widely applicable in the field of otolaryngology as a readily available, cost effective, and accurate method to evaluate patients with airway stenosis, measuring progression of stenosis, and quantifying interventional response.

5. Conclusion

This method for measuring airway stenosis is both accurate and reproducible, while also providing the advantage of readily available equipment and programing.

Acknowledgments

This work received funding support from the following sources:

NSF SBIR Award to Nanofiber Solutions, LLC: "Development of Tissue Engineered Trachea," Award #1315524.

NSF SBIR Award to Nanofiber Solutions, LLC: "Development of Tissue Engineered Trachea," Award #1456341.

Appropriate IACUC approval was received, and all national and institutional guidelines for the care and use of laboratory animals in scientific research were followed throughout this study.

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Fig. 1. Bronchoscopic and Fluoroscopic Images in both an ex-vivo (a–d) and in-vivo (ovine) model (e–h)

Calibration images with (b) and without (a) measurements are demonstrated. (c) and (d) show the *ex-vivo* images and measurements, while (e) and (f) demonstrate the *in-vivo* ovine model and measurements. 3-D rotational fluoroscopic images are shown in (g) and (h).

Table 1
Comparison of airway diameter of simulation tracheas by direct measurement and with Endoscopic Airway Measurement (EAM)

The internal diameters of three *ex-vivo* polyvinyl chloride tracheal models were measured using digital calipers (direct measurement) and endoscopically (EAM). The values from the two methods are compared.

Diameter from direct measurement	Diameter calculated from EAM	Absolute difference between two techniques	% Difference of area between techniques
13.6 mm	14.0 mm $\pm$ 1.1 mm	0.4 mm	2.9%
18.5 mm	18.7 mm $\pm$ 1.2 mm	0.2 mm	1.1%
24.2 mm	22.7 mm $\pm$ 0.8 mm	1.5 mm	6.2%

Table 2
Internal tracheal dimensions measured for five sheep with three different methods

The area and diameter of sheep tracheas (n = 5) were measured endoscopically (EAM) and with 3-D rotational fluoroscopy while *in-vivo*, and were measured with digital calipers after the tracheal segment had been resected. The measurements are recorded here.

	EAM		Measurement of resected tracheal segment		3-D fluoroscopic measurement	
	Area (mm2)	Diameter (mm)	Area (mm2)	Diameter (mm)	Area (mm2)	Diameter (mm)
Sheep 1	266.7	18.4	287.6	19.1	215.2	16.6
Sheep 2	260.5	18.2	275.4	18.7	196.8	15.8
Sheep 3	249.2	17.8	282.8	19.0	229.8	17.1
Sheep 4	223.9	16.9	268.7	18.5	295.3	19.4
Sheep 5	255.6	18.0	237.4	17.4	192.1	15.6

Table 3
Percent difference in tracheal dimensions when compared using all three methods

The percent difference in measurements of internal tracheal area are compared between *in-vivo* endoscopic (EAM) and 3-D rotational fluoroscopic methods as well as measurements of the resected tracheal segment taken with digital calipers.

	<u>EAM vs. Excised segment</u>	<u>3D fluoroscopy vs. Resected tracheal segment</u>	<u>EAM vs. 3D fluoroscopy</u>
	% Difference in area	% Difference in area	% Difference in area
Sheep 1	7.26	25.2	23.9
Sheep 2	5.41	28.6	32.4
Sheep 3	11.9	18.8	8.48
Sheep 4	16.7	9.90	24.2
Sheep 5	7.63	19.1	33.0
Average % difference	9.77 ± 4.51	20.3 ± 7.14	24.4 ± 9.90