Title
Subjective assessment using still bronchoscopic images misclassifies airway narrowing in laryngotracheal stenosis

Journal
Interactive CardioVascular and Thoracic Surgery, 16(5)

ISSN
1569-9293 1569-9285

Authors
Murgu, S.
Colt, H.

Publication Date
2013-02-13

DOI
10.1093/icvts/ivt015

Interactive CardioVascular and Thoracic Surgery 16 (2013) 655–660
doi:10.1093/icvts/ivt015 Advance Access publication 13 February 2013

Subjective assessment using still bronchoscopic images misclassifies airway narrowing in laryngotracheal stenosis

Septimiu Murgu[a,*] and Henri Colt[b]

[a] Department of Medicine, Division of Pulmonary and Critical Care Medicine, University of Chicago Pritzker School of Medicine, Chicago, IL, USA
[b] Department of Medicine, Division of Pulmonary and Critical Care Medicine, University of California, Irvine, CA, USA

* Corresponding author. Department of Medicine, Division of Pulmonary and Critical Care Medicine, University of Chicago Pritzker School of Medicine, 5841 South Maryland, MC 6076, Chicago, IL 60637, USA. Tel: +1-773-7024773; fax: +1-773-7026500; e-mail: tim.murgu@gmail.com; smurgu@medicine.bsd.uchicago.edu (S. Murgu).

Received 22 August 2012; received in revised form 17 November 2012; accepted 27 November 2012

Abstract

OBJECTIVES: Severity of airway narrowing is relevant to management decision-making processes in patients with laryngotracheal stenosis. Airway lumen is frequently assessed subjectively based on still images obtained during airway examinations or objectively using image analysis software applied to radiological or bronchoscopic images. The purpose of this study was to determine whether strictures classified as mild, moderate or severe degrees of airway narrowing based on subjective assessments by a group of experienced bronchoscopists using still images, matched the classifications derived from morphometric bronchoscopy measurements and whether the results of subjective assessments correlated with the level of bronchoscopic experience.

METHODS: Thirty-five bronchoscopic doublet still images of benign causes of laryngotracheal stenosis containing normal and abnormal airway cross-sectional areas were objectively analysed using morphometric bronchoscopy and classified as mild (<50%), moderate (50–70%) or severe (>70%). These images were then subjectively assessed by 42 experienced bronchoscopists participating in an interventional bronchoscopy course. Descriptive statistics were used to explore the accuracy of the participants' classifications. Correlation coefficients were used to study the relationship between participants' subjective assessments and bronchoscopy experience.

RESULTS: Only 47% of strictures were correctly classified by study participants (mean 16.48 ± 2.8). Of the 1447 responses included in this analysis, 755 were incorrect: 71 (9%) were over-classifications of strictures' severity and 684 (91%) were under-classifications. There was no correlation between number of strictures correctly classified and number of lifetime bronchoscopies or number of strictures seen by bronchoscopists in an average month.

CONCLUSIONS: Experienced bronchoscopists often misclassify the degree of airway narrowing when using still bronchoscopic images to subjectively assess strictures of benign aetiology.

Keywords: Morphometric bronchoscopy • Central airway obstruction • Bronchoscopy • Tracheal stenosis • Laryngotracheal stenosis

INTRODUCTION

The severity of an airway stricture affects airflow, symptoms, functional status and management decisions before and after treatment [1]. The work of breathing depends on the airway pressure drop along the stenosis, which in addition to being affected by the degree of airway narrowing, is subject to the effects of a stricture's morphology and flow velocity through the stenosis [2]. Airflow dynamic studies show, for example, that a <50% reduction in airway lumen cross-sectional area (CSA) results in a pressure drop of the same magnitude as the normal glottis opening, and is thus unlikely responsible for symptoms [3]. A reduction of more than 70%, on the other hand, results in a significant pressure drop even at low flow velocities, with a resultant impact on symptoms and functional status during minimal activities or at rest [2, 4]. These findings seem to justify classifying strictures as mild, moderate or severe based on the degree of airway narrowing and impact on airflow limitation.

When airway calibre is quantified using still images viewed directly during bronchoscopy or laryngoscopic examination, however, or afterwards using printed photos or digital images stored in electronic medical records, assessments are frequently subjective. Subjective assessments are dependent on airway examination conditions such as patient's respiratory effort (tidal breathing vs forced respiration), body position (supine vs sitting), neck position (flexion vs extension), distance between the tip of the scope and the stricture, extent and precision of bronchoscopic or laryngoscopic examination and physician's experience evaluating patients with laryngotracheal stenosis (LTS).

Spirometry is not feasible in very symptomatic, critically ill or uncooperative patients with LTS, does not identify the precise extent or morphology of the stricture within the airway and has low sensitivity for detecting mild to moderate reductions in airway calibre [5, 6]. Radiological studies such as multidetector computed tomography (MDCT) are used, but quantification of airway calibre is difficult in dyspnoeic or uncooperative patients

[7], or in patients with cognitive dysfunction and those hospitalized in the intensive care unit. Imaging results are affected by airway secretions that mimic airway narrowing [8], and significant intrasubject variations in airway lumen measurements across sites and respiratory cycles have been documented [9]. The risks of radiation exposure make these tests poorly suited for repeat testing, especially in younger patients [10], and the need for costly computer hardware and an experienced interpreter of radiographical findings limits their application in daily practice [11]. The role of radiological studies in this condition, however, has to be individualized based on patient- and institution-related factors. For instance, uncooperative patients with stable respiratory status can be administered anxiolytics and/or sedatives to facilitate CT scanning. In addition, experienced radiologists could differentiate secretions from stenosis and the risk of radiation is not relevant in life-threatening situations. Morphometric bronchoscopy uses image software-processing techniques that enable analysis of still digital images in order to measure airway lumen calibre, providing an objective quantification of the degree of airway narrowing in patients with various forms of central airway obstruction [12]. While certain limitations such as lack of real-time image analysis at the time of airway examination, use of calibration markers for absolute airway calibre measurement or lack of familiarity with the technique seem to have prevented this technique from becoming a universally accepted gold standard for quantifying airway calibre, morphometric bronchoscopy has been shown to reliably assess airway calibre in paediatric and adult patients with normal airways and tracheobronchomalacia. Results of studies also demonstrate high inter- and intraobserver reliability and show that measurements obtained by morphometric bronchoscopy correlate well with measurements performed by MDCT [12].

While no studies identify a universally accepted reference standard for assessing airway calibre, it is safe to say that to our knowledge, there are no published data regarding the accuracy of subjective assessments using still bronchoscopic images. The purpose of this study, therefore, was to determine whether strictures classified as mild, moderate or severe degrees of airway narrowing based on subjective assessments made by a group of experienced bronchoscopists using still images, matched the classifications of benign causes of LTS derived from morphometric bronchoscopy measurements, and whether the results of subjective assessments correlated with the level of bronchoscopic experience.

MATERIALS AND METHODS

Still bronchoscopic images were obtained from abnormal and normal airway lumen in patients with benign causes of laryngotracheal stenosis. A series of 35 bronchoscopic doublet images consisting of the bronchoscopic image of a benign LTS and of the normal airway distal to the stricture in the same patient were thus compiled from the authors' records of 35 different patients (study protocol # 2005–4236 was approved by UC Irvine's IRB committee). Images were captured using an Olympus BF 160 videobronchoscope positioned 1 cm proximal to the stricture or to a normal cartilaginous ring, respectively. The scope was kept centred so that the entire circumference of the airway lumen was visualized (Fig. 1). Images were saved on CD ROM using a Sony image-capturing device (Sony Digital Capture Unit UPA-P100 MD). Manual morphometric bronchoscopy was then performed by one of the authors (S.M.) on images from each of the 35 strictures. The CSA of the airway lumen was calculated using Image J analysis (software available free of charge at http://rsb.info.nih.gov/ij/). Using the manual method measurement technique, the area to be measured was selected after first opening the image using Image J [12]. This was followed by highlighting the area of interest using the Polygon Selections Tool. By selecting Analyse → Measure, the selected area was measured in pixels (Fig. 2). A Stenosis Index (SI) defined as the CSA of the obstructed area relative to that of normal airway lumen distal to the stenosis ($SI = CSA_{normal} - CSA_{abnormal}/CSA_{normal} \times 100\%$) was then calculated [12]; the greater the SI, the greater the degree of airway narrowing and more severe the obstruction. Based on the degree of airway narrowing, 63% (22 of 35) of strictures were classified as severe (>70% narrowing), 26% (9 of 35) were classified as moderate (50–70% narrowing) and 11% (4 of 35) were classified as mild (<50% narrowing). The aetiology, location, morphology, stenosis index and classification based on the degree of narrowing are presented in Table 1.

After a short instruction session conducted by one of the authors (H.C.), who remained blinded as to the calculated SI and classification based on the degree of narrowing, the 35 doublet images were subsequently shown to a group of 43 bronchoscopists participating in an interventional bronchoscopy course (Barcelona, Spain). Doublet images were projected on the auditorium screen one set at a time, with a move to a new image set

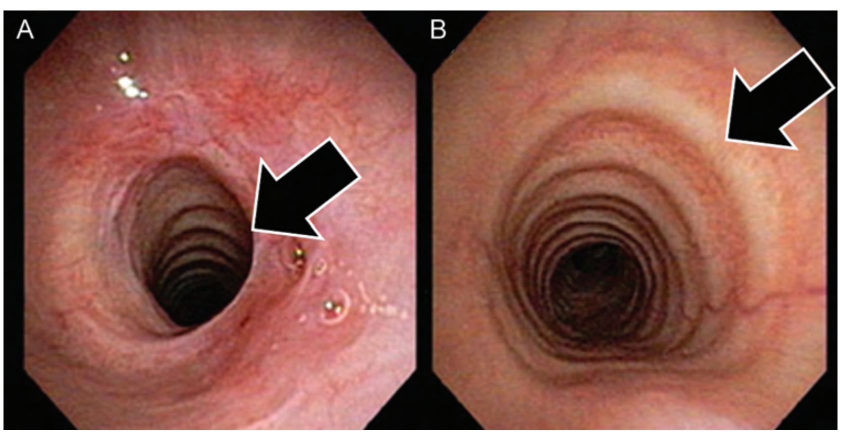

Figure 1: Bronchoscopic images of an idiopathic subglottic stricture (**A**) and the normal distal tracheal lumen (**B**); images were obtained with the scope being centred and positioned 1 cm proximal from the regions of interest (arrows) which are clearly visualized in their entire circumference.

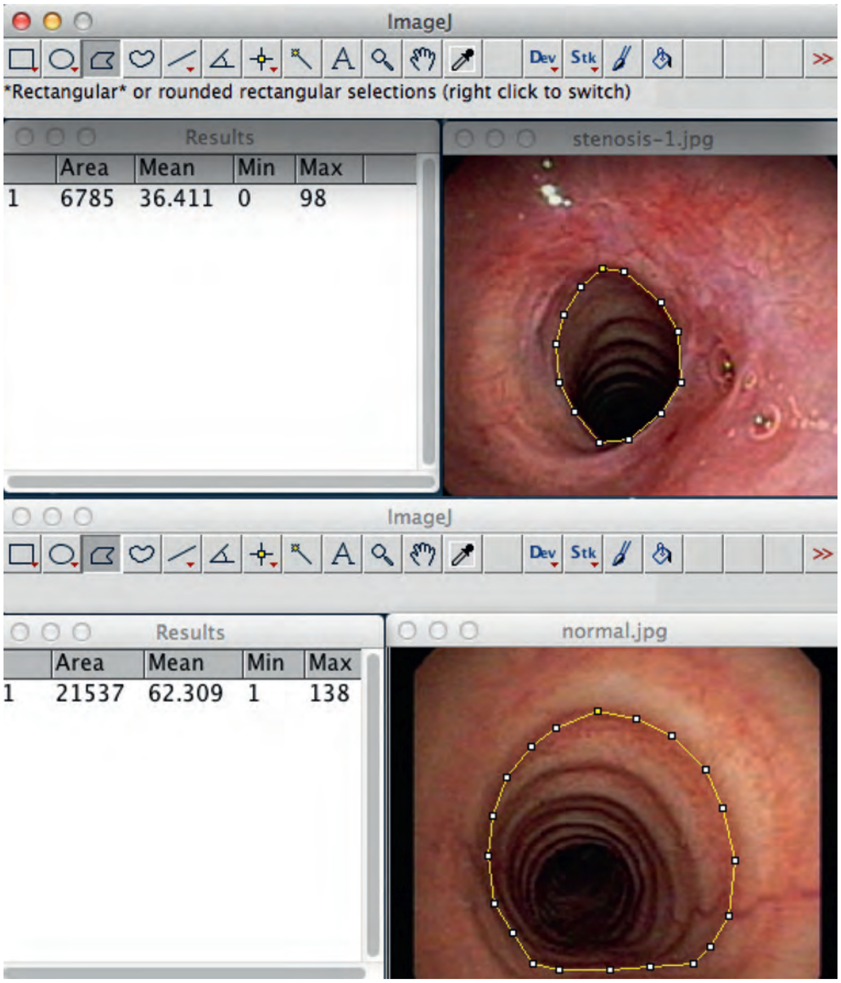

Figure 2: Example of morphometric analysis of the abnormal (top panel) and normal (bottom panel) airway lumen; the stenosis index was calculated at 67% labelling this stricture as moderate in regards to the degree of airway narrowing.

only after all participants had completed their assessments. Based on comparison with the image of the normal airway, participants were asked to independently classify each of the 35 strictures as mild (<50% narrowing), moderate (50–70% narrowing) or severe (>70% narrowing). Participants were also asked to estimate as accurately as possible their total lifetime number of bronchoscopies, and the number of patients with LTS they examined in an average month. All scoring sheets were kept anonymous.

Statistical methods

Results were tabulated using a Microsoft Excel-2007 spreadsheet and analysed using SyStat-13 (2009). Classification results based on the subjective assessments from the participants were compared with those derived from the objective measurements made by morphometric bronchoscopy. Means, standard deviations and ranges were calculated for the total number of correct stricture classifications and for the mild, moderate and severe subsets (i.e. the number of strictures classified as mild, moderate or severe by study participants that matched the classifications derived from morphometric bronchoscopic measurements). For each stricture, the number of correct classifications was also determined. Results were separately plotted for individual participants and for individual strictures in order to distinguish distribution patterns.

Descriptive statistics were used to assess the percentage of erroneous (under- or over-)classifications based on subjective assessments. Non-parametric (Spearman's Rank correlation coefficient) measures were used to analyse the relationship between the participants' classification results and level of experience based on the number of lifetime bronchoscopies and number of LTS seen monthly.

RESULTS

All 43 bronchoscopists in this interventional bronchoscopy course participated in the study, but one scoring sheet had to be excluded because it was almost completely blank. The 42 remaining scoring sheets were almost all completed properly, with a single response per image: the rate of blank and double responses was only 1.5% (23 of 1470 images), leaving 1447 responses for analysis. Of the 42 participants who completed the scoring sheets, 69% (29 of 42) had performed more than 1000 lifetime bronchoscopies, 26% (11 of 42) had performed between 200 and 1000 and 5% (2 of 42) had done 200 or less. Seven participants were seeing more than two strictures in an average

Table 1: Aetiology, location, morphology and stenosis index/degree of narrowing for the 35 strictures analysed

Stricture no	Stricture aetiology and location	Stricture morphology	Stenosis Index/degree of narrowing
1	Postintubation/tracheal	Elliptical	81%/severe
2	Idiopathic/subglottic	Circumferential	74%/severe
3	Idiopathic/subglottic	Circumferential	81%/severe
4	Postintubation/tracheal	Hourglass	82%/severe
5	Post-tracheostomy/tracheal	Triangular	83%/severe
6	Post-tracheostomy/tracheal	Triangular	71%/severe
7	Postintubation/tracheal	Hourglass	80%/severe
8	Postintubation/subglottic	Circumferential	86%/severe
9	Idiopathic/subglottic	Circumferential	65%/moderate
10	Postintubation/tracheal	Hourglass	76%/severe
11	Post-tracheostomy/tracheal	Triangular	55%/moderate
12	Post-tracheostomy/tracheal	Triangular	93%/severe
13	Idiopathic/subglottic	Circumferential	72%/severe
14	Wegener granulomatosis/subglottic	Circumferential	46%/mild
15	Postintubation/tracheal	Circumferential	84%/severe
16	Stent-related/tracheal	Circumferential	83%/severe
17	Wegener granulomatosis/subglottic	Circumferential	83%/severe
18	Idiopathic/subglottic	Circumferential	64%/moderate
19	Post-tracheostomy/tracheal	Triangular	74%/severe
20	Idiopathic/subglottic	Elliptical	53%/moderate
21	Post-tuberculosis/tracheal	Elliptical	70%/moderate
22	Postintubation/tracheal	Circumferential	20%/mild
23	Post-tracheostomy/tracheal	Triangular	62%/moderate
24	Post-tracheostomy/tracheal	Triangular	70%/moderate
25	Wegener granulomatosis/subglottic	Circumferential	60%/moderate
26	Post-tracheostomy/tracheal	Triangular	80%/severe
27	Idiopathic/tracheal	Circumferential	79%/severe
28	Postintubation/tracheal	Circumferential	73%/severe
29	Post-tracheostomy/tracheal	Triangular	76%/severe
30	Post-tracheostomy/tracheal	Triangular	16%/mild
31	Post-tracheostomy/tracheal	Triangular	74%/severe
32	Post-tracheostomy/tracheal	Triangular	77%/severe
33	Postintubation/tracheal	Hourglass	95%/severe
34	Post-tracheostomy/tracheal	Circumferential	20%/mild
35	Postintubation/tracheal	Elliptical	67%/moderate

month (21 participants saw 2 per month and 14 saw 1 per month).

Forty-seven percent of strictures (mean number of stricture 16.48 ± 2.8) classified as mild, moderate or severe by study participants matched the classifications derived from morphometric bronchoscopic measurements. The participants' distribution plot was relatively tight, with 79% of participants (33 of 42) correctly classifying between 40 and 57% of strictures (Fig. 3: top panel). Ten of the 35 strictures (29%) were correctly classified by 88–98% of participants; another 10 strictures (29%) were correctly classified by 40–70% of participants; 13 of 35 strictures (37%) were correctly classified by 0–17% of participants and 9 strictures (26%) were correctly classified by ≤5% of participants (Fig. 3: bottom panel).

Misclassifications were sorted by whether participants had under- or over-classified a stricture's degree of airway narrowing. Of the 1447 responses included in this analysis, 755 were incorrect: 71 (9%) were an over-classification of a stricture's severity and 684 (91%) were an under-classification. Each over-classification was by one degree (from mild to moderate, or from moderate to severe). Of the 684 under-classifications, 154 (23%) were under-classified by two degrees (from severe to mild) and 530 (77%) by one degree (from severe to moderate or from moderate to mild). Almost all incorrect classifications were in the severe and moderate categories, whereas almost all (161 of 168 or 96%) mild strictures were classified correctly.

There was no correlation between number of strictures correctly classified and number of lifetime bronchoscopies ($\rho = 0.17$) or number of strictures seen ($\rho = 0.09$); there was minimal correlation between the number of lifetime bronchoscopies with the number of strictures seen per month ($\rho = 0.23$). The lack of correlation between percentage of correctly classified strictures and number of bronchoscopies performed or strictures seen was confirmed by Spearman Rank test ($\rho = 0.21$ and $\rho = 0.15$, respectively).

DISCUSSION

The results of this study demonstrate that subjective assessment using still bronchoscopic images more often than not under-classifies and occasionally over-classifies the degree of airway narrowing in patients with benign causes of LTS, when compared with an objective measurement such as morphometric bronchoscopy. Subjective assessments were accurate for classifying mild strictures, but an under-classification by two degrees from severe to mild airway narrowing was noted for almost a quarter of the total number of incorrect classifications. These findings are relevant to patient care because: (i) alternative causes may be sought for a patient's shortness of breath if the stenosis is classified as mild, when in actuality it is moderate or severe, potentially delaying care, compromising safety and increasing costs;

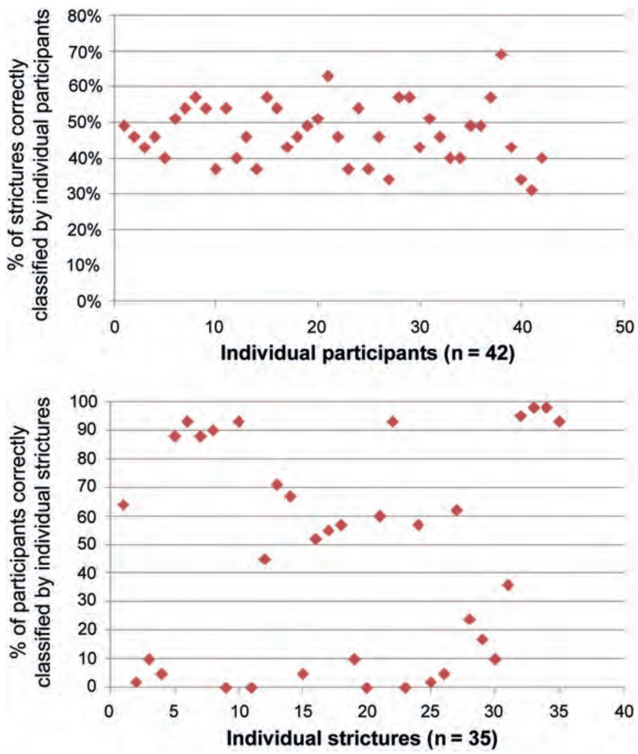

Figure 3: Distribution plots for strictures correctly classified by participants (average 47%) (top panel) and distribution plots for participants correctly classifying individual strictures (bottom panel) (see text for detail).

(ii) if strictures are unrecognized as severe (for example, a severe stricture is erroneously classified as mild or moderate), LTS can become critical in case of subsequent obstruction by mucus production or oedema from upper respiratory tract infection, which can also precipitate respiratory failure; (iii) over-classification (e.g. a mild or moderate stricture is erroneously classified as severe), may prompt referral for unnecessary invasive interventions despite a possibility of alternative explanations and management for their symptoms and (iv) accurate classification of the degree of airway narrowing allows physicians to accurately communicate with each other before and after therapeutic interventions, and more precisely employ a validated classification such as Myer–Cotton system when managing patients with LTS [1]. While we did not study this issue specifically, the findings of this study suggest the need for surgeons contemplating tracheal resection to be present at the time of bronchoscopy or to perform their own airway examination prior to surgical intervention.

Paradoxically, there was no correlation between bronchoscopist experience (based on the number of bronchoscopies and number of strictures seen per month) and the ability to accurately classify the degree of airway narrowing as mild, moderate or severe based on still bronchoscopic images. Other than suggesting a need for educational programmes pertaining to LTS, the impact of this finding on patient care is difficult to assess because treatment decisions in benign LTS are based not only on the degree of narrowing, but also on other factors such as extent, location, morphology of airway narrowing, vocal cord function, swallowing dysfunction, dyspnoea class and functional status [1, 13, 14]. The reasons pulmonologists underestimate the degree of narrowing are unclear and were not the purpose of this study. We did not find a correlation between operators' experience and ability to accurately estimate the degree of stenosis. Furthermore, as the airway narrowing was assessed on still images, it is unlikely that the participants' bronchoscopic technique contributed to these findings. One possible explanation for these findings is the lack of familiarity with the optics principle of image distortion partially caused by intrinsic lens properties but also by the location of the bronchoscope in relation to the stricture, factors which could significantly influence the airway size perception.

In order to accurately assess and classify airway strictures, several techniques have been proposed. Spirometry and flow-volume loops, however, do not precisely localize strictures, are insensitive diagnostic tests for mild to moderate narrowing and provide functional rather than accurate anatomical information [5, 6]. Results from ultrasonography correlate with bronchoscopic imaging with regard to airway lumen size estimations, but allow non-invasive measurements only of transverse cervical tracheal diameter [15]. MDCT, with or without 3D reconstruction, can be used to quantify the degree of airway narrowing [16, 17]. MDCT airway measurements correlate with results of objective bronchoscopic assessments [7, 18, 19]. Radiographical quantification of LTS, however, is not standardized, may be hindered by secretions, and scanning may be difficult or unreasonable in critically ill patients or in those who are uncooperative or have severe dyspnoea [7–9]. Morphometric bronchoscopy using image analysis software provides quantitative (using calibration bodies to report CSA in metric units) or semi-quantitative (reporting CSA as percentages of normal airway) measurements of degree of airway narrowing [12]. From a physiological standpoint, the latter parameter matters more than the absolute CSA or airway diameter in metric units. Given the airway size dependence on age, sex and body height, the percentage reduction in airway calibre is more relevant to flow limitation, symptoms and treatment decisions than the absolute CSA measured in metric units. Morphometric bronchoscopy measurements correlate well with clinical findings as well as with measurements made using MDCT in both experimental and clinical studies [18–22]. High intra- and interobserver reliabilities have been demonstrated [20–22]. Real-time morphometric bronchoscopic measurements can be obtained using new stereovision bronchoscopes [23], and in the near future, correlations between the degree of narrowing and pressure changes responsible for increased work of breathing will become possible intraoperatively [4].

This study has several limitations that impact the generalizability of our results. Because results were based on course participants' responses, the problems of recall bias, personal motivation or indifference at the time of data gathering must be recognized. The results of our survey may not be applicable to all practitioners. All participants were pulmonologists, so our results may not apply to bronchoscopists in other specialties such as thoracic surgery, ENT or anaesthesiology. Thirdly, morphometric bronchoscopy was used as a reference standard for objectively assessing airway narrowing because there is no true gold standard. While shown to be accurate in paediatric patients with both normal and abnormal airway findings [20], the manual method of morphometric bronchoscopy used in this study has not been rigorously studied in adult patients with LTS. From an optics standpoint, the airway size does not affect the morphometric bronchoscopy methodology; there is no physics rationale for expecting different results when measuring paediatric or adult airways. Further studies of this technique should, however, attempt to correlate the airway measurements with lung function testing or radiological investigations. Therefore, the use of calculated stenosis index on the margins of categories could occasionally be misleading. For example, stricture #6 was a triangular stenosis with a calculated SI of 71%, and stricture #20 had an SI of 53% (Table 1). If morphometric bronchoscopy technique has an error of ±3%, both of these strictures would be correctly classified by the participants, and incorrectly classified by morphometric bronchoscopy. Finally, from an optics standpoint, interpretations of airway findings are affected by the presence of image distortion [24] because length, perimeter and area measurements depend on the target's location within the field of view of the bronchoscope [25]. (It is noteworthy that airway targets move away from the bronchoscope lens during inspiration and towards the lens during expiration, causing an optical effect whereby the airway lumen appears greatest at end-expiration. While obtaining images for morphometric bronchoscopy, it is important, therefore, to keep the bronchoscope centred and at a fixed distance from the target regardless of the respiratory phase). This distortion, however, applies to both normal and abnormal airway images and therefore, should not affect the calculation of a stenosis index by morphometric bronchoscopy.

In summary, physicians and surgeons caring for patients with benign causes of LTS usually make management decisions after direct endoscopic airway visualization. Airway assessments provide information regarding a stricture's severity, extent, morphology, dynamics, vocal cord function and presence or absence of mucosal abnormalities. Results from this study suggest, however, that experienced bronchoscopists often misclassify the degree of airway narrowing when subjectively assessing strictures of benign aetiology using still bronchoscopic images. Whether in the bronchoscopy suite or post-procedure, caution is warranted when classifying airway strictures based on printed or digital still images captured at the time of airway examination.

ACKNOWLEDGEMENTS

We thank Pablo Diaz-Jimenez for facilitating the performance of the study at his interventional bronchoscopy course, Mohsen Davoudi for his help with statistical analysis and Stephanie Langer for her assistance with data gathering.

Conflict of interest: none declared.

REFERENCES

[1] Myer CM, O'Connor DM, Cotton RT. Proposed grading system for subglottic stenosis based on endotracheal tube sizes. Ann Otol Rhinol Laryngol 1994;103:319–23.

[2] Brouns M, Jayaraju ST, Lacor C, De Mey J, Noppen M, Vincken W *et al*. Tracheal stenosis: a flow dynamics study. J Appl Physiol 2007;102:1178–84.

[3] Brouns M, Verbanck S, Lacor C. Influence of glottic aperture on the tracheal flow. J Biomech 2007;40:165–72.

[4] Nishine H, Hiramoto T, Kida H, Matsuoka S, Mineshita M, Kurimoto N *et al*. Assessing the site of maximal obstruction in the trachea using lateral pressure measurement during bronchoscopy. Am J Respir Crit Care Med 2012;185:24–33.

[5] Miller RD, Hyatt RE. Evaluation of obstructing lesions of the trachea and larynx by flow-volume loops. Am Rev Respir Dis 1973;108:475–81.

[6] Hyatt RE, Black LF. The flow-volume curve. A current perspective. Am Rev Respir Dis 1973;107:191–9.

[7] Lee KS, Sun MR, Ernst A, Feller-Kopman D, Majid A, Boiselle PM. Comparison of dynamic expiratory CT with bronchoscopy for diagnosing airway malacia: a pilot evaluation. Chest 2007;131:758–64.

[8] Polverosi R, Vigo M, Baron S, Rossi G. Evaluation of tracheobronchial lesions with spiral CT: comparison between virtual endoscopy and bronchoscopy. Radiol Med 2001;102:313–9.

[9] Newth CJ, Lipton MJ, Gould RG, Stretton M. Varying tracheal cross-sectional area during respiration in infants and children with suspected upper airway obstruction by computed cinetomography scanning. Pediatr Pulmonol 1990;9:224–32.

[10] Nagataki S. Computed tomography and radiation exposure. N Engl J Med 2008;358:850–1.

[11] Neumann K, Winterer J, Kimmig M, Burger D, Einert A, Allmann KH *et al*. Real-time interactive virtual endoscopy of the tracheo-bronchial system: influence of CT imaging protocols and observer ability. Eur J Radiol 2000;33:50–4.

[12] Murgu S, Colt HG. Morphometric bronchoscopy in adults with central airway obstruction: case illustrations and review of the literature. Laryngoscope 2009;119:1318–24.

[13] Nouraei SAR, Nouraei SM, Upile T, Howard DJ, Sandhu GS. A proposed system for documenting the functional outcome of adult laryngotracheal stenosis. Clin Otolaryngol 2007;32:407–9.

[14] Herrington HC, Weber SM, Andersen PE. Modern management of laryngotracheal stenosis. Laryngoscope 2006;116:1553–7.

[15] Husein M, Manoukian JJ, Platt R, Patenaude Y, Drouin S, Giguère C. Ultrasonography and videobronchoscopy to assess the subglottic diameter in the paediatric population: a first look. J Otolaryngol 2002;31:220–6.

[16] Hoppe H, Walder B, Sonnenschein M, Vock P, Dinkel HP. Multidetector CT virtual bronchoscopy to grade tracheobronchial stenosis. Am J Roentgenol 2002;178:1195–200.

[17] De Wever W, Vandecaveye V, Lanciotti S, Verschakelen JA. Multidetector CT-generated virtual bronchoscopy: an illustrated review of the potential clinical indications. Eur Respir J 2004;23:776–82.

[18] Forkert L, Watanabe H, Sutherland K, Vincent S, Fisher JT. Quantitative videobronchoscopy: a new technique to assess airway caliber. Am J Respir Crit Care Med 1996;154:1794–803.

[19] Czaja P, Soja J, Grzanka P, Cmiel A, Szczeklik A, Sładek K. Assessment of airway caliber in quantitative videobronchoscopy. Respiration 2007;74:432–8.

[20] Rozycki HJ, Van Houten ML, Elliott GR. Quantitative assessment of intrathoracic airway collapse in infants and children with tracheobronchomalacia. Pediatr Pulmonol 1996;21:241–5.

[21] Masters IB, Ware RS, Zimmerman PV, Lovell B, Wootton R, Francis PV *et al*. Airway sizes and proportions in children quantified by a videobronchoscopic technique. BMC Pulm Med 2006;6:5.

[22] Masters IB, Eastburn MM, Wootton R, Ware RS, Francis PW, Zimmerman PV *et al*. A new method for objective identification and measurement of airway lumen in paediatric flexible videobronchoscopy. Thorax 2005;60:652–8.

[23] Hayashi A, Takanashi S, Tsushima T, Denpoya J, Okumura K, Hirota K. New method for quantitative assessment of airway calibre using a stereovision fiberoptic bronchoscope. Br J Anaesth 2012;108:512–6.

[24] Masters IB, Eastburn MM, Francis PW, Wootton R, Zimmerman PV, Ware RS *et al*. Quantification of the magnification and distortion effects of a pediatric flexible video-bronchoscope. Respir Res 2005;6:16.

[25] McFawn PK, Forkert L, Fisher JT. A new method to perform quantitative measurement of bronchoscopic images. Eur Respir J 2001;18:817–26.