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CHAPTER 3

Anesthesia for Airway Surgeries

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ABSTRACT

Airway lesions in children may occur due to congenital defects in the development and growth of the airway or be acquired following trauma or infection. Stridor is the most typical presenting symptom, but there may be potentially life-threatening airway obstruction. Airway surgery requires a collaborative team effort among the anesthesiologist, neonatologist, and surgeon. Preservation of spontaneous respiration during the induction process is the most recommended technique for children with upper airway obstruction. The key anesthetic consideration for airway surgeries is ventilation and oxygenation in the face of an open airway. The ventilation mode is chosen based on the nature of surgery and the requirement of surgical access to the operative site. Laser resection of the lesion presents its own set of challenges. The chapter provides an overview of etiopathology, the clinical presentation of various airway lesions commonly presenting to anesthesiologists for diagnosis and surgical treatment, and the multiple implications for anesthetic management of these lesions.

Keywords: Airway, pediatric, airway lesions, vocal cord malformations

KEY POINTS

- Airway disorders in children may be congenital or acquired.
- Laryngomalacia is the most common airway lesion, affecting approximately 75% of congenital airway disorders.
- Stridor is the most typical presenting symptom.
- The success of airway surgery depends on close coordination between the surgeon and the anesthesiologist.
- Preservation of spontaneous respiration during induction is the most recommended technique for children with upper airway obstruction.
- Airway management and ventilatory strategy are formulated mainly according to surgical needs.
- Airway fire protocol should be implemented immediately in the event of a fire during laser resection procedures.
- Postoperatively, close observation is necessary to detect early signs of airway obstruction due to either edema or retained secretions.

INTRODUCTION

Lesions of the airway are potentially life-threatening in any patient, but more so in the pediatric age group.[1] Providing anesthesia for procedures on the airway is one of the most challenging aspects of pediatric anesthesia. Inherent differences in airway anatomy between adults and those related to shared airways pose challenges concerning airway management and oxygenation.[1,2]

A child may present to the anesthesiologist for urgent lifesaving tracheostomy, diagnostic bronchoscopy, or for definitive management of the airway pathology. The safe conduct of anesthesia in these patients requires a thorough knowledge of airway anatomy and a collaborative team effort among the anesthesiologist, neonatologist, and surgeon.[2,3] This chapter provides an overview of the etiopathology and clinical presentation of common upper airway lesions in the pediatric age group, as well as the implications of surgical techniques on the anesthetic management of these lesions.

EMBRYOLOGY

The larynx first appears as an epithelial growth on the ventral aspect of the foregut known as the respiratory primordium, at around 3–4 weeks of gestation.[4-7] As the respiratory primordium develops, the respiratory diverticulum grows into it as a ventromedial outpouching of the foregut.[4,5] The epithelial lamina is obliterating the ventral lumen of the primitive laryngopharynx at this time.[8] Located ventral to the epithelial lamina is the laryngeal cecum, which becomes the laryngeal vestibule, and dorsal to it is the pharyngoglottic duct, which develops into the posterior glottis. The recanalization of the epithelial lamina leads to the combination of the laryngeal cecum and the pharyngoglottic duct.

Gradually, the respiratory diverticulum grows inferiorly and is detached from the esophagus by the tracheoesophageal septum.[8] This septum grows in a caudocranial direction. During the 5th and 6th weeks, the tracheoesophageal septum reaches the first tracheal ring. At the end of the 7th week of gestation, the cricoid ring is appreciable as a complete ring, the hyoid is visible below the epiglottis, and definitive tracheal cartilage appears. The larynx, trachea, and esophagus have developed by the end of the embryonic period.[4-8] From 8th to 32 weeks of gestation, the vocal processes are formed from the arytenoids, and the epiglottic and cricoid cartilages develop into mature cartilages.[5,7]

MALFORMATIONS INVOLVING THE AIRWAY

Airway lesions in children may occur due to congenital defects in the development and growth of the airway or be acquired following trauma or infection. Common causes and incidences of various congenital and acquired causes of airway obstruction are described in **Table 1**.[9-23]

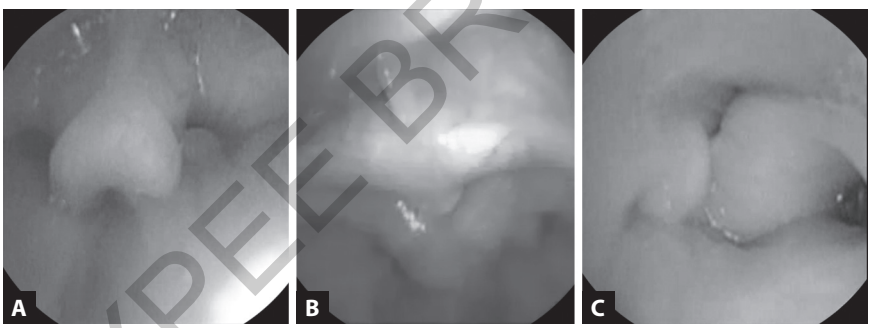
PATHOPHYSIOLOGY, DIAGNOSIS, AND MANAGEMENT OF VARIOUS LESIONS AFFECTING THE AIRWAY

Laryngomalacia

Laryngomalacia is a disorder in which supralaryngeal structures collapse upon the glottis during inspiration **(Fig. 1)**.[9,10,24] It is the principal cause of upper airway obstruction in infants.[3,24] Additional airway anomalies may coexist in up to 20% of infants with laryngomalacia (e.g., tracheobronchomalacia).[10,24] Laryngomalacia may be an isolated disorder or can be associated with other congenital syndromes (e.g., Down syndrome, DiGeorge syndrome).[9,11,24]

TABLE 1: Incidence of various congenital and acquired laryngeal anomalies.

Laryngeal anomalies	*Incidence*
Congenital	
• Laryngomalacia	65–70%[9-11]
• Vocal cord immobility	10–20%[9,12,13]
• Subglottic stenosis	15–19%[14,15]
• Subglottic hemangiomas	1.5%[9,10,16]
• *Miscellaneous*: Laryngeal atresia, laryngeal cleft, laryngeal cysts, laryngeal web, saccular cysts, vallecular cysts, etc.	Rare[8-10,15]
Acquired	
• Respiratory papilloma	4 per 100,000[17]
• Subglottic stenosis/tracheal stenosis	1–2%[18]
• Intubation granulomas	1:800 to 1:20,000[19]
• Laryngeal cyst	7%[20]
• Laryngotracheomalacia and tracheobronchomalacia	4.5%[21,22]
• Laryngeal web	Rare[14,23]



Figs. 1A to C: (A and B) Varying severity of laryngomalacia; and (C) Severe laryngomalacia with inward curling of epiglottis.

The etiology of laryngomalacia is not clear. Plausible mechanisms include immaturity or lack of tone in the laryngeal supporting cartilages, supraglottic redundant soft tissue, a petite aryepiglottic fold, neuromuscular disorders, and edema of supraglottic structures (possibly due to coexisting gastroesophageal reflux disease, which has been observed in 60–70% of cases).[24]

Within the first 2 weeks of birth, it presents with a high-pitched, inspiratory biphasic stridor that worsens with feeding, lying supine, or upper respiratory infections.[9-11,24] More severe cases manifest as apneic events, pulmonary hypertension, or failure to thrive. Diagnosis is usually confirmed with flexible fiberoptic nasendoscopy in the outpatient department.[9] Patients with progressive or nonconforming symptoms are taken up for rigid bronchoscopy under general anesthesia (GA).

The majority of children are managed conservatively, as the condition typically resolves spontaneously by age 12–24 months, and surgery is indicated in only 5–10% of cases. These cases may involve division of the aryepiglottic folds, epiglottopexy, and either surgical or laser supraglottoplasty.[24,25]

Tracheomalacia

Tracheomalacia results from the dynamic collapse of the trachea on expiration, leading to an obstruction of the airway >10–20% **(Fig. 2)**.[26] It may be primary due to soft, pliable tracheal rings or secondary, due to extrinsic compression. The child usually presents in early infancy with expiratory stridor, coughing, recurrent infections, or "dying spells".[26,27] It is self-limiting in most patients; however, in severe cases, treatment options include continuous positive airway pressure (CPAP), internal stenting of tracheal and bronchial segments, tracheostomy, and aortopexy.[27]

Congenital Vocal Fold Immobility

Vocal fold immobility (VFI) is the second most common congenital airway lesion.[9,12,13] Unilateral VFI is more common and typically manifests as a weak and breathy cry, feeding difficulties, and aspiration.[12] Bilateral VFI presents with biphasic stridor and a normal cry, but little or no airway compromise, though there may be severe respiratory distress in a few cases.[9]

Vocal fold immobility is idiopathic primarily but may also result from birth trauma, central or peripheral nervous system anomalies (cerebral palsy, cerebral dysgenesis, meningomyelocele, Arnold–Chiari malformation, myasthenia gravis, facioscapulohumeral myopathy, and spinal muscular atrophy), or cardiovascular anomalies (tetralogy of Fallot, Ortner syndrome, vascular rings, and patent ductus arteriosus).[9,13]

Diagnosis is achieved through flexible laryngoscopy and/or rigid bronchoscopy under GA to assess the airway and vocal fold motion. Other tests

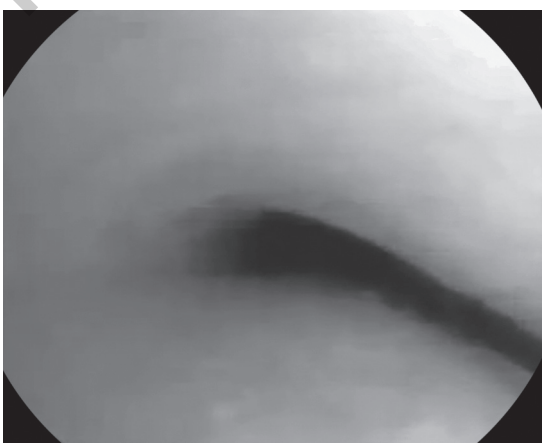


Fig. 2: Tracheomalacia showing collapse of the tracheal wall during expiration.

recommended include video contrast esophagography (to assess swallowing), laryngeal electromyography (to help differentiate between vocal fold fixation and paralysis), a computed tomography (CT) or magnetic resonance imaging (MRI) scan of the brain (to rule out brainstem pathology), and a chest radiograph or CT scan to look for mediastinal pathology.

Treatment is generally conservative, as idiopathic VFI instinctively recovers within 6–12 months of life. Children with bilateral VFI with significant airway compromise may require tracheotomy during this period. Patients with unilateral VFI may require nasogastric or gastrostomy tube insertion to ensure nutrition, as they are prone to aspiration. Medialization of the paralyzed vocal fold with injection of absorbable gelatin sponge or collagen also effectively reduces aspiration in older children. Thyroplasty is an alternative. Bilateral VFI may indicate vocal fold lateralization, partial cordectomy, arytenoidectomy, or anterior cricoid split with graft placement.[28]

Laryngeal Cysts

Laryngeal cysts are rare lesions that may be congenital or acquired.[9,10] Congenital cysts are formed due to abnormal embryonic development affecting the patency of the orifice between the saccule and laryngeal ventricle. Prolonged intubation in neonates is a common iatrogenic cause of acquired laryngeal cysts.[20] In this case, biphasic stridor and upper airway obstruction may occur after several months. Supraglottic cysts are more common than glottic or subglottic cysts.

De Santo subdivided the laryngeal cysts into saccular and ductal cysts, the latter being more common.[29] Saccular cysts can be confused with laryngoceles but can be differentiated by the absence of any opening into the laryngeal ventricle.[30]

The clinical symptoms of laryngeal cysts vary depending on their size and location. Large cysts present with variable severity of stridor, airway obstruction, dyspnea, hoarseness, and dysphagia.[31] The diagnosis of laryngeal cysts is confirmed on direct laryngoscopy. Other investigations include radiological examinations, ultrasound (USG), and CT scans of the neck, chest, and esophagus.

These children require urgent bronchoscopy and surgical marsupialization or laser excision of the cysts. Excision of the cyst by the external approach may be necessary in case of repeated recurrence.[31,32]

Laryngeal Atresia, Stenosis, and Webs

Laryngeal atresia is a rare condition that results from the failure to recanalize the larynx and trachea during embryogenesis.[33] It may be associated with other anomalies, e.g., tracheoesophageal fistula, esophageal atresia, limb defects, horseshoe kidney, urinary tract abnormalities, encephalocele, and low-set ears.[33-35] Characteristic presentation is severe asphyxia at birth despite strong respiratory effort. It may be suspected that, on prenatal ultrasonographic evaluation, ex utero intrapartum treatment (EXIT) procedure to secure the airway at birth can be planned.[34] In this procedure, placental support is continued until the airway is secure after birth. Laryngotracheal reconstruction (LTR) is later performed.[36]

Subglottic stenosis (SGS) can be either a congenital or an acquired condition, the latter being common (>95% cases) and occurring due mainly to intubation trauma.[14,15] It is a common anomaly in children with Down syndrome. Congenital cardiovascular abnormalities, neurological impairment, or syndromic anomalies may be associated.

Congenital SGS **(Fig. 3)** may be either cartilaginous or membranous, the latter being a more common and milder condition.[14]

Infants with SGS present in the first few months of life with dyspnea, severe airway obstruction, and biphasic stridor that worsens during respiratory tract infections. Mild cases may be asymptomatic but prove difficult to intubate for anesthesia. Severity of the SGS is classified using the modified Myer Cotton grading system **(Table 2)**.

Congenital SGS may improve as the larynx grows; failing which, balloon dilation and endoscopic laser surgery are the options for membranous stenosis. In cases of severe narrowing, tracheostomy is typically followed by LTR. A wedge from the costal cartilage is inserted anteriorly into a vertical incision in the cricoid cartilage to dilate the airway lumen.[38]

Laryngeal web is a rare congenital anomaly with an incidence of 1 in 10,000.[9,14,23] Anterior webs are more common than the posterior ones and occur due to partial failure of resorption of the epithelial layer that usually obliterates the laryngeal

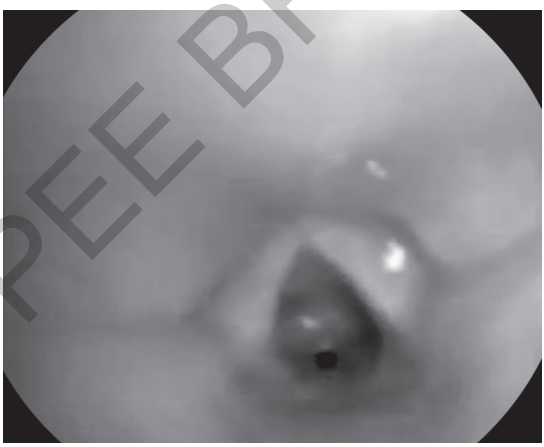


Fig. 3: Severe subglottic stenosis (grade 3).

TABLE 2: Modified Myer Cotton grading system severity grading of subglottic stenosis.[15,37]

Grades	*Degree of obstruction*
Grade 1	0–50%
Grade 2	51–70%
Grade 3	71–99%
Grade 4	Absent lumen

opening during embryonic period resulting in incomplete separation of the vocal folds **(Fig. 4)**.[9,10] Laryngeal webs are generally thin and membranous but may be thick and fibrous. Glottic level webs are the most common, but supraglottic or subglottic webs may also be seen rarely.[23]

The clinical presentation of patients with laryngeal web depends on the degree of glottic obstruction and grade of webbing **(Table 3)**.[39] The associated anomalies include SGS, submucous cleft palate, cardiac defects, particularly ventricular septal defect (VSD), which may occur in conjunction with 22q11 deletion as part of the DiGeorge/velo-cardio-facial syndrome.[23,39,40]

Flexible nasoendoscopy is used for preliminary diagnosis, but rigid laryngoscopy and bronchoscopy are typically necessary to determine the site, thickness, and full extent of the web. Anterior commissure webs are excised surgically or with a CO_2 laser.[23,39]

Laryngeal reconstruction, stenting, and tracheotomy may be indicated in patients with webs that include larger portions of the anterior and posterior glottis.

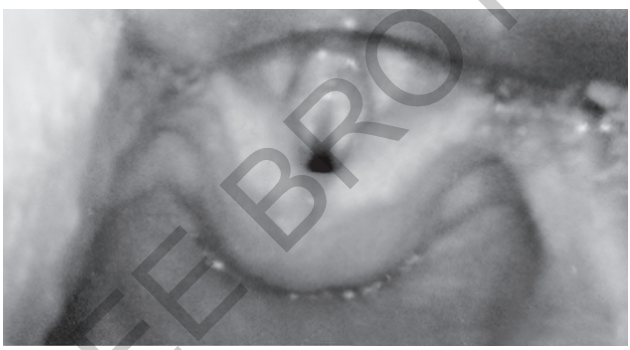


Fig. 4: Anterior laryngeal web type 3.

TABLE 3: Types of laryngeal webs based on the degree of occlusion of the glottic opening.[39,40]

Types	*Morphology*	*Clinical features*
Type 1	Web covers 35% of the anterior glottis	No airway obstruction, dysphonia is common. Slight hoarseness may be present
Type 2	35–50% occlusion of the glottic lumen with visible VC	Minimal respiratory distress, husky voice. Acute stress like infection or trauma may precipitate respiratory distress
Type 3*	50–70% occlusion of the glottic lumen VC may be visualized	Obvious vocal dysfunction, a weak cry or whispery voice
Type 4	75–90% occlusion of the glottis with VC not visualized	Severe respiratory obstruction and aphonia

*The most common type
(VC: vocal cords)

Laryngeal Clefts

Posterior laryngotracheal clefts (PLTCs) occur in approximately 1 in 10,000 to 1 in 20,000 live births and result from failure of union of the two lateral growth centers in the region of the posterior cricoid cartilage during 6–7 weeks of gestation **(Fig. 5)**.[8,9,41] PLTC can occur associated with various syndromes (e.g., VATER/VACTERL, Opitz Frias, CHARGE), or with craniofacial cardiac, gastrointestinal, genitourinary anomalies.[8,41] Clinical presentation usually involves stridor, noisy breathing, increased secretions, aspiration, hoarseness, feeding problems, failure to thrive, wheezing, respiratory distress, recurrent lung infections, and gastroesophageal reflux.[41,42] Rigid bronchoscopy is the mainstay of diagnosis and should involve examination of the interarytenoid region. Classification of laryngeal clefts is described in **Table 4**.[41] Minor clefts can be managed conservatively, and medical therapy can control gastroesophageal reflux. Injection of the interarytenoid region with fillers, such as hyaluronic acid, can help temporarily decrease aspiration as the child grows.[42] Operative repair requires involvement of the otolaryngologist and thoracic surgeon.

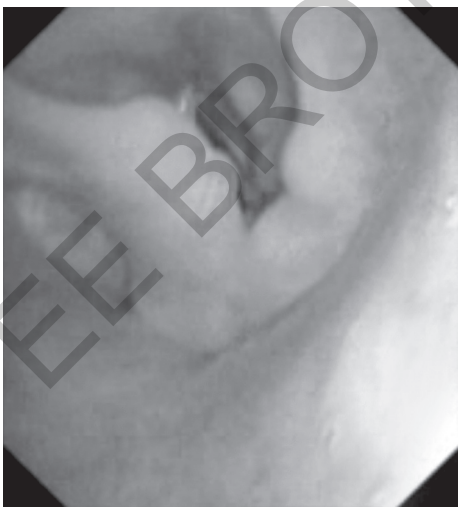


Fig. 5: Laryngeal cleft type 1 showing arytenoid separation.

TABLE 4: Classification of laryngeal clefts.[41]

Types	*Extent*
Type 1	Cleft confined to the supraglottic, interarytenoid region
Type 2	Partial cleft of the part of posterior cricoid cartilage (a mucosal bridge may be present across the cartilaginous gap)
Type 3	Cleft involves the whole cricoid cartilage and the cervical part of the tracheoesophageal membrane, lower extent is above the thoracic inlet
Type 4	Clefts with extensive involvement of major parts of intrathoracic tracheoesophageal wall

Subglottic Hemangioma

Subglottic hemangioma is a rare but potentially fatal vascular anomaly that is asymptomatic at birth. Later, the lesion undergoes rapid growth between 2 and 6 months.[43] Its size stabilizes between 12 and 18 months, and resorption occurs by 5 years of age.[43,44] Hemangiomas are usually diagnosed by history, physical examination, X-ray of the neck, and a distinctive endoscopic picture. X-rays of the neck may show asymmetric tapering of the subglottic region. Bronchoscopy typically shows a compressible, sessile, red-to-blue posterolateral lesion. Symptoms mimic SGS, presenting as biphasic stridor and frequent croup.[9,43] Other associated symptoms may include barking cough, hemoptysis, dysphagia, hoarseness, cyanosis, and failure to thrive. Cutaneous hemangiomas may be associated with up to 50% of infants, for example, in a combination of anomalies known as PHACE syndrome, which comprises posterior fossa brain anomalies, facial hemangiomas, arterial, cardiac, and eye abnormalities.[43]

Many clinicians manage these lesions conservatively, hoping that they will regress naturally.[43,44] Medical therapy was traditionally with systemic or intralesional steroids. Recently, propranolol has been advocated based on its action on vasoactive endothelial growth factor, which enhances regression of the hemangioma. Open surgical excision and laser ablation are options for lesions that do not extend circumferentially. Postoperative intubation with sedation would be indicated in these cases to splint the airway. Carbon dioxide (CO_2) laser ablation has been associated with significant scarring and can lead to SGS.[44] Potassium-titanyl-phosphate (KTP) laser may be preferable as it preferentially absorbs by hemoglobin and can be transmitted through flexible fiberscopes.

Respiratory Papillomatosis

Respiratory papillomatosis results from infection with types 6 and 11 human papillomavirus (HPV).[17] Transmission is usually from the mother, either during intrauterine life or at delivery. During the first year of life, the HPV lesions grow on or around the larynx. Juvenile onset disease affects 2–5% of 5-year-old children and typically involves the area of the true vocal cords and anterior commissure, but can also involve the entire respiratory epithelium.[17] Respiratory papillomatosis causes hoarseness, stridor, cough, dysphagia, pneumonia, failure to thrive, and even life-threatening airway obstruction. Multiple treatment modalities have been tried, including acyclovir, steroids, podophyllin, radiation, USG, and radiotherapy ablation.[45] Current management focuses on the timely surgical debulking of lesions to improve symptoms while minimizing scarring and laryngeal damage.

ANESTHETIC CONSIDERATIONS FOR AIRWAY SURGERY IN CHILDREN

Pediatric Airway

The airway in children has several unique features that magnify the challenges of airway surgeries.[1] Firstly, it is much narrower at the subglottis, with an internal diameter between 3 and 4 mm in a neonate. Any pathology halving the airway

radius would result in a 16-fold reduction in airflow during quiet breathing.[3,46] It also becomes turbulent and therefore requires the generation of a higher pressure difference to maintain a given flow rate during turbulent flow. Thus, stridor at rest implies upper airway narrowing of at least 60% of the lumen in children with an obstructive pathology.[3]

Secondly, the cartilaginous parts of the pediatric airway are pliable and therefore cannot provide the same structural support as an adult airway skeleton. Therefore, prolonged postoperative stenting is required for support following a laryngotracheal repair.[3] This increased malleability of the trachea of a neonate increases its propensity to develop tracheomalacia. Notwithstanding, the suppleness of the pediatric trachea also facilitates long-segmental resections, i.e., up to 50% of its length may be resected without undue tension on the anastomosis.[1,3,38]

Pediatric patients tolerate prolonged intubation but are also more prone to pressure-induced mucosal ischemia-related injury, especially at the posterior commissure of the larynx (injury to cricoarytenoid joints leading to posterior glottic stenosis) and the subglottis (circumferential strictures of the cricoid).[47]

Preoperative Assessment

A detailed history and examination should be used to assess the severity and level of upper airway obstruction. Symptoms of laryngeal obstruction may vary from mild stridor to drooling, dysphagia, and dyspnea. The presence of agitation may be an early sign of hypoxia in such patients. Obstruction at the supraglottis or glottis level manifests as inspiratory stridor; subglottic obstruction presents as biphasic stridor. In contrast, obstruction at the distal trachea or any of the main bronchi manifests as expiratory stridor.[3] The history of upper respiratory tract infection (URTI) necessitates rescheduling of the procedure to prevent adverse respiratory events. Other preoperative considerations include the patient's general condition and the presence of any intercurrent systemic illness, such as coexistent gastroesophageal reflux in a child with laryngomalacia.[48]

The head and neck should be examined for evidence of exterior airway compression. Investigations may include airway imaging (radiographs of the neck, upper thorax, and chest, as well as CT or MRI), and flow-volume loops (spirometry). Fiberoptic endoscopy is a beneficial investigation, although in many cases, rigid bronchoscopy is required to delineate the extent of the lesion.[23,39] Some clinicians are of the view that patients with stridor should be initially evaluated with a CT scan instead of diagnostic bronchoscopy, as this may lead to dangerous airway bleeding in cases where a hemangioma is present or an airway polyp that can become swollen or dislodged after bronchoscopy, potentially lethally obstructing the airway. Recently, three-dimensional (3D) imaging of the airway has been introduced, making the delineation of the extent of specific airway lesions significantly more accurate.[49]

Preoperative Preparation and Planning

Airway surgeries are critically dependent on teamwork and good preoperative planning.[1] Surgical needs should be ascertained before formulating an airway

management and ventilatory strategy. The initial agreed-upon plan should include measures for continuous oxygenation and the delivery of anesthetic agents, and it should be flexible enough to accommodate the safety requirements of both parties. For example, intubation is not the best plan for clearing respiratory papillomatosis. Surgery would be complicated with an endotracheal tube (ETT) in place, and there is the possibility of distal seeding of the papillomata during intubation.[46] Similarly, intubation may become mandatory when oxygenation is compromised, even though it encroaches on the surgical field. Rescue plans should also be discussed and ready for patients with severe stenotic lesions. The Storz ventilating bronchoscope is an excellent tool for rescuing lesions with dynamic airway collapse, mainly when the lesion is located within the thorax.[1,3] In high extrathoracic airway lesions, a tracheostomy at the beginning or as an initial rescue plan would be preferred to secure the airway. An intensive care unit (ICU) bed should be scheduled, and the patient's family should be informed of the risks and outcomes.

Children with any space-occupying lesion in the airway may develop total airway obstruction after induction of anesthesia. Therefore, skilled assistance, appropriate supplies, and an ENT surgeon experienced in performing tracheostomies in children should be ensured. A well-equipped difficult airway cart, including a videolaryngoscope, a fiberoptic bronchoscope, a ventilating rigid bronchoscope, needle cricothyroidotomy, and surgical airway access, should be kept in the vicinity before anaesthetizing these children.[50-52] A suggested scheme for a DA cart for infants and children is described in **Box 1**. The videolaryngoscope should be preferred over the conventional laryngoscope, as it provides a magnified view of the glottis, which helps to delineate the pathology and allows for assessment of the available glottic chink and atraumatic intubation.[40] The smallest ETT (2 mm ID) should be available in the operating theater (OT) for neonates with airway pathology, as failure to intubate with even a 2.5 mm ID ETT necessitating tracheostomy has been reported.[40,53] Suction should be turned on, and emergency medications should have been prepared.

BOX 1: Suggested contents of difficult intubation trolley.[50-52]

- *Top and sides:* Fiberoptic bronchoscope with all accessories (VBM masks, Berman Airways, angle piece with opening Straight connectors), videolaryngoscope (VL) inclusive of its monitor [e.g., C-MAC, Glidescope, Airtraq VL (size 0, 1, and 2 blades)]
- *Drawer 1:* Laryngoscope blades: Macintosh (1, 2, 3), Miller (0, 1), McCoy (1, 2); two laryngoscope handles; rigid ventilating bronchoscopes
- *Drawer 2:* ETT of assorted sizes (inclusive of size #2), uncut MLT #6, 7, 8, 9, LMA #1, 1.5, 2, 2.5, 3
- *Drawer 3:* Bougies (including infant bougie), small and medium-sized stylets, airway exchange catheters (8, 11, 14 Fr)
- *Drawer 4:* Cricothyroidotomy kit (13G, 16G, and 18G), jet ventilation catheter, scalpel blade, curved hemostat for tracheostomy
- *Drawer 5:* Oropharyngeal and nasal airways (all sizes), oxygen tubings and anesthetic machine connector, suction catheters (6, 8, 10, 12 Fr)
- *Drawer 6:* Jet ventilator (e.g., MANUJET)—inclusive of all components

(BVM: bag-valve-mask; ETT: endotracheal tube; LMA: laryngeal mask airway)

All equipment for laser safety and tackling airway fires (goggles, laser-safe ETTs such as Laser-Flex ETT, a bucket of water, etc.) should be available in laser surgery.[54-56] Specialized equipment for ventilation, such as low-frequency jet ventilation (LFJV) and high-frequency jet ventilation (HFJV), should also be available.[55,56]

Premedication with oral atropine (20 µg/kg) or oral glycopyrrolate (50 µg/kg) decreases secretions; however, sedatives should be avoided in patients with airway obstruction. Percutaneous local anesthetic cream should be applied to the dorsum of the hand to prevent pain during venepuncture. A standard fasting period should be followed: 2 hours for clear fluids, 4 hours for breast milk, and 6 hours for solid food and formula milk. In an emergency, we should proceed after taking due precautions to prevent a full stomach, including a degree of head-up tilt, prokinetic agents, and the passage of a nasogastric or orogastric tube after induction. Rapid sequence induction has no role in cases with airway narrowing.

Anesthetic Management

Anesthesia for airway surgeries is challenging and complex, even for experienced hands. A senior anesthetist should administer the anesthetic in such cases. The significant perioperative concerns include:[1-3,56,57]

- Risk of total airway obstruction and dynamic airway collapse
- Risk of aspiration of gastric contents
- Slow anesthesia induction
- A child with upper airway obstruction may be unable to lie flat on the OT table.

The anesthetic technique must consider the potential for a narrow airway, difficult intubation, and difficult ventilation.

Inhalational Anesthesia

Inhalational anesthesia is usually used for the induction of GA in a child with an obstructive pathology (e.g., SGS).[2,3,46,50,51] Anesthesia should be induced in a position most comfortable to the child. This may be sitting upright and leaning forward. Achieving appropriate depth for intubation without concomitant hypoventilation and hypercapnia is difficult to accomplish in a neonate, as they have immature respiratory centers and their functional residual capacity (FRC) is reduced.[1,2,46,52]

Inhalational induction is performed using graded increments of either 1–8% sevoflurane or 1–5% halothane in 100% oxygen. After adequate depth, an intravenous cannula can be secured. Airway topicalization (using 1–2% lignocaine) reduces the volatile agent requirements for the endoscopic evaluation.[2,46] In a neonate, this may be particularly important as the required minimal anesthetic concentration (MAC) without a topical agent can be as high as 2.5. In contrast, apnea and/or hypotension may be precipitated with 2 minimum alveolar concentrations (MACs) of sevoflurane. Furthermore, the induction may be prolonged due to the narrowed airway. Still, with modest amounts of CPAP and patience, the required depth spraying of the airway can be achieved, and topical lidocaine (3–5 mg/kg) can be used.[1-3] A deep level of anesthesia should

be ensured during topicalization; otherwise, coughing, laryngospasm, and desaturation may occur during the induction. This technique has the advantage that volatile agents also have bronchodilatory effects, thereby preserving spontaneous ventilation. This technique is indispensable for children with upper airway compromise, as it maintains a degree of muscle tone and helps to maintain gas exchange profoundly during even prolonged attempts at intubation.[1,2,46,50] If the plane lightens, they breathe more; if it deepens, they become breathless. This technique can be used for almost all patients, but supplementation with intravenous agents may be necessary in older children. However, $EtCO_2$ monitoring may be difficult and therefore, the child must be observed for smooth respiratory excursions and a patent airway. $EtCO_2$ tracking can be done intermittently by placing an ETT or a small airway exchange catheter into the trachea to ensure that CO_2 levels do not rise too much. Environmental pollution remains a concern with this technique.

Full stomach concerns prevail in emergencies, but rapid sequence induction has no role.[46] Giving a neuromuscular blocker (NMB) can prove life threatening as intubation is anticipated to be difficult, and the ability to bag-mask ventilate the child may be lost.

Total Intravenous Anesthesia

Propofol and remifentanil infusions can be used for total intravenous anesthesia (TIVA) as an alternative to the inhalational technique during airway surgery.[46,52,57,58] The induction is performed using either a volatile agent or an intravenous bolus of propofol (1–5 mg/kg). Following this, 100% oxygen is provided via the anesthetic circuit, and infusions of propofol (6–15 mg/kg/h) and remifentanil (0.1–0.2 mg/kg/ min) are initiated.[57-59] The initial dose of propofol is injected gradually over 3–5 minutes to maintain spontaneous respiration. In cases of apnea, CPAP and gentle respiratory assistance are usually sufficient.[46,58,60] Hypotension and bradycardia may complicate the process. The remifentanil infusion rate should be incrementally adjusted by 0.05 μg/kg/min to achieve the desired respiratory rate. In contrast, the propofol infusion rate is adjusted using bispectral index (BIS) monitoring or based on patient movement. Lidocaine topical spray is useful for bronchoscopy and helps to reduce coughing and laryngospasm.[2,46] Complications include unwanted movement and a slightly higher rate of apnea.[58,59] The antitussive effects of remifentanil and the blunting of upper airway reflexes by propofol are suitable for airway surgeries, providing smooth anesthesia.[59,60] Principal benefits of TIVA are unhindered surgical access, ability to assess the dynamic airway function, ability to provide deep anesthesia, not dependent on respiratory mechanics or airway condition, and pollution free.

Airway and Ventilatory Management

The principal anesthetic consideration for airway surgeries is ventilation and oxygenation in an open airway. Conventional intermittent positive pressure ventilation (IPPV) with endotracheal intubation is often impossible to achieve in many of these procedures because the airway is occupied by the endoscopist's

TABLE 5: Ventilatory strategies for airway procedures.[46,52,55,60,61]

Characteristics	*IPPV*	*LFJV*	*HFJV*
Ability to ventilate open airway	No	Yes	Yes
Operative field immobile	No	No	Yes
Specialized equipment required	No	Simple gas injector	Yes, specialized ventilator
Barotrauma risk	Less	Intermittently high	High
Airway gas monitoring	Accurate	Difficult	Difficult
Airway pressure monitoring	Yes	No	Possible in some ventilators

(HFJV: high-frequency jet ventilation; IPPV: intermittent positive pressure ventilation; LFJV: low-frequency jet ventilation)

instruments, smoke, and debris, and the ETT must be removed from the surgical field to allow access to the surgical instruments.[60]

Advances in tracheobronchial surgeries have led to a proliferation of ventilatory techniques. Options include apneic oxygenation, spontaneous ventilation with or without alternating intubation, jet ventilation, and cardiopulmonary bypass.[46,52,54,57,60,61] The ventilation mode is determined based on the type of surgery performed and the required surgical access. Various ventilatory strategies used during airway surgeries have been compared in **Table 5**.

Intermittent Apnea without Endotracheal Intubation

The patient is handed over to the surgeon after induction of anesthesia and paralysis. Surgery proceeds during apnea, and bag-mask ventilation is intermittently provided in the event of desaturation.[61] This technique offers an unobstructed surgical view but with several disruptions. Also, there is a lack of airway protection and control of anesthesia depth.

Spontaneous Ventilation

Using topical anesthesia and sedation: This allows patients to maintain control of their airway. However, because of patient discomfort and lack of cooperation in children, only fiberoptic bronchoscopy, nasoendoscopies, and some needle drainage procedures may be tolerated with this technique.[52]

Spontaneous respiration with GA: Insufflation of 2–5% halothane or 2–8% sevoflurane in oxygen into the pharynx via a nasal cannula may be an option for maintaining anesthesia during short airway procedures. Intermittent positive pressure ventilation should be provided by a face mask as required. TIVA with airway topicalization may also be used as an option.[46,61] GA via laryngeal mask airway (LMA) facilitates airway management during fiberoptic bronchoscopy in infants and allows for a larger fiberoptic bronchoscope passage.

Intermittent Positive Pressure Ventilation

This is a common technique using either standard ETT smaller than the required size (for younger patients) or microlaryngoscopy tubes (30 cm length, 4–6 mm ID cuffed), which lie between the arytenoid cartilages. It provides an unobscured view of the anterior two-thirds of the glottis and gives reasonable surgical access to the larynx.[2,52] This enables positive pressure ventilation using standard anesthetic equipment, and the breathing system connections can be moved away from the surgeon. The inflated cuff protects the lower airway from contamination. However, this technique can only be used in older children, and there is often limited access to the posterior third glottic area.[52,61] The operative field moves with respiration and may be inconvenient to the surgeon. IPPV may also be provided by a Jackson Rees circuit attached to the side port of a ventilating bronchoscope, though it will not be as effective.[61]

Low-frequency Jet Ventilation

Low-frequency jet ventilation with a Sander's gas injector **(Fig. 6)** allows positive pressure ventilation without a gas-tight system.[62] A stream of high-velocity gas (15 psi) is delivered by operating a manual toggle switch at a rate of 10–20 breaths/min in children or using an electronically timed ventilator. It can be delivered supra-, infra-, or transglottally.[55,61] Each bolus entrains 2–3 times its volume of ambient air to increase the tidal volume while diluting the oxygen concentration of the inspired gas. LFJV is easy to perform and produces an unobstructed view of the operative field. However, barotrauma is risky, especially if the jet is infraglottic.[61] Therefore, the upper airway must remain patent. Ventilation adequacy is assessed by monitoring chest movements, as end-tidal CO_2 monitoring is not feasible in this setting.[63] TIVA is required as inhalational anesthesia may not be reliable. Further, the operative field is mobile, and gastric insufflation can occur if the suspension laryngoscope is poorly aligned with the glottis.[52,55] Blood, debris, and smoke may be entrained during LFJV.

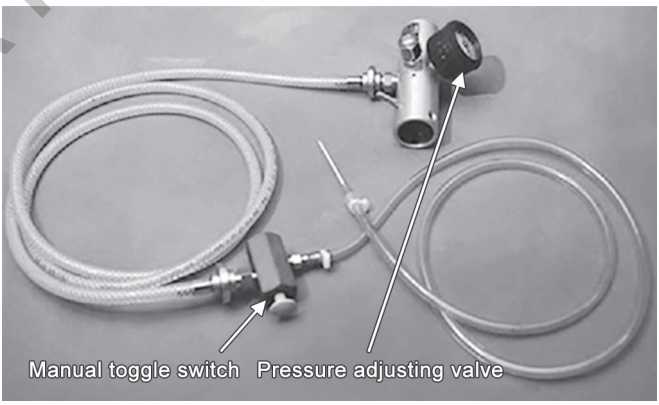


Fig. 6: Sander's jet injector.

High-frequency Jet Ventilation

High-frequency jet ventilation can be delivered either via a cannula attached to a suspension laryngoscope to provide supraglottic ventilation, a longer catheter placed through a port in a bronchoscope or laryngoscope subglottically or transglottically via a cricothyroid cannula.[2,52,64,65] The onset and end of inspiration are controlled by a pneumatic or electronic high-frequency flow interrupter, which entrains air and delivers small tidal volumes (up to 2.5 mL/kg) with lower peak airway pressures.[64] Therefore, it can be beneficial for ventilation across stenosis.[65] The modifiable parameters include inspired oxygen concentration, driving pressure of gas, ventilatory rate (typically ranging from 60 to 600 breaths/min), and inspiratory time (usually 30% of the respiratory cycle).[64]

This technique provides a clearer operative field view, a stable surgical field, and acceptable gas exchange with minimal hemodynamic instability. Disadvantages include difficulty in monitoring CO_2 concentration, an unprotected airway, the need for TIVA, complex equipment, and the risk of barotrauma. Newer technology ventilators heat and humidify the gas and continuously monitor airway pressure. Transglottic cannulas are typically used in adults; however, even a 2–3-mm cannula is impractical in infants, as it may cause barotrauma and lead to air trapping.

Superimposed High-frequency Jet Ventilation

In this technique, two jet streams with different frequencies are superimposed upon each other. The lower-frequency jet (8–20 bpm) removes CO_2.[65] The high-frequency jet (400–800 bpm) delays expiration and prevents the lung from completely collapsing. The anesthetic technique employed is TIVA with muscle relaxation.

High-flow Nasal Cannula

High-flow nasal cannula (HFNC) has recently been utilized as an alternative for oxygenation in pediatric patients undergoing tubeless airway surgery.[60] The combination of HFNC with spontaneous respiration (STRIVE Hi) has been reported to maintain oxygenation and airway patency in adults with an obstructed airway. Furthermore, this method causes CO_2 to rise more slowly than with transnasal humidified rapid insufflation ventilatory exchange (THRIVE), resulting in longer anesthesia times. Recently, Xiong et al. described the safe use of HFNC as an airway management technique in children (including neonates) with severe laryngeal obstruction undergoing prolonged airway surgeries (up to 60 minutes) under GA.[66] Transcutaneous CO_2 did not rise significantly, and oxygen saturation was maintained.

Advanced Management Techniques

Cardiopulmonary bypass has been used in the case of a neonate with near-total occlusion.[67] Hyperbaric oxygenation has been described during airway loss during a tracheal tear repair.[68]

Extubation and Postoperative Management

After airway surgery, careful monitoring is mandatory postextubation to detect early signs of airway compromise due to increased secretions, bleeding, or airway edema. All patients should be administered humidified oxygen. The patients should be placed in a semisitting position, and the trachea should be extubated either fully awake or under deep anesthesia to minimize the risk of laryngospasm. An LMA can be replaced with an ETT as a bridging device for deep extubation. Ensuring complete reversal of neuromuscular blockade reduces the risk of aspiration. Postextubation airway obstruction can be managed using helium as a useful short-term measure, as it may reduce the work of breathing. Heliox contains 21% oxygen in 78% helium, and additional oxygen may be added as required.[52] A difficult airway trolley comprising the equipment required for emergency airway access should be immediately available in the recovery area **(Box 1)**, and staff competent in life support and airway management should be in the vicinity until the patient is ready for discharge.

Intraoperative administration of dexamethasone (250–500 µg/kg) and topical 1:10,000 epinephrine aids in reducing postoperative airway edema.[2,52,61] Nebulized epinephrine (1:1,000, 3–5 mL) can reduce airway edema in patients with croup, and intravenous dexamethasone can be repeated 12 hours later. One size smaller ETT should be chosen for patients requiring postoperative ventilation to prevent additional swelling, and the patient should be adequately sedated to avoid excessive movement.

ANESTHETIC CONCERNS FOR SPECIFIC AIRWAY PROCEDURES

Laryngoscopy and Bronchoscopy

Flexible or rigid laryngoscopy and bronchoscopy are used for diagnosis as well as for therapeutic interventions for lesions of the airway. Flexible bronchoscopy enables the dynamic assessment of the upper airway during spontaneous respiration and an evaluation of the peripheral tracheobronchial tree.[11,24] It is particularly beneficial for evaluating conditions such as laryngomalacia, tracheomalacia, and bronchomalacia.[9,24] It is commonly performed through an endoscopy mask, ETT, or an LMA to allow concomitant oxygen inhalation and inhalational anesthetic during the procedure. Patient's age, comorbidities, and the indication for endoscopy will influence the type of anesthesia and ventilation needed for the procedure. Preoperative communication with the surgeon about the procedural components will facilitate decision-making. The primary goal should be to ensure smooth interdisciplinary coordination and maintain optimal oxygenation, ventilation, and surgical access.[1]

A history, physical examination, and radiological studies should be reviewed to identify and assess the severity of existing airway obstruction, as it may worsen with the loss of pharyngeal muscle tone that accompanies the deep plane of GA or may present difficulty with endotracheal intubation.[3,69] Intravenous atropine or glycopyrrolate is frequently administered to decrease airway secretions and prevent vagal-induced bradycardia and bronchoconstriction during airway manipulation. Personnel having expertise in decision analysis (DA), along with

all appropriate DA equipment, including equipment for tracheostomy, should be available.

After anesthetic induction with sevoflurane or propofol, intravenous and topical lignocaine can be administered to prevent gag and laryngospasm.[61] Along with a short-acting opioid, it will also attenuate the stress response to instrumentation. A recently published meta-analysis concluded that intravenous and topical/atomized lidocaine (<1 mL) may decrease the risk of laryngospasm.[70] As the airway remains open for a large percentage of time during the procedure, TIVA is preferred for an uninterrupted GA.[60]

The general principle of managing DA dictates preserving spontaneous breathing, ensuring ventilation is maintained in the presence of an open airway. Adequate depth of anesthesia should be ensured to obliterate airway reflexes and prevent movement, while maintaining sufficient cardiorespiratory stability. These goals can be achieved by the incorporation of topical anesthesia and newer anesthetic agents such as dexmedetomidine that minimally affect respiration.

Neuromuscular blockers are administered only after adequacy of ventilation has been checked. Neuromuscular blockade and intermittent positive pressure ventilation provide optimal oxygenation and ventilation, ensuring the absence of patient movement during airway manipulation. However, the technique's significant disadvantage is the possibility of airway loss at any time during the surgery.

Laser Endoscopic Resection Procedures

Laser resections are preferred for airway surgeries in children because they offer precise tissue excision in a narrow surgical field, which is not amenable to conventional surgical equipment.[71] A CO_2 laser is commonly used as it produces the least thermal energy, which might damage the surrounding tissues.[56,57] The ability to deliver laser energy through a fiber (through a bronchoscope) is making potassium titanyl garnet (KTP) or the neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers an increasingly attractive choice for distal airway procedures.[55,56] Different types of lasers used in airway surgeries, along with their application and photochemical properties, have been summarized in **Table 6**.

TABLE 6: Laser types and applications.[54-57,71]

Laser	*Application*	*Wavelength (nm)*	*Effect*	*Tissue penetration (mm)*
CO_2	Treatment of disorders involving oral cavity, tonsils, larynx, laryngoceles, stenosis	10,600	Thermal	<0.25
Nd: YAG	*Lesions of the nose and trachea*: Telangiectasis, obstructing lesions	1,064	Thermal	2–6
KTP-diode	Lesions of the nose, larynx, oral cavity: Telangiectasis, polyps, carcinomas, sleep apnea tissue removal	532	Thermal	0.5–2

(Nd:YAG: neodymium-doped yttrium aluminum garnet; KTP: potassium titanyl phosphate)

Laser procedures pose significant risks, including damage to healthy tissue, airway fire, and injury to theater staff. Surgical fires are rare but potentially catastrophic. Of the three elements necessary for fire ignition, all exist during surgeries involving the airway: an oxidizer (oxygen, nitrous oxide), a fuel (sponges, ETTs), and an ignition source (lasers, electrocautery).[56,57,71] Systemic operating procedures, including "fire drill", should be in place, and staff must be well-versed with laser surgery and local safety policies.[56] Pairs of eye protection glasses should be available for the staff, and a prefilled 50 mL syringe of 0.9% saline solution should always be readily accessible.

The anesthetic plan may include maintenance of spontaneous or controlled ventilation with TIVA.[54,57,71] Induction can be achieved using propofol 2–3 mg/kg and dexmedetomidine. For maintenance, infusion of propofol 200–500 μg/kg/min, dexmedetomidine 0.2–0.7 μg/kg/h, and remifentanil 0.3 to 1 μg/kg/min can be used. Topicalization of vocal cords allows a good level of immobility, while still permitting relatively rapid emergence. Episodes of apnea, laryngospasm, coughing, and desaturation are common in these procedures, requiring close monitoring and vigilance to titrate the anesthetic.[57,71] The oxygen content of the anesthetic gas mixture should be reduced as low as possible to maintain SpO_2 between 98 and 100% throughout the procedure. Nitrous oxide should be avoided, and helium should be used as an alternative. Capnography is impossible during jet ventilation or insufflation techniques. If arterial CO_2 must be monitored, transcutaneous CO_2 monitoring will provide a reasonable estimate.

Airway management options include:[57,71]

- Shielded (wrapped in aluminum foil) or specifically designed ceramic-coated ETT (Laser-Flex ETT)
- LFJV through a suspension laryngoscope
- High-frequency jet ventilation

Laser-safe tubes resist thermal damage and dissipate the laser's energy, thus decreasing the risk of airway fire and reflection damage to adjacent healthy tissue. Though fire resistant, they are not fire-proof, and ETT cuffs can be inadvertently perforated, resulting in higher pharyngeal oxygen concentrations.[56,71] In a study comparing various types of ETTs for laser compatibility, a plain red rubber ETT, a Foam-cuff laser ETT, a Laser-Flex ETT, and a Laser-shield ETT could all be burnt with the laser within 12 seconds while the 3M No. 425 or venture copper foil tape wrapped red rubber ETTs were not affected for even 1 minute exposure to the laser beam and was therefore advocated as safer.[72] If a cuffed ETT is used, the cuff should be filled with water or saline. Some anesthesiologists inject methylene blue into the saline that is injected into the cuff to enhance the detection of its breakage with the laser. If necessary, the ETT can be removed intermittently during laser treatments to optimize visualization for the surgeon and eliminate a potential source of an airway fire.

The manual jet ventilation technique has several advantages over ETT in laryngeal laser surgery, including good surgical access (especially to the posterior commissures) and absence of ignitable substances in the field.[55,57] Subglottic jet ventilation is uncommon in children because an adequate air outlet between

BOX 2: Immediate steps to tackle airway fire.[54,56,57,71]

- *Extract/eliminate/extinguish:*
  - Flood surgical field with saline
  - Stop LASER
  - Disconnect breathing circuit, stop ventilation and gases
  - Extubate and remove the burning fragments
- *Evaluate:*
  - Ensure no burning fragments
  - 100% oxygen by bag and mask
  - Review airway damage with flexible or rigid bronchoscopy
  - Secure airway
  - If no airway damage, one can proceed with surgery
  - Severe airway injury—tracheostomy or oral intubation, elective ventilation
- Remove endotracheal tube (ETT)
- Stop flow of gases
- Remove all flammable/burning materials from airway
- Pour saline or water into the airway
- Reestablish ventilation by mask using room air
- Extinguish and examine the ETT and consider bronchoscopy
- Assess the patient's condition, and plan for ongoing care

cycles is difficult.[71] For supraglottic jet ventilation, a metal injector is inserted into the side port of the suspension laryngoscope with its distal end 1–2 cm above the glottic opening. Respiratory movements are closely observed during each breath to prevent air trapping.

All usual laser precautions should be strictly followed. The energy from the laser is absorbed by the intracellular fluid, causing the cells to vaporize and produce a laser plume, which is suctioned away to protect the OT personnel. The child's eyes should be securely covered with wet saline gauze. All skin surfaces should be covered entirely with damp sheets or drapes to protect them from inadvertent exposure to misdirected laser beams. The OT staff should wear protective goggles to prevent ocular injury.[71] Prevention is the ultimate goal in managing airway fire, but airway fire protocol should be immediately followed in case of fire **(Box 2)**.[54,56,57,71]

Debulking Procedures for Laryngeal Papillomatosis

A microdebrider or CO_2 laser is used for surgical debulking of papillomatosis.[17] Laser resection has a higher risk of scarring and is less often used. Additionally, the use of a laser device can aerosolize virus-laden particles, potentially leading to cross-infection among theater staff.[56,71] Special masks are worn to prevent this risk. Tracheal intubation has been implicated in the distal seeding of papillomas; therefore, an "open airway" technique is considered ideal.[46,73] Adjuvant treatments may be attempted with papillomavirus vaccinations, intralesional cidofovir, and propranolol.[46] Tracheotomy is reserved for the most severe cases, as it is thought that tracheotomy may hasten the spread of the papillomas to the trachea.[73] Anesthetic management involves a strategy for maintaining spontaneous ventilation for suspension laryngoscopy.[73] Intubation with a small-sized ETT

and manual ventilation may be required when papillomatosis is extensive. Clear communication with the surgeon is necessary for determining the needed depth of anesthesia that will allow for safe suspension without secondary injury from patient movement or laryngospasm, yet is not so deep to induce apnea and hence, maintains oxygenation. Intraoperative steroid cover is given in major resections to prevent airway edema.[57,71]

Laryngotracheal Reconstruction

Laryngotracheal reconstruction is the primary surgical treatment for laryngotracheal stenosis (LTS), with the subglottis (SGS) being the most frequently affected site.[14,18,74] Mild LTS can be treated with repeated balloon dilatation and stenting techniques.

Surgery is usually required when there is >70% obstruction of the lumen.[74] For mild to moderate SGS, endoscopic posterior cricoid split and rib graft are effective treatments.

In patients with grade III or IV lesions, grafting the posterior and anterior trachea with stent placement is necessary to minimize granulation tissue formation and maintain arytenoid cartilage positioning.[14,36,74] The cartilage graft is harvested from the fourth or fifth rib, or less commonly thyroid cartilage, and an ETT is left in place for approximately 7–14 days to allow for graft healing.[75] Anesthesia is provided via tracheostomy, and a Montgomery T-tube stent may be placed after the reconstruction to maintain airway patency. If the patient does not have a tracheostomy, a cuffed nasotracheal tube is placed to stent open the airway until the graft(s) heal. Situations involving unintentional extubation, sedation, and reintubation should be thoughtfully planned out ahead of time because the airway may be challenging to secure postoperatively due to possible laryngotracheal collapse.[75] A dexmedetomidine infusion in combination with low-dose midazolam and fentanyl is a well-tolerated sedation regimen for improving ETT tolerance with few side effects in children.[75]

CONCLUSION

Pediatric airway surgery is a complex procedure that a dedicated interdisciplinary team should undertake. The anesthetic plan is usually formulated after careful evaluation of the entire airway, as these children generally have complex and multiple airway anomalies. Anesthetizing these children can be highly challenging due to their young age, the need to share the airway with the surgeon, the constant risk of airway collapse, and total airway obstruction under anesthesia. With an individually tailored and comprehensive anesthetic approach, most children can have their normal airways restored successfully.

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