

## REVIEW ARTICLE

# Pediatric airway anatomy may not be what we thought: implications for clinical practice and the use of cuffed endotracheal tubes

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### Summary

One of the long held tenets of pediatric anesthesia has been the notion that the pediatric airway is conical shape with the narrowest area being the cricoid region. However, recent studies using radiologic imaging techniques (magnetic resonance imaging and computed tomography) or direct bronchoscopic observation have questioned this suggesting that the narrowest segment may be at or just below the glottic opening. More importantly, it has been clearly demonstrated that the airway is elliptical in shape rather than circular with the anterior–posterior dimension being greater than the transverse dimension. These findings coupled with the development of a new generation of cuffed endotracheal tubes (ETTs) with a thin, polyurethane cuff have caused a transition in the practice of pediatric anesthesiology with an increased use of cuffed ETTs, even in neonates and infants. The following article reviews the historical data leading to the assumption that the pediatric airway is conical as well as the more recent imaging and direct bronchoscopic observational studies which refute this tenet. The transition to the use of cuffed ETTs is discussed and potential advantages presented in both the operating room and the intensive care unit. Issues regarding the monitoring of intracuff pressure and techniques to limit potential morbidity related to a high intracuff pressure are outlined.

### Introduction

Airway management in infants and children remains an integral component of various facets of care in the operating room and the intensive care. Regardless of the scenario, effective airway management is mandatory to ensure successful outcomes in our patients. In the middle of the 20th century, the technique of endotracheal intubation became more common in the practice of pediatric anesthesia. Unfortunately along with the technique of endotracheal intubation came morbidity and mortality related to its practice. Several of the tenets of the pediatric airway were proposed in a sentinel and often quoted report in 1951 by Dr. Eckenoff (1). In this manuscript, five key differences were identified between the adult and the pediatric airway which laid the

groundwork for our understanding of the anatomy of the pediatric airway. These differences involved:

1. The position of the larynx
2. The shape of the epiglottis
3. The vocal cords
4. The mucous membranes
5. The cricoid ring

The primary differences that impacted airway management included the position of the larynx, the epiglottis, and the cricoid ring. It was noted that the larynx is more cephalad than in an adult. With advancing age, the larynx moves caudad from the C3-4 position in a neonate to its adult level so that the rima glottidis is at the C4-5 level. It was also emphasized that the epiglottis is markedly different in an infant being longer, stiffer

and more 'U' or 'V' shaped. Furthermore, the angle of the epiglottis with the anterior pharyngeal wall was noted to be different (45° in an infant vs lying closer to the base of the tongue in an adult). It was also suggested that although the narrowest part of the airway is the rima glottidis in adults, this may not be the case in neonates and infants. Referring to studies using moulages (plaster casts) in cadavers, it was suggested that the cricoid ring might represent the narrowest part of the airway and that the pediatric airway was funnel (conical) shaped. As the child grows, the cricoid plate becomes more vertical and the conical shape disappears.

In addition to the descriptive findings delineating the differences between the adult and pediatric airway, the potential for morbidity and mortality related to inappropriate airway management was illustrated by a case reported in the manuscript in which a 2-year-old toddler had progressive respiratory compromise following cleft palate repair. Intraoperatively, although the endotracheal tube (ETT) could be advanced through the vocal cords, it kinked when advanced farther into the airway. Airway management intraoperatively was continued with the ETT at a position which was thought to be just above the cricoid ring or at least above the area of resistance. Postoperatively, the patient developed a croupy cough which progressed to necessitating tracheostomy. The child eventually died and autopsy revealed edema and ulceration 0.5 cm below the vocal cords and a narrowing of the larynx. Based on this, it was recommended that 'a tube that cannot be advanced through the cricoid ring should not be left *in situ* but should be replaced with a smaller tube or the anesthesia completed without an endotracheal tube'.

These statements regarding the airway including its 'conical shape' with the narrowest portion being at the cricoid ring were frequently referenced and repeated throughout the anesthesia and critical care literature in manuscripts, textbooks, and lectures. These beliefs led to the widespread practice of using uncuffed endotracheal tubes (ETTs) in infants and children <8 years of age (2). As noted in a recent editorial, although these statements and facts are frequently attributed to Dr. Eckenhoff's manuscript published in *Anesthesiology* in 1951, the description of the pediatric larynx was not based on his own data, but rather taken from work that was done 50 years earlier by Bayeux (see below) (3,4). Furthermore, in the manuscript from 1951, Dr. Eckenhoff clearly cautioned that as the studies were performed in cadavers, the measurements may not be the same in living specimens (see below).

More recent studies using direct observation of the larynx during bronchoscopic or radiological imaging (magnetic resonance imaging or computed tomography)

have provided evidence-based medicine to question this contention. This manuscript will review the historical study of Bayeux on which the hypothesis of the conical shaped larynx is based, present more recent studies using bronchoscopic observation or radiological imaging of the pediatric airway, and discuss the implications for these findings on airway management in infants and children as they relate to the use of cuffed ETT's.

### Historical studies of the airway

As noted above, the classic teaching regarding the pediatric airway, which is still prevalent in many textbooks, clearly states that the narrowest portion of the adult airway is the rima glottidis while it is the cricoid ring in neonates, infants, and children up to 6–8 years of age. In 1897, Bayeux used moulages or plaster castings and anatomical sections of cadaveric larynxes from 15 children, ranging in age from 4 months to 14 years (4). When the plaster casts were removed, the circumference of the airway was measured at the glottis, the cricoid level, and the trachea. In all 15 patients, the internal circumference of the cricoid ring was noted to be narrower than other parts of the airway including the glottis and the upper trachea. No specific comment was made on the geometric shape of the airway (spherical vs circular). Based on these findings, it was postulated that the larynx of the adult resembles a cylinder as it has equal dimensions at the vocal cords (rima glottidis) and at the cricoid ring. However, in children <8 years of age, it was suggested that the larynx was conical with the narrowest portion at the cricoid ring. While the plaster casting was a historically accepted technique, with the loss of tone and natural shape of a cadaveric airway, the distending pressure of the plaster in the distensible part of the airway may have altered the dimensions when compared to nondistensible regions including the cricoid. Even in the oldest patient in this study, a 14 year old, the same dimensions were noted with the circumference of the cricoid being the narrowest. An additional concern of the initial study was the limited number of patients especially in the context of the considerable age range. In his article, Dr. Eckenhoff cautioned that 'the measurements so derived may not be completely applicable to the living.' Despite these concerns, these findings led to the tenet of the conical shaped pediatric airway which persisted for almost a century in the pediatric airway literature (5).

### Contemporary airway studies

More recent airway imaging using newer modalities including bronchoscopic examination or radiologic

imaging (CT or MRI) have questioned the time-honored tenet of the conical shaped airway. More importantly, they have questioned the geometry of the area suggesting it is more spherical rather than circular. Litman *et al.* (5) evaluated airway dimensions using MR imaging in a cohort of 99 children, ranging in age from 2 months to 13 years, who were deeply sedated and breathing spontaneously. No attempt was made to compensate for the phase of the respiratory cycle (inspiration vs expiration). The authors reported that the relationship of the transverse and anterior–posterior (AP) diameters at the vocal cord level, sub-vocal cord level, and the cricoid level did not change during development. All of the dimensions increased linearly with age and maintained an elliptical rather than a circular shape with the AP diameter being greater than the transverse diameter. The transverse diameters increased linearly in a caudad direction while no change was noted in the AP dimensions. Unlike the historical studies, the narrowest portion of the airway was the transverse diameter at the level of the vocal cords. Despite their findings, the authors cautioned that the more cephalad structures of the airway at the level of the vocal cords may have more displaceable and yielding structures when touched by an ETT. The extent of the pressure and its impact on the upper vs lower portions of the airway may also be impacted by the presence or absence of neuromuscular blockade. As such, the authors cautioned that the cricoid ring may still be the area of concern as it is rigid and unyielding making its mucosa and deeper structures prone to damage from excessive pressure exerted by an ETT. They supported these concerns with references to several pathologic reports demonstrating that the most extensive area of damage following prolonged endotracheal intubation is generally along the entire length of the glottis region including the vocal cords (6–11).

Similar airway findings were noted by Dalal *et al.* (12) using direct bronchoscopic measurements of the pediatric airway. The cohort for their study included 135 infants and children (seven were eventually excluded due to poor image quality), ranging in age from 6 months to 13 years. The airways were measured using a technique known as video-bronchoscopic imaging (13,14). The technique is described in ref. (13) and involves calculation of airway dimensions using a suction catheter with a known diameter that is passed through the bronchoscope and protruding 1–2 cm past its tip (13). Prior to the *in vivo* aspect of the study to obtain airway dimensions, the validity of the technique was demonstrated by measurement of various cylindrical objects. Diameters of these objects were measured using video-bronchoscopy as well as manually by two independent blinded

observers. Unlike the study of Litman *et al.*, the patients in this study were anesthetized, paralyzed, and apneic. Despite these differences, the data are generally in agreement with the findings of Litman *et al.* The authors noted that the larynx of children is more cylindrical, as in adults, than funnel shaped. They noted no change in ratios of the airway diameters with age. The cross-sectional area (CSA) at the cricoid was larger than the glottic-CSA ( $48.9 \pm 15.5 \text{ mm}^2$  vs  $30 \pm 16.5 \text{ mm}^2$ , respectively).

Similar findings were noted by a more recent study using CT imaging to obtain airway measurements in a cohort of 130 spontaneously breathing patients, ranging in age from 1 to 114 months (15). The narrowest airway dimension was the transverse diameter at the subglottic region (Table 1). A linear increase in the size of airway dimensions between both levels was observed with age ( $r > 0.7$ ). The authors concluded that their data demonstrated that the airway characteristics between the subglottic area and the cricoid ring changes from an elliptical to a more circular shape in children. Again, they noted that their findings were contrary to the tenet of the conical shaped airway. A narrower subglottic transverse dimension suggests that the limitation of endotracheal tube passage is likely not caused by the cricoid ring as previously reported.

All three of these studies reach the same conclusion using different imaging modalities including direct bronchoscopic measurement, computed tomography, and magnetic resonance imaging. Two included sedated and spontaneously breathing patients while one was performed during apnea and neuromuscular blockade. These studies question the validity of what we were generally taught during our training and what is repeated in many textbooks, the presence of a conical shape of the pediatric airway. More importantly, it demonstrates a previously infrequently discussed topic, the geometry of the cross-section of the airway, which is generally assumed to be circular. In fact, these studies clearly demonstrate it to be elliptical with a greater AP than transverse diameter. Both of the findings may have significant impact on our choice of airway management devices for endotracheal intubation.

### Implications for current airway management

Given the findings outlined above, one is compelled to question the reasons for use of an uncuffed ETT in infants and children <6–8 years of age. In fact, the elliptical shape leads one to question the time-honored assumption that hearing a ‘leak’ with an uncuffed ETT ensures that a correct size has been chosen. Given the

**Table 1** Anterior–posterior (AP) and transverse (T) diameters at the subglottic and cricoid\*

	Subglottic region			Cricoid region		
	Overall	Females	Males	Overall	Females	Males
AP (mm)	9.2 ± 1.8	9.3 ± 1.8	9.1 ± 1.9	8.5 ± 1.7	8.43 ± 1.6	8.55 ± 1.9
T (mm)	7.5 ± 1.6	7.4 ± 1.5	7.5 ± 1.6	8.3 ± 1.5	8.2 ± 1.5	8.42 ± 1.6

\*Data from ref. (15).

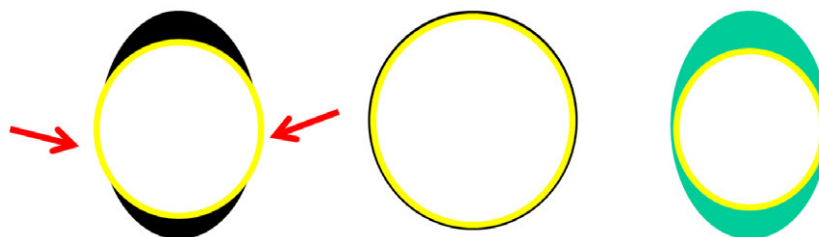
elliptical shape of the airway, it is feasible to have a leak and yet have significant pressure on the lateral walls with the use of an ETT that has a cross-sectional circular shape. The circular shaped ETT may not seal the airway, allowing for a leak even if there is significant lateral pressure on the mucosa of the trachea (Figure 1). These findings further support the safety and efficacy of considering the switch in practice to the use of cuffed ETTs in the pediatric population.

#### Advantages of a cuffed ETT

One of the early studies regarding the use of cuffed endotracheal tubes in children appeared in 1997 (16). In this prospective study, 488 children, who were 8 years of age or less, were randomized to general anesthesia using either a cuffed or an uncuffed ETT during surgical procedures that were estimated to be 60 min or less. Of note, the authors developed a new regimen for the sizing of the ETT. They used the time-honored formula of age/4 + 4 for an uncuffed tube, but adopted the formula of age/4 + 3 for sizing of a cuffed ETT. The latter was chosen to compensate for the increased outside diameter (OD) of an ETT imposed by the presence of a cuff. The authors noted that using these formulae, the correct sized ETT without a significant air leak was chosen in 99% of patients when using a cuffed ETT vs only 77% of those in whom an uncuffed ETT was used. Most

importantly, there was no difference in the incidence of stridor. As a follow-up to this study, Duracher *et al.* (17) evaluated the Khine formula for estimating the correct size of a cuffed ETT in a cohort of 204 children, ranging in age from 1 day to 15 years. The size of the cuffed ETT to be used was at the discretion of the attending anesthesiologist. The main criterion of judgment was the comparison of the leak before and after inflating the cuff at a pressure of 20 cmH<sub>2</sub>O. Overall, they noted that only 21% of the cuffed ETTs were in accordance with the size predicted by the Khine formula, the majority needing to be larger than that predicted. The authors concluded that Khine's formula underestimates optimal ETT size by 0.5 mm and recommended the use of the formula: age/4 + 3.5 in children more than 1 year of age.

Similar findings to the original study of Khine *et al.* demonstrating the efficacy of using cuffed ETTs were reported in a much larger and more rigorous study performed across 24 European centers in a total of 2246 pediatric patients (cuffed in 1119 and uncuffed in 1127) who were 5 years of age or less (18). The actual age was 1.93 ± 1.48 years in the cuffed group and 1.87 ± 1.45 years in the uncuffed group. Postextubation stridor was noted in 4.4% of patients with a cuffed ETT vs 4.7% with uncuffed ETTs ( $P = \text{NS}$ ). The need to exchange the ETT was 2.1% in the cuffed and 30.8% in the uncuffed groups ( $P < 0.0001$ ). The minimal



**Figure 1** Diagram showing that the presence of an endotracheal tube (ETT) with a cross-sectional circular shape in an elliptical-shaped airway (left) and a circular airway (center). When placed in an elliptical airway, there may be lateral pressure on the mucosa of the trachea with room for a leak during a continuous positive airway pressure (CPAP) test above and below the ETT in the anterior–posterior diame-

ter. When a cuffed ETT is placed into the airway, the pliable cuff can be slowly inflated to ensure sealing of the airway with equal pressure at all levels. When a cuff (green) is inflated in the elliptical airway, the airway can be sealed with equal pressure on all aspects of the tracheal wall (right).

intracuff pressure required to seal the trachea was  $10.6 \pm 4.3$  cmH<sub>2</sub>O.

Subsequently, several other advantages have been demonstrated when comparing cuffed with uncuffed ETTs in the pediatric population including better sealing of the airway resulting in more reliable ventilation and oxygenation; a more precise endtidal carbon dioxide tracing; and decreased consumption of inhalational anesthetic agents (16,19,20). The ability to provide effective ventilation may be particularly beneficial during procedures such as laparoscopy and thoracoscopy where alterations in compliance and ventilation may result in the need to alter peak inflating pressures. Effective sealing of the airway may also be beneficial in situations where prevention of oropharyngeal contamination with inhaled anesthetic gases may be desired. The latter is a concern not only related to exposure of healthcare providers to volatile anesthetic agents, but also contamination of the oropharynx with a high concentration of oxygen. A high concentration of oxygen in the oropharynx is particularly relevant during surgical procedures on the oropharynx such as adenotonsillectomy where there is a risk of airway fire (21–24). Regardless of the composition of the inhaled gas mixture, use of a cuffed endotracheal tube has been shown to eliminate any risk of contamination of the oropharynx during both positive pressure and spontaneous ventilation (25). In fact, the Practice Advisory for the Prevention and Management of Operating Room Fires from the American Society of Anesthesiologists states: 'For cases involving surgery inside the airway, consultants and ASA members both agree that a cuffed endotracheal tube should be used instead of an uncuffed endotracheal tube when medically appropriate' (26). Although in many instances, the inspired concentration of oxygen (FiO<sub>2</sub>) can be decreased to accomplish this purpose, patients with comorbid respiratory disorders may require a higher FiO<sub>2</sub> to maintain acceptable oxygen saturations. Additionally, it has been demonstrated that depending on the fresh gas flow rates, inspired oxygen concentration, and the minute ventilation, it may take several minutes to see the desired effect on the expired oxygen concentration after the FiO<sub>2</sub> is decreased (27,28).

Additional advantages were reported by Calder *et al.* (29) who demonstrated a decreased incidence of sore throat when comparing endotracheal intubation for surgical procedures using a cuffed vs an uncuffed endotracheal tube. In the prospective study of 500 patients, ranging in age from 3 to 16 years, 111 (22%) developed a sore throat. The incidence was higher with an uncuffed compared to a cuffed ETT (37% vs 19%,  $P < 0.005$ ). This study further supports the potential implications of an elliptical vs a circular area (see above), as excessive

pressure on the lateral walls may be present with an uncuffed ETT despite the presence of a leak at the anterior and posterior margins. Also noted was an increased incidence of sore throat as the intracuff pressure increased when a cuffed ETT was used. With an intracuff pressure of 11–20, 21–30, 31–40, and  $\geq 40$  cmH<sub>2</sub>O, the incidence of a sore throat was 4%, 20%, 68%, and 96%, respectively.

### Concerns with use of a cuffed ETT

Despite the initial enthusiasm with the use of cuffed ETTs, it was made readily apparent that not all cuffed ETTs are equal. Weiss *et al.* (30) evaluated 11 cuffed and four uncuffed ETTs from four different manufacturers which ranged in sizes ranging from 2.5 to 7 mm ID. They expressed concerns regarding the shape, design, and position of the cuff on the ETT. With several of the ETTs, the cuff may be within the glottis with mid-tracheal placement of the ETT. This effect results from the position of the cuff on the shaft of the ETT as well as the more elliptical shape of the cuff in older cuffed ETTs vs the spherical shape of the cuff in the newer versions (Figure 2). When the cuff was placed 1 cm below the glottis, they noted that the end of the endotracheal tube may be too low. In this and a subsequent study, the sealing characteristics of the cuffs were noted to be different (30,31). When inflated to an intracuff pressure of 20 cmH<sub>2</sub>O, the older versions of the cuffed ETTs would not cover the internal tracheal diameter. Furthermore, a later study by the same investigators demonstrated that the intracuff pressure required to seal the airway for positive pressure ventilation to a peak inflating pressure of 20 cmH<sub>2</sub>O was lower with the new generation cuffed ETTs (32). In a prospective trial, 80 children, ranging in age from 2 to 4 years, were sequentially intubated with a size 4.0 mm ID ETT from four different manufacturers (Microcuff P-HVLP, Mallinckrodt Hi-Contour P, Rüschelit Super Safety Clear, and Sheridan CF). The intracuff pressure (mean and range in cmH<sub>2</sub>O) to seal the airway to a PIP of 20 cmH<sub>2</sub>O was lowest with the Microcuff P-HVLP endotracheal tube (6–11, 11–26) when compared to the other three ETTs (Mallinckrodt 36, 18–48; Rüschelit 21, 8–46; and Sheridan 26, 18–60).

The greatest concern regarding use of a cuffed ETT remains the potential for damage to the tracheal mucosa from excessive inflation of the cuff. This relates not only to the instantaneous intracuff pressure, but also the duration of endotracheal intubation. In general, the intracuff pressure should be maintained at  $\leq 20$ –30 cmH<sub>2</sub>O. Various assumptions are made when arriving at the recommendation to limit intracuff pressures





**Figure 2** Distal end of older vs newer version of cuffed endotracheal tubes. The longer profile of the elliptical shape of the cuff (upper) results in the potential for the cuff to herniate through the glottic opening when the end of the endotracheal tube is in the mid-trachea location.

to this level. Although the capillary perfusion pressure of the tracheal mucosa in man is 22 mmHg, the pressure at the arterial end is approximately 30 mmHg. Obstruction of venous outflow results in an increase at the arterial end so that pressures in excess of 50 mmHg are needed to cause tracheal mucosal injury in an animal model (33). In an endoscopic study evaluating tracheal blood flow in man, it was noted that obstruction to mucosal blood flow occurred at a lateral pressure above 22 mmHg (30 cmH<sub>2</sub>O) (33). No difference in damage to the tracheal mucosa, assessed using scanning electron microscopy, was been reported in an animal model when comparing inflation of the cuff to seal the airway to a PIP of 20 cmH<sub>2</sub>O (median intracuff pressure of 14 cmH<sub>2</sub>O) vs inflation of the cuff to an intracuff pressure of 20 cmH<sub>2</sub>O (34). In a large retrospective study that included 2953 pediatric patients over a 4-year period, the incidence of stridor was <1% when a slight leak around the ETT was noted with the application of 25 cmH<sub>2</sub>O of pressure to the airway (35). These studies have led to the current recommendations to limit the intracuff pressure to <20–30 cmH<sub>2</sub>O. However, many other factors likely play into the risk of developing damage related to prolonged endotracheal intubation including comorbid conditions including those which affect cardiovascular function and perfusion pressure, genetic factors, and duration of endotracheal intubation.

However, with the introduction of a new practice (use of cuffed ETTs), it may be that strict adherence to regulation and monitoring of intracuff pressure may fall behind the introduction of the devices. In a prospective observational trial where intracuff pressure was measured following the widespread introduction of cuffed ETTs in a pediatric operating room, we noted significant variation in clinical practice resulting in excessively high intracuff pressures (36). The cohort for the study included 200 patients, ranging in age from 1 month to 17 years. Although the average intracuff pressure was

23 ± 22 cmH<sub>2</sub>O in the cohort, it was ≥30 cmH<sub>2</sub>O in 47 of the 200 patients (23.5%). Fortunately, no immediate perioperative morbidity was noted related to the high intracuff pressure, but the findings suggest the need to introduce techniques to ensure an acceptable intracuff pressure.

Unfortunately, the validity of one of our common techniques in pediatric anesthesia has been called into question. It has been taught to check a leak using a continuous positive airway pressure technique or leak test whereby the fresh gas flow was increased to 3–5 l·min<sup>-1</sup> with the pop-off valve closed and a stethoscope or more commonly the precordial stethoscope was placed in the suprasternal notch. The leak was determined as the pressure within the circuit at which an audible sound could be heard emerging from around the ETT. Alternatively, the pressure is held at a preset level (20 cmH<sub>2</sub>O) and the cuff slowly inflated to seal the airway. However, the validity of these tests has been questioned and significant interpractitioner variability reported (37,38). Feeling the compliance of pilot balloon has also been shown to be invalid (39).

Outside of the United States, devices which autoregulate the intracuff pressure may be used in various operating rooms (40). However, such devices are not currently available in all countries. One option is the routine availability of manometers in all locations where endotracheal intubation may occur (Figure 3). These initiatives may result in significant costs as these manometers cost approximately \$300 each. With numerous anesthetizing locations, it may not be feasible or cost effective to have a manometer at every site. With repeated use in a busy operating room, they may be damaged or lost. Infectious disease initiatives discourage the use of reusable equipment and the manometers must be appropriately cleaned between cases thereby further increasing the cost. In attempt to bridge these gaps, two recent syringe devices have been introduced into the market. These devices provide a relatively low-cost, portable, and disposable method of measuring the intracuff pressure. The first is a novel device built into a 10-ml syringe (AnapnoGuard Cuffill, Hospitech Repsiration; Kiryat Matalone, Petach-Tikva, Israel) so that it can be used to inflate the cuff (Figure 4). It provides a digital readout of the intracuff pressure, has an automatic shut-down, and is FDA and CE approved. Although it is disposable and ideal for single patient use, it can provide up to 100 readings. The device has been shown *in vivo* and *in vitro* to correlate well with pressures obtained from a standard manometer (41). It is significantly less expensive than a standard manometer (\$8–10 vs \$300). Similar accuracy has been shown for another syringe device to monitor intracuff pressure (Figure 5) (42). The

color-coded device known as the Tru-Cuff (AES Inc, Black Diamond, WA, USA) has three zones on the barrel of the syringe (green, clear, and red). According to the manufacturer's description of the device, the green zone correlates to an intracuff pressure of 20–30 cmH<sub>2</sub>O, the clear zone to 30–40 cmH<sub>2</sub>O, and the red zone to 40–60 cmH<sub>2</sub>O. Acquisition costs are approximately \$2 per device (\$97.50 for a box of 50 devices). Given their cost, both of these devices may fill the need both in the operating room as well as various other locations where endotracheal intubation occurs. They may also be beneficial for use by emergency medical personnel such as paramedics who provide airway management outside of the hospital setting.

Another issue to consider with the measurement of intracuff pressure is that it is likely not a static process.



**Figure 3** Commercially available hand-held manometer for inflation and measurement of intracuff pressure (Posey Cufflator Endotracheal Tube Inflator and Manometer™; JT Posey Company, Arcadia, CA, USA).



**Figure 4** Novel device for measuring intracuff pressure that is built into a 10-ml syringe (AnapnoGuard Cuffill, Hospitech Respiration; Kiryat Matalone). It provides a digital readout of the intracuff pressure.



**Figure 5** Color-coded device (Tru-Cuff; AES Inc) which has a color-coded pressure indicator built into a syringe that allows the provider to inflate the cuff of the endotracheal tube to an appropriate pressure levels.

Various patient-related factors may affect the intracuff pressure including body temperature, head position, depth of anesthesia, and the presence of neuromuscular blockade (43,44). These variations and those that may occur in the ICU setting suggest that techniques to continuously monitor the intracuff pressure may be beneficial.

Numerous methods and devices have been employed to measure, monitor, and regulate the intracuff pressure (45–50). In some of the devices, a detachable device is attached to the pilot balloon which not only monitors the intracuff pressure, but also acts as a 'pop-off' valve to regulate pressure at or below a preset value (51,52). Other attempts to improve the safety margin have included modifications of the design of the cuff, the ETT, and inflation of the cuff with agents other than air (53–56). More recently, it has been shown that a standard pressure transducer that is commonly used to monitor invasive arterial or central venous pressure (Transpac IV Monitoring Kit; ICU Medical Inc, San Clemente, CA, USA and Philips Medizin Systems, Boeblingen, Germany) can also be used to monitor the intracuff pressure (57,58). For this purpose, an air column is used as there is no need to fill the device with normal saline. The end of the device is then attached to the pilot balloon of the ETT (Figure 6). The device provides not only a simple digital readout on the screen with other monitors, but also allows a continuous mea-



**Figure 6** Set-up for the use of an invasive pressure manometer to measure the intracuff pressure.

sure of what may be a dynamic process. Despite all of these innovations, none of them have found widespread use in clinical practice for various practical and economic reasons.

### Studies from the intensive care unit

The implications of using cuffed ETTs may have even a greater impact in the ICU setting where the duration of endotracheal intubation is measured in days or weeks when compared to hours in the operating room setting. Despite these concerns, the advantages may particularly relevant with the ability to seal the airway and allow for effective ventilation when comorbid respiratory conditions may affect resistance and compliance. A cuffed ETT allows the airway to be effectively sealed when an air leak is present and obviates the need to perform a second laryngoscopy to change an ETT. This may be particularly relevant in the critically ill ICU or trauma patient where repeated laryngoscopy may fail or be associated with adverse hemodynamic effects. An additional issue in the ICU setting is the current practice of instituting early enteral nutrition based on a wealth of evidence-based medicine demonstrating the beneficial role that this practice has on both morbidity and mortality in patients with various comorbid conditions (59–63). In a prospective evaluation of the incidence of aspiration in a cohort of 50 children <4 years of age whose tracheas were intubated with an uncuffed endotracheal tube, aspiration was noted in eight (16%) of the patients (64). This was accompanied by changes on the chest radiograph in five and a significant decrease in  $\text{PaO}_2$  in three. When comparing patients whose tracheas were intubated with a cuffed vs an uncuffed ETT in a limited cohort of 22 pediatric patients, dye positive tra-

cheal aspirates were reported in 11% of those with a cuffed ETT vs 70% of those with an uncuffed ETT (65). More recently, it has also been demonstrated that the type of cuff may impact the incidence and severity of aspiration (66). A decreased incidence and volume of fluid aspirated has been demonstrated with a polyurethane cuff which is thinner and seals the trachea more effectively than a polyvinylchloride cuff which may fold and lead to a passage for aspiration.

### Conclusions

For many years, it had been proposed and generally accepted that the larynx in infants and children is 'funnel or conical shaped' with the narrowest point at the cricoid. It was also assumed that as a child matures, the transverse dimension of the larynx assumes the more cylindrical shape of the adult larynx. This description of the pediatric larynx was based on plaster casting of cadaveric tracheas which likely led to distortion of the true anatomy. At the time, the available cuffed ETTs were bulky with a cuff that added significantly to the OD of the ETT which necessitated using an ETT than was 1–2 sizes less than an uncuffed ETT thereby resulting in the potential for increased work of breathing. These ETTs also had markedly different cuffs than the endotracheal tubes of today with higher intracuff pressures and lower volumes. These factors led to the common practice of using uncuffed ETTs in patients <6–8 years of age.

More recent studies using imaging or direct bronchoscopic measurements have refuted these findings, demonstrating that the AP to transverse ratio of the airway does not change significantly with age, being the narrowest in the transverse diameter at the level of the vocal cords or immediately below. These studies also demonstrated the airway to be elliptical and not circular in shape. These changes in our understanding of the anatomy of the pediatric airway and the development of a new generation of ETTs with a polyurethane cuff have led to a change in the practice of pediatric anesthesiology with an increased use of cuffed ETTs in infants and children. This change in practice is starting to appear in review articles and textbooks. The current guidelines of Pediatric Advances Life Support by the American Heart Association recommend the use of cuffed ET tubes as an acceptable alternative to uncuffed ET tubes (67,68).

However, this practice should not be blindly accepted. It is mandatory to ensure that the appropriate type of cuffed ETT is used to avoid damage to the airway. The ETT should have clear depth markers along the tube with an appropriate high-volume, low-pressure cuff with a low profile to maintain an acceptable internal to external diameter. Many centers including ours have adopted



the Microcuff® ETT (Kimberly-Clark, Roswell, GA, USA), which differs from previous versions of cuffed ETTs by having an ultrathin (10 µm) cuff made of polyurethane. The cuff is located more distally on the endotracheal tube shaft, facilitated by the omission of the Murphy eye. This modification more reliably places the cuff below the nondistensible cricoid ring. Despite these modifications, monitoring of intracuff pressure should become part of our routine practice. There are several options for this practice which allow for either an instantaneous or continuous measure of the intracuff pressure. It is recommended that all operating rooms and ICUs develop standards to ensure at least the intermittent monitoring of intracuff pressure.

Despite all of these modifications and improvements, the recent literature shows us that we still have work to do. Sathyamoorthy *et al.* (69) describe three cases of postextubation airway swelling in young infants. The cases are noteworthy because the endotracheal tube used in all three infants was the newly developed cuffed endotracheal tube called the Microcuff® (Kimberly-Clark), which has been specifically designed for use in pediatric anesthesia. The accompanying editorial pointed out that two of the infants in the report weighed <3 kg and that the manufacturer of the Microcuff® tube recommends their smallest size (3.0 mm) ETT for full-term infants weighing more than 3 kg (70). The other infant was a 3 week old, 4 kg infant whose trachea was intubated with a 3.5 mm ETT. The manufacturer recommends the 3.5 mm Microcuff® ETT for infants from 8 months to

2 years of age. Based on this, the authors of the editorial concluded that: 'in the three described infants, the use of Microcuff® tube sizes greater than that recommended by the manufacturer was likely more responsible for the airway swelling than the tube and cuff design'.

The neonatal population especially those born pre-term remain the population in which more work is required. These infants may require repeated trips to the operating room or prolonged intubation for mechanical ventilation. In many centers, common clinical practice remains the use of uncuffed ETTs. This practice is recommended for those that are pre-term and weigh <3 kg as the appropriate sized cuffed ETT is currently not available. Outside of this population, the literature has demonstrated many potential advantages which support the recent change in practice with an increased use of cuffed ETTs in the pediatric population.

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### Conflict of interest

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