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SYSTEMATIC REVIEW

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The anatomy of the pediatric airway: Has our knowledge changed in 120 years? A review of historic and recent investigations of the anatomy of the pediatric larynx

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Summary

Background: There is disagreement regarding the anatomy of the pediatric airway, particularly regarding the shape of the cricoid cartilage and the location of the narrowest portion of the larynx.

Aims: The aim of this review is to clarify the origin and the science behind these differing views.

Methods: We undertook a review of published literature, University Libraries, and authoritative textbooks with key search words and phrases.

Results: In vivo observations suggest that the narrowest portion of the airway is more proximal than the cricoid cartilage. However, in vitro studies of autopsy specimens measured with rods or calipers, confirm that the nondistensible and circular or near circular cricoid outlet is the narrowest level. These anatomic studies confirmed the classic "funnel" shape of the pediatric larynx. In vivo studies are potentially misleading as the aryepiglottic, vestibular, and true vocal folds are in constant motion with respiration. These studies also do not consider the effects of normal sleep, inhalation agents, and comorbidities such as adenoid or tonsil hypertrophy that cause some degree of pharyngeal collapse and alter the normal movement of the laryngeal tissues. Thus, the radiologic studies suggesting that the narrowest portion of the airway is not the cricoid cartilage may be the result of an artifact depending upon which phase of respiration was imaged.

Conclusion: In vivo studies do not take into account the motion of the highly pliable laryngeal upper airway structures (aryepiglottic, vestibular, and vocal folds). Maximal abduction of these structures with tracheal tubes or bronchoscopes always demonstrates a larger opening of the glottis compared to the outlet of the cricoid ring. Injury to the larynx depends upon ease of tracheal tube or endoscope passage past the cricoid cartilage and not passage through the readily distensible more proximal structures. The infant larynx is funnel shaped with the narrowest portion the circular or near circular cricoid cartilage confirmed by multiple in vitro autopsy specimens carried out over the past century.

KEYWORDS
age, airway, child, infant, neonate, otolaryngology, techniques

†Robert Carroll MD passed away unexpectedly on August 13, 2016.

1 | INTRODUCTION

The lumen of the infant larynx is described as oval, cylindrical, spherical, conical, and funnel shaped with the narrowest portion being the nondistensible cricoid cartilage. Following publication of Eckenhoff's classic paper, the descriptor "funnel shaped" was widely adopted.[1] However, recent in vivo investigations and reviews have questioned the shape and location of the narrowest portion of the infant larynx,[2-8] however, one in vivo study documented a circular outlet of the cricoid ring.[9] We were intrigued by these assertions that contradict traditional anatomic concepts.[1,10-15] As a correct understanding of airway anatomy is fundamental to the safe use of tracheal tubes in infants and children, these contradictory observations prompted our review.

2 | MATERIALS AND METHODS

Using the key words and phrases: *"pediatric/infant anatomy of the airway, larynx, dimensions, narrowest part of, pediatric laryngoscopy—bronchoscopy, difference from adults"*, we searched PubMed, the University Library Liège, 4000 Liége, Belgium, for Historical French language articles not found on the Internet, Springer Book archives, the University Library Cologne, Kerpenerstrasse 62, 50937, Germany, and Deutsche Zentralbibliothek für Medizin, Gleuelerstrasse 60, 50931 Köln, Germany (Table 1), original research and textbooks. We investigated in vitro anatomical descriptions dating back to 1897 and in vivo endoscopic and radiologic airway assessments. We concentrated on dimensions of the laryngeal lumen, the narrowest part of the larynx, and the shape of the cricoid outlet. Only anatomy reports presenting at least 2 methods of investigation (measurements, calibrations, and photographs) were selected.

3 | RESULTS

Our search revealed autopsy data from hundreds of pediatric larynges[10-14,16-18] and one textbook.[15] In vivo studies also reported data from hundreds of children.[2,3,6-9] All investigations examined children from preterm to 15 years (Table 1).

3.1 | Chronological in vitro autopsy reports

In 1897, Bayeux[10] reported autopsy data from 28 infants and children. After abandoning plaster casts which distorted the anatomy, he used wax castings and calibration rods which proved to be more accurate; as wax liquefies at 40°C it molds to surfaces without distortion or dilatation. In all specimens, the A-P dimension of the glottis was larger than the cricoid ring (Figure 1A). Calibration rods demonstrated that the nondistensible cricoid outlet was the narrowest part of the larynx and that it was nearly circular. To further assess the caliber of the glottis, he divided the arch of the cricoid ring (Figure 1B), confirming that the transverse dimension of the vocal cords is larger than the cricoid ring. This observation supported the notion of a funnel shape. He concluded that *"the cricoid cartilage is unquestionably the narrowest part of the pediatric larynx"*, noting that this configuration could persist into adolescence. Peter[11] reported additional anatomical details: (i) The cricothyroid membrane *(conus elasticus)* slants posteriorly impinging on the laryngeal lumen narrowing the anterior aspect of the subglottic space Figure 2A). (ii) In infancy, the laminae of the cricoid tilt posteriorly. As the length of the cricoid cartilage in infants is 8.4 ± 1.4 mm, this posterior angulation should confer an ellipsoid shape to the subglottic space.[9] Indeed, Peter reported that the A-P dimension of the glottis is larger than the near circular cricoid outlet (funnel shape). During development, the posterior laminae gradually assume an upright position (Figure 2B).

In his classic paper, Eckenhoff compared the investigations of Bayeux and Peter with his clinical observations during direct laryngoscopy.[1] With the vocal cords widely abducted, the outlet of the cricoid ring appeared smaller than the glottis. He concluded that *"in the infant, the lamina is inclined posteriorly at its superior aspect, so that the larynx is funnel shaped with the narrowest point of the funnel at the laryngeal exit"* (Figures 2B, 3A-D). This report brought scientific descriptions of the pediatric larynx to the attention of anesthesiologists and introduced the descriptor "funnel shaped" and the concept of a round cricoid.

Butz[12] examined 24 fresh unpreserved laryngeal autopsy specimens (premature infants to adolescents). Using dilators in 7 specimens, he found that the glottis accepted sizes 4 Fr larger than the tracheal origin; the larynx became consistently narrower from the glottis to the cricoid outlet (funnel shape). The cricoid ring in all specimens tended to be circular in cross-sections.* Too-Chung and Green[16] investigated the rate of growth of the cricoid cartilages. They examined larynges (only 5/68 preserved) from 15 newborns (1 day-1 week), 44 infants (>1 week-1 year), and 9 children (2-15 years). They measured the interior dimension of the cricoid ring at its lower border with a Vernier caliper. They observed a slightly larger transverse cricoid diameter in neonates and a gradual crossover to a larger A-P diameter in children until 2 years. At 5 months, they reported a circular outlet and at 15 years, they observed average A-P/transverse diameters of 1:0.97. The ratio of all groups was between 1:0.91 and 1:1.1, near circular. Tucker et al[17] published serial cross-sections of larynges from 21 children (3 months-4 years) and demonstrated the "V"-shape of the backward tilted cricoid laminae (Figure 4A). This observation explains both the funnel shape of the cricoid lumen and the posterolateral endocricoid ulcerations commonly associated with prolonged tracheal intubation.[15,19] Holinger et al[15] expanded upon these observations based upon combined endoscopic experiences from GF Tucker and B. Benjamin.[17,19] They concluded that: *"The lumen of the glottis is somewhat pentagonal in shape, as the vocal folds taper inferiorly into the subglottic larynx, where the lumen is elliptical with the greater diameter in the A-P*

*In anatomy, there never exist geometrical structures like rings, funnels, or ellipses, only similarities to these geometrical forms.

TABLE 1 Summary of in vitro and in vivo studies with comments and conclusions

Author (y)	N	Age	Cricoid-A-P/transverse diameter ratio (r) and conclusions	Comments
In vitro studies				
Bayeux (1897)[10]	28	4 mo-14 y	Calibration, splitting of cricoid arch, caliper measurements.	"The cricoid cartilage is unquestionably the narrowest part of the pediatric larynx."
Peter (1936)[11]	15	1 d-17 y	r = 1/1.1 The cricoid outlet has a near circular shape (moderately larger in the transverse dimension). He confirmed that the A-P dimension of the glottis is larger than the cricoid outlet (funnel shape).	
Butz (1968)[12]	18	1 d-1 y		"In all cases the glottis accepted a dilator at least 4 Fr larger that the tracheal origin" "the larynx seems to consistently funnel down to the opening diameter of the trachea." (7 infant larynges)
Too-Chung & Green (1974)[16]	15	1 d-1 wk	r = 1/1.08 The cricoid is near circular, described with a slightly larger transverse cricoid diameter in neonates with crossover at 2 y to near circular at 15 y	"It was noticeable immediately that the child's cricoid is elliptical in shape, the coronal diameter being greater."
	52	2 wk-1 y	r = 1/0.91 Slightly larger A-P diameter	
	9	2-15 y	r = 1/1.02 (circular diameter)	
Tucker et al (1977) [17]	21	3 mo-4 y	"V" shape of backward tilted lamina	
Eckel et al (1999)[20]	43	1-60 mo	They measured glottic length in mm; subglottic cartilaginous cross-section, subglottic airway and tracheal airway in mm^2. All cross-sections were shorter than glottic length, tracheal diameters always larger than the subglottic airway, showing the subglottic airway as the narrowest part of the pediatric larynx	
Sellars & Keen (1990)[18]	21	1 d-2 wk	r = 1:1.13 in 16/21 r = 1:0.87 in 5/21 This large contrast between A-P/transverse diameters has never been reported in the literature	
Holinger (1997)[15]			Large experience over more than 20 y of airway endoscopy and teaching together with Tucker an Benjamin	"When viewed from the side, the laryngeal lumen is slightly larger superiorly at the glottic level and narrower at the inferior aspect of the cricoid cartilage" "The cricoid ring is a smooth round circle"
Fayoux et al (2006)[13]	150	Preterm-3 mo		"The narrowest part of the airway was the cricoid area. . .in each age group."
Fayoux et al (2008)[14]	274[a]	15-41 wk gestation	There was no significant difference between the A-P and lateral diameter of the cricoid (circular)	"The diameter of the cricoid lumen was significantly less than that of the trachea and glottic lumen."
	26[a]	1 d-1 m	Same ratios as in the premature group	
Total examinations	672			
In vivo studies				
Litman et al (2003)[2]	99	2 mo-13 y		"The narrowest portion of the larynx was the transverse dimension at the level of the vocal cords." "Transverse dimensions were narrower than A-P dimensions at all levels of the larynx above the cricoid ring and in most children at the cricoid ring." "The cricoid ring is functionally the narrowest portion of the larynx."

(Continues)

TABLE 1 (Continued)

Author (y)	N	Age	Cricoid-A-P/transverse diameter ratio (r) and conclusions	Comments
Dalal et al (2009)[3]	128	6 mo-13 y	Videos at the glottis and superior aspect of cricoid ring were obtained. Pictures were plotted on graph paper. Mean cross-sectional areas of cricoid and paralyzed glottis were compared (cricoid ellipsoid).	"Our study reveals the Cricoid-A-P dimension is larger than its Cricoid-transverse dimension suggesting that the cricoid is ellipsoid rather than round." "in anesthetized paralyzed children, the glottis is narrower than the cricoid from infancy to adolescence."
Wani et al (2016)[6]	130	1 mo-9 y	r = 1/1.02 (practically circular)	"The cone shaped airway characteristic, which has been historically proposed, was not observed. Given that the subglottic transverse diameter is the smallest area dimension, one must assume this is the most likely area of resistance for the passage of an endotracheal tube rather than only the cricoid." "The subglottic area and the cricoid change from an elliptical to a round (circular) shape."
Wani et al (2017)[7]	40	1 d-12 mo[c]	r = 1/1.36 at subglottic region. r = 1/1.098 at cricoid level (near circular)	"Increase in transverse dimensions observed from subglottis to cricoid... A-P dimensions showed a decrease from subglottis to the cricoid." "The mean cross-sectional area at the 2 levels were similar." "The cricoid is not round as has been observed in older children" "The ratio between the transverse and A-P diameters at the cricoid was 0.89."
Wani et al (2017)[b,8]	54	2 mo-8 y	Air volumes in the subglottic, cricoid to the tracheal regions were examined. The coaxial view of the airway from the caudad end shows a funnel shape	"An increase in airway volumes was observed from the subglottis (0.17 mm^3) to the cricoid (0.19 mm^3)."
Wani (2016)[b,21]	102	1 mo-10 y (9 age groups)	r = 1:1.0 overall but ranged from 0.91 to 1.06. Age groups 2-3, 6-8 y had a moderately larger transverse than A-P diameter of the cricoid (near circular)	
Total	553			

[a]Note that 150/300 larynges were also reported in their 2008 publication (personal communication).
[b]It is not known if some of these patients were included in prior publications.
[c]Note that 11 patients were reported in a prior study.

dimension. At the inferior aspect of the cricoid cartilage the lumen and the cartilage are a smooth round shape (Figure 3B,C,D)". The authors illustrated the 2-dimensional inverted funnel shape in coronal sections as typical for adducted vocal cords in autopsy specimens. They further described the glottic level as pliable and larger than the rigid cricoid outlet. To have a holistic view of the lumen of the larynx, A-P and coronal sections of the larynx should be combined with the cross-sections of the larynx at different levels (Figure 3); the authors confirmed the common site of injury from tracheal tubes and the autopsy work of previous investigators.[10-12,16,17]

Sellars and Keen[18] reported A-P/transverse diameters of 21 autopsy specimens (newborn-2 weeks) at the inner aspect of the cricoid ring (measurements higher in the larynx were not made). In 16/21 specimens, the A-P diameter exceeded the transverse, however, in 5 specimen transverse diameters were considerably larger than the A-P diameters (different from Too-Chung). Thus, the A-P/transverse ratios in this age group may vary. Eckel et al[20] examined 43 larynges (<5 years) by the method of plastination which preserves the larynx as it appears in situ and found that cricoids tended to be circular. Mid-larynx cross-sections proximal to the cricoid arch demonstrated the transverse diameter to be wider than the glottis (Figure 4B). They also found that the transverse diameter of the cadaveric glottis was narrower than the A-P dimension, resulting in an almost triangular shape (Figure 4B). This is consistent with what is expected as in death, the soft tissues of the upper airway revert to their neutral position (Figure 3B) similar to several in vivo reports (see further).[6,7] More recently, Fayoux et al[13] examined serial sections from 150 nonpreserved infant larynges (preterm-3 months)

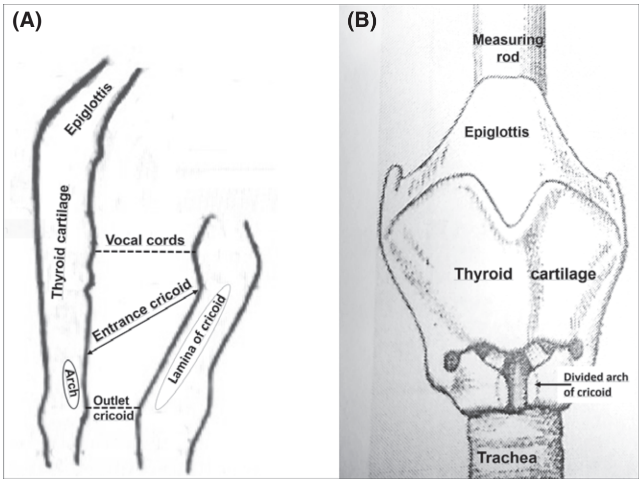

FIGURE 1 A, Soot print from a wax casting (Bayeux) showing a lateral view of pediatric larynx from a 5-year-old child. The A-P diameter at the level of the cricoid outlet is about 44% smaller than at the level of the vocal cords. B, Depiction of the anterior view of pediatric larynx from another 5-year-old child by Bayeux. A measuring rod could not exit the outlet of the cricoid ring until the arch of the cricoid ring was divided, demonstrating that the outlet of the cricoid ring is the narrowest part of the pediatric larynx

within 6 hours after death (near physiologic conditions). They used 3 methods to evaluate the laryngeal lumen: (i) tracheal tubes (analogous to Bayeux's calibration rods); (ii) nondilatable, cylindrical balloons, recording the change in pressure as the balloon was moved along the length of the larynx; and (iii) determination of the A-P/transverse diameters with calipers of the cricoid ring and the interarytenoid distance (IAD) at the vocal processes at the posterior glottis. The narrowest diameters in anteroposterior and transverse laryngeal plane (28 weeks gestational age (GA) until the 3rd month of life) was the cricoid ring (Fig. S1) (funnel shape). Building upon other investigations,[12,15] these measurements provide important insights regarding the mechanism of injuries during airway instrumentation: (i) the risk for glottic injury increases if tracheal tubes with an OD larger than the IAD are introduced in the larynx; and (ii) the risk for injury at the level of the posterior cricoid cartilage increases if a tracheal tube with an OD smaller than the IAD, but larger than the outlet of the cricoid ring is introduced.[19] In a second series, they examined cricoid and tracheal diameters from 274 nonfixed larynges (15-41 weeks GA) and 26 infants (0-1 month) within 6 hours after death.[14] They concluded that *"Cricoid diameters were always significantly less than tracheal diameters and IAD"* and *"there was no significant difference between the A-P and lateral diameter of the cricoid."* This study confirmed that throughout intrauterine life until the first month of life that the cricoid ring is narrower than the glottis (funnel shape). They further documented the triangular-shaped lumen of the glottis in all specimens.

Unpublished observations from 2 authors (JH and MHR)[‡] of 16 autopsy specimens (0-7 months), demonstrated a ratio of 1/1.02 at the cricoid outlet and that the cricoid arch and posterior lamina have a 4-fold height discrepancy which creates an oblique entrance to the cricoid ring (Figure 4C). Therefore, methods which identify the cricoid cartilage by the tip of the lamina vs the superior aspect of the anterior cricoid arch are likely to demonstrate different measurements (Figure 3). All outlets of the investigated larynges were round with A-P/transverse ratios between 1/0.99 and 1/1.05.

[‡]MA Rothschild, Institution of Legal Medicine, University of Cologne, Germany.

3.2 | In vivo clinical reports

Litman et al[2] reviewed laryngeal MRIs in 99 anesthetized, spontaneously breathing children (2 months-13 years). The A-P/transverse diameters of the larynx were measured at the vocal cords and cricoid level. Transverse diameters increased linearly in a caudad direction through the larynx, while A-P diameters did not change much relative to the different laryngeal levels. The larynx was described as conical in the transverse (coronal) section with the apex at the vocal cords and as cylindrical in the A-P dimension. The narrowest portions of the larynx were at the glottic opening and the immediate sub-vocal cord level but functionally, the cricoid ring was described as the narrowest portion of the larynx. In the horizontal view, they described the subglottic superior aspect of the cricoid ring as ellipsoid. They also commented that contraction of the laryngeal muscles influenced the dimension of the larynx above the cricoid ring. Dalal et al[3] photographically estimated the cross-sectional areas of the larynx at the glottis and superior aspect of cricoid ring in 128 children under anesthesia and neuromuscular blockade. They reported that the relaxed glottis was narrower than the cricoid ring. They also found that the infant larynx was cylindrical in the A-P dimension but conical in the transverse dimension. Interestingly, the authors stated: *"Further studies are needed to determine whether these static airway measurements in anesthetized and paralyzed children reflect the dynamic characteristics of the glottis and cricoid in children"*, acknowledging differences between in vivo and in vitro studies.

Wani et al[6] have reported several studies. They initially reported observations from 130 laryngeal CT scans in children (1 month-9 years); a description of the glottis was not part of that study. All children were under natural sleep, sedation, or sevoflurane anesthesia. They estimated the A-P/transverse dimensions from immediately below the vocal cords and at the level of the cricoid ring; the lumen of the larynx was ellipsoid immediately below the vocal cords (A-P 9.2 mm vs transverse 7.5 mm) changing to a circular shape at the level of the cricoid outlet (A-P 8.5 mm vs transverse 8.3 mm, a circle). Thus, the A-P dimension at the subglottic level was greater than that of the cricoid but the transverse diameter of the cricoid was larger than at the subglottic level; the cross-sectional areas at the 2 levels were not different. They concluded: *"The cone shaped airway characteristic, which has been historically proposed, was not observed. Given that the subglottic transverse diameter is the smallest area dimension, one must assume this is the most likely area of resistance for the passage of an endotracheal tube rather than only the cricoid."* These authors published a similar study examining the ratio of the cricoid cartilage to the left mainstem bronchus from 102 CT scans

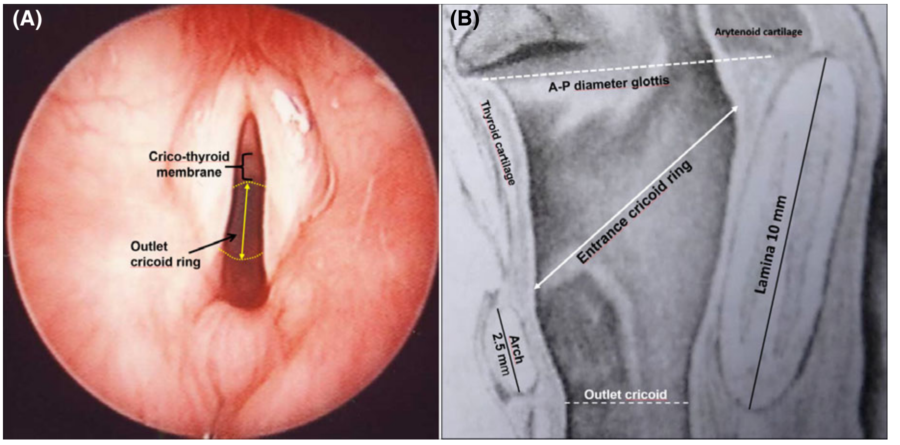

FIGURE 2 A, Endoscopic picture (2.2 mm Hopkins lens, JH) of the glottis of a 1-year-old child, spontaneously breathing under inhalation anesthesia. Note that the vocal cords are in an almost parallel (adducted) position. The anterior subglottic narrowing is caused by the posteriorly slanting thyroid cartilage and the cricothyroid membrane, narrowing the subglottic space anteriorly. B, Drawing showing the lateral view of an A-P section through a neonatal larynx (autopsy specimen by Peter).[11] The backward tilted lamina results in a cricoid lumen which has a large, slanting entrance and an approximately 46% smaller circular outlet. The height ratio between arch and lamina is 1:4 (see also Figure 4C)

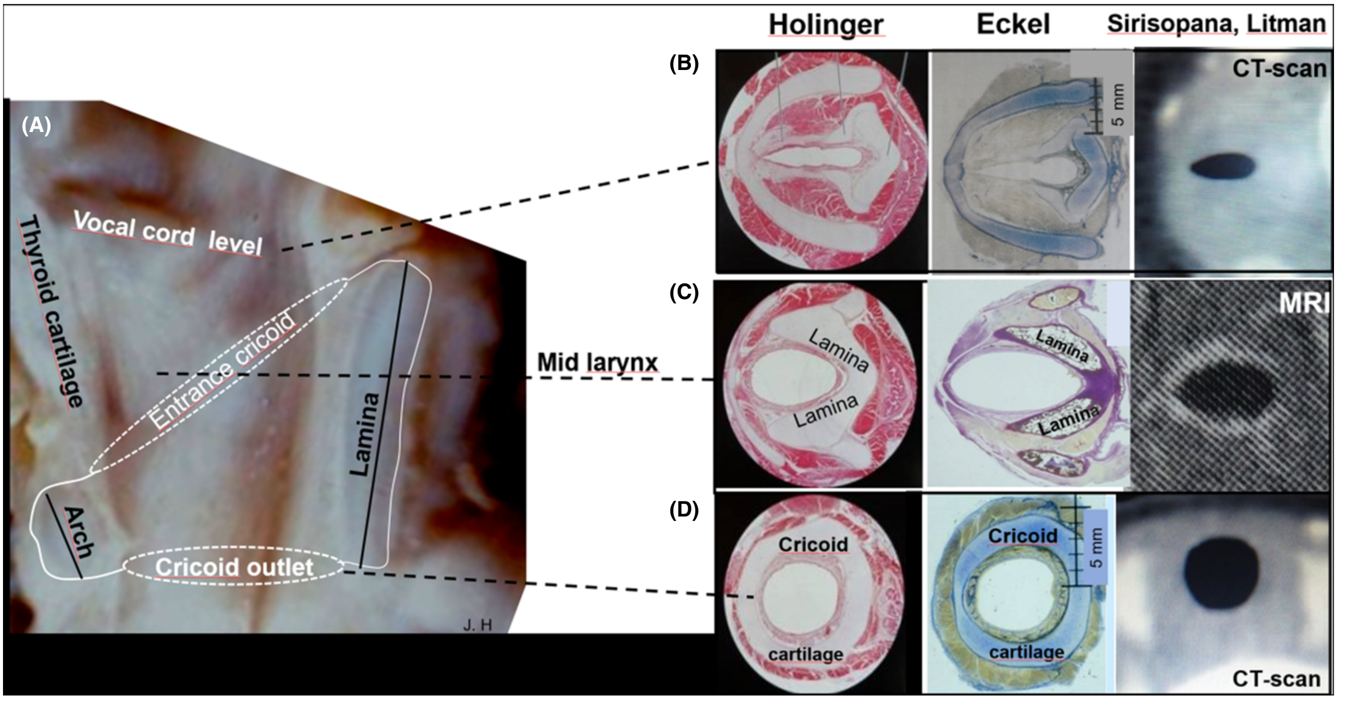

FIGURE 3 Influence of the level of cross-sections on the configuration of the laryngeal lumen, regardless of the method of investigation. A, A-P section of the larynx of an 8-month-old infant specimen (JH). B, Cross-sections at the vocal cord level from autopsy specimens (Holinger et al, 8-month-old infant, and Eckel et al, 3-month-old infant, with permission by Wolters Kluwer and Springer).[15,20] "Tear-drop"-like entrance to the glottic opening (CT-scan by Sirisopana et al,[9] child <3 y, with permission of Wolters Kluwer) showing a clear tissue-air interface but no cartilaginous structures. C, Cross-sections at mid-level of the larynx show an oval shape. The posterior V-shape of the lamina is visible in these anatomical cross-sections (Holinger,[15] Eckel, courtesy of the author).[20] The hyperdense lining of the lumen in the MRI (not depicting cartilages!) represents the intensely perfused laryngeal mucosa (Litman et al[2] with permission by Wolters Kluwer). D, Cross-sections through the outlet of larynx showing a circular configuration (Holinger et al[15] Eckel, courtesy of the author.[20] CT-scan (Sirisopana et al[9] with permission by Wolters Kluwer)

from children 1 month to 10 years of age.[21] This report did not assess subglottic dimensions but confirmed the near circular cricoid with the A-P diameter slightly greater than the transverse (A-P/transverse diameter 1.02/1) similar to their previous study.[6] Another study[7] reported observations of 40 laryngeal CT scans of infants (0-12 months) during similar conditions as the studies above (11 had

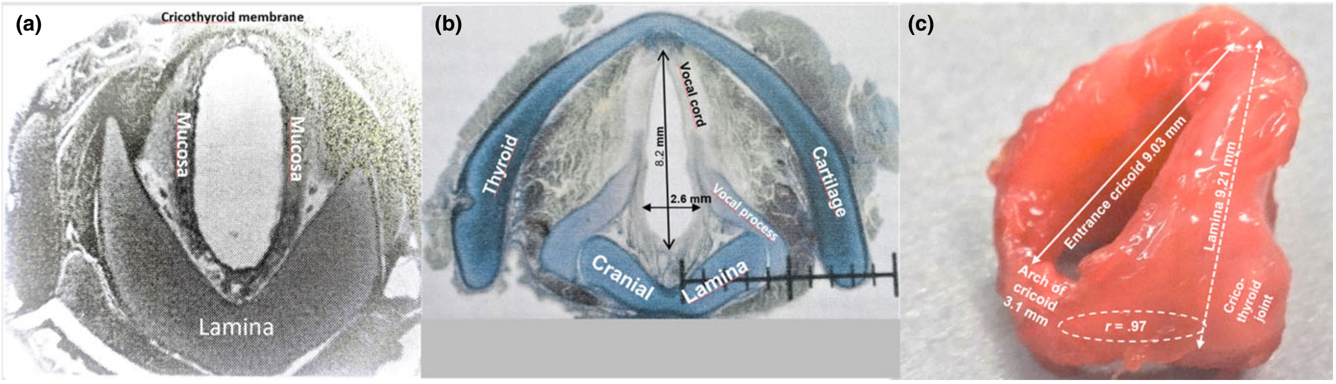

FIGURE 4 Influence of the level of cross-section on the configuration of the laryngeal lumen, regardless of the method of investigation. A, Cross-section above the arch of the cricoid ring of an infant larynx at the level of the anterior ligamentous cricothyroid membrane (Tucker et al[17] with permission from Rights Link). The V-shaped lamina of the cricoid, bounding the oval lumen of the mid-larynx by two-thirds from posterior, demonstrates an "elliptical" mucosal lumen at this level, obscuring the underlying surface" of the cricoid. B, Cross-section at the level of the vocal cords (2-month-old infant, plastination technique, Eckel et al[20] with permission of Springer). The cranial part of lamina and vocal processes of the arytenoid cartilages are clearly visible, demonstrating the tight connection between the vocal cords, the vocal process, and the superior lamina. C, Photo of a freshly trimmed cricoid ring of a neonate (autopsy specimen, courtesy MA Rothschild, Institution of Legal Medicine, University Cologne, Germany, from unpublished data). The high lamina, the short arch, the oblique entrance of the cricoid ring, and of the plane level of the circular cricoid outlet (see Figures 2B and 3A) demonstrate the difficulty of precisely defining the anatomy of the pediatric cricoid ring by cross-sections only

been previously reported to have a circular outlet[5]). They found that the cricoid had a larger A-P than transverse diameter (6.7 vs 6.1 mm) but at the subglottic level, they again found that the transverse diameter was less than the cricoid and the A-P diameter was greater (7.2 A-P vs 5.3 mm transverse). They concluded that the airway in neonates and infants between the subglottic area and the cricoid remains ellipsoid, "*that the airway is wider anteroposteriorly and narrows in the transverse dimension from the subglottis to the cricoid in infants.*" However, the mean cross-sectional area at the 2 levels was similar (29.9 vs 32.1 mm^3). It is possible that this ellipsoid shape is secondary to the slices not being exactly perpendicular to the axis of the cricoid. They also acknowledged that they did not standardize the phase of respirations which might also have impacted their measurements by the variable position of the vocal cords. A fourth study reported 3D CT scan reconstructions of the upper airway at 3 mm intervals from 54 children 2 months to 8 years[8] but only 4 were infants. The airway volumes in subglottic and cricoid levels were 0.17 ± 0.06 vs 0.19 ± 0.07 mm^3, respectively. The authors commented that the narrowest portion of the airway was subglottic but *"we cannot comment whether this region or others such as the cricoid represent the most rigid aspect of the airway."*

4 | DISCUSSION

Our literature review revealed 2 views of the infant larynx: the traditional "funnelists" and the "nonfunnelists". The in vivo studies[2,3,6-8] all suggest that the narrowest portion of the pediatric larynx in spontaneously breathing sleeping or anesthetized infants and children is at the laryngeal inlet (nonfunnelists), whereas the in vitro studies describe the narrowest portion of the pediatric larynx as the nondistensible cricoid cartilage (funnelists).[10-14,16-18] How can we reconcile these apparent contradictory observations? Is the larynx funnel-shaped or cylindrical? Is the narrowest portion at the level of the glottis or the cricoid ring? We believe that these divergent views reflect the methods of evaluation used (in vivo vs in vitro). Autopsy data confirm the nondistensible cricoid ring[10-15,20] as the narrowest portion, however, the laryngeal lumen varies in form and size at different levels (predominantly cylindrical in transverse but conical in A-P dimensions). As the pediatric larynx consists of pliable (supraglottis, glottis, and proximal subglottis) and rigid parts (the cricoid ring) (Figures 3, 4C), describing laryngeal anatomy depends upon the methodology used for assessment. Studies which employ horizontal cross-sections to identify the level of the cricoid outlet by CT scans or MRI are less precise than autopsy specimens for several reasons: a slice thickness of 2.5-3.0 mm, the angulation of the cricoid, and inability to precisely show the cartilaginous structures.[10-12,15,16] More importantly, these measurements may vary greatly in vivo compared with in vitro because the laryngeal tissue folds (vocal, vestibular, and aryepiglottic folds) are dynamic, pliable structures[13] that change position and shape with the phase of respirations (change in transverse but minimal in the A-P dimension).[7,8,22] With inspiration, the laryngeal muscles contract, stretching open the aryepiglottic, vestibular (false cords), and vocal folds, so that the distance between these structures increases (Figure 5A). With expiration or neuromuscular blockade (Figure 5B), these soft tissue folds return to a neutral position by the stability of the cuneiform and corniculate cartilages.[23] With voluntary glottic closure (lifting heavy weights), or involuntary glottic closure (laryngospasm), contraction of the intrinsic laryngeal muscles closes the larynx at 3 levels (aryepiglottic, vestibular, and vocal folds). Thus, the various tissue folds of the larynx are in constant motion and the distance between them depends upon the phase of respiration during which the examination was made (or death).[23] Although the paralyzed vocal cords are always in a near cadaveric position (Figure 5B), they never impede the advancement of tracheal tubes. A further consideration is what happens to these structures during sleep or anesthesia compared to the awake state. It is well known that there is collapse of pharyngeal tissues during natural sleep and during anesthesia. Such narrowing of the upper airway facilitates apposition of the laryngeal tissue folds further narrowing the upper airway above the cricoid cartilage, particularly if there is accompanying tonsillar or arytenoid hypertrophy.[24,25] The effects of sleep, anesthetic medications, or arytenoid/tonsillar hypertrophy were not considered in the in vivo studies.

The maximum interarytenoid diameter (IAD) can be measured in vivo, but in vitro measurements may be more accurate with measuring rods or calipers[13] as these tissue folds are easily distended. After neuromuscular blockade, the vocal cords relax and assume a parallel position (Figure 5B). Transverse interarytenoid diameters (IAD) vary from zero (laryngospasm) to a maximum diameter when fully abducted.[13] In autopsy specimens, the vocal cords adopt a cadaveric position; in vivo they are adducted to different degrees depending upon the phase of respiration but rarely maximally abducted as seen in Figure 5A.

Litman et al,[2] Dalal et al,[3] and Wani et al[6-8] presented age related but seemingly constant A-P diameters of glottis and proximal subglottis. Litman specifically stated that *"active contraction of the laryngeal muscles influenced the dimension of the larynx"*. Wani et al commented that they did not control for the phase of respirations; the patients in the Dalal et al study were paralyzed. These investigators reported upper transverse laryngeal diameters narrower than those from autopsy specimens. We assume that this is because their methodologies did not consider the conditions at the time of evaluation, ie, the pliability of the tissues in vivo and respiratory related motion of glottis and proximal subglottic structures. In contradistinction, autopsy studies measured A-P diameters of the glottis and cricoid outlet in hundreds of specimens with calipers or rods providing the most accurate means for determining the narrowest level of the larynx (similar to tracheal tubes)[10,13,14]; the maximum IADs were always larger than the rigid cricoid outlet (Figure 6A,B). When studying the laryngeal anatomy from the viewpoint of intubation, the only meaningful way to compare the lumen at various levels of the larynx, is by gently introducing measuring rods (or tracheal tubes)[10,12,13] which maximally distend the soft tissues of the laryngeal folds without injury.

Wani et al[6-8] have presented several studies with possible overlapping patient populations. Given that several hundred CT scans were retrospectively reviewed and only 40 selected for one study (11 previously reported) and 56 for another, it is possible that observer bias could have influenced their conclusions regarding the shape of the cricoid and the subglottic region. It is also unclear if the CT cuts were obtained at sufficiently thin intervals to allow accurate assessment the cricoid outlet. Wani et al[8] did not cite the 300 investigations by Fayoux et al who documented the opposite of their assertions (Fig. S1). Furthermore, in their most recent study of 3D CT-imaging, they found a mean airway volume difference between the subglottic area and the cricoid outlet of only 0.02 mm^3 which is of uncertain clinical relevance. Furthermore, two of their other studies found no difference in cross-sectional areas of these same 2 levels.[6,7] These differences in the transverse measures between the subglottis and the cricoid are likely clinically unimportant in contrast to the A-P dimensions (Figure 6B). It is unclear to us why the resistance to tracheal tube passage would differ with similar cross-sectional areas. Wani et al's[8] observations of the cricoid cartilage are similar to Peter's; there appear to be minute differences of cricoid dimensions from study to study that overall indicate that the cricoid outlet is nearly circular.

5 | CONCLUSION

We reviewed 9 autopsy studies published over the last century that documented the narrowest portion of the infant larynx as the nondistensible cricoid cartilage, supporting the concept that the infant larynx is in fact funnel-shaped.[10-16,18,20] Six in vitro studies described the cricoid cartilage as circular or nearly circular[10-15]; two

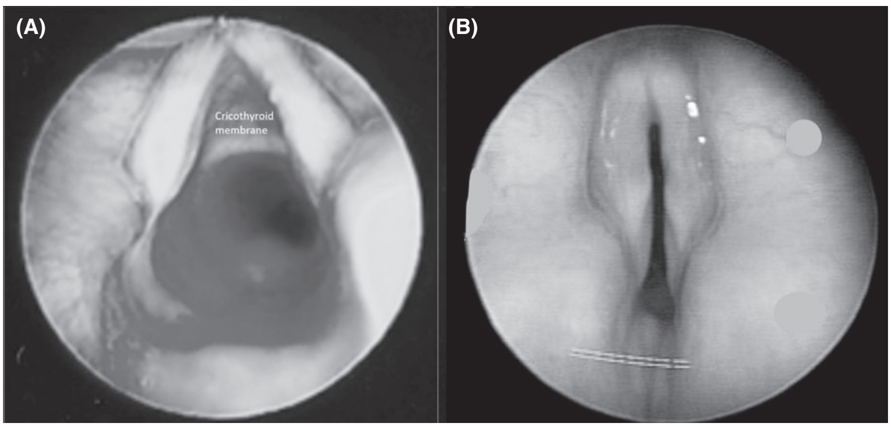

FIGURE 5 A, Fully abducted vocal cords during inspiration under inhalation anesthesia for functional checkup. Note the pronounced cricothyroid membrane and the tapering down to the narrower outlet of the cricoid ring (JH). B, Adducted vocal cords after neuromuscular blockade (JH), ie, return to neutral position from the stabilizing effect of cuneiform and corniculate cartilages

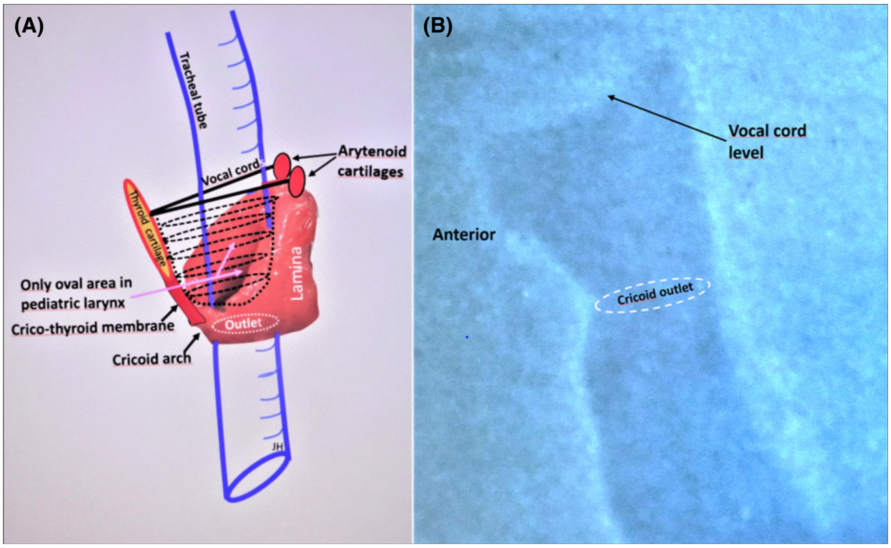

FIGURE 6 A, Reconstruction of an infant larynx based on fresh autopsy specimen (see Figure 4C) and investigations by Bayeux, Peter, and Eckel. An oval-shaped lumen of the cricoid can be described only above the cricoid arch (=oblique, oval entrance to the cricoid ring) which tapers down to the narrower, circular outlet, being narrower than the glottic and cricoid inlet. Thus, a tracheal tube which is passed through the cricoid is always located posteriorly within the pediatric larynx because of the funnel shape (always a smaller outlet at the cricoid compared with the more proximal, larger, and distensible structures) which forces the tracheal tube posteriorly and limits the amount of leak behind the tube (see Fig. S2). B, Lateral neck xerogram of a 2-day-old term infant (CJC). The image demonstrates clearly the more posteriorly located position of the cricoid outlet and the overall funnel shape

in vitro studies reported an ellipsoid cricoid outlet.[16,18] Thus, there is some disagreement about the actual shape of the cricoid ring. Two studies described the cricoid ring as V-shaped in the posterior part and a near circular cricoid outlet without comparing it with the glottic level[15,17] but providing important information about the cricoid structure. Two in vivo studies described the cricoid as ellipsoid in shape[3,21] but 4 in vivo studies reported it as circular or nearly circular[2,8,9,21]; most in vivo studies describe the cricoid as either circular or near circular which permits safe intubation with round tracheal tubes which contrary to one review, permit a minimal leak during mechanical ventilation (Fig. S2).[4] Five in vivo studies reported that the narrowest portion of the larynx was proximal to the cricoid cartilage[2,3,6-8] but there was no difference in cross-sectional area or volume when the 2 levels were compared.[6-8]

It is clear that the nonfunnelists believe that the cricoid outlet is larger than the subglottic region; however, they did not fully consider in vivo laryngeal dynamics or the known effects of sedatives and sleep upon upper airway tone and secondary mild obstruction. As there is enormous pliability of the laryngeal tissue folds, the resistance to passing a tracheal tube through the vocal cords and structures above the cricoid arch is very low. Thus, these structures can be actively opened (Figure 5A), whereas the cricoid ring is rigid and nondistensible. The real issue is not what appears to narrow the larynx by continuous motion of soft tissues above the cricoid but rather the actual narrowest nondistensible portion of the larynx where intubation injuries are most likely if too large tracheal tubes are placed. Overall, all studies that we reviewed are in agreement despite differing conditions at the time of evaluation (natural sleep, anesthesia, and autopsy).

We therefore submit that the original conclusions of Bayeux in 1897 supporting the "funnelist viewpoint" remain valid today[10]:

"If the intubating hand feels a small resistance against the passing of a tube, it is not caused by the vocal cords but the cricoid ring. If one wanted to grant the active vocal cords within a surrounding of pliable muscles a greater importance for tube selections than the non-dilatable cricoid ring, it would mean to support a theory that the resistance of the perineum is larger (for the passing newborn head) *than that of the entrance of the pelvis)".*[10]

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ETHICAL APPROVAL

The photos of the endoscopic pictures and the autopsy specimen were anonymously archived according to the ethical standards of the respective institutions.

CONFLICT OF INTEREST

The authors report no conflict of interest.

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REFERENCES

1. Eckenhoff JE. Some anatomic considerations of the infant larynx influencing endotracheal anesthesia. *Anesthesiology*. 1951;12:401-410.
2. Litman RS, Weissend EE, Shibata D, Westesson PL. Developmental changes of laryngeal dimensions in unparalyzed, sedated children. *Anesthesiology*. 2003;98:41-45.
3. Dalal PG, Murray D, Messner AH, Feng A, McAllister J, Molter D. Pediatric laryngeal dimensions: an age-based analysis. *Anesth Analg*. 2009;108:1475-1479.
4. Tobias JD. Pediatric airway anatomy may not be what we thought: implications for clinical practice and the use of cuffed endotracheal tubes. *Pediatr Anesth*. 2015;25:9-19.
5. Motoyama EK. The shape of the pediatric larynx: cylindrical or funnel shaped? *Anesth Analg*. 2009;108:1379-1381.
6. Wani TM, Bissonnette B, Rafiq Malik M, et al. Age-based analysis of pediatric upper airway dimensions using computed tomography imaging. *Pediatr Pulmonol*. 2016;51:267-271.
7. Wani TM, Rafiq M, Akhter N, AlGhamdi FS, Tobias JD. Upper airway in infants-a computed tomography-based analysis. *Pediatr Anesth*. 2017;27:501-505.
8. Wani TM, Rafiq M, Talpur S, Soualmi L, Tobias JD. Pediatric upper airway dimensions using three-dimensional computed tomography imaging. *Pediatr Anesth*. 2017;27:604-608.
9. Sirisopana M, Saint-Martin C, Wang NN, Manoukian J, Nguyen LH, Brown KA. Novel measurements of the length of the subglottic airway in infants and young children. *Anesth Analg*. 2013;117:462-470.
10. Bayeux R. Tubage du larynx dans le croup. *Presse Mèdicale*. 1897;6:29-33.
11. Peter K. *Handbuch der Anatomie des Kindes [Handbook of the Anatomy of the Child]*, Peter KW, Heidreich F, eds. pp. 525-590. Berlin, Germany: Springer; 1936.
12. Butz Jr RO. Length and cross-section growth patterns in the human trachea. *Pediatrics*. 1968;42:336-341.
13. Fayoux P, Devisme L, Merrot O, Marciniak B. Determination of endotracheal tube size in a perinatal population: an anatomical and experimental study. *Anesthesiology*. 2006;104:954-960.
14. Fayoux P, Marciniak B, Devisme L, Storme L. Prenatal and early postnatal morphogenesis and growth of human laryngotracheal structures. *J Anat*. 2008;213:86-92.
15. Holinger LDG, Green CG. Anatomy. In: Holinger LDL, Lusk RP, Green CG, eds. *Pediatric Larnygology and Bronchoesophagology*. Philadelphia, PA: Lippincott-Raven; 1997:16-33.
16. Too-Chung MA, Green JR. The rate of growth of the cricoid cartilage. *J Laryngol Otol*. 1974;88:65-70.
17. Tucker GF, Tucker JA, Vidic B. Anatomy and development of the cricoid: serial-section whole organ study of perinatal larynges. *Ann Otol Rhinol Laryngol*. 1977;86:766-769.
18. Sellars I, Keen EN. Laryngeal growth in infancy. *J Laryngol Otol*. 1990;104:622-625.
19. Benjamin B. Prolonged intubation injuries of the larynx: endoscopic diagnosis, classification, and treatment. *Ann Otol Rhinol Laryngol Suppl*. 1993;160:1-15.
20. Eckel HE, Koebke J, Sittel C, Sprinzl GM, Pototschnig C, Stennert E. Morphology of the human larynx during the first five years of life studied on whole organ serial sections. *Ann Otol Rhinol Laryngol*. 1999;108:232-238.
21. Wani TM, Rafiq M, Terkawi R, Moore-Clingenpeel M, AlSohaibani M, Tobias JD. Cricoid and left bronchial diameter in the pediatric population. *Pediatr Anesth*. 2016;26:608-612.
22. England SJ, Bartlett Jr D, Daubenspeck JA. Influence of human vocal cord movements on airflow and resistance during eupnea. *J Appl Physiol Respir Environ Exerc Physiol*. 1982;52:773-779.
23. Fink BR, Demarest RJ. *Laryngeal Biomechanics*. Cambridge, MA: Harvard University Press; 1978:1-14.
24. Litman RS, Kottra JA, Berkowitz RJ, Ward DS. Upper airway obstruction during midazolam/nitrous oxide sedation in children with enlarged tonsils. *Pediatr Dent*. 1998;20:318-320.
25. Donnelly LF, Casper KA, Chen B. Correlation on cine MR imaging of size of adenoid and palatine tonsils with degree of upper airway motion in asymptomatic sedated children. *Am J Roentgenol*. 2002;179:503-508.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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