Developmental anatomy of the airway

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Abstract

The airway develops from the primitive foregut at 4 weeks' gestation. Congenital anomalies may result when this process is abnormal. The anatomy of the airway at birth is uniquely different from older children and adults, with a large tongue, long floppy epiglottis, large occiput and cephalad larynx. These features affect the technique required for facemask ventilation, supraglottic airway use and endotracheal intubation. A neutral head position and straight bladed laryngoscope are usually used for intubation. Neonates are also obligate nasal breathers and simultaneously suckle and breath. Minute volume is rate dependent and the highly compliant chest easily displays sternal and intercostal recession during respiratory distress, and early onset of fatigue. From the neonatal period onwards the anatomy gradually begins to resemble that of adults. The cricoid descends caudally, the epiglottis becomes firmer and shorter, and the relatively large occiput recedes. The conventional wisdom of the cricoid ring being the narrowest part of the paediatric airway is not supported by contemporary investigation. The consequence of these findings on endotracheal tube selection and the rationale for increasing use of cuffed endotracheal tubes in children is discussed.

Keywords Airway; anaesthesia; anatomy; larynx; paediatric; trachea endotracheal tube

Royal College of Anaesthetists CPD Matrix: 1A00, 2A01

Learning objectives

After reading this article, you should be able to:

- describe the changes in airway anatomy from neonate to older child
- understand how the more common congenital abnormalities of the airway arise
- understand how the developmental anatomy from neonate to older child might influence paediatric airway management
- reconcile, the apparent conflicting information from in vitro and in vivo studies on laryngeal and upper airway development
- correctly size paediatric uncuffed and cuffed endotracheal tubes

Embryonic and fetal development

Development of the human airway starts at week 4 of gestation. Most of the structures of the face and neck originate from the pharyngeal (branchial) arches. These develop as paired structures lateral to the developing foregut and laryngotracheal groove. The first three pharyngeal arches give rise to the maxilla, mandible and hyoid bone with their accompanying nerves and muscles, whereas arches 4–6 give rise to the laryngeal cartilages with their associated muscles and are supplied by branches of the vagus nerve. The tonsils arise from the second pharyngeal pouch. Disruption of the neural crest cell development results in craniofacial abnormalities. Interruption of mandibular development leads to micrognathia and retro-displacement of the tongue. This may manifest as Treacher-Collins syndrome (mandibulofacial dysostosis) or Robin sequence (micrognathia, cleft palate and glossoptosis).

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The anterior two-thirds of the tongue is derived mostly from the first arch and the posterior one-third from the third and fourth arches. The epiglottis also develops from the third and fourth pharyngeal arches via the hypopharyngeal eminence. The primary palate begins at week 5 fusing to become the nasal tip and upper lip, followed by the secondary palate at week 7 forming the soft and hard palate. The palate is formed from lateral palatine processes which project medially on each side of the tongue and fuse with the nasal septum. Cleft lips and palates result from failure of this process.

The larynx, trachea and bronchi originate from the median laryngo-tracheal groove. As the groove deepens, its lips fuse forming a tube lined with endoderm, which becomes the epithelial lining of the respiratory tract. The cranial end of the tube becomes the larynx, mid-section the trachea, and the caudal end bifurcates into two buds – the bronchi and lungs. This process starts by week 7, with the alveolar ducts and primitive alveoli being completed by 27 weeks. Incomplete fusion or abnormality of the tracheo-oesophageal septum may result in laryngeal cleft or tracheo-oesophageal fistula.

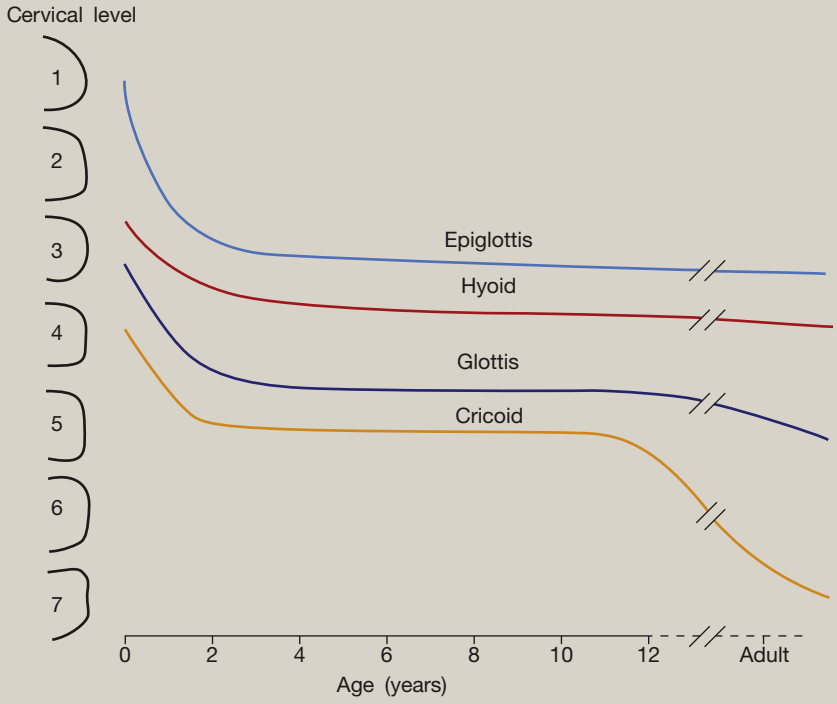
Incomplete development (laryngeal atresia, tracheal stenosis) at any level of the airway or extrinsic compression in utero (teratoma, cystic hygroma) can result in significant airway obstruction in the neonatal period. Rarely the obstruction can be so severe that life threatening Congenital High Airway Obstruction (CHAOS) can occur, necessitating Ex Utero intrapartum Treatment (EXIT) to rescue the baby.

The airway at birth

The neonate has a large head, short neck and prominent occiput. The mandible is underdeveloped and when combined with a prominent mid-face, results in a degree of relative micrognathia. Most of the tongue lies within the oral cavity at birth. The arrangement of the larynx (epiglottis–hyoid–glottis–cricoid complex) at birth is more cephalad and more compressed than later in life (Figure 1). The tip of the epiglottis is at the mid-level of C1, the glottis at mid C3 and the cricoid at the superior border of C4 at birth.[1] These structures may be up to half a vertebral body more cephalad in premature neonates.

The epiglottis is intimately related to the base of the tongue superiorly. Inferiorly, it is attached to the thyroid cartilage by the thyro-epiglottic ligament and suspended from the hyoid bone by

The change in level of laryngeal and related structures relative to the cervical spine with age



From Westhorpe RN. The position of the larynx in children and its relationship to the ease of intubation. *Anaesth Intens Care* , 1987; 15: 384–8.

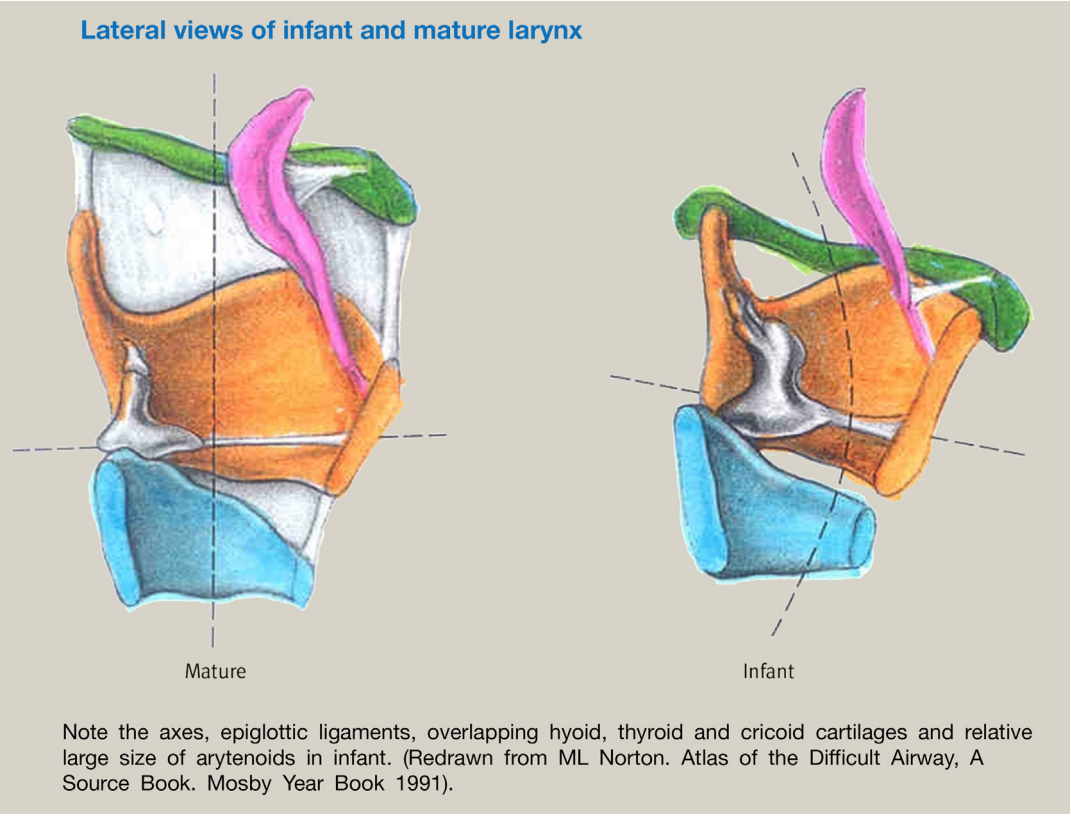
Figure 1

the hyo-epiglottic ligament that initially attaches close to the base of the epiglottis (Figure 2). Together this explains the 'down-folded' position of the epiglottis that projects at approximately 45° to the vertical. The tip of the epiglottis makes contact with the soft palate and when supine touches the posterior pharyngeal wall. Although this may cause problems with visualizing the larynx at intubation, the apposition of the epiglottis and uvula in the midline effectively separates a midline pathway into the trachea for air (neonates are nasal breathers) and two lateral channels (piriform fossae) leading into the oesophagus for milk; allowing swallowing and breathing at the same time. Another feature of the epiglottis at birth is its attachment to the arytenoid cartilages by relatively prominent and fleshy ary-epiglottic folds. This gives rise to an omega or inverted U-shaped complex that further protects against aspiration while breathing during suckling. Active, synchronized muscle tone during the respiratory cycle is required for patency of the upper airway and larynx. Lack of maturation leads to the most common upper airway problems in early infancy – laryngomalacia and vocal cord paresis.

The large occiput, relative micrognathia, large tongue and downfolded epiglottis can make mask ventilation and endotracheal intubation challenging. Supporting the shoulders and maintaining a neutral head position may counter this. The 'downfolded' position of the epiglottis makes it susceptible to being pushed against the laryngeal inlet if too long an oral airway is used. When using a supraglottic airway (SGA) device in a neonate or infant, meticulous care needs to be taken with positioning. Frequently the epiglottis will be visible if a flexible laryngoscope is passed through a SGA. During spontaneous ventilation this reflects the normal position, but will require the epiglottis to be lifted if the SGA is being used as a conduit for intubation.

The cephalad position of the larynx creates an acute angle with the base of tongue, making it appear *anterior* at direct laryngoscopy (Figure 2). Furthermore the relative inferior attachment of the hyo-epiglottic ligament makes for an inefficient lever if a laryngoscope is inserted into the vallecula (as with a MacIntosh blade in adult practice). For these reasons, a straight bladed laryngoscope inserted lateral to the tongue (to counter the extreme angle) with the tip positioned under the epiglottis, is preferred by many paediatric anaesthetists. The laryngeal inlet and inferior surface of the epiglottis are innervated by the vagus nerve, which may be stimulated by this technique resulting in bradycardia. Videolaryngoscopy may improve visualization particularly with micrognathic syndromes, abolishing the need to displace the tongue into the submandibular space.

Weak intercostal and diaphragmatic muscles (lack of type 1 fibres), horizontal ribs and a protuberant abdomen results in earlier onset of fatigue and less efficient ventilation. Minute volume is rate dependent, and a gas-filled over-distended stomach easily splints the diaphragm. Chest wall-specific compliance is higher, and intercostal or sternal recession is readily visible with increased respiratory effort or airway obstruction.



Note the axes, epiglottic ligaments, overlapping hyoid, thyroid and cricoid cartilages and relative large size of arytenoids in infant. (Redrawn from ML Norton. Atlas of the Difficult Airway, A Source Book. Mosby Year Book 1991).

Figure 2

Postnatal development of the airway

The paediatric airway gradually becomes adult-like, with a similar laryngeal view by year 4–5 (Figures 1 and 3). The posterior part of the tongue descends into the oropharynx, the tip of the epiglottis descends to the mid C3, the hyoid to the C3–C4 interspace, the glottis to the C4–C5 interspace and the cricoid to mid C5. During puberty there is slight further descent; predominantly the glottis to mid C5 and the cricoid to the C6-7 interspace.[1]

The tongue size relative to the oral cavity decreases and the prominent occiput recedes in infancy. The epiglottis adopts a firmer, flatter and more adult orientation. The ary-epiglottic folds become less prominent and the epiglottis is 'freed' from its attachment to the arytenoid cartilages, becoming more easily lifted by a laryngoscope placed in the vallecula. A 'sniffing the morning air' position combined with a curved MacIntosh laryngoscope is usually appropriate.

Lymphatic tissue, comprising the adenoids in the nasopharynx and the faucial tonsils, increases in size during the first decade. Maximal adenoid hypertrophy compromising the nasopharyngeal airway occurs in the early childhood years, and enlarged tonsils are the most common cause of obstructive sleep apnoea in children. This is exacerbated by inhalational anaesthesia when pharyngeal tone decreases, and may compromize mask ventilation.

The importance of the cricoid ring is that it is the only part of the larynx (and the lower airway) that is completely enclosed by cartilage. Its internal lining of mucous membrane is thus susceptible to oedema and inflammation due to excessive lateral pressure limiting perfusion. The cartilage is composed of a posterior plate-like portion (lamina) and an inferior ring portion (arch). Development of the cricoid ring is important in determining endotracheal tube selection and subglottic stenosis may arise from prolonged intubation.

The growth and development of the laryngeal cartilages in the first 3 years results in increasing separation of hyoid, thyroid and cricoid cartilages and, importantly, the cricothyroid membrane. Cricothyroid puncture whether by needle or knife, is exceedingly difficult before this age.

The neonatal trachea is 5 cm long, increasing the risk of inadvertent endobronchial intubation or unplanned extubation. It grows to 8 cm by 12–18 months of age. At birth less than one-tenth of the terminal air sacs are developed with 95% of the alveoli developing throughout infancy, resulting in 300–600 million alveoli before adolescence.

Laryngeal development: reconciliation of in vitro and in vivo observations

Classical teaching, based upon in vitro anatomical studies, has been that the infant larynx is conical or funnel shaped with its narrowest part at the non-distensible cricoid ring.[2] This belief shaped paediatric practice with the use of uncuffed tracheal tubes to produce a small air leak with positive pressure ventilation. However, recent in vivo studies using MRI-, CT- and bronchoscopy- derived measurements have questioned this long-held belief.[3–5] These studies suggest that the narrowest part of the

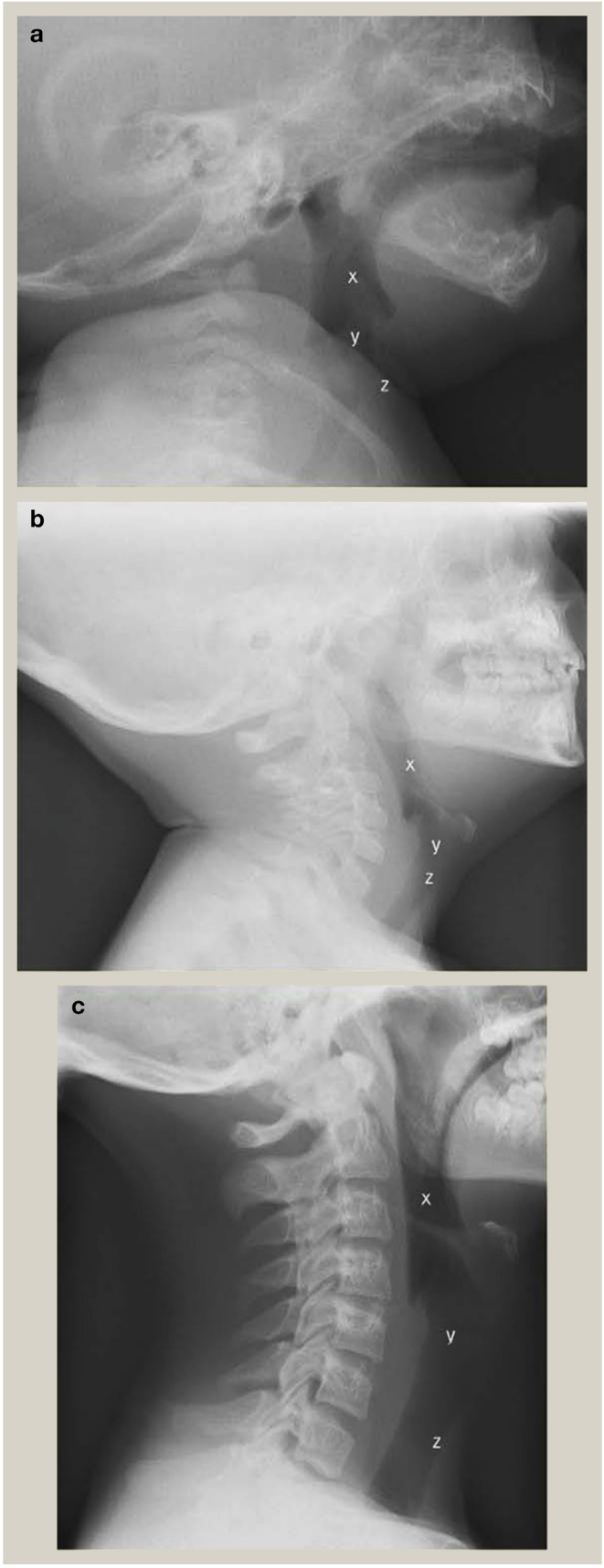


Figure 3 Lateral soft-tissue neck radiographs of children aged (**a**) 1 month, (**b**) 3 years and (**c**) 15 years, showing descent of the larynx with age. The tip of the epiglottis (x), the level of the vocal cords (y) and the level of the cricoid (z) are shown in each case. (Reproduced, with permission, from Kubba M, Moores T. *Anaesthesia and Intensive Care Medicine* 2006; 7: 158–60).

infant larynx occurs at the laryngeal inlet where the airway is elliptically shaped; the transverse diameter being significantly narrower than the AP diameter (Figure 4). The trachea from the glottis to the cricoid is cylindrical in its AP diameter, whereas it is funnel shaped in its transverse diameter, but with the apex of the funnel at the level of the glottis rather than the cricoid ring.This finding led to the increased use of cuffed tracheal tubes.

The accuracy of these in vivo studies, however, has recently been questioned. The laryngeal inlet is a distensible structure whose dimensions vary with the phase of respiration, depth of anaesthesia and neuromuscular relaxation. These factors were not controlled for in studies and so the assertion that the laryngeal inlet is the narrowest part of the infant larynx may be inaccurate. An in vitro study of fetus and infant has shown that the intra-arytenoid distance was greater than either the AP or transverse diameters of the cricoid outlet.[6] Below this level, the in vivo studies show that although slight differences in shape persist, the cross sectional area of the subglottic and cricoid regions are not different.

Although the exact anatomical shape of the infant larynx may still be unclear, several assertions can be made regarding airway management and intubation. Firstly, an uncuffed tube, even when a leak is audible, may cause lateral pressure at the glottis or the cricoid ring. Secondly, because the vocal cords are distensible but the cricoid ring is not, the cricoid remains the site at which circumferential oedema is likely to have the most impact on the airway.Thirdly, with the smaller cross section area of the paediatric airway, comparatively minor degrees of inflammation, oedema and secretions may result in substancial airway obstruction. Fourthly, because of the relative prominence of the arytenoid cartilages in the infant larynx, pressure injury in this area remains a risk with long term intubation regardless of endotracheal tube type.

Consideration of **Poiseuille's law**, where flow down a tube is proportional to the fourth power of the radius of that tube, shows that a 1-mm circumferential reduction in airway size from mucosal oedema at the cricoid in an infant would decrease the cross-section area by 75% and increase resistance 16- to 32-fold in an adult the cross section area decrease would be 44% and the increase in resistance would only be 3- to 5-fold.

Endotracheal intubation

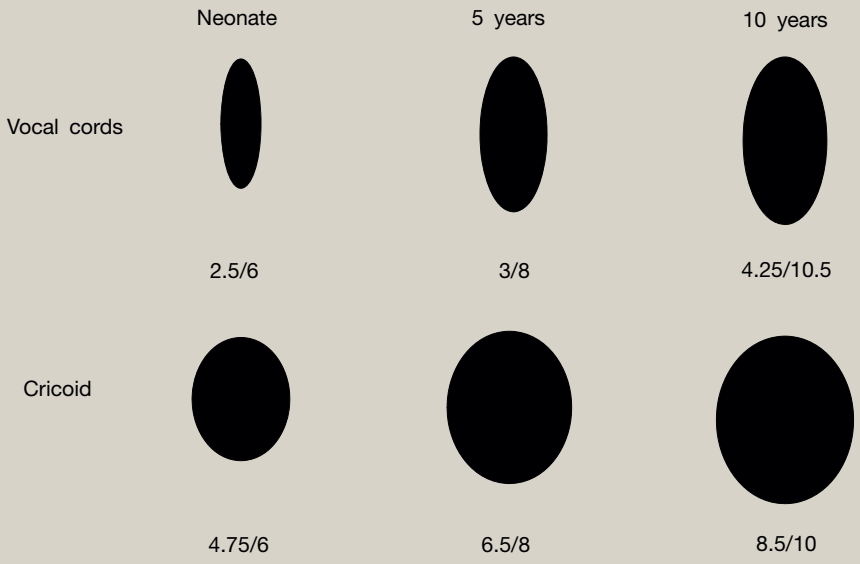
Cuffed and uncuffed tracheal tubes are available for children. Uncuffed tracheal tube size is based on the internal diameter of the tube. A range of tubes of smaller and larger internal diameter should be available and an audible leak check performed:

- premature neonate $<$ 2 kg; 2.5 mm
- premature infant 2–3 kg 3.0 mm
- term neonate- 6 months 3.5 mm
- infant 6–18 months 4.0 mm.

Children 2 years and older years the formula:

$$\text{Size} = (\text{age}/4) + 4.0\,\text{mm}$$

Comparative size and shape of the airway at the level of vocal cords and cricoid cartilage in children aged 10, 60 and 120 months, showing different cross section area and transverse diameter ratios.



(Drawn using data from Litman RS, et al. Developmental changes of laryngeal dimensions in unparalyzed, sedated children. Anesthesiology, 2003; 98: 41e5).

Figure 4

Cuffed tracheal tubes of the Microcuff type[a]

Age	Size	Internal diameter/mm	External diameter/mm	Cuff resting diameter/mm
> 3 kg–8 months	3.0	3.0	4.3	10
8 months–< 2 years	3.5	3.5	5.0	12
2–< 4 years	4.0	4.0	5.6	12

[a] MICROCUFF™ tracheal tubes are not recommended for use in infants weighing less than 3 kg. There are specific instructions for insertion and the size of endotracheal tube chosen for a particular child will differ from other varieties of cuffed tracheal tube.

Table 1

The formula used for ETT length is:

$$\text{Length} = (\text{age}/2) + [12\text{ mm (oral)}] \text{ or } [14\text{ mm (nasal)}]$$

This provides a rough estimate but position should be confirmed by observation of the tracheal tube through the vocal cords and presence of equal bilateral chest movement and breath sounds.

Paediatric cuffed tracheal tubes are available for use in neonates 3 kg and greater. These tracheal tubes have a cuff more distal on the tube and one that allows a high-volume, low-pressure ultrathin seal. Advantages include low-flow anaesthesia, reduced atmospheric pollution, decreased tracheal tubes exchanges to achieve correct 'fit', higher airway pressures achievable in non-compliant lungs, improved end-tidal carbon dioxide monitoring, and possible aspiration prevention during long-term ventilation. The main disadvantages are the need to reduce the diameter of the ETT by 0.5–1 mm (thereby increasing both airway resistance and work during spontaneous respiration) and removal of the murphy eye. Size recommendations are shown in Table 1. ◆

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