Challenges of the Neonatal Airway

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Overview

It has been well known in pediatric medicine that children are not just small adults—whether it is in response to stress, disease presentation, or overall anatomic and physiologic adaptation. It is also true that neonates are not just small children with respect to exactly the same set of differences. The neonatal airway is especially different from larger children's due mostly to the small size of all tubular structures, a proportionally large head and occiput, and the position of all these structures relative to the entire airway. These factors generally differentiate the neonate from the older child and adult, however, more specific differences exist as well.

The Neonate vs. the Adult

Anatomical Differences: Overview

Non-airway anatomical differences relate to head size, tongue size, jaw angle, the palatal arch, overall position, and muscle tone. One major difference is that the narrowest point of the neonatal airway is at the cricoid ring not the vocal cords as in adults [45]. This fact may be very important in explaining why many neonatologists intubating small infants can pass an endotracheal tube past the vocal cords but not advance beyond. The glottis opening is higher at C-1 and more anterior than adults [27]. Often there is a perception that there is some sort of obstruction, when it is simply the level of the cricoid cartilage that is reached. This has been considered a factor in referrals to pediatric ENT in many neonatal and infant intensive care units. Microscopic laryngoscopy bronchoscopy after referrals usually is normal in these infants, which highlights the importance of having bronchoscopy done at a center experienced with operating room set-up and equipment. It is very common that an infant referred for an airway obstruction ultimately has a normal bronchoscopy, reflecting only the normally occurring narrowed cricoid cartilage (Fig. 1).

The Upper Airway

The airway of the younger child is very different from that of the older child or adult, and these pediatric features are usually present until about age 8 or 9. After this age, the airway becomes more adult-like in configuration, and the generalist emergency physician is on more familiar grounds. There are many levels of differences from the nose and mouth to the tracheal bifurcation and, generally, more malacia of structures due to a relatively greater amount of connective tissue and weak supraglottic tissue. In general, the segments of the upper airway include the nasopharynx, oropharynx, hypopharynx, and larynx.

Nasopharynx

One of the most important factors in the infant's anatomical differences is the nasal anatomy. It is long standing common knowledge amongst neonatal physicians and caregivers that the infant is an obligate nose breather until approximately 3–6 months of age [32]. The obvious consequence of this fact is that they are reliant upon patent nares for adequate ventilation. Even the smallest nasal congestion is thought to potentiate

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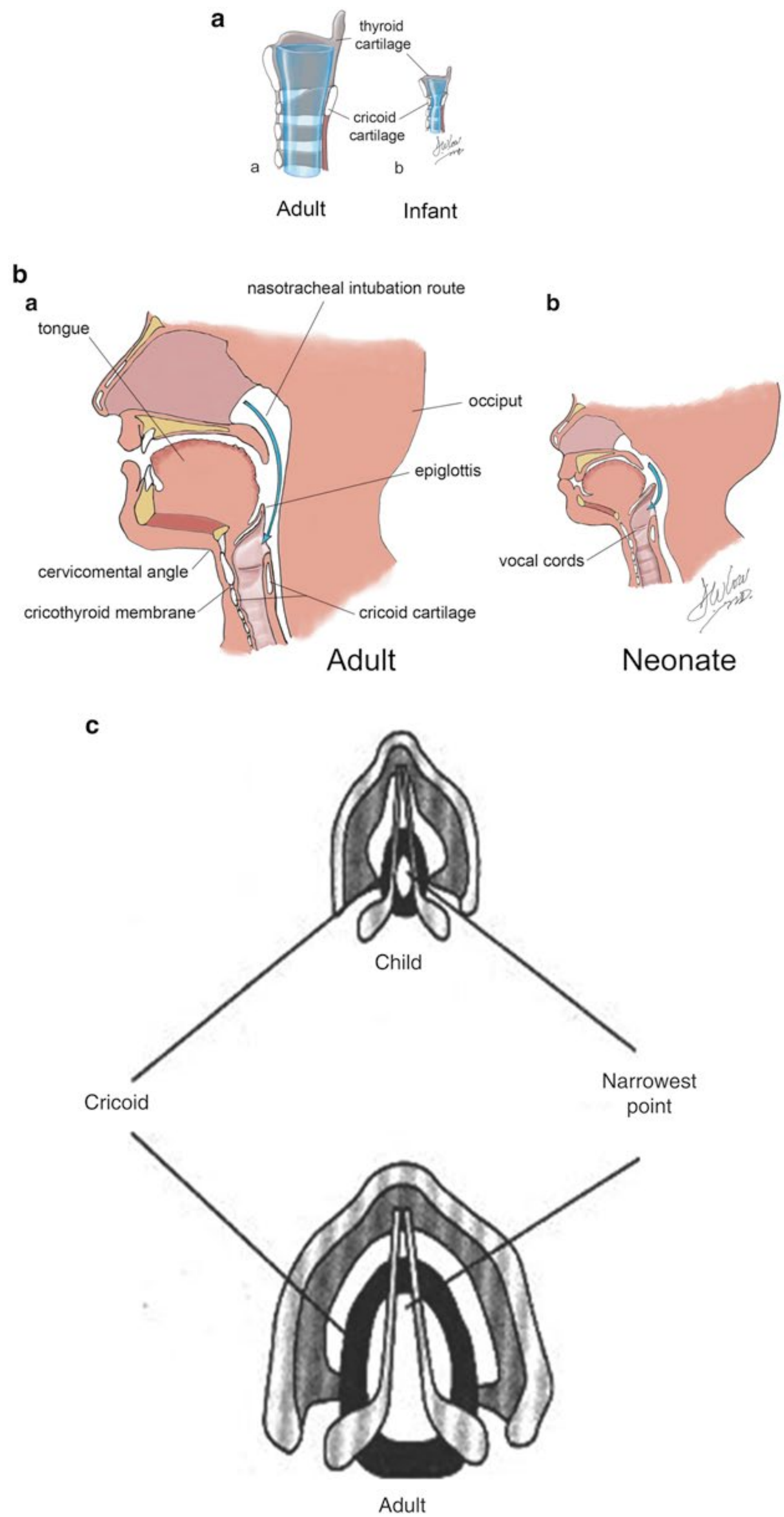
Fig. 1 (**a**) Narrowest point of airway: Adult vs Neonate. Note the more superior position of cricoid ring in the neonatal airway vs adult. (Courtesy of David Low, CHOP). (**b**) Sagittal View of the Adult vs Neonatal Airway. Note the reduced nasopharyngeal space and larger occiput of the neonate contributing to the tendency for tongue based obstruction during airway emergency situations. (Courtesy of David Low, CHOP). (**c**) Cross section of the narrowest point of the airway: Neonates vs Adults, (adapted from Wheeler and Shanley, et al. eds. Resuscitation and Stabilization of the Critically Ill Child). Springer, 2009. (**d**) Major anatomic differences between infants and adults



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	Infant	Adult
Head	Large, prominent occiput	Flat occiput
Tongue	Relatively larger	Relatively smaller
Larynx	Cephalad position Opposite to C2–C3	Opposite to C4–C6
Epiglottis	Omega-shaped & soft	Flat and flexible
Vocal cords	Short & concave	Horizontal
Narrowest portion	Cricoid ring, below cords	Vocal cords
Cartilage	Soft	Firm
Lower airways	Smaller, less developed	Larger, more cartilage

obstructive apnea. Due to a high metabolism, small lung volumes, and reduced functional residual capacity, the oxygen reserve is relatively decreased, which can relate to rapid desaturations and cyanosis. Interestingly, however, recent studies have shown that infants can mouth breathe during both spontaneous breathing and nasal occlusion. [3]. The term preferential nose breathers may be a better term as, under normal circumstances, the infant does breathe through the nose. Subsequently, any decrease in airway diameter due to secretions or inflammation can significantly add to the infant's work of breathing. As such, rapid respiratory rate, grunting, and nasal flaring are key signs of respiratory distress in infants.

In considering the nasal anatomy, there are also some common conditions that obstruct the nasal cavity in neonates. *Choanal stenosis/atresia*, a posterior nasal obstruction, is seen approximately one in every 5,000–7,000 births and increasingly diagnosed with the utilization of high definition prenatal ultrasound. Rarely, nacrimal duct cyst or nasal mass can present as nasal obstruction and must also be ruled out by CT during the evaluation process. The surgical outcome for choanal stenosis/atresia is largely dependent upon the degree of bony atresia, size of the infant, and frequency of restenosis [25, 26, 42]. *Congenital pyriform sinus aperture stenosis*, also a rare condition, is a cause of nasal obstruction but a different entity than choanal atresia by virtue of location. In this case, obstruction occurs at the anterior nasal bony inlet, and the diagnosis carries genetic significance in that it is associated with holoprosencephaly, hypopituitarism and septo optic dysplasia [26, 42, 48]. Nonetheless, surgery is required for both conditions with stent placement and long hospitalization, giving rise to many potential airway obstructive episodes during the healing process. Other less common causes of nasal obstruction include nasal encephaloceles, nasal septal deviation, and tumor of the nasopharyngeal cavity (Fig. 2).

Oropharynx

The oropharynx consists mostly of the tongue and palatal structures. Macroglossia with tongue-based obstruction is frequently seen in neonates with certain genetic conditions such as trisomy 21 and Beckwith Weidmann syndrome, which can require tracheostomy in extreme cases. The palatal structures usually do not cause airway obstruction by themselves, unless congenital malformations of the palate occur causing complete oropharyngeal obstruction. In addition, tumors arising from the palate may be the source of oropharyngeal obstruction in rare cases (Fig. 3).

Mandible

Retrognathia and micrognathia cause life-threatening airway obstructions in neonates if either is present in a severe form. While retrognathia relates to a recessed position of the jaw, micrognathia relates to the actual size of the mandible with both causing tongue-based obstructions. Many genetic syndromes like Robin sequence and Stickler syndrome can be associated with these conditions and should be ruled out. Treatments such as tongue–lip adhesion and tracheostomy have long been the mainstay of treatment for tongue-based obstruction. Of particular interest, mandibular distraction osteogenesis has recently proven to be an effective technique in relieving the obstruction in a relatively short period of time (Fig. 4).

Tongue

In proportion to the adult, the infant tongue is larger and potentially more obstructive [45]. Although instrumental in the suck-and-swallow mechanism, the tongue can compromise the pulmonary status of the infant by falling to the back of the pharynx and causing an airway obstruction. Generalized neck muscle or pharyngeal muscle hypotonia can exist with other conditions and together create a tongue-based obstruction and airway emergency. It is well known and obvious to those caring

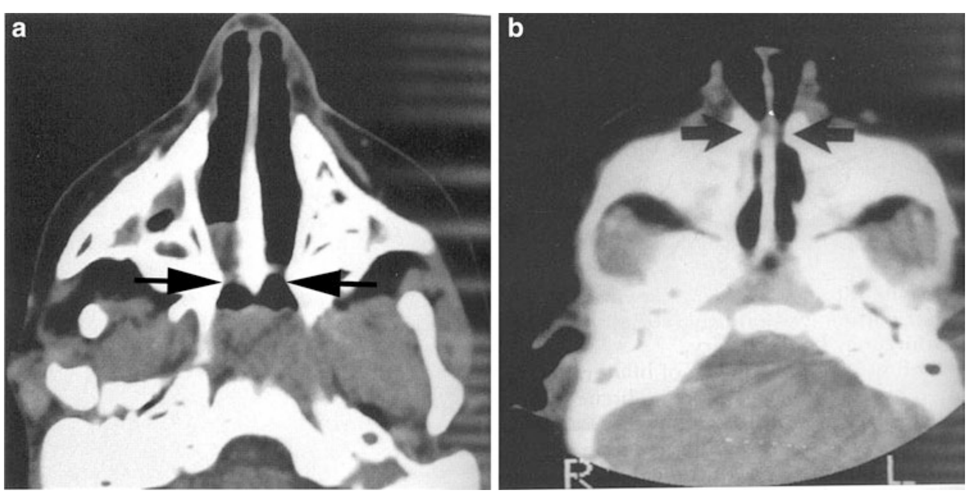

Fig. 2 (**a**, **b**) CT scan of head showing: (**a**) Choanal atresia and (**b**) pyriform aperture stenosis. Note the differences in location of these embryologically different but similar clinical nasal obstructions. (Courtesy of Steve Sobol, CHOP Neonatal Airway Program)

Fig. 3 (**a**, **b**) Photographs of infants with complete oropharyngeal airway obstruction: (**a**) oropharyngeal teratoma and (**b**) Epignathus (Courtesy of Alan Flake MD, Children's Hospital of Philadelphia)

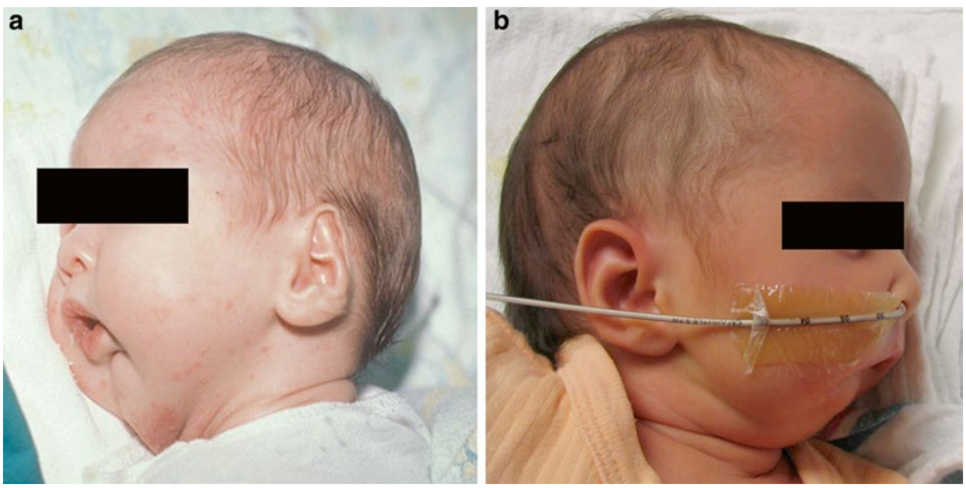

Fig. 4 (**a**, **b**) Photographs of infants with severe Micrognathia (**a** and **b**), (Courtesy of Jesse Taylor MD, Children's Hospital of Philadelphia)

for sick neonates that the tongue always seems too large for the mouth. As such, the tongue frequently impedes intubations and is one of the major causes of failure to maintain a stable airway. Conditions such as Trisomy 21 and Beckwith-Wiedemann syndrome are regularly associated with large tongues. Flexion may also provide a positional contribution to upper airway obstruction in these neonates. Many of these tongue-based obstruction syndromes are underappreciated and are often mistaken for central apnea, gastroesophageal reflux, or other cardiovascular episodes causing an unstable situation. During an emergency, insertion of an oral airway is important in maintaining a patent airway in these types of infants. In neonates, anything that is inserted into the nose or mouth can obstruct the airway further. However, in a spontaneously breathing infant a nasopharyngeal trumpet or a simple nasopharyngeal endotracheal tube is often underutilized and should be considered when intubation is impossible (Fig. 5).

Fig. 5 Photograph of infant with Beckwith-Wiedemann syndrome showing extreme macroglosssia (Courtesy of Ian Jacobs MD, Children's Hospital of Philadelphia)

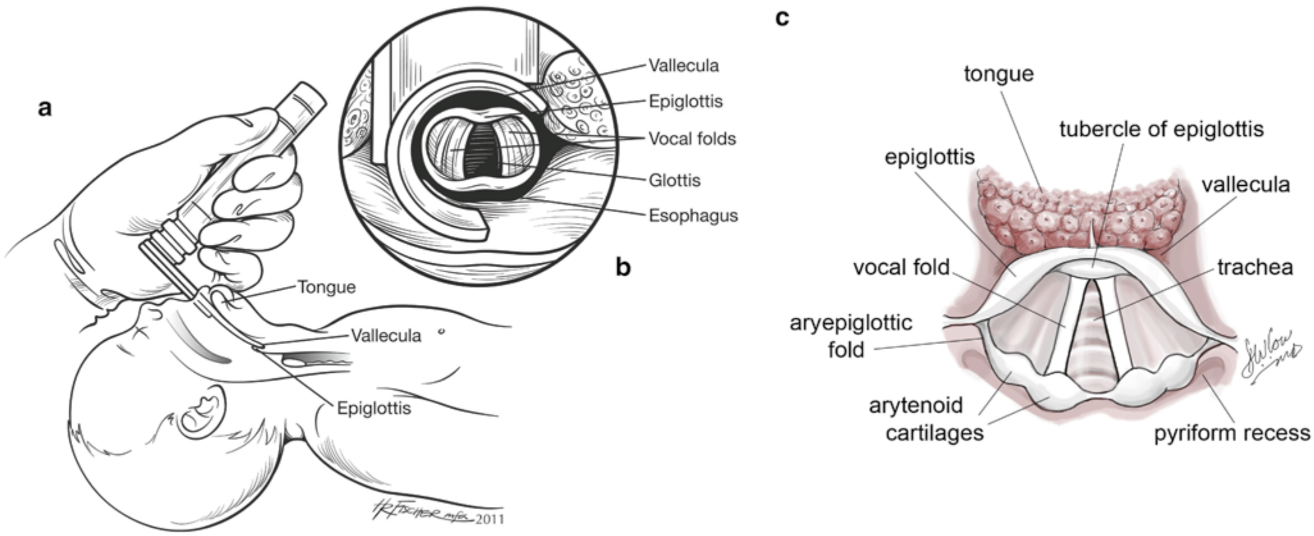

Fig. 6 (**a**–**b**) Proper view during laryngoscopy of the neonate. Note the correct position of the blade in relation to the glottis opening. Compare with the detailed anatomic drawing of the neonatal airway showing all structures in relation to one another. (adapted from Weissman and Donn. Steve Donn, et al. Manual of Neonatal Respiratory Care, 3rd ed. Springer 2012. (**c**) (Courtesy of David Low, CHOP)

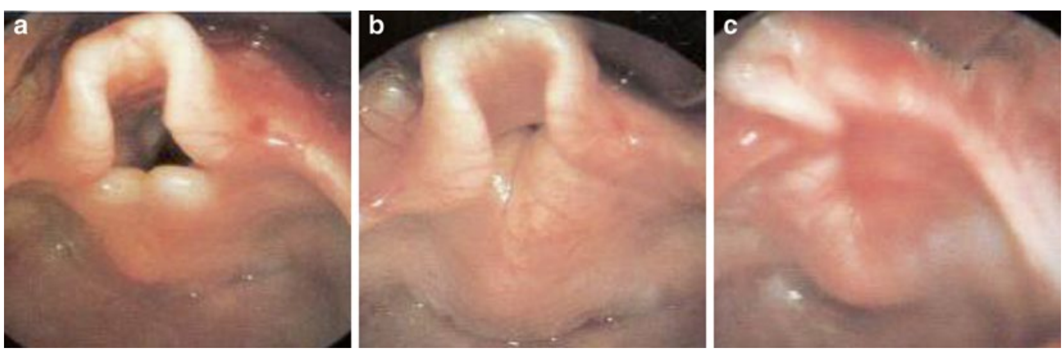

Fig. 7 (**a**–**c**) Photographs showing severe laryngomalacia. (Courtesy of Steve Sobol, Neonatal Airway Program, CHOP)

Hypopharynx and Larynx

The hypopharynx includes the structures seen during intubation such as the epiglottis and vallecula, and the larynx is the entrance to the airway including both the true and false vocal cords.

Typically described as being cone-shaped with the narrowest segment at the level of the cricoid cartilage the infant larynx lies higher in the neck in relation to the cervical spine [27, 28] (Fig. 8). The larynx is also proportionally smaller, while the surrounding arytenoids and folds are larger relative to the surrounding larynx [26, 42]. The larynx descends as the infant grows into a child and is similar to an adult airway by the age of six. The most important structure, the epiglottis differs in infants from adults in three ways: it is proportionally longer, narrower, larger, less flexible, and often Omega-shaped. These factors may lend to airway obstruction under certain conditions and also make it extremely susceptible to trauma during intubating, suctioning, or examining the infant upper airway.

The supraglottic and glottic anatomy in the neonate is more compact and difficult to visualize for the inexperienced. The aryepiglottic folds, arytenoid cartilages, and epiglottis can all look like one structure when secretions and edema obscure a clear view. Critical landmarks for exposure include the base of the tongue, tip of epiglottis, and vallecula. When intubating with a rigid blade, knowledge of these landmarks is essential to successful intubation (Fig. 6).

Laryngomalacia is a major and common problem in certain neonates resulting from a combination of the aforementioned anatomic characteristics and the physics of airflow through a tube (Bernoulli's effect of less pressure on tubular walls with fast flow and Venturi effect of collapse of these low pressure walls with inspiration) [26, 42]. Recent use of supraglottoplasty surgery with release of tight aryepiglottic folds early in neonates with severe laryngomalacia has allowed earlier feeding and discharge. Previously many of these neonates experienced repeated bouts of airway obstruction, some even going on to tracheostomy (Fig. 7).

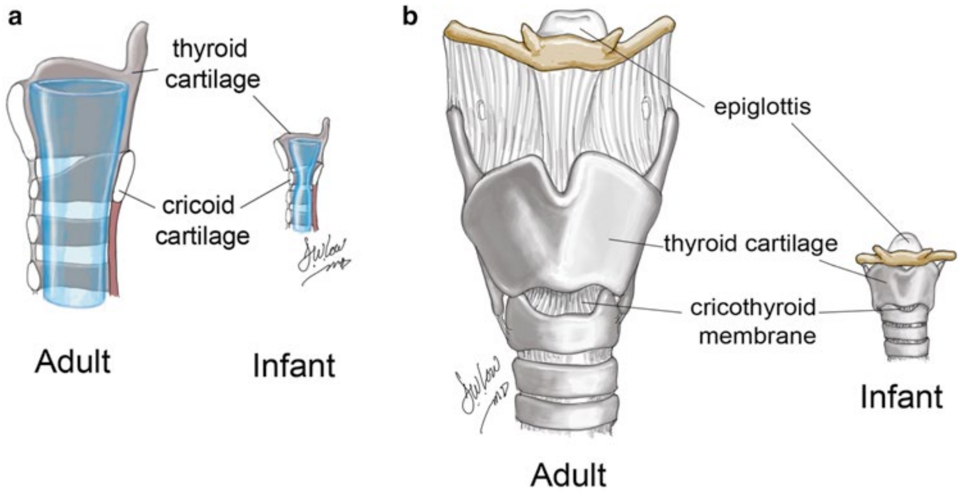

Fig. 8 (**a**, **b**) Differences in the size and location of cricothyoid membrane, cricoid and thyroid cartilage in infants and adult. (Courtesy of David Low, CHOP)

	Tracheal length	Tracheal diameter
Neonate	3 cm	6.5 mm
Toddler	5-7 cm	6 mm
Adult	9-15 cm	14-16.5 mm

Fig. 9 Table of tracheal dimensions: neonates vs adults (Adapted from Chap. 25, Ian Jacobs, MD Fundamentals of Pediatric Surgery, in Peter Mattei editor: Springer

The larynx is separated from the trachea by the cricoid cartilage which is and is entirely composed of cartilage [26, 42].

The narrowest point in the infant airway is the cricoid cartilage ring (in contrast to adults—which is the epiglottis). Due to the narrowing of the airway of this cricoid ring, many people refer to the infant airway as funnel shaped. A 3-D image of the neonatal trachea looks more like an "hourglass" than a tube. Again, it is the cartilaginous cricoid cartilage making up the narrowest part of neonatal airway with a point of resistance at the cricoid ring, often a common area of difficulty in a preterm infant during intubation of a difficult/critical airway by most neonatologists (Fig. 8a, b). This natural narrowing is the reason that uncuffed endotracheal tubes are used almost exclusively in neonates. Anatomically, this area forms a complete cartilaginous ring approximately 2 cm in length starting below the vocal cords. Knowledge of these airway differences is the most important factor in determining the skill and ease of airway visualization and access and ultimate success in intubation [27, 28].

The Lower Airway

The cricoid cartilage marks the true beginning of the lower airway.

The first structure encountered is the trachea, which ends at the carina. The tracheal size and length vary with age (Fig. 9).

The neonatal trachea is much shorter, narrower, and more compact than the adult trachea proportionally, and a high tracheal position at C1-2 can result in anteroposterior differences. There are major differences in the length and diameter of the trachea at different age groups (Fig. 9). The trachea is "C" shaped with soft trachealis muscle posteriorly and a 3:1 ratio of rings/muscle circumference. The soft muscle provides flexibility during breathing but can be the source of severe collapse in cases of significant tracheomalacia [45]. At the level of the cricoid ring any mucosal edema will encroach on the lumen, resulting in exponential increases in resistance to airflow per Poiseuille's law (that is, air flow is proportional to the fourth power of the airway radius) [27, 28].

Neck

The neck of the infant compared to the adult is much shorter, composed of more subcutaneous fat, and often requires different maneuvers while intubating when compared to a child or an adult. Cricoid pressure is often necessary during intubation to overcome the limited space and lack of anatomical landmarks easily seen in adults or children.

Airway Resistance

The diameter of the pediatric airway is much smaller than the adult airway, making it far more vulnerable to obstruction by either foreign objects or edema. Minor narrowing from respiratory infections or bronchospasm may result in

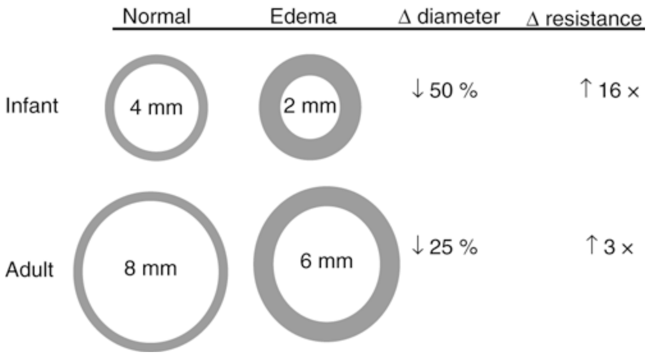

Fig. 10 Differences in luminal size and airway resistance with 1 mm circumferencial edema: Adult vs Infant. (Adapted from Wheeler et al., [56]. In Wheeler et al., Resuscitation and Stabilization of the Critically Ill Child). Springer, 2009

profound airway difficulties in the pediatric patient. Airflow through a pipe like the bronchi is described by Poiseuille's equation. Airflow in the narrowed airway meets resistance that is described by an inverse proportion to the fourth power of the radius of the airway for laminar airflow, and to the fifth power for turbulent airflow (Fig. 10).

$$R = 1/r^4$$

(R is resistance and r is the radius)

Illustrating that a mere 1 mm of circumferential edema in an infant's airway will increase the airflow resistance 16-fold. With turbulent airflow, such as in a crying child, the work of breathing increases 32-fold.

Soft Tissue

Developmental changes in the soft-tissue structures of the upper airway occur with age. Radiographic studies show that bony structures remain proportionately the same size. Adenoidal tissue disproportionately increases in the size between 3 and 5 years of age, resulting in a narrowing of the nasopharyngeal airway. Subsequently, bony growth outstrips soft tissue growth, and the airway dimensions increase [34]. Therefore, due to these anatomic differences when muscle tone is reduced, for example, in the setting of a reduced level of consciousness, the head will flex and pharyngeal tone will diminish, resulting in reduced oropharyngeal volume and occlusion of the oropharynx by the tongue. Accordingly, airway-opening maneuvers are required to maintain airway patency. Here, the application of basic adult principles is usually sufficient to provide airway support until additional pediatric help is available. Simple airway-opening techniques, such as head tilt and jaw thrust, are usually sufficient to open the child's airway [9, 10].

Physiological Differences

First, it is well known that lung function in neonates is like no other time in life. There are notable differences with chest wall compliance, functional residual capacity, oxygen metabolism, and muscle fiber type and function. Term healthy infants have reduced functional lung capacity due to more compliant rib cages, a challenging diaphragm angle with unfavorable insertion anatomy for minimal work of breathing. However, by the age of 8, the overall lung function, alveolar growth, and airway properties are very similar to that of an adult [45]. The child's chest wall is more compliant than an adult's because it is more cartilage than bone. The diaphragm is higher due to the relatively larger size of the abdominal contents and the smaller lung volumes of the child. Additionally, the child's lungs are also small in relation to the child's metabolic needs, so there is a smaller margin than in the adult. Infants and children have basal oxygen consumption twice that of adults [27, 28]. Overall, infants and small children are at high risk of respiratory problems because of their immature physiologic responses. The infant will become apneic and bradycardic in response to a hypoxic challenge, instead of increasing the respiratory effort and heart rate.

Differences in pulmonary physiology also affect airway management. Infants have higher oxygen consumption rates (6–8 mL/kg/min vs. 4–6 mL/kg/min) than adults. Infants also have a higher ratio of minute ventilation to functional residual capacity. This results in steep declines in arterial oxygen partial pressures if the airway becomes occluded and subsequently requires more rapid resolution of airway compromise if hypoxic injury is to be avoided [46]. The child's diaphragmatic muscles can be fatigued by increased work of respiration, and the mechanics of the child's inspiration can suffer. Likewise, a distended stomach can compress the diaphragm, even after intubation.

Identifying Potential Airway Emergencies

Overview

An airway emergency in a neonatal intensive care unit can be disastrous without the right training, the right equipment, and the right people capable of responding within minutes. Additionally, knowledge about the differences between preterm and term neonates compared with the pediatric patient and even the adult is necessary to ensure rapid adaptation during an emergency. Practical guidelines for extreme airway emergencies in neonates do not exist as they do for pediatric or adult patients, and neonatal resuscitation program (NRP) guidelines are often used for resuscitation in community delivery room settings [63].

Neonatal and infant airway emergencies are often chaotic and there needs to be an organized team effort. Babies are

Fig. 11 Common diagnosis posing potential airway emergencies in neonate

Level of Obstruction	Conditions
Nasal	Choanal Stenosis Choanal Atresia Nasal Encephalocele Nasal Dermoid Pyriform Aperture Stenosis Nasal Cyst Nasal Septal Deviation Tumor/Teratoma Nasal Polyps
Pharyngeal	Vallecular Cyst Cleft Palate Tumor/Teratoma Micro/Retrognathia Macroglossia Hypotonia/Reduced Pharyngeal tone
Cervical	Lymphatic Malformations (Cystic Hygroma) Teratoma
Laryngeal	Laryngomalacia Laryngeal Cleft Ventricular or Other Laryngeal Cysts Subglottic Stenosis Vocal Cord Paralysis
Tracheal	Congenital Tracheal Stenosis Complex Tracheomalacia (esophageal atresia) Vascular Ring Tracheal Cyst
Bronchial	Bronchial Tumors
Pulmonary	Bronchopulmonary Dysplasia Congenital Cystadenomatoid Malformation
Chest wall (Mechanical/ Neuromuscular)	Asphyxiating Thoracic Dystrophy Muscular Dystrophies
Multiple Craniofacial/ Airway Anomalies	Pierre Robin Sequence Treacher Collins syndrome Crouzon syndrome Apert syndrome Trisomy 21 Beckwith-Wiedemann syndrome

often admitted to neonatal units with unrecognized problems, which can quickly become emergencies during accidental extubations or onset of acute illness. Thus, having a well-thought-out approach to identifying potential airway emergencies is imminently important. The following table lists common disorders associated with neonatal airway emergencies (Fig. 11).

Airway Emergency Profiles

Non-Intubated (Unanticipated Emergencies)

A surprisingly common group of patients that develop airway emergencies are non-intubated. Thus, these cases represent unanticipated emergencies. The origin of the emergency often relates to comorbidities and the onset of acute illness (i.e. sepsis). Additionally, an emergency may develop during attempts at anesthesia. These patients are not labeled as airway risks, but the potential for emergency is realized as additional problems arise. For example, a neonate will get sick and require an airway, but the airway is surprisingly difficult to establish. In these attempts, the airway problem is revealed. Perhaps unsurprisingly, these are the most shocking cases because you can never predict which patients will fall into this category.

Unplanned Extubation (Unanticipated Emergencies)

This group of patients presents with an endotracheal tube already in place. However, they have no previously identified

Fig. 12 Difficult vs. critical airway

Difficult Airway	***Critical Airway***
Non-life threatening History of difficult intubation	Life threatening Impossible visualization
BMV-LMA possible	BMV-LMA impossible
Experienced intubator necessary	ENT required
Mild craniofacial micrognathia Midface hypoplasia Macroglossia Anterior larynx Subglottic narrowing Small mouth	Fresh tracheostomy < 1week Laryngeal web Severe subglottic stenosis Tracheal clefts Severe craniofacial defect Severe micrognathia Severe macroglossia Oropharyngeal tumor Lymphangioma Obstructing Neck mass

airway issues. It is often in the case of an inadvertent extubation that the problem is uncovered. Upon replacing the endotracheal tube, the patient becomes classified as a difficult airway. The key in this subset of patients is that they would never be realized as a potential airway emergency until the need to reestablish the airway.

Tracheostomy Patients

Classically high-risk patients with tracheostomies are especially high-risk in the first week of placement when the stoma is not well formed. Essentially, an open wound still exists, in other words a "fresh tracheostomy." As such, stay sutures are necessary because of the high potential for a problem.

Fresh Tracheostomy with Accidental Decannulation in the First Week

The most obviously high-risk patients that exist in the neonatal ICU are those who had a tracheostomy placed in the last week due to the lack of maturity of the stoma and the nature of the fresh wound. In these cases, it is extremely easy to false track a tracheostomy tube while reinserting. Often, unsuccessful attempts at replacement can lead to false passage into the mediastinum, resulting in pneumothorax/pneumomediastinum and potentially death.

Mature Tracheostomy Reinsertion Difficulty with Distress

Occasionally, an infant with a mature tracheostomy can still have difficulty with insertion of a tube upon changing. Since routine cleaning (approximately every 7 days) and upsizing make reinsertion of tube relatively frequent events, there is a high potential for complications. Even with a mature stoma, there is still a risk of false tracking. Additionally, during upsizing of tracheostomy tubes, accidental false passage can occur if the procedure is not correctly followed or the wrong size tube is applied. An over- or undersized tube inherently leads to poor fitting and placement, substantially increasing risk of emergency. Sadly, neonatal patients can go home with mature tracheostomies and die at home because reestablishment of the tracheostomy becomes unexpectedly difficult during routine maintenance.

Labeling Patients

As noted previously, the neonate that represents a challenge in establishing an airway is classified as either a difficult airway or a critical airway. Labeling patients with regards to airway risk severity is an important aspect of avoiding and responding to emergencies (Fig. 12).

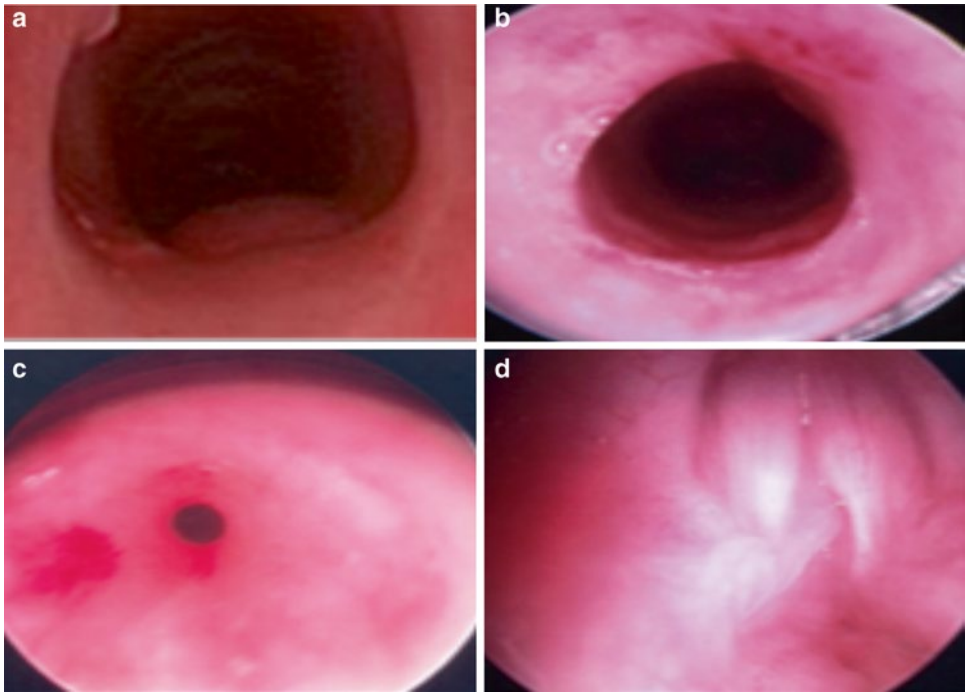

Fig. 13 (**a–d**) Myer-Cotton staging for subglottic stenosis. (**a**) Grade 1–50 % obstruction. (**b**) Grade 2: 51–70 % obstruction. (**c**) Grade 3 >70 % obstruction. (**d**): Grade 4—No detectable lumen. (Courtesy of Steve Sobol MD, Children's Hospital of Philadelphia)

Difficult Airway

The American Society of Anesthesiologists Task Force on Difficult Airway Management defined use of the term *difficult airway* to represent a clinical situation where an experienced, conventionally trained anesthesiologist encounters difficulty with bag mask ventilating or intubation or both [24, 39, 43]. This definition also includes but is not limited to difficulties with visualization on laryngoscopy. A difficult airway is usually when bag mask ventilation is ultimately successful, but intubation can only be accomplished by a skilled, high-level clinician, and the risk of death is low. Although these guidelines are now 10 years old, they still hold true today. While defined by anesthesiologists, this classification is important for the neonatologist as airway management skills in the neonate falls within their scope of practice.

Critical Airway

As an extension of the difficult airway, the critical airway is defined by a situation where bag mask ventilation is unsuccessful and fiber optic intubation by high-level ENT clinician is required to establish an airway. Neonates with a critical airway are at serious risk of cardiopulmonary decompensation and would ultimately die without the airway. Also included in this category are patients with a fresh tracheostomy in the first week of placement. While still a particularly stressful clinical scenario, "the critical airway can be safely and effectively managed when a composed surgeon follows a sensible thought process and conducts a directed work up as part of a multidisciplinary care team" [63].

A common example of patients with a critical airway is witnessed in cases of acquired subglottic stenosis. The Myer-Cotton staging system is useful for mature, firm, circumferential stenosis confined to the subglottis. It describes the stenosis based on the percent relative reduction in cross-sectional area of the subglottis as determined by differing sized endotracheal tubes. Four grades of stenosis are described with this system: [35] (Figs. 13 and 14).

Summary

Knowledge of the differences between adult and neonatal airway size, structure and function is essential in understanding the specific conditions both congenital and acquired that affect neonates. Awareness and familiarity of different levels of anatomic and physiologic distress will be vital in responding to airway obstruction requiring different emergent treatment solutions. Finally, understanding the differences between "difficult" and "critical" airways is necessary for proper preparation and anticipation for airway emergencies that cannot be predicted beforehand.

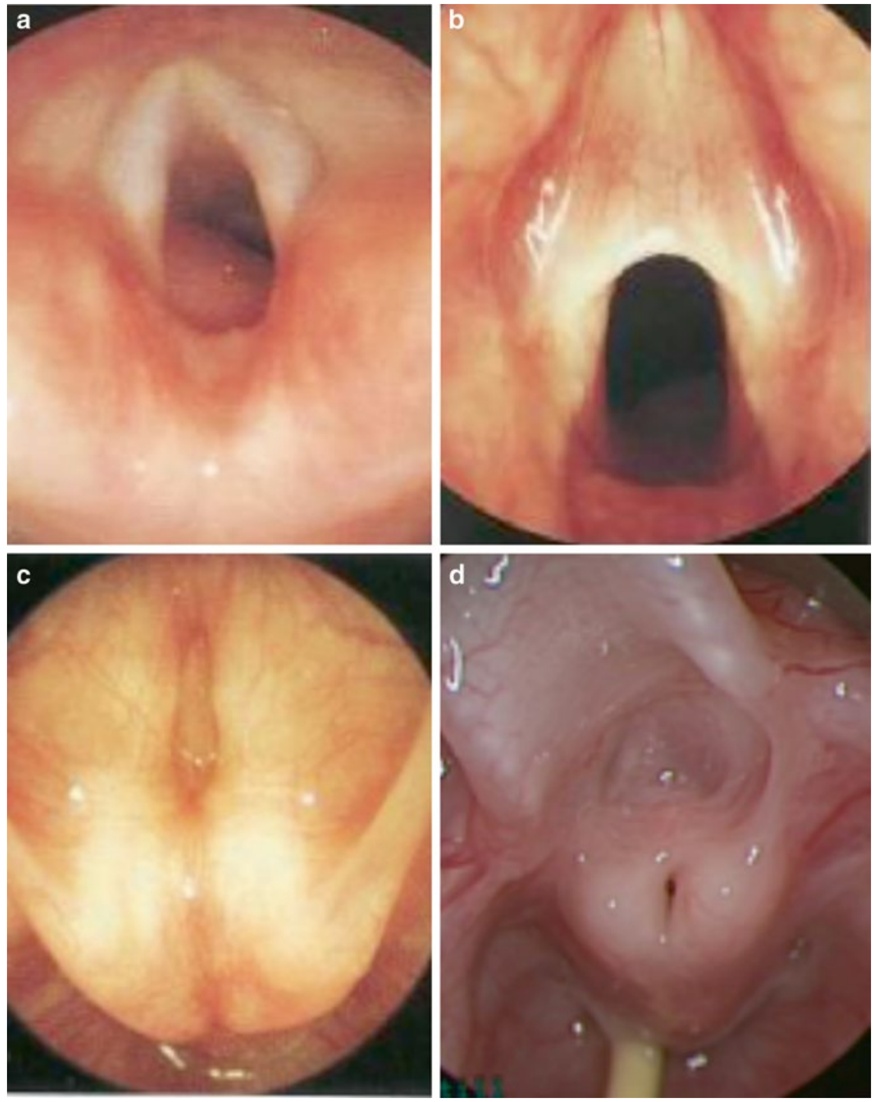

Fig. 14 (**a–d**) MLB pictures of congenital laryngeal anomalies causing airway obstruction. (**a**) Glottic lymphangioma; (**b**) Laryngeal Web; (**c**) Tracheal Atresia; (**d**) Vocal Cord Atresia. (Courtesy of Ian Jacobs, Children's Hospital of Philadelphia)

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