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Review article

Anatomy and assessment of the pediatric airway

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Summary
Airway and respiratory complications are the most common causes of morbidity during general anesthesia in children. The airway changes in size, shape and position throughout its development from the neonate to the adult (1). Knowledge of the functional anatomy of the airway in children forms the basis of understanding the pathological conditions that may occur. This in turn allows a comprehensive assessment of the pediatric airway to take place, including a detailed medical history, clinical examination and specific investigative procedures.

Keywords: pediatric; airway; anatomy; assessment

Introduction

The airway extends from the external nares to the junction of the larynx with the trachea. It includes the nose, the paranasal sinuses, the pharynx and the larynx (2). Functions of the airway include phonation, olfaction, digestion, humidification and warming of inspired air (3). The pediatric airway differs from the adult airway particularly in infancy, with differences becoming much less marked as the child grows older (4,5). During the course of pediatric anesthesia, airway and respiratory complications are the most common causes of morbidity and frequently occur in healthy children, particularly infants. A comprehensive method for assessment of the pediatric airway is facilitated by knowledge of the normal anatomy.

Anatomy

The skull develops from a membranous and cartilaginous neurocranium. The membranous neurocranium gives rise to the flat bones of the skull (the cranial vault) and the cartilaginous neurocranium (chondrocranium) forms the skull base. The shaping of the skull base is a dynamic process involving reciprocal influences between the cranial base, the pharynx, the face and the palate (1). In the fetus, the rapid growth of the brain leads to a predominance of neural influences; whilst in the neonate and young child, nasal influences play a major role. Later, because of changing nutritional requirements and the development of speech, the pharynx also influences the development of the skull base. Children have a proportionally larger head and occiput relative to body size. This causes neck flexion, leading to potential airway obstruction when lying supine (5).

Nose

The nose originates in the cranial ectoderm and is composed of the external nose and the nasal cavity (1). The external nose is made up of the nasal bones, the nasal part of the frontal bones and the frontal processes of the maxillae. The nasal cavity is subdivided by the nasal septum into two separate compartments that open to the exterior via the nares and into the nasopharynx via the choanae or posterior

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nasal apertures (6). Immediately within the nares lies the vestibule, which contains an area of arterial anastomosis known as Little's area. Epistaxis commonly occurs from this zone. The sensory innervation of the nasal mucosa is via the maxillary division of the trigeminal nerve.

During development, the nasal cavities extend under the influence of the posteriorly directed fusion of the palatal processes. These changes cause the membrane that separates the palatal processes from the oral cavity to become progressively thinner and eventually rupture to form the choanae or posterior nasal apertures (1). Failure of this membrane to rupture results in choanal atresia. In a child, the nose is soft and distensible, with relatively more mucosa and lymphoid tissue than in the adult (7). Deviation of the nasal septum occurs in all ages of children and may be the result of nasal injury or irregular development of the nasomaxillary complex (8). Racial differences in the dimensions of the nasal cavity have also been described (9).

Each side of the nose has a roof, a floor, a medial wall and a lateral wall (6). The roof slopes upwards and backwards to form the bridge of the nose, with the floor being concave from side to side. The medial wall is the nasal septum and the lateral wall has a bony framework which includes three scroll-like conchae or turbinate bones. The major nasal air passage lies beneath the inferior turbinate, and during nasal intubation the endotracheal tube should be encouraged to follow this route by passing it directly backwards along the floor of the nose. The posterior end of the inferior turbinate may occasionally be hypertrophied, resulting in resistance to the passage of the tube (6).

Nasal breathing increases the resistance to airflow (7). In children, the smaller nasal apertures are easily obstructed by secretions, edema or blood. As infants are obligate nasal breathers, such conditions may increase the work of breathing, and similarly contribute to difficulties with management of the airway under general anesthesia.

Paranasal sinuses

The paranasal sinuses are out-pouchings from the lateral wall of the nasal cavity into which they drain, and comprise the ethmoidal, maxillary, frontal and sphenoid sinuses (6). The ethmoidal and maxillary sinuses are present at birth. The frontal sinuses develop later and can usually be demonstrated radiologically by the age of 5 or 6 years. The sphenoid sinuses develop late in childhood and are not usually clinically significant until adolescence (7). They separate the nasopharynx from the sella turcica containing the pituitary gland (6). Sinusitis may lead to airway obstruction caused by copious and tenacious secretions within the small passageways. Cellulitis, edema or abscess formation may also occur.

Pharynx

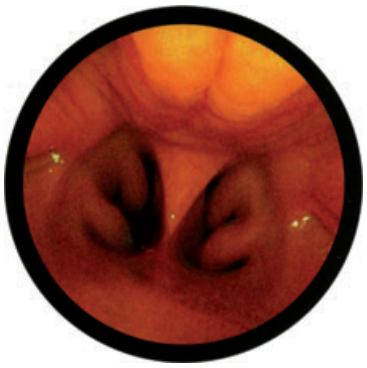
The pharynx forms the common upper pathway of the respiratory and alimentary tracts. It is in free communication with the nasal cavity, the mouth and the larynx, forming the nasopharynx, oropharynx and laryngopharynx, respectively.

Nasopharynx

The nasopharynx lies behind the nasal cavity and above the soft palate. It communicates with the oropharynx via the pharyngeal isthmus, which becomes closed off during the act of swallowing (6). Its sensory innervation is derived from the trigeminal nerve and the glossopharyngeal nerve (10). During development, the depth of the nasopharynx increases as a result of remodeling of the palate as well as changes in angulation of the skull base, eventually producing an enlarged nasal airway in the adult (1). The pharyngeal opening of the pharyngotympanic (Eustachian) tube lies on the lateral wall of the nasopharynx. The nasopharyngeal tonsils (adenoids) lie on the roof and posterior wall of the nasopharynx in children (6). Although these atrophy with age, enlargement in early childhood may obstruct breathing through the nose. Nasopharyngeal tonsils may also become dislodged during instrumentation of the nose (10) (Figures 1 and 2).

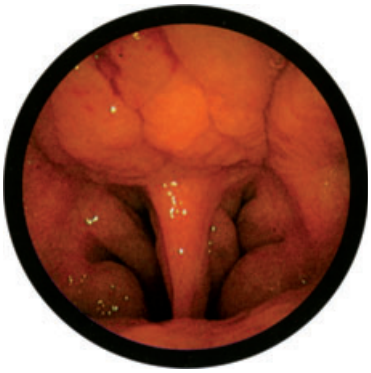
Oropharynx

The oropharynx extends from the soft palate to the tip of the epiglottis. It is attached anteriorly to the base of the tongue via the glossoepiglottic folds. Between these folds lie the valleculae. The sensory innervation of the oropharynx is derived from the glossopharyngeal nerve and the superior laryngeal branch of the vagus nerve, which transmits afferent



4 The nasopharynx of an infant photographed with the 120° retrograde telescope. The adenoids are small, the posterior nasal septum and the posterior ends of the turbinates are seen with the Eustachian tube openings visible on each side.

Figure 1
Nasopharynx of an infant (reproduced with permission from Benjamin B: Atlas of Paediatric Endoscopy, Oxford University Press, 1981).



5 The nasopharynx of a 5-year- old with mild congestion of the posterior end of the septum and the turbinates. The patient's left Eustachian tube opening is just visible.

Figure 2
Nasopharynx of a 5-year-old child (reproduced with permission from Benjamin B: Atlas of Paediatric Endoscopy, Oxford University Press, 1981).

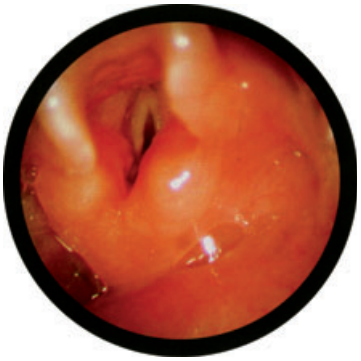
impulses from the base of the tongue and the valleculae (10). The reflex circulatory responses to direct laryngoscopy and tracheal intubation result largely from stimulation of the pharyngeal wall by the laryngoscope blade. A smaller additional response is produced by the passage of an endotracheal tube through the vocal cords (11,12).

At the entrance to the oropharynx is a collection of lymphoid tissue known as Waldeyer's ring. This consists of the lingual tonsil at the base of the tongue and bilateral palatine tonsils. The nasopharyngeal and tubal tonsils also form part of this ring. Inflammation of these lymphoid tissues may obstruct breathing efforts in conscious patients and may make laryngoscopy difficult because of an increase in size of the tissue or associated masseter spasm (10). Gender and ethnic variations in the dimensions of the oropharynx have been demonstrated, together with a relationship between oropharyngeal dimensions and sleep disordered breathing (13). Tonsillar asymmetry has been reported to occur in the absence of pathology in some children (14).

The relatively large tongue decreases the size of the oral cavity in children and more easily obstructs the airway. Decreased muscle tone also contributes to passive obstruction of the airway by the tongue. In infants lying supine, the tongue tends to flatten out against the soft palate in inspiration and may remain in the same position for the passive expiration through the nose (7). Extension of the head at the atlanto-occipital joint, with anterior displacement of the cervical spine, may result in improved hypopharyngeal airway patency but does not necessarily change the position of the tongue (4).

Laryngopharynx

The laryngopharynx extends from the tip of the epiglottis to the lower border of the cricoid cartilage. The larynx bulges back into the center of the laryngopharynx, leaving a recess on either side, known as the piriform fossa. This is a common site for impaction of swallowed sharp foreign bodies (6) (Figure 3).



8 The right piriform fossa and part of the post cricoid region as seen with the oesophagoscope, as a preliminary to oesophagoscopy.

Figure 3
Right piriform fossa (reproduced with permission from Benjamin B: Atlas of Paediatric Endoscopy, Oxford University Press, 1981).

Larynx

The larynx is situated between the pharynx and trachea, extending from the base of the tongue to the cricoid cartilage. It is the organ of phonation and protects the tracheobronchial tree during swallowing and coughing (10). The development of the respiratory system begins at approximately 3 weeks of gestational age, with the formation of the laryngotracheal tube from the ventral wall of the foregut. A definite larynx can usually be identified by 41 days gestation. The cricoid and thyroid cartilages begin chondrification at about 7 weeks of gestation. The primitive glottis is formed at 10 weeks gestation when the true vocal cords split. Failure of this process results in a congenital laryngeal web, or in some cases, congenital atresia of the larynx. Incomplete division of the embryonic foregut into the anteriorly positioned trachea and the posteriorly positioned esophagus results in tracheo-oesophageal fistula (1).

The larynx consists of the thyroid cartilage, the cricoid cartilage, the paired arytenoids and the epiglottis, together with the small corniculate and cuneiform cartilages. These form a framework of articulating cartilages linked together by ligaments, which move in relation to each other by the action of the laryngeal muscles (6). The largest of these cartilages is the thyroid cartilage, which is open posteriorly and forms the laryngeal prominence (Adam's apple) anteriorly (10). Beneath the thyroid cartilage is the cricoid cartilage, in the shape of a signet ring with the widest portion lying posteriorly. This is the only complete cartilage ring found in the respiratory tract. At birth, the lower border of the cricoid cartilage lies opposite the lower border of the fourth cervical vertebra. At 6 years of age it is at the level of the fifth cervical vertebra (7) and in the adult it lies at the level of the sixth cervical vertebra (10). Because of the small size of the cricoid cartilage in children, and the fact that it is a complete ring, the presence of mucosal edema at this site will severely compromise the airway. Young children are also at risk of acquired subglottic stenosis when exposed to prolonged or repeated tracheal intubation (4) (Figures 4 and 5).

The paired arytenoid cartilages articulate at the posterosuperior aspect of the cricoid cartilage (10). Each arytenoid has an anterior process, the vocal process, to which the vocal ligament is attached. At the apex of each arytenoid lies a triangular corniculate cartilage, attached by a perichondrium (6). The vestibular folds, or false cords, are created by the mucosa that covers the thyroarytenoid muscles. The true vocal cords are the vocal folds covered by mucosa. Reflex adduction of the true and false cords is known as laryngospasm and may result from local stimulation of the larynx, or from surgical stimulation in the absence of adequate anesthesia. The cricothyroid membrane is a tough, elastic connective tissue sheet that spans the joint between the inferior process of the thyroid cartilage and the cricoid cartilage (10). Puncture or incision of this membrane allows the creation of a surgical airway when acute airway obstruction occurs at or above the larynx (6).

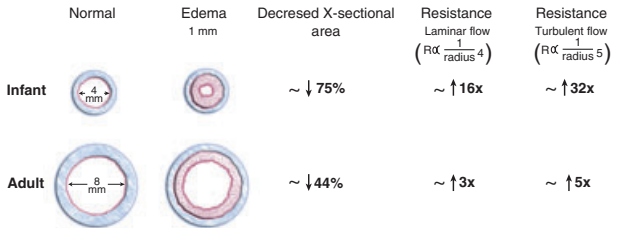


Figure 4
Relative effects of airway edema in an infant and an adult. The normal airways of an infant and an adult are presented on the left; edematous airways (1mm circumferential, reducing the diameter by 2mm) on the right. Note that resistance to airflow is inversely proportional to the radius of the lumen to the fourth power for laminar flow (beyond the fifth bronchial division) and to the radius of the lumen to the fifth power for turbent flow (from the mouth to the fourth bronchial division). The net result in an infant with a 4mm diameter airway is a 75% reduction in cross-sectional area and a 32- fold increase in resistance to airflow, compared with a 44% reduction in cross-sectional area and a 5-fold increase in resistance to airflow in an adult with a similar 2mm reduction in airway diameter. (Reproduced with permission from Cote CJ, Lerman J, Todres ID: A practice of Anesthesia for Infants and Children, Saunders Elsevier, 2009)

The epiglottis is a leaf-shaped structure attached to the posterior border of the thyroid cartilage by the thyroepiglottic ligament. In the adult, the epiglottis is broad, with its axis parallel to that of the trachea. The epiglottis in the infant is narrower, softer and more horizontally positioned than in the adult. The straight laryngoscope blade facilitates lifting of the epiglottis and is therefore useful during tracheal intubation in younger children. At laryngoscopy, the epiglottis in the neonate appears more deeply furrowed at its free end, and in some babies it has a V-shaped appearance (6). By the age of 4 or 5 years, the epiglottis is usually firm enough to allow visualization of the vocal cords using a curved

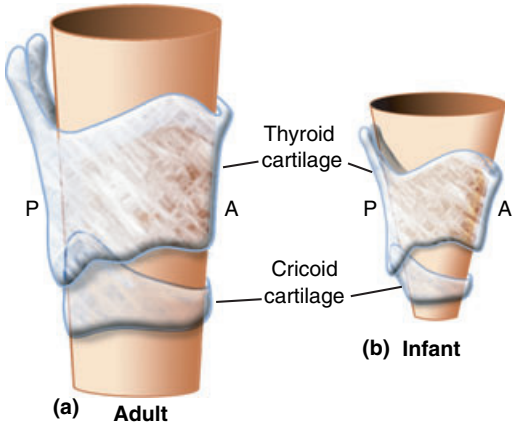


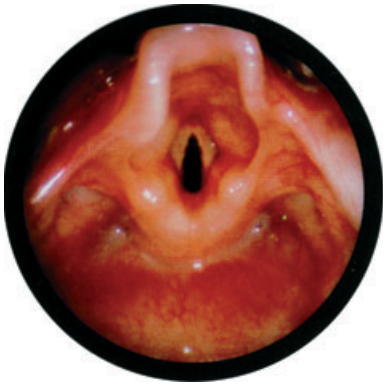
Figure 5
Configuration of the larynx in an adult (a) and an infant (b). Note that in both adult and infant the larynx is somewhat funnel-shaped, with an exaggeration of this shape in the infant. (Reproduced with permission from Cote CJ, Lerman J, Todres ID: A practice of Anesthesia for Infants and Children, Saunders Elsevier, 2009)

laryngoscope blade (7). The cuneiform cartilages lie anterior to the corniculate cartilages, in the aryepiglottic folds (6) (Figure 6).

The more superior location of the larynx in children may create difficulty in visualizing laryngeal structures because of the more acute angulation between the base of the tongue and the laryngeal opening (4). During laryngoscopy, a neck or shoulder roll will relieve the hyperflexion of the infant's neck caused by the relatively large occiput.

The nerve supply to the larynx is from the vagus nerve, via its superior and recurrent laryngeal branches. The superior laryngeal nerve gives rise to an internal laryngeal branch which runs beneath the mucosa of the piriform fossa. In this position, it is easily blocked by the topical application of a local anesthetic agent to provide anesthesia for laryngoscopy and bronchoscopy (6). The laryngeal inlet and the inferior surface of the epiglottis are innervated by the vagus nerve. When the epiglottis is lifted with a straight laryngoscope blade, bradycardia and hypotension may occur as a result of a vagal reflex. When a curved blade is used, the tip is placed in the angle between the epiglottis and the base of the tongue. This theoretically reduces the risk of bradycardia because the superior surface of the epiglottis and the valleculae are innervated by the glossopharyngeal nerve (15). Damage to the recurrent laryngeal nerve results in paralysis of the corresponding vocal cord, causing it to lie motionless in the midline and at a lower level than the opposite side. Bilateral paralysis results in complete loss of vocal power. The two paralyzed cords may then flap together to cause a valve-like obstruction during inspiration, producing dyspnea and inspiratory stidor (6).

The pediatric airway is highly compliant and the cartilaginous support is less developed than in the adult airway. This leads to increased susceptibility to dynamic airway collapse in the presence of airway obstruction (5). Studies have demonstrated that airway obstruction during general anesthesia is related to a reduction in laryngeal muscle tone. Loss of muscle tone in the pharynx leads to airway obstruction at the level of the soft palate and epiglottis (16). Laryngomalacia is a congenital abnormality of the larynx and results from the laryngeal structures being more pliable and less rigid than in the adult (10).



6 The glottic and supraglottic structures in a 6-month-old infant. The epiglottis, valleculae, piriform fossae, hypopharynx, and the laryngeal introitus are all normal.

Figure 6
Normal larynx of a 3-year-old child (reproduced with permission from Benjamin B: Atlas of Paediatric Endoscopy, Oxford University Press, 1981).

Assessment of the pediatric airway

Assessment of the pediatric airway is often difficult because the child is frequently unable to cooperate with the provision of information from the medical history and clinical examination. Clinical investigations may similarly be difficult to perform in children.

History

Assessment of the pediatric airway should begin with enquiries about the child's medical history, including

details of the birth and subsequent development. Previous respiratory illness should be noted, together with a history of any injuries or surgical procedures involving the airway. Details should be taken of any complications occuring during previous anesthesia, particularly those related to the airway. Specific questions should also be asked about the child's respiration, feeding and phonation, as well as the presence and nature of any cough.

Noisy breathing often signifies abnormalities within the pediatric airway. Enlarged adenoids and tonsils are associated with snoring and hyponasal speech (10). Nasal congestion and an impaired sense of smell occurring without rhinorrhea may also be consistent with enlarged adenoids. A history of cessation of breathing or excessive daytime somnolence is suggestive of obstructive sleep apnea.

There may be a history of respiratory distress in relation to feeding, when the child is in a particular position, or possibly in association with previous anesthesia or tracheal intubation. Episodes of apnea may have a central pattern or an obstructive pattern and can occur in association with prematurity or sleep disordered breathing. A history of apnea together with cyanosis or signs of respiratory obstruction may be indicative of choanal atresia (1). Abnormal feeding patterns occur with respiratory insufficiency in the infant, particularly when associated with aspiration, as suggested by choking, coughing and vomiting (10).

Enquiries about the child's voice or cry can provide valuable information about the airway. Hoarseness or diminished cry are signs of laryngomalacia. Changes in the quality of the voice occur in the presence of unilateral vocal cord paralysis (10).

Cough is a common symptom of respiratory abnormality and is often associated with upper respiratory tract infection. It may be caused by stimuli arising in the mucosa of any part of the respiratory tract. The frequency, severity and character of the cough are dependent on several factors including the situation and nature of the lesion responsible for the cough, the presence or absence of sputum, and the presence of coexisting abnormalities such as impairment of ventilatory function. In acute respiratory tract infection, the cough is usually productive and associated with purulent nasal secretions. A croup-like cough in the absence of infection may signify subglottic stenosis (10). Sudden onset of cough in the absence of systemic illness suggests inhalation of a foreign body.

Examination

Information about the pediatric airway can be obtained from the general appearance of the child, with particular reference to body mass index and characteristics of the face. Failure to thrive is a recognized consequence of obstructive sleep disordered breathing, particularly when the etiology is adenotonsillar hypertrophy (17). Abnormalities of the airway and respiratory function at rest have been described in obese children (18–20), and reports suggest that in some children obstructive sleep apnea mimics the adult model in which obesity plays a major etiological role (21). Kohler *et al.* reported that in children who snore, obesity is a significant predictor of upper airway obstruction during sleep. The contribution of body mass index to upper airway obstruction amongst Caucasian children is much milder than that typically found amongst African-American children (20).

The child's facial expression or the presence of nasal flaring may suggest respiratory distress. Mouth-breathing or drooling often occur in the presence of enlarged tonsils or adenoids. Examination of the child's mucous membranes may detect cyanosis secondary to hypoxemia. There may be signs of previous trauma or surgery to the head and neck. Evidence of neuromuscular disease, congenital abnormalities or dysmorphic features should be noted, together with anatomical variants of normal including mandibular hypoplasia, small mouth or limited mouth opening (5). Spontaneous mid-inspiratory pharyngeal airway obstruction occurs during snoring in infants with micrognathia (22). Horn *et al.* (23) have demonstrated that even in the absence of obvious congenital abnormalities such as severe micrognathia, smaller mandibular size is associated with a history of an apparent life-threatening event. The patency of the nasal apertures should be assessed, as well as the amount, nature and color of any nasal discharge. The tongue, teeth, pharynx and palate should be inspected if possible. Macroglossia and retrocline of the lower incisors are known to be associated with sleep apnea (24,25). Loose deciduous dentition commonly occurs in children between 6 and 12 years old.

Examination of the neck may reveal deformity, limited mobility of the cervical spine or cervical lymphadenopathy. The shape of the chest should be observed, noting the frequency and depth of respiration. Further inspection should reveal the degree of chest expansion, the mode of breathing and the presence of any chest wall recession. Deviation of the trachea may be detected on palpation. Auscultation of the lungs has an important place in the diagnosis of certain respiratory diseases such as bronchial asthma.

The child's voice or cry should be noted, because hoarseness or a weak cry may occur in the presence of airway obstruction at the level of the vocal cords. Stridor is a high-pitched sound that is indicative of laryngeal or tracheal obstruction. Inspiratory stridor suggests obstruction at or above the upper trachea, because extrathoracic obstruction is exacerbated by the negative intrathoracic pressures generated during inspiration. Expiratory stridor suggests obstruction of the lower trachea or bronchi, with exacerbation as the airways are compressed during forced expiration. In laryngomalacia, excessive flaccidity of the soft epiglottis and the loose aryepiglottic folds causes these structures to collapse on inspiration, resulting in stridor. This collapse is exaggerated on crying because the inspiratory effort is greater, leading to increased collapse of the soft supraglottic structures. Inhalation induction of anesthesia often leads to a decrease in the stridor of laryngomalacia, because of a reduction in the force of respiratory movements (10).

Investigations

Lung function tests may be useful in the assessment of the pediatric airway. Tests of ventilatory mechanics include assessment of forced expiration and measurements obtained using spirometry. In the absence of shock or poor perfusion, pulse oximetry provides an accurate assessment of arterial oxygenation in children of all ages. Transcutaneous measurement of oxygen tension is reasonably accurate in the newborn infant, but becomes less accurate as the child grows older (26). Arterial blood gas measurement is occasionally of some value in the assessment of physiological compromise, particularly in situations of chronic airway obstruction and compensated respiratory acidosis. However, the procedure of arterial puncture is often very traumatic for the child and may potentially aggravate any underlying airway obstruction as a result of dynamic airway collapse (4). Analysis of capillary blood may be useful in some circumstances.

Imaging

Radiological evaluation of the airway offers noninvasive data on the structure of the pediatric airway (27–29). Standard radiographs provide information about the anatomy of the airway, with fluoroscopy being an additional tool. Cephalometric radiography is used to study the relationships between bony and soft tissue landmarks (24). More recently, computed tomography and magnetic resonance imaging have been valuable in providing anatomical details comparable with endoscopy (27).

Endoscopy

Endoscopy of the pediatric airway involves the use of either fibreoptic or rigid instruments. Flexible pernasal laryngoscopy is possible even in neonates, using a small-caliber fibroscope. It can be performed without general anesthesia, with the application of local anesthesia to the nasal fosse. Flexible endoscopy may be used with or without general anesthesia and provides views of the nasal fosse, choanae, pharynx and larynx, even in the neonate (30). It is also possible to achieve dynamic views of laryngeal and upper airway function. Rigid bronchoscopy is performed under general anesthesia. Direct microlaryngoscopy, using a suspension laryngoscope, also requires general anesthesia and allows detailed examination of the larynx and pharynx.

Sleep studies

Sleep disordered breathing refers to a pathophysiological continuum that includes snoring, upper airway resistance syndrome, obstructive hypopnea syndrome and obstructive sleep apnea. Polysomnography is considered to be the best investigation to ascertain the severity of sleep disordered breathing in children (25). Measurements of the upper airway pressure-flow characteristics may be useful in evaluating upper airway function (31) and sleep

nasendoscopy has been used to determine the site of obstruction during sleep.

Conclusion

Assessment of the pediatric airway involves obtaining a comprehensive history, performing a detailed clinical examination and appropriate investigations to determine or exclude abnormalities which may complicate general anesthesia. Knowledge of functional airway anatomy is required for an understanding of the pathological airway conditions occurring within the pediatric population.

Conflicts of interest

The authors have declared no conflicts of interest.

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