New Advances in Pediatric Ventilation: Revolutionizing the Management of Pediatric Intubation with Cuffed Tubes

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Kühn Tube with Stylet 1899–1911

Pediatric Microcuff Endotracheal Tube 2006

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Foreword

It is my pleasure to present you with this special publication regarding the new advances that have been made in pediatric ventilation.

Traditionally, it has been taught that only uncuffed endotracheal tubes (ETTs) should be used for intubation in children under 8 years of age. Recent advances to the design of ETTs have fostered a debate on the use of uncuffed versus cuffed ETTs. This educational supplement features a history of pediatric intubation, issues and “work arounds” to current practices, and clinical experiences using a new cuffed endotracheal tube.

Increased knowledge about the advances discussed in this supplement will hopefully help us to improve patient management in the future.

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Endotracheal Tube Use in Children: History as Pretext for Current Teaching

Lynne G. Maxwell, MD, FAAP

INTRODUCTION

Endotracheal intubation has a long, rich history (see fig. 1), having even been described in the Bible. However, early experimentation with endotracheal tubes really began with Vesalius’s and Hooke’s work with animals in the 16th and 17th centuries. Vesalius demonstrated his technique of sustaining life in dogs and pigs by rhythmically inflating the lungs. In 1667, Robert Hooke, the great experimentalist, further expanded this practice by performing a tracheostomy on a dog and preserving its life by breathing for it with the use of a bellows. These experiments illustrate that, by the 17th century, a mechanical means of ventilation had firmly been established, and by 1796, endotracheal tubes were beginning to be used for resuscitation purposes in humans.

TRACHEOSTOMY FOR ANESTHESIA

Metal Tubes

In 1869, German surgeon Friedrich Trendelenburg accomplished the first application of tracheostomy for administering anesthesia in humans. The tracheostomy tube had an inflatable cuff on it. The purpose of the cuff was to provide a seal between the tube and the tracheal wall to prevent passage of pharyngeal contents into the trachea, and to ensure that no gas leaks passed the cuff during positive pressure ventilation. Anesthesia was administered via the insertion of a funnel covered with flannel.

Endotracheal Tube for Anesthesia

The first endotracheal tube for anesthesia in the present-day sense was devised and used in 1878 by the surgeon, Sir William MacEwan. He recommended insertion of tracheal tubes by mouth instead of tracheostomy and in so doing performed the first oral intubation. His flexible metal endotracheal tubes developed to deliver anesthesia via orotracheal intubation were the first tubes used for the maintenance of spontaneous ventilation in adults.

Developments in Pediatric Intubation During the Late 19th and 20th Centuries

Having firmly laid the foundation for administering anesthesia to adults via endotracheal intubation, anesthesiologists then actively sought to find ways to resuscitate children in the operating room. To that end, in 1888, they turned to an American pediatrician, Dr. Joseph O’Dwyer. He, along with surgeon, Dr. George Fell, developed a pediatric-sized tube for artificial ventilation of anesthetized pediatric patients. The Fell-O’Dwyer apparatus, as it came to be known, was made with different size tips and was also available for adult patients. Although first developed to rescue children whose airways were obstructed because of diphtheria, it was soon adapted to rescue children with asphyxia due to anesthetic overdose in the operating room. Its purpose was not to provide long-term ventilation but rather facilitate acute resuscitation in children in the operating room (see fig. 2).

Fig. 1. Timeline showing major events in endotracheal intubation.
Dr. Eisenmenger’s endotracheal tube soon followed. His device, developed in 1893, consisted of a metal tube that had a cuff applied to it and had all the features of a modern cuffed endotracheal tube. It had a pilot balloon as well as an additional balloon to inflate the cuff to seal the lower airways against air leakage and aspiration of secretions (see fig. 3).

Early in the 20th century, Franz Kühn, a German surgeon, modified endotracheal tubes for easier intubation. His patient-oriented studies led to vast improvements in patient safety. Kühn’s device was a flexible metal tube used to keep the respiratory tract clear during narcosis and featured 3 important benefits. The first was an oral airway to prevent the patient from biting the tube, the second was a small attachment on the side of the tube that helped hold the tube to the patient’s face, and the third was a stylet to help the tube maintain its rigidity during placement. Kühn’s tubes were inserted via manual intubation (see fig. 4.)

**Rubber Tubes**

Rubber tubes were first developed in the 1940s and 1950s. The Cole tracheal tube, developed in 1945, was initially designed for emergency use in pediatric anesthesia (see fig. 5). The Cole tube was made of rubber and had no connectors on it. This form of endotracheal tube had a wide proximal portion with a sloping shoulder leading to a narrow distal tip to prevent the tube from being advanced too far in the trachea. Other uncuffed endotracheal tubes at the time were of uniform diameter along the entire axis. The tube was thought to be an improvement over the uniform diameter tubes, due to lower resistance to airflow in the wider lumen. However, there were several adverse outcomes that directly resulted from the tube’s shoulder, such as impingement on the vocal cords which could cause laryngeal dilation and postoperative

![Fig.2. The Fell-O’Dwyer apparatus for artificial ventilation of anesthetized patients. Adapted from Brandt L. *Illustrierte Geschichte der Anästhesie.* Wissenschaftliche Verlagsgesellschaft mbH. 1997.](image)

![Fig.3. The Eisenmenger tube with pilot balloons. Adapted from Gillespie NA. *Endotracheal Anaesthesia, Third Edition.* University of Wisconsin Press. 1963.](image)

![Fig.4. Kühn tube with stylet. Adapted from Brandt L. *Illustrierte Geschichte der Anästhesie.* Wissenschaftliche Verlagsgesellschaft mbH. 1997.](image)
croup. Interestingly, the modern Cole tube with the same configuration is still popular for intubation of veterinary patients and still has the narrowing.

Connectors Come Into Practice

In the 1950s, a wide range of uncuffed and cuffed tubes was available, but all lacked metal connectors that required attachments. Connectors, either straight or curved, had to be attached, depending on their intended use. There were two types of connectors, the Ayres Y-piece and the Ayres T-piece, which used connectors with rubber tubes. They were connected to a source of oxygen flow and allowed expiratory gas to escape. There were numerous problems with the connectors, however, such as frequent kinking at the joint between the connector and the tube, resulting in obstruction of the tube. As a solution, various devices were invented to join the connector to the tube without narrowing the orifice of the tube.

By the 1940s and 1950s, anesthesiologists finally began to realize the advantages of cuffed tubes and attempted to add cuffs to existing tubes by hand. Manual devices with large clamps and other accessories that were inserted into the cuffs to stretch them were developed. See figure 6 for the Waters cuff apparatus, an extremely complicated example of the devices of this period.

The Murphy Tube

To address the difficulty of manually adding cuffs to existing tubes, the Murphy tube was developed in the 1940s by FJ Murphy. His tube came complete with its own manufactured cuff, a pilot balloon and the infamous Murphy eye. The eye was a side vent between the cuff and the tip of the endotracheal tube to prevent tube obstruction if the beveled end of the tube became blocked by mucus or sealed by contact with the tracheal wall. Often, the bevel of the tube was in line with the curve of the tube and could abut the tracheal wall. The eye on the tube surface opposite the end hole allowed ventilation to occur despite occlusion of the end of the tube. It was also believed that if there was inadvertent mainstem intubation, the Murphy eye would allow ventilation of the other side, or in situations of deliberate intubation of the right mainstem bronchus, allow ventilation of the right upper lobe.

Manufactured cuffed rubber tubes were developed in the 1950s and are still in existence. They are currently used primarily in laser surgery after wrapping with metal foil or other non-flammable materials, although their use has declined in the last decade because of increasing concern about the prevalence of latex allergy. These very small tubes came with exceptionally long cuffs, which made it impossible for them to be used in infants, in whom it was unlikely to get the entire cuff below the vocal cords without having a mainstem intubation.

Plastic Tubes

In 1962, Dr. Brandstater wrote the first description of the use of plastic polyvinyl chloride (PVC) endotracheal tubes in the routine intubation of small children. Dr. Brandstater felt there needed to be a satisfactory alternative to the hazards of tracheostomy, which was the standard of care of patients of that time, but which was also unfortunately associated with significant morbidity and mortality in small children. These plastic tubes were developed in 1959 through the work of David Sheridan, an engineer, and their introduction helped advance pediatric anesthesiology and critical care. This technique allowed prolonged mechanical ventilation in children, since the tubes softened at body temperature and were much less likely to cause subglottic stenosis than their metal or rubber counterparts.

With the development of so many tubes, standardization was imperative. As such, guidelines for endotracheal tube selection in children were published by Smith in 1959 in Anesthesia for Infants and Children. The guidelines recommended using plain Magill tubes, which lacked the Murphy eye, for children up to 6 years of age. An uncuffed tube was thought to be more suitable for children ages 8 and younger, because the narrowest part of the airway of children of that age was thought to be the subglottic area at the level of the cricoid ring.

Prior to standardization, there were major discrepancies in tube measurements with tube dimensions being expressed in either French sizes or inner diameter in millimeters. Finally, in 1960, the American Society of Anesthesiologists (ASA) advocated that there should be standards for endotracheal tube sizes, making millimeters the universal unit for internal...
diameter. This was codified with the development of the American Standards Specifications for Anesthetic Equipment: Endotracheal Tubes in collaboration with the American Standards Association. Further ASA guidelines stipulated that the tubes should have graduation markings placed from the tip to indicate the depth of intubation, radiopaque lines throughout the length of the tube to allow radiographic assessment of the exact location of the tube, and a standard 15-millimeter connector added to ensure compatibility with circuit connectors.

**ADULT LARYNX VS CHILD LARYNX**

Anatomical dissection of cadavers of children, initiated with Bayeux in 1897 and subsequently spread by others in the 1950s and 1960s, concluded that the adult larynx resembles a cylinder with equal dimensions at the cords and the cricoid. They found that children under the age of 8, however, had a cone-shaped larynx with the narrowest portion at the cricoid ring. This differs from adults, in whom the vocal cords form the narrowest portion of the larynx and trachea, and are the limiting dimension for determination of appropriate tube size.

In 1951, Dr. Eckenhoff advanced Bayeux’s theory by stating that the tube should be sized according to the dimensions of the cricoid, since it was the area of vulnerability being the only complete cartilage ring of the airway (trachea). A study based on MRI dimensions of the airway from cords to the cricoid in sedated, unparalyzed children, by Litman in 2003 found that the narrowest part of the airway, especially in the transverse diameter, is actually at the cords and subglottis (see fig. 7). The discrepancy in the findings may be because Litman’s subjects were alive; therefore he was looking at dynamic dimensions of the airway, as opposed to the cadaver studies, which were not dynamic.

**IDEAL LEAK PRESSURE**

The origin of the ideal leak pressure was determined by case reports using cuffed tubes, which stated that inserting a ‘too large’ tube was associated with no leak, especially if left in for an extended period of time, increased the risk of subglottic injury. Both animal and human studies supported this finding and the conclusion was that cuffed tubes with leak pressures > 30 cm of water reduced mucosal blood flow in adults resulting in ischemia.

**RECENT CASE STUDIES**

In 1997, Khine et al published a study, which observed the performance of cuffed tubes in children under 8. The author concluded that leak pressure may not be reproducible among observers, and that complications of long-term intubation occur with both cuffed
and uncuffed tubes. Koka found that postintubation croup in children was associated with higher leak pressure. A recent study found that leak pressure greater than 25 cm of water was associated with increased incidence of postoperative stridor. These, as well as earlier studies identifying complications of intubation in children were all done with uncuffed tubes, or with rubber tubes. On the contrary, recent studies and case series have yet to find increased adverse events with modern cuffed tubes.

References
Prior to the 1960s, most children who required prolonged intubation were given tracheotomies, which was associated with significant morbidity and mortality. However, prolonged endotracheal intubation was not without its own risks, and the first reports of ETT blockage and subglottic stenosis started to appear in the literature. Since 1966 it has been known that there are a number of factors to consider when tracheal intubation is needed in children. The first is the size of the tube. According to Stocks’ important article published in the *British Medical Journal* in 1966, “Selection of an appropriate size of tracheal tube is fundamental to the success of prolonged nasal intubation in children.” This can not be overstated. Stocks knew that an endotracheal tube (ETT) that was too small would make intermittent positive pressure ventilation difficult because of gas leaks through the larynx, and one that was too large could possibly cause subglottic stenosis.

There are many indications for tracheal intubation such as airway protection, maintenance of airway patency, pulmonary toilet, application of positive-pressure ventilation, maintenance of adequate oxygenation, predictable FiO₂ and positive end-expiratory pressure. However, endotracheal intubation is not without its risks.

**RISKS OF INTUBATION**

As with many things in medicine, there are risks associated with endotracheal intubation: Dental injuries, which vary between 1 in 150 to 1 in 1000 cases, are the most common; cervical or neck problems; laryngotracheal trauma; corneal abrasion; uvular damage, vocal cord paralysis; or esophageal or bronchial intubation. The most serious complication is subglottic injury, which takes the form of stenosis or dilatation, and is manifested through stridor. Studies have shown that between 2–18% of patients will exhibit signs of stridor post-anesthesia.

**SIZE OF THE TUBE**

In order to prevent injury and to obtain appropriate ventilation in an intubated child, a correctly sized ETT is needed. Multiple age-based formulas have been used to predict the appropriate size of the uncuffed ETT in the pediatric population. For children less than 6 years of age, Slater et al, recommended using the sum of 3.75 + age divided by 4; and for children 6 and up, the sum of 4.5 + age divided by 4. These formulae have since been simplified into: 4 + age divided by 4. It has been suggested that for a tighter-fitting tube the base number should be 4.5 + age divided by 4 (see fig. 1).

**FORMULAS FOR ENDOTRACHEAL TUBE SELECTION**

Formulas are not perfect. One problem is that ETTs have different external diameters. Even a fraction of a millimeter variation in external diameter size may be consequential in smaller children with smaller diameter airways. A study conducted by King et al in 1993 concluded that in about 97.5% of patients, the age-based formula accurately predicted the correctly sized ETT. However, the study also determined that the formulas do not take into account the natural variations between patients and tend to be very inaccurate if the age of the patient is unknown.

**LEAK AROUND TUBE**

The “appropriate” size of ETT has been defined as that size of ETT which allowed an audible air leak around the ETT occurring between 15 and 25 cm H₂O pressure. In a large retrospective study in 2953 pediatric patients over a 4 year period, Black et al found that a slight leak around the tube with the application of 25 cm of pressure to the airway resulted in a less than 1% incidence of stridor requiring re-intubation. We now know that a leak at a pressure greater than 30 cm of water probably predisposes patients to subglottic injury, especially in prolonged intubation. A pressure of less than 15 cm H₂O may result in inadequate ventilation in patients with poor pulmonary compliance from intrinsic lung disease or to changes in chest wall or abdominal compliance.

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**Formulas for Endotracheal Tube Selection**

<table>
<thead>
<tr>
<th>Under 6 years of age</th>
<th>Over 6 years of age OR for a tighter-fitting tube</th>
<th>Simplified Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75 + age / 4</td>
<td>4.5 + age / 4</td>
<td>4 + age / 4</td>
</tr>
</tbody>
</table>

**Fig.1.** Formulas for Endotracheal Tube Selection
RELIABILITY OF LEAK TEST
In any case, the leak test is unreliable. In 1993, Schwartz et al conducted a study of 242 patients using standard conditions for the leak test, defined as 5 liters of fresh gas flow in neutral head position and neuromuscular blockade. Thirty patients were excluded because they did not have leaks at a pressure greater than 50 cm of water. Among the results, a 38% variance between observers was seen, especially at levels above 30 cm H2O.11

In 2000, Pettignano et al repeated the study to determine reproducibility of the leak test.12 Thirteen patients were enrolled, personnel were trained for at least an hour, and standard conditions for the leak test were used. The study concluded that neither interobserver nor intraobserver variability was statistically significant when a standardized method was used to determine the leak.12 However, because of the small population studied, the results seem to contradict other studies showing significant intraobserver variance in the leak test.

CHANGES IN ENDOTRACHEAL TUBE LEAK
In addition to variance between observers, the leak is not a constant and changes depending on patient positioning and degree of paralysis or sedation. Finholt’s study conducted in 1985 with 80 patients between 2 weeks and 11 years of age, intubated with uncuffed ETTs, found that a patient whose head was in a neutral position had a smaller leak than if their head was turned sideways. He also noted that the degree of paralysis or sedation significantly affected the leak. However, the leak was not affected by fresh gas flow or endotracheal tube depth.9

IMPORTANCE OF AIR LEAK
In 2006, Suominen et al, conducted a study in 234 pediatric patients ranging in age from newborn to 9 years, requiring tracheal intubation for elective or emergency surgery. The tube size was calculated using a modified Cole formula (age/4 + 4.5). An audible air leak at 25 cm H2O or below was associated with a significantly lower incidence of stridor (9%) compared with an absent air leak at the same pressure (19%). This study concluded that 25 cm H2O is the threshold where complications begin to arise.13 A separate study by Mhanna et al, however, concluded that the air leak test was age dependent as a predictor of stridor in children. The authors found that the test has a low sensitivity when used in children younger than 7, whereas in children older than 7, the test may predict postextubation stridor.14

COMPLICATIONS OF A LARGE LEAK
Multiple complications may arise if there is a large leak. Inaccurate measurements of ventilation function, calorimetry and indirect cardiac output are just a few. Limiting patients’ and healthcare workers’ exposure to environmental pollution is a consideration. Lower fresh gas flow results in less agent being used, which in turn decreases the cost of drug used for the anesthetic. It is known that the leak changes with regards to position, sedation and use of neuromuscular blockade and this may affect the ability to ventilate.4,7

CUFFED OR UNCUFFED ENDOTRACHEAL TUBES
The next logical question is whether the complications can be altered by use of a cuff or uncuffed tracheal tube. It has been widely accepted that uncuffed endotracheal tubes be used for the intubation of children younger than 8 to 10 years of age.4 The primary reasoning being that uncuffed endotracheal tubes allow for use of a tube of larger internal diameter, which minimizes resistance to airflow and the work of breathing in the spontaneous-breathing patient. This advantage is not as valid for maintenance of anesthesia in the 21st century, when very few patients are allowed to breathe spontaneously under anesthesia for prolonged periods of time. In the intensive care, patients often do breathe spontaneously, but with modern ventilators and modern ventilation techniques, the work of breathing from smaller diameter ETts can regularly be overcome. As far back as 1977, a study by Battersby et al concluded that there was no subglottic stenosis from proper use of uncuffed endotracheal tubes for long term intubation.15 Black et al confirmed this thinking in a 1990 study published in the British Journal of Anaesthesia.10

Black et al’s study included 2953 pediatric intensive care admissions over a 4-year period. The overall complication rate was 8%. Endotracheal tube blockage occurred in about 2.6% of the patients. Of note, 80% of these occurred in patients who had an internal diameter less than 3.5. A study by Newth et al in 2004 showed that the incidence of ETt blockage is greater in patients that go to the operating room when the internal diameter of the tube is less than 4 mm than in those that stay in a unit with proper humidification of gases. Stridor occurred in less than 1% of the patients, with 14 having had preexisting laryngeal pathology (leak test less than 25 cm H2O).16

Deakers et al studied 243 patients in a pediatric intensive care unit during a 7-month period to compare cuffed and uncuffed endotracheal tube utilization and outcome.17 Patients who were less than 1 year of age, or who had tubes in place for less than 72 hours were more likely to have had insertion of an uncuffed endotracheal tube. Patients who were more than 5 years of age or for whom long term intubation was expected, were more likely to have an insertion of a cuffed ETt. Inflation pressures were kept to less than 25 cm of water. The overall incidence of postextubation stridor was 14.9%, with no significant difference between the 2 ETt groups even after controlling for patient age, duration of intubation, trauma, leak around ETt before extubation, and pediatric risk of mortality score.

Newth et al studied 597 patients (210, cuffed; 387
uncuffed) in the first 5 years of life using an age-based formula. They found no difference in clinically detected subglottic edema between the 2 groups. The authors even went as far to state that cuffed tubes should be the first-line choice in critically ill patients. In the anesthesia literature, there are no reports of subglottic stenosis from short-term intubation irrespective of tube size or cuff pressure, and the incidence of stridor seems to be similar among cuff and uncuffed tubes.¹⁶

**ADVANTAGES OF CUFFED TUBES**

There have been several studies done to determine the need for changing from an uncuffed endotracheal tube to a cuffed one in the pediatric population. Most studies seem to conclude that there are more advantages associated with the use of cuffed tubes as opposed to uncuffed ones. In a 488-patient study conducted by Khine et al, they determined that cuffed tubes provided both an environmental benefit—decreasing operating room contamination, as well as an economic one—requiring lower fresh gas flow over uncuffed endotracheal tubes in children between the ages of 2 weeks to 8 years.¹⁸ In addition, Murat’s study supports this significant drop in operating room pollution with the simple change to cuffed endotracheal tubes.¹⁹

Fine et al studied 20 patients in 3 age groups and found there was less chance at reintubation and laryngoscopy with cuffed tubes. By decreasing the number of laryngoscopies, one directly decreases the chance of causing trauma to the upper airway. It was also concluded that there was less incidence of hypoventilation if 200 mL per minute per kilo of fresh gas flow was used.²⁰

Silver et al conducted a multicenter study in burn centers and determined that in these large pediatric burn centers there was a preference for cuffed endotracheal tubes. With significant burns, more patients were likely to be changed from uncuffed to cuffed ETT especially if there was lung injury.²¹

In an aspiration study, Browning and Graves compared cuffed to uncuffed tubes in 22 children (9 cuffed; 13 uncuffed). Their study showed that 11% of cuffed patients exhibited dye positive tracheal aspirations not affected by PEEP, compared to 70% of uncuffed patients.²² Goitein et al with 50 infants using uncuffed endotracheal tubes found an 8% incidence of clinically significant aspirations.²³

There are several case reports of retrograde leak of ventilating gases, especially oxygen, during electrocautery in tonsillectomies where the polyvinyl tubes have caught fire. All of these case reports were in uncuffed endotracheal tubes.²⁴⁻²⁶

In conclusion, the literature suggests that the benefits of cuffed tubes include: decreased attempts at intubation; less OR contamination anesthetic gases; less ICU contamination (from droplet spread of pathogens); less chance of hypoventilation; better patient ventilatory management with more accurate end tidal CO₂ monitoring especially in patients with changes in pulmonary compliance; decreased risk of aspiration and decreased incidence of airway fires (see fig. 2). These factors speak for themselves as to the advantages of cuffed over uncuffed ETts.

**ENDOTRACHEAL DEPTH PLACEMENT**

Endotracheal tube length, like size, is dependent on the age and size of the individual child. There are formulas that confirm successful placement, but mostly this applies to children older than 2 years of age. Auscultation is always a method for correct endotracheal depth placement. However, in a study conducted by Verghese et al, where they did 153 intubations in the cardiac catheterization lab, auscultation did not detect proper placement in 11.8% of the patients who had a right mainstem intubation. In 19% of the patients, they were within one centimeter of the carina. All of these patients were less than 5 years of age, and they attributed this to the Murphy’s eye, which reduces the reliability of chest auscultation in detecting endobronchial intubation.²⁷

To establish correct depth, the only 100% certain method is via radiologic confirmation, but that would expose children to unnecessary radiation. Similarly, Hsieh et al showed that the Murphy’s eye could cause confusion during ultrasounds of the diaphragm.²⁸ Palpitation of the endotracheal tip above the sternal notch was advocated in 1975 by Bednarek et al,²⁹ but I find that most children have thick necks, making palpitation difficult.

**WORK OF BREATHING**

As anesthesiologists, we very rarely let children breathe under anesthesia spontaneously for prolonged periods of time. In fact, a study by Bock et al in Chest, showed that new mechanical ventilators are so good they can overcome the work of resistance irrespective of endotracheal tube internal diameter.³⁰

**THE FUTURE OF ENDOTRACHEAL TUBES**

There are exciting product developments currently being studied that will facilitate endotracheal intubation. These include an ultrathin-walled endotracheal tubes.³¹

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**Fig. 2. Advantages of cuffed endotracheal tubes**

- Decreased attempts at intubation
- Less OR and ICU contamination
- Less risk of hypoventilation
- Better patient management and changes in pulmonary compliance
- Decreased incidence of aspiration
- Less risk of airway fires
- More accurate ETCo₂ monitoring
tube as described by Okhuysen, a no-pressure seal design used by Reali-Forster, and the thinner, more distensible cuffed tube, Microcuff, which was specifically designed for the pediatric anatomy.\textsuperscript{31,32} This tube employs a short cylindrical microthin polyurethane cuff that helps secure placement in the lower trachea (not the pressure-sensitive larynx), depth markings to ensure a cuff-free subglottic zone, and four pre-glottic placement markings. Having been developed and thoroughly studied by Dullenkopf, Gerber, and Weiss, this tube may very well represent a new standard for pediatric airway management.

References
Uncuffed endotracheal tubes have been the norm in the pediatric population for 50 years and are still widely used today. As a result, pediatric anesthesiologists are accustomed to this means of intubating and ventilating children. Switching to cuffed endotracheal tubes may not seem like a necessary choice considering the success and widespread use of uncuffed ones, however, as this article will point out, there’s much to be gained from using cuffed endotracheal tubes.

VITAL LINK

The endotracheal tube is the link between our most expensive and our most sophisticated object, our anesthesia machine, and our most delicate and most precious subject, our pediatric patients. This vital link should fulfill 2 requirements: 1) it should be precise, consistent and reliable, and 2) it should be leak proof and never damage the airway. The leak proof aspect of the endotracheal tube is necessary in order to efficiently exchange gases and vapors, to transmit precise pressures, to monitor respiratory and anesthetic gases, and to protect against the aspiration of fluids. While achieving these things, the tube must simultaneously not obstruct mucosal perfusion or cause direct mechanical trauma to the airway. The traditional method of obtaining such acceptable leak tightness in uncuffed endotracheal tubes is through cricoidal sealing.

CRICOIDAL SEALING WITH UNCUFFED TUBES

The key to securing acceptable sealing with uncuffed tubes is by matching the diameter of the endotracheal tube to the diameter of the cricoid ring. Getting this right, of course, is the challenge. If a tube is too small, unreliable ventilation, unreliable monitoring, and risk of aspiration are high. If a tube is too large, mucosal compression and mechanical trauma will occur. Having a very small, mandatory leak that does not interfere with precise ventilation may, to a certain extent, guarantee that the tube is not too big. As is evident, selection of the right tube size is paramount, but it is not an easy task in cricoidal sealing. Despite formulas that help calculate the size of uncuffed endotracheal tubes, up to 30% of the tubes have to be exchanged due to incorrect size.

TRACHEAL SEALING WITH CUFFED TUBES

The lack of success in calculating the size of the uncuffed endotracheal tube is directly attributed to anatomy. A study in 2003, by Ronald Litman, based on MRI dimensions of the airway from cords to the cricoid in sedated, unparalyzed children provided new insight into the structure and size of the larynx in children. Litman’s findings produced evidence that this region in children is not funnel-shaped or circular, but rather an ellipsoidal structure. This explains why matching the circular structure of the tube to the non-circular portion of the larynx is difficult to accomplish with uncuffed endotracheal tubes. The more accurate and logical approach is to employ tracheal sealing, via a cuff, which can accommodate different sizes and shapes. This allows the pressure that is exerted by the cuff on the tracheal wall, which is slightly distensible, to be measured and adjusted as needed. Through tracheal sealing, a properly sealed airway is achieved, permitting precise ventilation and monitoring, and protection against aspiration (see figures 1&2).

SHORTCOMINGS OF THE CUFFED TUBE

Not surprisingly, along with the gains cuffed endotracheal tubes offer, some also have flaws and/or shortcomings. Many commercially available pediatric cuffed endotracheal tubes are poorly designed and have limitations with the outer diameter, cuff position,
cuff diameter and depth markings. Since endotracheal tubes are chosen according to internal diameter, the differences in outer tube diameters, more often than not, go unnoticed. This may lead to the use of oversized, ill-fitting tubes, which can cause damage to the subglottis. In addition many endotracheal tube cuffs require inflation to a high pressure for sealing. Presently, there is no data about cuff pressure limits in children; in adults acceptable cuff pressure is 25–30 cm H₂O. Accordingly cuff pressures in children should be ≤ 20 cm H₂O. In many cuffed tubes, the upper border of the cuff corresponds to the upper border of the depth marking of the next larger sized uncuffed endotracheal tube. The reduced margin of safety with regard to endobronchial intubation of cuffed endotracheal tubes, even with the cuff placed within the larynx, is a serious problem with current cuffed tubes. Not all cuffed tubes have depth markings, and in the ones that do have them, the distances from depth markings to tube tip are greater than the age-related minimal tracheal length (see fig. 3). A satisfactory cuffed tube size in children depends on the size of both the outer tube and cuff diameter with sealing pressure at less than 20 cm H₂O.

**IDEAL PEDIATRIC CUFFED TRACHEAL TUBES**

Ideally a cuffed pediatric tracheal tube should be designed to accommodate a high-volume low-pressure cuff with a short cuff length. It should have the following attributes:

- The cuff should be located below the cricoid ring, at the level of the tracheal cartilages, which are able to expand.
- The tube must not be intra-laryngeal, which can cause vocal cord palsy; the length of the cuff and the presence of a Murphy eye are important determinants of final upper cuff position in cuffed pediatric tracheal tubes.
- Adequate depth markings are needed to guarantee a cuff position below the cricoid and a tip far enough above the tracheal carina.
- Importantly, a good tube has correct depth marking.
- Verified recommendations for using the correct tube.

Reliable depth markings are a must to position a tube correctly. If it is placed according to the depth mark, then the tip of this tube must lie somewhere in the middle part of the trachea, such that there is a wide enough margin of safety. For example, if the head is extended, the tip of the tube will move cranially, but the cuff should still be below the larynx. The tube will travel caudally when the head is flexed, but nonetheless the tip should not reach the carina.

Recently, our group assisted the development of a new cuffed pediatric tube, the Microcuff pediatric tube. This tube employs a patented cuff capable of sealing at very low pressures.

**A CORRECTLY SIZED TUBE ELIMINATES THE NEED FOR FORMULAS**

In our institution our goals were to have a sealed airway at low cuff pressures, a low tube exchange rate, and to move away from the various sizing formulas, which really only represent a best guess. In reviewing the literature, my colleague, Markus Weiss considered the available radiological and anatomical data about the pediatric airway and carefully calculated the age specific dimensions for an ideal cuffed pediatric tube. We used a modified version of the Cole formula as our basis for the tube size selection. In our experience, the 3.5 mm tube can fit children as young as eight months. (See figure 4).

![Fig. 4. Illustration of the calculated tube dimensions in case of a 1 year old child (ID 3.5 mm). The shortest tracheal length in this age group is 43 mm corresponding to 100%. The tip of a tube inserted 27 mm into the trachea would be at 63% of tracheal length.](image)
We feel strongly that there is no need for a Murphy eye, as it makes the tracheal part of the tube unnecessarily long. Using a correct depth mark will ensure that the tube will not encroach on the carina. That is better than hoping that a Murphy eye will still allow bilateral ventilation if the tube is too deep.

MICROCUFF DEPTH AND SIZE RECOMMENDATIONS

Correct insertion depth is critical for cuffed tubes, so we ensured that Microcuff employ a clear mark. This mark must be situated between the vocal cords and the 4 “alerting bars”, helps ensure correct positioning when a perfect view of the glottis cannot be obtained, or when a tube is initially inserted too deep.

Instead of various formulas for tube selection, we decided on explicate size recommendations. This sizing chart is provided with all Microcuff packages.

STUDIES WITH MICROCUFF PEDIATRIC TUBE

To ensure that the Microcuff tube fulfills our expectations, we have so far conducted 7 studies with over 1000 patients and have confirmed that Microcuff fits and performs well.

The most important study was published in Acta Anaesthesiologica Scandinavica and included 500 patients from neonates up to 16 years of age. In almost all patients (98.4 %), Microcuff fit well. We also found that the depth marks and dimensions were correct. The tube was too large in only 8 out of 500 patients and was never found to be too small. This was expected since a cuffed tube can accommodate various sizes and shapes of the airway. When the tubes were inserted according to the depths markings on the tube, all the tubes were within a safe tracheal range, and the cuff was situated safely below the cricoid with flexion and extension of the head. This was confirmed with endoscopic and radiological studies. We found the tube tips

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**Fig.4 continued:** In all age groups, there must be a cuff-free subglottic zone (blue bars). The burgundy bars represent the region of the cuff. The end of the yellow bar is the tip of the tube in neutral head position. The tip will move downward towards the carina with flexion of the head, but should not go further than the green bars. The dark uppermost columns represent the margin of safety so the tube is never situated on the carina or in the main bronchus.

**Fig.5.** Photograph depicting the clear depth marks on the Pediatric Microcuff Endotracheal Tube to ensure correct positioning.

**Fig.6.** Microcuff Sizing Chart

<table>
<thead>
<tr>
<th>Tube Size</th>
<th>Age/Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.D.</td>
<td>Years/kg</td>
</tr>
<tr>
<td>3.0 mm</td>
<td>term/≥ 3 kg – 8 months</td>
</tr>
<tr>
<td>3.5 mm</td>
<td>8 months – 2 years</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>2 – 4 years</td>
</tr>
<tr>
<td>4.5 mm</td>
<td>4 – 6 years</td>
</tr>
<tr>
<td>5.0 mm</td>
<td>6 – 8 years</td>
</tr>
<tr>
<td>5.5 mm</td>
<td>8 – 10 years</td>
</tr>
<tr>
<td>6.0 mm</td>
<td>10 – 12 years</td>
</tr>
<tr>
<td>6.5 mm</td>
<td>12 – 14 years</td>
</tr>
<tr>
<td>7.0 mm</td>
<td>14 – 16 years</td>
</tr>
</tbody>
</table>
were correctly placed in the middle of the trachea, between the vocal cords and the carina and that there was an adequate margin of safety when the head is flexed or extended. No tube became located endobronchially and there was no accidental extubation with head extension.

**THE MICROCUFF SEAL**

The Microcuff seal is clearly exceptional. Made of ultra thin polyurethane, the cuff fills the gap between tube and tracheal wall without folds and channels. It virtually drapes and clings to the wet mucosa similar to the way household plastic wrap clings to meat. This attribute results in better sealing at lower pressures compared to PVC. In addition, leaking does not occur between the cuff and the wall, as one would imagine, but through the cuff itself, as illustrated when the cuffed tube is inserted into a glass tube (see fig. 7).

We also confirmed this excellent sealing *in vivo*. In figure 8 we see the cuff pressures required in our 500-patient study. The mean pressure was around 10 cm of water.

In figure 9 we have in vivo cuff pressures of various well-known endotracheal tubes. Again the Microcuff sealed at a mean pressure of 10 cm of water, whereas the other tubes required mean cuff pressures of 20 and 35 cm of water.

**WITH MICROCUFF PEDIATRIC TUBE THERE IS A LOW INCIDENCE OF STRIDOR**

The main concern is for the cuffed tube not to cause airway damage, and we found that Microcuff had a low incidence of stridor. We know that severe subglottic swelling results either from inadequate perfusion or mechanical trauma by tubes that are too large.

Another cause is multiple intubations. Comparing the incidence of postintubation croup is difficult because of variable definitions. As such, we measured postintubation stridor, a clinical surrogate symptom for early airway damage.

In our studies, we have found postintubation stridor in 1.8% of patients, with 2 patients needing epinephrine inhalation. This incidence is comparable to the work of Khine, who in 1997 found an incidence of 2.4% with cuffed tubes and 2.9% for uncuffed tubes. In an older, large retrospective study (n=7875) from Koka conducted in 1977, the overall incidence of postintubation croup was 1%; the incidence in patients 1 to 4 years of age was 5%. And in a separate study by Newth in 2004 on intensive care patients with longer duration of intubation, an incidence of 4.8% with cuffed and 6.9% with uncuffed tubes was found.

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**Fig. 7.** As these CT scans illustrate, contrast dye leaks through the unnamed cuff through folds and cracks. There is no leaking through the Microcuff because there are no such folds.

**Fig. 8.** Adapted from Dullenkopf A, Gerber AC, Weiss M. Fit and seal characteristics of a new paediatric tracheal tube with high volume-low pressure polyurethane cuff. *Acta Anaesthesiol Scand.* 2005.
In our department, we've been using cuffed tubes in children regularly for 5 years, which comes to over 15,000 patients. We have not seen any long term morbidity in our patients. This was confirmed by Prof. Isabelle Murat from Paris who has even more experience with cuffed tubes.14

MONITORING CUFF PRESSURE MUST BECOME ROUTINE

The results we have obtained with cuffed tubes are very reassuring, but there is one very important point. Cuffed tubes should only be used in children if the commitment is made to control cuff pressure. As anesthesiologists, we spend more time than we care to think about measuring. We measure blood pressure, central venous pressure, atrial and pulmonary pressure, gas pressure, and cerebral perfusion pressure. Now, we just have to include cuff pressure into our pressure routine. Cuff pressure can be measured and controlled with a simple manometer or with an electronic cuff regulator, which is what we use on all our anesthesia machines.10

MICROCUFF — A NEW ERA IN PEDIATRIC AIRWAY MANAGEMENT

For more definitive proof, Microcuff pediatric endotracheal tube is currently undergoing a large, prospective, randomized, controlled study in 24 European centers. The goal is to enroll 5000 pediatric patients, from neonates up to 5 years of age, corresponding to tubes from ID 3.0 to 4.5 mm. The study should be completed in 2007. However, for cuffed tubes to be routinely used not only is a large prospective study needed, clinical standards and textbook recommendations must also change. Such a change has already begun.

The American Heart Association (AHA) and the International Liaison Committee on Resuscitation (ILCOR) state in their guidelines for pediatric resuscitations that the use of cuffed tubes in infants and children is now an accepted alternative to uncuffed tubes in infants and children. Likewise, Dr. Golden of the Society for Pediatric Anesthesia (SPA) has also stated in an SPA newsletter that cuffed tubes are suitable as an alternative from size 4.0 mm on, and that they are actually preferred in patients at risk for pulmonary aspiration, those with low lung compliance (including laparoscopy, thoracoscopy, cardio-pulmonary bypass) and in whom precise ventilation and CO₂ control is important.

CONCLUSION

Using uncuffed tubes in children up to 8 years of age has been the paradigm for the last 50 years. With uncuffed tubes a sealed airway can only be obtained with an oversized tube. The recommendation to use a tube which fits snugly through the cricoid ring with a slight air leak at 20 cm of inflation pressure allows acceptable ventilation and monitoring. However, a high tube exchange rate is unavoidable due to variations of size and shape of the airway and due to the fact that a circular tube does not fit ideally into the ellipsoidal cricoid cartilage. Tracheal sealing with a cuffed tube is a much more logical way of obtaining a leak proof link between the anesthesia machine and the patient. The gap between a deliberately smaller tube and the trachea is filled by a cuff inflated to a cuff pressure ≤ 20 cm H₂O. The new Microcuff pediatric tube has been designed and tested to fit the dimensions of the pediatric airway, to seal at cuff pressures below 20 cm H₂O and to allow precise positioning due to clear and correct depth markings. With such an endotracheal tube pediatric anesthesiologists can safely switch to cuffed tubes in infants and small children.

References


