Chapter 7. Oxygenation techniques for children with difficult airways

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7.1 Introduction

It is important for the pediatric airway practitioner to maintain oxygenation and avoid trauma when managing a child with a difficult airway. While these two objectives are compatible, it is also known that oxygen therapy can lead to significant harm. This chapter will include a discussion of various forms of oxygenation techniques during pediatric airway management, with an emphasis on avoiding hypoxia during all phases of the perioperative process. Included in this discussion will be mention of the deleterious effects of hypoxia, hyperoxia and potential dangers of some oxygenation techniques.

7.1.1 Hypoxia

Respiratory events are the most common cause of adverse events during pediatric anesthesia. (1) These complications are age dependent, with neonates and infants being at highest risk. Perioperative hypoxia is relatively common during pediatric anesthesia. The reported incidence is dependent on the definition of hypoxia and the reliability of objective recording using pulse oximetry. In a prospective analysis of 575 non-cardiac surgery patients, aged between 0 and 16 years, true hypoxemia (defined as $SpO2 \leq 90\%$ for at least 1 minute without recording artifact) occurred in 6% of cases. Of these 67 cases, 28% occurred at induction, 46% occurred during maintenance and 25% occurred during emergence. The incidence of hypoxemia increases significantly in younger patients. The highest incidence was in neonates where up to 50% of patients suffered some degree of hypoxia.

Patients at risk of hypoxia included those with:

- respiratory complications (40% of hypoxic cases), including sputum, atelectasis and hypoventilation
- complications secondary to procedural problems (24% of cases), including tracheobronchoscopy, laparoscopy and high ventilation pressures
- intubation related factors relating to endobronchial intubation, tracheal tube (TT) and supraglottic airway (SGA) use
- dislodgement of the airway device (19% of cases)
- laryngeal or bronchial spasm (13% of cases)
- hypoxia related to congenital heart disease (1% of cases)
- equipment failure (1% of cases). (2)

7.1.2 The consequences of hypoxia

The clinical consequences of brief periods of hypoxia during pediatric anesthesia are unknown. Hypoxemia, defined as SpO2 $\leq$ 90% for at least 1 minute, are common and usually well tolerated, provided normal oxygen saturations are rapidly restored. Extreme prolonged hypoxemia, however, has severe consequences. A study of central venous oxygen saturation measurements ($S_{CV}O_2$) in pediatric cardiac patients found that measurements of $S_{CV}O_2 < 60\%$ were associated with poor clinical outcomes and $S_{CV}O_2 < 40\%$ for > 18 minutes was the most predictive indicator of major adverse events.(3)

Infants and neonates are most at risk for adverse respiratory events and consequential cardiac arrest during anesthesia. (4) In a multicentre study of perioperative cardiac arrest, infants accounted for 55% of anesthesia-related cardiac events. (5) Practitioners need to be aware of the warning signs of cardiac arrest in children. Hypoxia is frequently associated with bradycardia which is the most common warning sign of cardiac arrest in children (54%). This is followed by hypotension (49%), low oxygen saturation (46%), unmeasurable blood pressure (25%), abnormal end tidal carbon dioxide (21%), cyanosis (21%) and cardiac arrhythmias (16%). (5)

7.1.3 The perils of oxygen

Oxygen is the most commonly used gas in medicine and a component of all general anesthetics. Yet, despite the ubiquitous presence of therapeutic oxygen, it is not without adverse effects, particularly when administered in high concentrations to premature neonates. (6, 7)

Neonatal resuscitation and oxygen toxicity

Neonates are susceptible to life threatening hypoxic episodes at birth which can occur in up to 6-10% of deliveries. Such events can then lead to death or severe morbidity including hypoxic encephalopathy, developmental delay, epilepsy and cerebral palsy. Resuscitation of the newborn is now recommended with air, due to growing recognition of poor outcomes from neonates resuscitated with 100% oxygen. A Cochrane review found a reduction in mortality in infants resuscitated with room air, but there is insufficient evidence to recommend the ideal oxygen concentration for neonatal resuscitation or to recommend a policy of using air over 100% oxygen or vise versa. (8)

High concentrations of oxygen administered during neonatal resuscitation are associated with oxidative stress, possibly due to oxygen free radicals. Immature neonates are unable to avoid the damage caused by oxygen free radicals because they lack the antioxidant system which is necessary to limit hydroxyl radical formation. A prospective study of severely asphyxiated term neonates, resuscitated with room air or 100% oxygen, found less oxidative stress, less cardiac and less renal damage when neonates were resuscitated with air rather than 100% oxygen.(9) There is also evidence of long term morbidity following brief exposure to 100% oxygen at birth, including childhood leukemia, indicating potential DNA mutation. (10) These problems seem to be age specific and exposure of 100% oxygen to older children is not associated with the same effects. The groups at most risk of the effects of oxidative stress are preterm neonates (gestational age <37 weeks). The International Liaison Committee on Resuscitation (ILCOR) has reiterated concerns about 100% oxygen used during resuscitation of the newborn by stating that air is as effective as 100% oxygen for neonatal resuscitation. (11)

Retinopathy of prematurity

The aetiology of retinopathy of prematurity (ROP) seems to be multifactorial. A number of factors have been linked to this condition, including extremes of arterial oxygenation (hypoxemia and hyperoxia), antenatal and neonatal exposure to inflammation, and genetic polymorphins. There are no anesthesia related cases of ROP, but a reasonable target is to use a minimum inspired oxygen concentration to achieve oxygen saturations between 90% and 94%. There is no evidence that anesthesia is a causative factor in ROP. (6)

Bronchopulmonary dysplasia

Bronchopulmonary dysplasia (BPD) is a condition of extremely premature infants (<1000 g, gestation 23-28 weeks). These neonates invariably require mechanical ventilation which can then lead to interstitial dysplasia of the lung which is associated with 20-40% mortality. The aetiology of BPD is thought to be a combination of external factors (prematurity, postnatal infection, ventilator induced lung injury, oxygen toxicity) and genetic factors in a susceptible host. The 'susceptible host' refers to the presence of a gene which allows an individual to tolerate oxidative stress. An anesthetic plan would aim to minimise airway stimulation, avoid hypoxia and hyperoxia, optimise lung function preoperatively, avoid high airway pressures and optimise postoperative oxygenation and analgesia.(6)

Atelectasis

High F_IO_2 is associated with absorption atelectasis in the lung which can occur rapidly within 5 minutes after the induction of anesthesia. This combined with high oxygen consumption, typically seen in neonates and infants, can lead to ventilation perfusion mismatch. Lung inhomogeneity then occurs when closed, recruitable and overdistended alveolar regions co-exist. This then sets up ventilator-induced lung injury. Protective ventilation strategies can be applied to minimise lung injury by judicious and controlled use of oxygen, low tidal volume ventilation, positive end expiratory pressure and recruitment manoeuvres. Alveolar volume recruitment has been applied to children < 2 years with beneficial effects using 30 cmH_2O for 10 seconds. (12)

Atelectasis tends to occur in dependent parts of the lungs and is one factor associated with postoperative pulmonary complications. The deleterious effects of atelectasis can be mitigated by limiting F_IO_2.

Other limitations of oxygen therapy

The duration and concentration of oxygen therapy should be limited in certain groups of patients. Children receiving chemotherapy agents are at risk of adverse effects from hyperoxia. Bleomycin with high F_IO_2 can cause acute interstitial pneumonia and chronic pulmonary fibrosis. Children at risk of high pulmonary vascular resistance and systemic vascular resistance require careful titration of F_IO_2 to maintain oxygenation, but avoid hyperoxia, which is associated with increased vascular resistance.

Oxygen should be treated like any other drug. Concentrations should be measured and titrated to provide the ideal dose to match the condition of the patient. Practitioners should be mindful of the adverse effects and interactions with other drugs before prescribing and administering oxygen. It is equally important to be careful of the extremes of oxygen therapy and understand the chronic effects of hyperoxia, but also the life-threatening impact of hypoxia.

7.2 Airway management techniques for children

The following techniques have been developed to maintain oxygenation for the patient, so that the practitioner can more easily provide careful airway management, without trauma.

7.2.1 Pre-oxygenation

In the presence of a difficult airway, preoxygenation buys valuable time for laryngoscopy and tracheal intubation before the onset of hypoxia and is recommended by current adult airway management guidelines (13-15). Preoxygenation techniques increase oxygen reserve in the lungs and therefore increase the duration of apnea without desaturation reaching ≤ 90% (DAWD). (16) Given the poor predictive value of bedside screening tests in children and adults, it is wise to be prepared for the unexpected difficult airway. It is therefore sensible to preoxygenate all patients. For some uncooperative children, this is not a practical option, however, many of these children receive an inhalation induction with 100% oxygen and a volatile agent, which can effectively achieve denitrogenation of the lungs.

Without oxygen, following the induction of anesthesia and the onset of apnea, oxygen desaturation occurs rapidly after the oxygen saturation falls to 94%, particularly if the airway is obstructed during apnea. A study by Hardman et al, using the Nottingham Physiology simulator, demonstrated that the onset of oxygen desaturation was age dependent. Modelling healthy virtual children who were 1 month, 1 year, 8 years and 18 years old, following apnoea, it was found that oxygen desaturation occurred in the order of age, with the 1 month neonate exhibiting oxygen desaturation first, followed by the 1, 8 and then the 18 year old. This modelling was conducted with open and obstructed airways, and repeated with preoxygenation periods of 0, 1 and 3 minutes. The rate of oxygen desaturation of hemoglobin from 90 to 40% was approximately the same for all ages (~ 33%.min $^{-1}$ for an obstructed airway, and ~ 26%.min $^{-1}$ for an open airway). Preoxygenation delayed the onset of oxygen desaturation in all age groups, but the benefit of preoxygenation was least in the 1 month neonate. In the absence of preoxygenation and an open airway, a 1 month old neonate desaturated in only 6.6 seconds compared to 33.6 seconds for the eight year old child. This difference can be explained by the physiology of the neonate which has a larger minute ventilation to functional residual capacity (FRC) ratio, a high metabolic rate and low maximal SaO_2 compared to older children. (17)

The DAWD to ≤ 90% depends on the pre-oxygenation technique, oxygen reserve at the start of apnea, oxygen consumption and the amount of oxygen required to maintain S_PO_2 at 90%. In a theoretical healthy adolescent or adult, that time is 6.9 minutes with 100% oxygen therapy and 1 minute if the patient is breathing air.

Pre-oxygenation involves tidal volume breathing (TVB), with 100% oxygen through a sealed face mask for 3 minutes. A fast technique of equivalent efficacy to TVB involves eight deep breaths of 100% oxygen for 60 seconds. The endpoint for these techniques is an end-tidal oxygen concentration of 90% ($F_EO_2 = 0.9$). Another fast technique using four deep breaths of

100% oxygen over 30 seconds is not recommended and is inferior to the TVB 3 minute and 8 deep breaths techniques. (16, 18) Failure to reach $F_EO_2 = 0.9$ can be attributed to a decreased fresh gas flow, low F_IO_2, inadequate pre-oxygenation time and leaks around the mask. The DAWD depends on the quality of the pre-oxygenation technique, the lung function residual capacity (FRC) and oxygen consumption. Pre-oxygenation can be optimized by sitting the patient up to increase their FRC. Application of positive end expiratory pressure (PEEP) has been studied in this context, and several studies show improved denitrogenation conditions and prolonged DAWD with PEEP.(19) As discussed, infants have a relatively small FRC and high metabolic rate compared to an adult, which aggravates the rapidity of hypoxia onset during apnea, particularly in association with airway obstruction. This physiology reduces the DAWD and explains the benefit of prolonging oxygenation after induction of anesthesia.

7.2.2 Apneic oxygenation

The concept of delivering oxygen to apneic patients was first described by Holmdahl in 1956.(20) It was recognized that during apnea oxygen is taken up by the blood from the functional residual capacity (FRC) at a rate that exceeds the outflow of carbon dioxide. This occurs because of the relatively high solubility of CO_2 in the blood. Flow rate differential then occurs between oxygen removal from the alveoli and CO_2 excretion. This generates a negative pressure gradient of -20 cmH_2O creating bulk flow of oxygen from the upper airway to the alveoli. Oxygen can be delivered from the nose, facemask, pharynx or trachea at varying flow rates and F_IO_2. The effectiveness of apneic oxygenation varies depending on the delivery technique and the age and physical status of the patient.

Using this technique with preoxygenation and apneic oxygenation through a tracheal tube, normal oxygen saturations can be maintained for at least 10 minutes in children, but infants may desaturate after only 3 minutes of apnea. In this study of 28 children and infants, PaO2 decreased at 4.1 kPa.min^{-1} which is three times faster than an adult. (21) A similar study demonstrated that after preoxygenation and apneic oxygenation with 0.1 liter kg^{-1}min^{-1} through a tracheal tube, oxygen desaturation was prevented for 3 minutes. In a control group breathing air, oxygen desaturation occurred after 116 seconds in patients who were 3-10 kg; 147 seconds if weight was 10-20 kg and 217 seconds if the child weighed > 20kg. (22)

A limitation of this technique is the steady increase in $PaCO_2$ of 0.4 - 0.8 kPa.min^{-1} due to absent ventilation and clearance of CO_2. Over time, this can cause respiratory acidosis and an associated spectrum of complications including cardiac arrhythmias and vasodilation.

7.2.3 Nasal cannula for low flow oxygenation

In 1977 Wung described the insufflation of nasal oxygen at 10 L.min^{-1} via corrugated tubing for newborns with respiratory distress syndrome. A nasal tracheal tube was then intubated via the other nostril. This technique had the desired effect of reducing the incidence of hypoxia and bradycardia.(23) The use of nasal cannula to extend oxygenation into the post-induction phase of anesthesia is now recommended during laryngoscopy and tracheal intubation by recent adult airway management guidelines.(14) Dry nasal oxygen at 15 L/min for an adult can achieve near 100% FIO_2, but has limitations for pre-oxygenation because of patient intolerance due to nasal desiccation. Despite this limitation, this technique is effective at prolonging apnea time after the administration of sedatives and muscle relaxants. (19) This technique has been given the acronym NO DESATS for nasal oxygen during efforts securing a tube. (24) In adults and adolescents, pre-oxygenation can comfortably start with 2 L.min^{-1} nasal oxygen, and the flow can increase to 15 L.min^{-1} after induction.

Oxygen through nasal prongs has also been used to oxygenate infants during tracheal intubation. (25) The nasal prongs are applied with no flow under the face mask during pre-oxygenation, without any problems caused by leaks around the mask. After induction of anesthesia with a muscle relaxant and apnea, nasal oxygen flow is turned to 6-8 $L.min^{-1}$. With this technique, the author reports infrequent bradycardic and desaturation episodes during airway management. The importance of proper patient positioning is emphasized with neck extension using a shoulder roll to avoid airway obstruction.

7.2.4 Heated humidified high flow nasal cannula (HHHFNC)

The upper limit of gas flow through nasal cannula is primarily limited by patient tolerance. Cool dry gas becomes very uncomfortable at high flows. By heating nasal gas to body temperature and providing humidification to >99% relative humidity, nasal gas can be administered to patients comfortably, using flow rates equal to or exceeding the patient's inspiratory flow rate. (26) This technique was originally described in 2000 for pediatric intensive care patients as a form of respiratory support for premature neonates. (27) Heated humidified high flow nasal cannula (HHHFNC) has also been used successfully to treat infants with bronchiolitis, reducing the need for tracheal intubation and the need for intensive care admission. There is also a role for HHHFNC in transporting critically unwell children where intubation rates have fallen as a result of this treatment. Other benefits in children have been described including the management of obstructive sleep apnea, post-extubation stridor and viral induced wheeze.(26)

Physiological advantages of HHHFNC include decreased work of breathing, partial ventilation with limited CO_2 clearance and continuous positive airway pressure (CPAP) at approximately 0.45 cm H_2O pressure per 1 $L.min^{-1}$ flow rate. As a result of high gas flow and CPAP, improved washout of nasopharyngeal deadspace occurs and alveolar ventilation is possible which allows lung recruitment from positive distending pressure.(26).

Partial carbon dioxide clearance is seen with HHHFNC in adult apneic patients. In an adult study this clearance resulted in a modest $PaCO_2$ increase during apnea of 0.15 $kPa.min^{-1}$

compared to $PaCO_2$ of 0.4 - 0.8 $kPa.min^{-1}$ without HHHFNC.(28). There is currently no evidence to suggest that this CO_2 clearance with HHHFNC occurs in children.

Rare complications have occurred with HHHFNC therapy. Abdominal distension has been reported in two small case reports in children with intra-abdominal pathology requiring restricted use of this therapy in this context. Infection reported in 2005 from *Ralstonia spp* infection was linked to a Vapotherm 2000i HHHFNC system. This system was temporarily withdrawn and modified to prevent recurrence of this problem. No further infections have been reported since the product was re-introduced. Barotrauma has been reported in a small number of children associated with HHHFNC therapy. Pneumothoraces occurred in two children, pneumomediastinum in one child and subcutaneous scalp emphysema, pneumo-orbitis and pnemocephalus without pneumothorax or pneumomediastinum was reported in a premature infant receiving HHHFNC therapy.(26)

To mitigate the risk of barotrauma it is important that an adequate leak is provided around the nares by ensuring that the nasal prongs do not exceed 50% of the nasal diameter. This provides protection against excessive lung distending pressure. Application of HHHFNC in conjunction with face mask ventilation is also contraindicated because of the risk of excessive flow and airway pressure due to outflow obstruction. Another practical point is the importance of maintaining an open upper airway during HHHFNC therapy. This may require simple upper airway maneuvers such as a jaw thrust.

The Optiflow® (Fisher and Paykel Healthcare, Auckland, New Zealand) is a heated humidified high flow delivery system. The nasal cannulae are specifically designed for this purpose to withstand high flows of gas. The cannulae are made of soft silicon and are designed with skin applicators for the face to improve patient comfort during prolonged use.

Adult flow rates of 70 $L.min^{-1}$ have been described for transnasal humidified rapid-insufflation ventilator exchange (THRIVE). (28) Recommended pediatric flow rates appear in Table 1.

Weight	Flow rate
0-15 kg	2 $L.kg.min^{-1}$
15-30 kg	35 $L.min^{-1}$
30-50 kg	40 $L.min^{-1}$
>50 kg	50 $L.min^{-1}$

Table 1. Suggested flow rates for children receiving HHHFNC oxygen/air (personal communication from A/Prof Andreas Schibler, Mater Research Institute, University of Queensland, Brisbane, Australia).

An early report of 20 infants less than 3 months old undergoing tracheal intubation with HHHFNC, found that the benefit seemed to depend on whether the child was sick or healthy. Oxygen saturation remained normal throughout the intubation for 12 healthy children with normal lungs, but five of the eight sick children desaturated. It is unknown whether the sick children would have been worse without HHHFNC. (29)

The use of HHHFNC therapy during pediatric anesthesia is still novel compared to the extensive experience in pediatric intensive care. Potential applications during pediatric anesthesia might include HHHFNC for preoxygenation, tracheal intubation, laryngeal and other upper airway surgery, endoscopy and anesthesia recovery.

In adult patients, HHHFNC has also been used effectively in the ICU during difficult tracheal intubation and as a primary oxygenation mechanism for prolonged periods of apnea during surgery. (28, 30)

7.2.5 Bag mask ventilation

Bag mask ventilation (BMV) is a core skill in airway management and is the default technique when all others fail. Airway narrowing is the main cause of difficult ventilation, and children with a collapsible upper airway, such as that seen in laryngomalacia, will benefit from continuous positive airway pressure (CPAP) which stents the airway and increases functional residual capacity.

Creating an adequate mask seal can be challenging during BMV for children with dysmorphic features and distorted anatomy. A novel approach to mask seal in a term infant with a frontonasal encephalocele was achieved by using an inverted adult size five face mask over the infant's face (31).

Maintaining a patent airway during an inhalation induction of anesthesia can be particularly challenging in infants with micrognathia. Optimum BMV techniques may be required in these patients. This technique includes two people: one ventilates the bag using 100% oxygen and a respiratory rate consistent with the resting respiratory rate of the child. A double C-E grip with fingers on the jaw and mask helps to create a jaw thrust and minimises leaks around the mask. Airway manoeuvres include jaw thrust, head tilt and chin lift. Of these, jaw thrust is the most effective to open the obstructed airway in an anesthetised child (32). Airway adjuncts can be used to improve airway opening, including Guedel and nasopharyngeal airways.

7.2.6 Tracheal intubation

An analysis of airway management complications in children with difficult tracheal intubation found that temporary hypoxemia was the most frequent cause of non-severe complications. In this prospective cohort analysis from the Pediatric Difficult Intubation registry (PeDI), 1018 children were studied over an interval from 2012 to 2015. Hypoxemia was defined as a 10% decrease from the pre-intubation oxygenation saturation for more than 45 seconds. The overall finding of hypoxemia during tracheal intubation was 9% (94/1018). Of that number of hypoxemic patients, 65 (8%) were anticipated difficult intubations and 29 (15%) were unanticipated.

Although the incidence of difficult laryngoscopy (DL) is lower in children than in adults (1.37 vs 9%), the incidence of DL in infants is significantly higher than in older children (4.7 vs 0.7%) (33). The incidence of DL is doubled in children undergoing cardiac anesthesia due to the relatively high incidence of concomitant congenital syndromes such as CHARGE and DiGeorge (34). Difficulty to intubate can change as the child matures. Children with Treacher Collins syndrome, for example, become more difficult to intubate with age, whereas Pierre Robin syndrome improves with age (35).

Direct laryngoscopy attempts may be prolonged for infants with difficult airways, increasing the likelihood of patient hypoxia, trauma and awareness. Administering oxygen and maintaining normal oxygen saturations during an intubation attempt has obvious advantages for the patient by avoiding the adverse effects of hypoxia which have already been discussed. There are also human factor benefits because a well oxygenated child allows the practitioner to remain calm, take time and perform a less rushed and potentially less traumatic attempt at intubation. The absence of oxygen desaturation during intubation also reduces the need to withdraw the laryngoscope for BMV re-oxygenation. This could mean fewer intubation attempts.

Multiple intubation attempts are a leading cause of severe complications in pediatric airway management due to laryngeal trauma and potential airway obstruction. (36) This is particularly relevant to neonates and infants who have lax supraglottic and subglottic mucosae, making them predisposed to swelling. This age group has a relatively narrow airway. From birth to adolescence, the trachea more than doubles in length, triples in diameter and increases by six-fold in cross-sectional area.(37). The relationship between gas flow and lumen diameter is explained by Poiseuille's law. ($Q = \frac{\pi P r4}{8\eta l}$)

(Poiseuille's law: Q=flow, P=pressure, r=radius, η=viscosity, l=length)

For a neonate with a pre-existing small tracheal radius, a small amount of mucosal swelling can have a large detrimental impact on gas flow because of the r^4 factor.

A careful, controlled intubation attempt without the stress of hypoxia may lead to improved first pass success, avoiding multiple airway manoeuvres and associated awareness. A study of awareness in children found that the only predictive factor identified for awareness was multiple airway manoeuvres.(38)

Another benefit of oxygen treatment during intubation is education. (25) A trainee can safely perform tracheal intubation in a child or infant under supervision without the stress generated by pulse oximeter alarms signalling hypoxia. Awareness is avoided by total intravenous anesthesia and the educational experience is enhanced by videolaryngoscopy where the whole intubation attempt is seen by the supervisor and potentially recorded and played back for review.

7.3 Pharyngeal oxygenation

There are various ways of administering oxygen during tracheal intubation. Low flow and high flow nasal cannula oxygenation have already been discussed but there are alternative techniques.

7.3.1 Laryngoscopes

Early attempts to add oxygen to a laryngoscope were described by Wung in 1977. A number 8 French suction catheter was taped to a size 0 Miller laryngoscope blade and oxygen was given at 2 $L.min^{-1}$. (23) Next came the Oxyscope by Todres and Crone in 1978 which had a more robust design involving a built-in modification to size 0 and 1 Miller blades. These laryngoscopes were used to intubate newborn babies with 2 $L.min^{-1}$ of oxygen, and the same modification was soon added to Macintosh blades. The modification consisted of a metal tube running down the length of the blade to supply oxygen to the tip. A clinical study published in 1981 described a decreased incidence of hypoxia and bradycardia when neonates with hyaline membrane disease were intubated with oxygen rather than air. (39)

The concept of laryngoscope delivery of oxygen applies to other devices including the Bullard® laryngoscope with an integrated 3.7 mm working channel suitable for insufflation of oxygen. The Bullard laryngoscope® (Circon-ACMI) is rigid and anatomically shaped with a viewing lens and a fiberoptic light. It is available in adult and paediatric sizes. It can be used for laryngoscopy without head manipulation, and because of its very narrow profile, it allows intubation with only 6 mm of mouth opening. This laryngoscope has become less popular and has been superseded by other devices.

7.3.2 Optical stylets

Several optical stylets are equipped with side ports to attach oxygen for use during tracheal intubation. The oxygen flows inside the tracheal tube to the tip of the stylet. This mechanism is used in the Brambrinck and Bonfils optical stylets (Karl Storz Endoscopy; Tuttlingen, Germany) and the Shikani and Levitan stylets (Clarus Medical; Minneapolis, MN, USA). Optical stylets are used clinically as adjuncts to laryngoscopes during direct laryngoscopy, or as stand-alone intubation devices for patients with difficult airways. The tip of the optical stylet is navigated to the vocal cords and the tracheal tube is then advanced down the trachea. If supplementary oxygen is used with the optical stylet, it is normally delivered via the tip of the laryngoscope blade to the larynx. Apart from treating hypoxia, the oxygen flow can help to clear the lens of the optical stylet from debris or fogging.

7.3.3 Videolaryngoscopes

The Truphatek Truview PCD™ Optical Video laryngoscope (Truphatek International Ltd. Netanya, Israel) has a pediatric size laryngoscope which features a channel suitable for oxygen insufflation to the tip of the blade. (Figure 1. The Truphatek Truview videolaryngoscope with oxygen tubing attached) A study by Steiner et al used laryngoscope apneic oxygenation and measured time for a 1% drop in SpO_2 from baseline. They also measured the slope of overall desaturation vs time in pediatric patients undergoing tracheal intubation. The patients were intubated with either a standard Macintosh laryngoscope without supplementary oxygen in Group 1, or a Truview PCD videolaryngoscope (VLO_2) with an oxygen attachment in Group 2, or a modified Macintosh laryngoscope with an oxygen catheter taped to the side of the blade in Group 3. Groups 2 and 3 received oxygen at 2 -3 $L.min^{-1}$ depending on the size of the blade or catheter in Groups 2 and 3. Patients in Groups 2 and 3 with insufflated oxygen demonstrated significant increased times to 1% desaturation and significant reduced overall rate of desaturation compared to Group 1 that did not receive oxygen. There was no significant difference in results between Groups 2 and 3. (40)

Pharyngeal oxygenation has also been studied by Windpassinger et al with an Airtraq laryngoscope (AirTraq, Prodol Meditec S.A., Vizcaya, Spain). A randomised controlled trial used a standard cuffed RAE tube through the AirTraq. Following induction of anesthesia and preoxygenation, children aged 0 to 2 years were randomised to receive no gas or oxygen at 4 $L.min^{-1}$ through the tracheal tube throughout the intubation phase. The mean laryngoscopy time was 60 seconds. The trachea was then intubated and the cuff was inflated. The oxygen tubing was then removed and the time for oxygen saturation to drop from 100% to 95% was measured. There was a significant prolonged time before desaturation in the oxygen group.

7.3.4 Tracheal oxygenation

Great care is required when connecting oxygen to any airway device, particularly when the oxygen is delivered below the vocal cords. Oxygen can be delivered through airway exchange catheters (AEC) using fittings designed for 15 millimeter and jet ventilator connections. Examples of AEC oxygen fittings are the Cook Rapifit connectors (Cook Critical Care; Bloomington, USA). Airway exchange catheters are used for tracheal tube exchange and as a place holder in the event of failed extubation and re-intubation with a tracheal tube. They have also been used as primary ventilation devices for elective surgery in infants and neonates with severe laryngotracheal stenosis (41), and as a rescue airway device for neonates with severe airway obstruction in conjunction with the Ventrain. (42)

Numerous reports of barotrauma confirm the potential dangers of airway exchange catheters. A review of the use of AECs to insufflate or jet ventilate oxygen into the airway found that 11% of adult patients receiving jet ventilation through an AEC sustained pulmonary barotrauma. (43) Two pediatric case series collectively reviewed 31 patients. (41, 44) All patients received manually assisted or volume controlled ventilation through the AEC. There were no reports of barotrauma. One neonate became hypoxic requiring a tracheotomy.(41)

Oxygen can be administered by high pressure jet ventilation or low pressure insufflation. Barotrauma is less common when insufflation is used, however, the authors of the systematic review recommend avoiding routine use of oxygen through AECs. (43)

7.3.5 Rigid bronchoscope

A rigid bronchoscope is a recommended instrument to manage a difficult pediatric airway. This device has numerous advantages: it can be used as a ventilation device to deliver 100% oxygen, with or without a volatile anesthetic agent; it can splint open an obstruction in the airway; it can push an obstructing foreign body beyond the trachea; it can facilitate suctioning; and it can accommodate surgical instruments to remove foreign bodies. The Difficult Airway Society pediatric airway guideline recommends the rigid bronchoscope as a final option to secure the obstructed airway before front of neck access.(45)

Following successful intubation and re-oxygenation with the bronchoscope, a definitive intubation can be achieved with a tracheal tube (TT) by inserting an airway exchange catheter down the middle of the bronchoscope, removing the bronchoscope and railroading an appropriate size TT.

7.3.6 Supraglottic airways

Supraglottic airways have multiple applications in the management of children with difficult airways, including: a primary airway; a conduit for tracheal intubation; a rescue ventilation device during resuscitation; and rescue during a failed airway. These devices can be used for extended periods of time for various surgical and medical indications (46).

Absolute contraindications to SGA use include increased risk of pulmonary aspiration, airway obstruction beyond the glottis and high airway pressure. Relative contraindications include a partially collapsible lower airway, restricted access to the airway and inexperience using a SGA (47). Airway obstruction in neonates during induction of anesthesia can be avoided by inserting a supraglottic airway (SGA) following topicalisation of the upper airway .(48) The SGA then functions as a conduit for flexible bronchoscope guided tracheal intubation.

7.3.7 Flexible bronchoscopy

Flexible bronchoscopy and tracheal intubation is a valuable technique for management of the difficult pediatric airway. Hypoxia is a common cause of morbidity during flexible bronchoscopy. Older children can tolerate an awake flexible bronchoscope intubation with local anesthetic and sedation. Oxygen treatment during this procedure may include nasal cannula with low or high flow oxygen. An adult study using HHHFNC up to 70 L.min^{-1} through the Optiflow™ during conscious sedation, found that this technique was well tolerated and effective at preventing hypoxia during awake intubation. (49). For nasal flexible bronchoscopy a Hudson Mask can be positioned below the mouth to provide low flow oxygen. Alternatively, a nasopharyngeal airway can be inserted in one nostril for oxygen insufflation, while the flexible bronchoscope and tracheal tube are intubated via the other nostril. (50)

If the child needs a general anesthetic for flexible bronchoscopy, ventilation with oxygen can be continued through a pediatric endoscopy face mask (VBM Medizintechnik, Sulz, Germany). The flexible bronchoscope and a tracheal tube are passed through the middle of the facemask, through the nose or the mouth and into the trachea.

Children can present with a range of airway anomalies that create difficulties with ventilation and intubation. Complete airway obstruction can occur during induction with both intravenous and gaseous induction techniques. To avoid this problem, an airway can be secured with awake intubation of a SGA. This technique was first described in 1994 by

Johnson and Sims who successfully intubated a neonate with Goldenhar's syndrome after initially placing a size 1 laryngeal mask airway (LMA) having nebulized 2% lignocaine at a dose of 6 $mg.kg^{-1}$. (51) Once the LMA is placed in the airway, a swivel connector is applied to the circuit and a gas induction can be completed. Using this technique, two appropriated size tracheal tubes (TT) were pushed together and mounted onto the flexible bronchoscope. This extra TT length allowed easy removal of the LMA without dislodging the distally placed TT. Once the LMA is removed, the proximal TT is disconnected and the 15 mm connector is replaced on the distal TT in readiness for ventilation. (Figure 2. LMA used for tracheal intubation for a neonate with a neck mass) There is now a range of SGAs which are suitable as tracheal intubation conduits for awake or anesthetised pediatric patients with difficult airways, including the AirQ (Cookgas LLC; Saint Louis, MO, USA), Ambu Aura-1 and Ambu AuraGain (Ambu® Ballerup, Denmark). (52) Using these airways and tools designed to push a TT through the SGA, intubation through a SGA has become simpler. (Figure 3. AirQ with insertion tool connected to a tracheal tube) Local anesthetic techniques have also developed with innovative techniques using local anesthetic in a pacifier (48), mucosal atomizer devices (MAD) (Teleflex, Morrisville, NC, USA) and the DeVilbiss nebuliser.

Some flexible bronchoscopes are designed with a working channel which has been used as a conduit for insufflation of oxygen. This practice is not recommended because of the risk of barotrauma. A case report described a term four day old neonate that was intubated with a 3.1 mm external diameter flexible bronchoscope pre-mounted with a 3.5 mmID tracheal tube. The flexible bronchoscope had a working channel of 1.2 mm that was used to insufflate oxygen at 2 $L.min^{-1}$. After flexible bronchoscope intubation, skin crepitus, decreased air entry and hypoxia were noticed. A chest x-ray confirmed bilateral pneumothorax, unilateral tension pneumothorax, pneumopericardium and surgical emphysema. This life-threatening situation required cardiopulmonary resuscitation and bilateral chest drains. The authors of this case report warn against the use of oxygen treatment through the suction channel of a flexible bronchoscope. They also suggest oxygen can be safely delivered via an endoscopy mask or a SGA/swivel connector and finally they recommend treating pneumothorax immediately with chest drains rather than needle thoracostomy.

7.4 Emergency oxygenation for front of neck access

Options described to manage an emergency front of neck access (FON) procedure include small bore cannula (<4 mm in diameter), large diameter cannula in kits (>4 mm diameter) and surgical airway with a scalpel. There is very little evidence to support a decision in favor of one of these options. Most reported successful attempts at FON have been by surgical tracheotomy, usually performed by a surgeon.

7.4.1 Small cannula

Ventilation through a small cannula requires a high pressure gas source to overcome the resistance of the cannula. Various options have been proposed to manage cannula ventilation. Devices can be divided into flow regulated volume ventilation and pressure regulated volume ventilation.

Pressure regulated devices in the presence of small lung volumes and outflow obstruction can deliver potentially dangerous airway pressures leading to barotrauma and surgical emphysema. Devices such as the Manujet III (VBM Medizintechnik, Sulz, Germany) transtracheal jet ventilator (TTJV) include pressure ranges on their regulator for different age groups: baby 0-1 bar (0-14.5 psi or 0-100 kPa); infant 1-2.5 bar (14.5-36.3 psi or 100-250 kPa); adult 2.5-4 bar (36.3 – 58 psi or 250-400 kPa). There is very little published evidence to support the safe use of these devices in children. Two expert panels advised cautious use of the Manujet III starting at the lowest driving pressure and titrating up according to chest movement. Respiratory rate is determined by the time for the chest to recoil and fully expire.(45)

It is essential to down-regulate TTJV prior to use, operating the jet ventilator while holding the cannula and feeling for surgical emphysema. Inspiratory time is kept to a minimum. Start with minimum pressure and increase until chest movement can be seen. Focus should be on the chest, with a goal of restoring oxygenation rather than ventilation. Extreme care must be exercised during use of the jet ventilator, particularly if upper airway obstruction is suspected. Adequate time needs to be allowed for the chest to recoil and expire before giving another breath. Every effort should be used to open the upper airway using jaw thrust or airway adjuncts such as oropharyngeal airways or SGAs. The patient should have been paralysed to eliminate laryngospasm. Jet ventilators are associated with a high incidence of complications and are relatively contraindicated for use in neonates, infants, or any other patient with upper airway obstruction.

Flow regulated volume ventilation includes the Enk oxygen flow modulator (Enk OFM) (Cook Medical Inc.; Bloomington, USA) and the Rapid O_2™ insufflator (Meditech Systems Ltd. Shaftesbury, UK). These are both Y-connector variants with equivalent outflow diameters. There are no reports of these devices being used for emergency airway management. The Advanced Paediatric Life Support (APLS) guidelines recommend that oxygen flow should be initially set at 1L/min/year of age through a Y-connector. An I:E ratio of 1:4 at a rate of 12 breaths per minute is then recommended. The Enk OFM has been experimentally validated with these settings. Care is required with flows through a flowmeter in excess of 15 L/min because of excessive oxygen flow causing the Enk OFM to fail as an on-off device. The Enk OFM is designed with five ventilation holes. All of these holes need to be occluded to achieve inflation during inspiration.(53)

Self-made devices for emergency cannula ventilation are potentially very dangerous. A three-way tap in the oxygen line for ventilation is unsafe due to uncontrolled continuous inflation, even during the expiratory phase. This can rapidly lead to barotrauma because of inadequate expiration through the three way tap side port and therefore this technique is not recommended. (54) Bag ventilation through a cannula is inadequate to support oxygenation in adults. (55) There is one report of this technique being used successfully in an 11 month old, 9 Kg child, following an emergency 16G cannula cricothyroidotomy.(56)

7.4.2 Ventrain

The Ventrain (Dolphys Medical, Eindhoven, The Netherlands) is a flow regulated oxygen ventilation device which is capable of limiting high intrathoracic pressure by withdrawing inspired gas during the expiratory phase. This occurs due to the Bernoulli principle. The Ventrain is capable of oxygen insufflation and expiratory ventilation assistance (EVA). EVA occurs when the bypass channel of the Ventrain is occluded, creating a subatmospheric pressure (up to -217 cm H_2O) at the side port. Inspiratory flow is controlled by the oxygen flow meter. Negative pressure with the Ventrain requires proximal airway obstruction. To assist EVA in this situation, the upper airway may need artificial obstruction.

An animal study using pigs compared the performance of the Ventrain and TTJV during open, partial open and obstructed airways and found minute ventilation and avoidance of high airway pressures were superior with the Ventrain compared to TTJV. (57)

Two cases refer to neonates where the Ventrain was used to ventilate successfully through an 8 French Cook Frova intubating catheter (FIC) (Cook Critical Care; Bloomington, USA) using oxygen flows of 4-6 $L.min^{-1}$ and respiratory rates of 40 -100 breaths per minute. In these cases, conventional tracheal intubation failed due to extreme upper airway obstruction following multiple attempts at direct laryngoscopy. The Frova was used to establish an airway through the vocal cords and the Ventrain ventilated through the FIC applying EVA.(42)

7.4.3 Large bore cannula emergency ventilation devices

Various large bore cricothyroidotomy kits are available for children, including the pediatric Cook Melker and the Quicktrack Child device. (58) Animal studies have been conducted on both of these airways. (59, 60) There is no clinical evidence to suggest these airways perform better than a scalpel technique.

7.5 The EXIT procedure

The EX utero Intrapartum Treatment (EXIT) procedure is performed by a multidisciplinary team during Caesarean section. It is indicated when the neonate's airway is at significant risk of severe obstruction immediately after birth. The technique allows the foetus to be partially delivered and the airway to be controlled while placental perfusion is maintained. It was originally used in 1989 to deliver a foetus with a large anterior neck mass (61). It then became part of the antenatal treatment of congenital diaphragmatic hernias. In this condition, it was discovered that prenatal obstruction of the trachea using surgical clips could allow expansion and maturation of foetal lungs. The EXIT procedure allowed removal of the tracheal clips prior to delivery while the foetus remained well oxygenated on placental bypass (62). The EXIT procedure is now indicated for other foetal conditions where airway obstruction immediately after birth is a significant risk. These conditions include giant foetal neck masses, lung or mediastinal tumours, congenital high airway obstruction syndromes (CHAOS), EXIT to extra-corporeal membrane oxygenation (ECMO) for certain congenital cardiac conditions and congenital cystic adenomatoid malformation (CCAM). Recently, EXIT to airway for severe micrognathia has been added to this list (63). An EXIT procedure provides the opportunity to maintain oxygenation for up to 60 minutes prior to placental separation. This window of opportunity can be used to safely intubate the airway prior to delivery. (64)

Conclusion

There is a range of oxygenation techniques which can decrease the incidence of hypoxia during airway management for children with difficult airways. Each of these techniques should be selected to meet the individual requirements of the patient. It is important to be mindful of the potential dangers of some forms of oxygen treatment. The principle goals of managing any child with a difficult airway should be to maintain oxygenation and avoid trauma.

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Legends for Table and figures

Weight	**Flow rate**
0-15 kg	2L.kg.min^{-1}
15-30 kg	35 L.min^{-1}
30-50 kg	40 L.min^{-1}
>50 kg	50 L.min^{-1}

Table 1. Suggested flow rates for children receiving HHHFNC oxygen/air (personal communication from A/Prof Andreas Schibler, Mater Research Institute, University of Queensland, Brisbane, Australia).

Figure 1. The Truphatek Truview videolaryngoscope with oxygen tubing attached.

Figure 2. A neonate with a large cystic hygroma neck mass. Intubation through a LMA and swivel connector. Tracheal tubes are mounted on a flexible bronchoscope. Oxygenation and anesthesia is maintained via and anesthetic circuit connected to the swivel connector.

Figure 3. AirQ with insertion tool connected to a tracheal tube.