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EDUCATIONAL REVIEW

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Emerging trends, techniques, and equipment for airway management in pediatric patients

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Abstract

Pediatric patients present unique anatomic and physiologic considerations in airway management, which impose significant physiologic limits on safe apnea time before the onset of hypoxemia and subsequent bradycardia. These issues are even more pronounced for the pediatric difficult airway. In the last decade, the development of pediatric sized supraglottic airways specifically designed for intubation, as well as advances in imaging technology such that current pediatric airway equipment now finally rival those for the adult population, has significantly expanded the pediatric anesthesiologist's tool kit for pediatric airway management. Equally important, techniques are increasingly implemented that maintain oxygen delivery to the lungs, safely extending the time available for pediatric airway management. This review will focus on emerging trends and techniques using existing tools to safely handle the pediatric airway including videolaryngoscopy, combination techniques for intubation, techniques for maintaining oxygenation during intubation, airway management in patients at risk for aspiration, and considerations in cannot intubate cannot oxygenate scenarios.

KEYWORDS

airway, techniques and devices, difficult airway, equipment

1 | INTRODUCTION

Pediatric patients present unique anatomic and physiologic considerations in airway management, which impose significant physiologic limits on safe apnea time before the onset of hypoxemia and subsequent bradycardia. These issues are even more pronounced for the pediatric difficult airway. Adding to these inherent challenges, airway devices are generally developed for the pediatric population by proportionally downsizing adult devices to "fit" the pediatric patient. In the last decade, the development of pediatric sized supraglottic airways (SGAs) specifically designed for intubation, as well as advances in imaging technology such that current pediatric airway equipment now finally rival those for the adult population, has significantly expanded the pediatric anesthesiologist's tool kit for pediatric airway management. Equally important, techniques are increasingly implemented that maintain oxygen delivery to the lungs, safely extending the time available for pediatric airway management. This review will focus on emerging trends and techniques using existing tools to safely handle the pediatric airway.

2 | PEDIATRIC RIGID VIDEOLARYNGOSCOPY

2.1 | Expansion in available options

Videolaryngoscopes appropriate for pediatric patients continue to proliferate. Increasingly, vendors are expanding product lines to provide a more comprehensive set of videolaryngoscopes that generally include both hyperangulated and nonangulated options. Nonangulated blades are those that maintain the design of standard direct laryngoscopy (DL) blades such as the Miller and the MacIntosh but have a video added adjacent to the light source.

These nonangulated blades may be used for DL, video-assisted DL, or purely for videolaryngoscopy (VL). In contrast, hyperangulated videolaryngoscopes are designed with a significant curvature at the end of the blade, which allows improved visualization of the larynx. These hyperangulated blades are not designed to be used for DL. Videolaryngoscopes that have conduits or channels to pass an endotracheal tube (ETT) alongside the blade are another type of hyperangulated videolaryngoscope commonly referred to as a channeled videolaryngoscope. A universal product line with a comprehensive range of both nonangulated and hyperangulated videolaryngoscopes for patients would offer the most utility to providers. Table 1 provides an overview of commonly used VL systems, including classification and sizes of available blades. Given the absent to minimal data comparing which particular manufacturer design may be advantageous, no evidence-based recommendations for our diverse set of pediatric patients are available.

Key points

- Providing supplemental oxygen should be prioritized to prolong safe apneic time during airway management and potentially reduce adverse events
- Routine video-assisted direct laryngoscopy (DL) is an emerging trend, particularly in training institutions, for the intubation of neonates and infants, and pediatric patients with the potential for difficult DL
- Combined techniques for airway management can incorporate the benefits and minimize the pitfalls of individual techniques
- Point-of-care ultrasound may have a role in the evaluation of gastric contents in children to assess risk of regurgitation

2.2 | Hyperangulated vs Nonangulated VL

Though VL is increasingly used in children, evidence to guide the choice between hyperangulated vs nonangulated videolaryngoscope blades is insufficient, particularly for difficult intubations. Generally, hyperangulated blades are recommended for airways in which a provider would not expect to obtain any view of the larynx with conventional DL. Although the greater angulation of a hyperangulated videolaryngoscope blade will generally facilitate a view of the glottis, this acute distal blade angulation together with the inherent anatomic complexities of such patients can introduce difficulty in converting an adequate view to a successful intubation.[1] In an analysis from the Pediatric Difficult Intubation Registry (PeDI-R), the rate of successful intubation with a GlideScope® hyperangulated (GVL) blade given a Cormack-Lehane[2] grade 1 or 2a view was 64%, while in patients less than 10 kg, it was 53%.[3] Thus, in infants, nearly 50% of attempts failed despite having an adequate view of the laryngeal inlet. Zhang et al studied over 187 patients less than 6 years of age having GVL intubations with 35% having had a history of difficult intubations. The authors observed an 80% first-attempt intubation success rate and 98% overall intubation success rate, while 58% of the attempts encountered a technical difficulty. The most common technical difficulty was advancing the ETT through the plane of the arytenoid cartilages to just beyond the vocal cords.[4]

Though nonangulated blades lack the viewing angle of the hyperangulated blades, the relative lack of angulation may translate into less complicated tube passage when an adequate glottic view is obtained. Currently, there is an ongoing analysis comparing efficacy and complications of hyperangulated vs nonangulated videolaryngoscope blades within the PeDI-R that may provide additional

TABLE 1 Commonly used pediatric videolaryngoscope systems

	Hyperangulated			Non-angulated		
Manufacturer	Neonatal/ Infant	Pediatric	Teen	Neonatal/Infant	Pediatric	Teen
GlideScope[a] (Verathon)	+	+	+	Forthcoming	Forthcoming	+
Storz C-MAC[b] (Karl-Storz)	+/-	+	+	+	+	+
McGrath[c] (Medtronic)	-	-	+	+	+	+
Airtraq[d]	+	+	+	-	-	-
Truview PCD (Truphatek)	+	+	+	-	-	-
UE Scope (Unrelenting Efforts)	-	+	+	+	-	-
King Vision[d]	+	+	+	-	-	-

[a]Miller 0, 1, and 2 GlideScope videolaryngoscopes are expected to become available in early 2020, in addition to existing Mac 3 and 4 blades.

[b]Storz C-MAC pediatric hyperangulated blade (D-BLADE), may be used in infants, but is less well suited for small or premature neonates. Storz C-MAC non-angulated videolaryngoscopes are available in both Miller and Mac blades.

[c]McGrath non-angulated videolaryngoscopes are available in Mac blades.

[d]Airtraq and King Vision offer a channeled hyperangulated videolaryngoscopes.

insight on the relative merits of each type of blade in patients who are considered difficult to intubate. A large-scale randomized controlled trial to obtain the necessary data is essential to make any evidence-based recommendations.

2.3 | Routine VL in children

In pediatric patients who are not anticipated to be difficult to intubate, it is unclear whether routine VL provides a clinical advantage. Pediatric data evaluating efficacy of VL vs DL are somewhat limited and contradictory. Sun and colleagues conducted a meta-analysis of VL vs DL in pediatric patients, which demonstrated that, while VL was associated with improved glottic visualization, there was prolonged time to tracheal intubation and higher incidence of failure.[5] A recent Cochrane review of VL vs DL in children reached the same conclusion.[6] These results should be interpreted knowing that the analysis included a limited number of studies, many with small sample sizes, and included patients both with and without anticipated difficulty, as well as studies of both hyperangulated and nonangulated blade types. Conversely, a Cochrane review of VL vs DL in neonates concluded that although VL did not decrease the time to intubation, it did increase first-attempt intubation rate,[7] and a randomized trial of VL vs DL in children under 2 years of age demonstrated equivalence with respect to time to intubation.[8] Recognizing the limited data comparing VL and DL, the multi-center, VL in small infants trial (ClinicalTrials.gov identifier: NCT03396432) was initiated. The primary outcome of this randomized controlled trial will be comparing first-attempt intubation success of standard DL with C-MAC VL in otherwise healthy infants. Additional outcomes include time to intubation, number of attempts, and complications. The pending results will hopefully aid clinicians on this currently controversial topic.

2.4 | Video-assisted DL

Video-assisted DL is a technique in which the laryngoscopist uses a nonangulated videolaryngoscope to perform DL. Because the videolaryngoscope blade is modeled after traditional laryngoscopy blades, the user can perform DL, with immediate availability of the indirect technique via the video screen should direct visualization prove difficult or impossible. Advantages of video-assisted DL include confirmation of successful endotracheal intubation by an observer, and when used to aid in teaching, the instructor can use the view seen on the screen to help trainees identify relevant anatomy and provide directed feedback.[9] The familiar structure of the blade and lack of angulation is expected to decrease technical complications compared with a hyperangulated blade.[10] The ability to convert from a direct to indirect technique within the same airway attempt may minimize attempts, and thus, complications, as the need for multiple intubation attempts, have been associated with increased rates of hypoxemia even in otherwise healthy neonates and infants.[3,11,12]

3 | COMBINED TECHNIQUES

The expansion of equipment for pediatric difficult airway management has allowed the development of combination techniques utilizing two or more individual devices. Such combinations allow providers to rectify weaknesses in individual tools and thereby optimize airway management. Three combination techniques that are increasingly used are reviewed below. Given that comparative data are lacking, the technique chosen should be based on the clinical situation, the personal available, and the experience of the team. Whichever intubation technique is chosen, supplemental or apneic oxygenation should be used as will be discussed in a following section.

3.1 | Hyperangulated rigid video laryngoscopy + flexible video laryngotracheobronchoscopy

Although VL with hyperangulated blades provides improved glottic visualization and has higher first-pass success rates in children who are difficult to intubate than traditional DL, difficulty may still be encountered in guiding the ETT through the glottic opening and into the trachea.[3,4] Successful combination of VL with a hyperangulated blade and flexible video laryngotracheobronchoscopy (flexible scope) has been described in adults with anticipated difficult intubations using the flexible scope as a dynamic stylet.[13] In this technique, the ETT is placed over a flexible scope rather than a rigid stylet. The first step involves insertion of the videolaryngoscope into the oral cavity followed by maneuvers to optimize the view of the larynx. If an adequate view of the larynx is obtained, the ETT and flexible scope are inserted together and dually guided into the laryngeal inlet under video visualization from both videoscopes. The flexible scope allows improved range of motion and manipulation to pass through the glottic opening and then advance into the trachea together with the ETT, while both are observed via the rigid videolaryngoscope as they enter, allowing the practitioner to guide the ETT past any potential difficulties. In cases where only a poor view or no view of the larynx is obtained with VL, the videolaryngoscope remains in the oral cavity to create space and displace soft tissue. Again, the ETT and flexible scope are inserted together, but in this circumstance, subsequent manipulation is guided by the view from the flexible scope to identify the glottic opening and advance into the trachea. Systems are in development that will allow a picture-in-picture simultaneous visualization of both the view from the flexible scopes (Table 2) and rigid videolaryngoscopes. Unfortunately, the smallest size currently available for the picture-in-picture feature has an external diameter of 5.0 mm suitable for size 6.0 ETT.

A randomized controlled trial of 160 adult patients with anticipated difficult airways demonstrated the use of this combined technique of VL with a flexible scope as stylet resulted in higher first-pass success rates, shorter time to successful intubation, and lower rates of airway injury when compared with hyperangulated VL alone.[14]

TABLE 2 Commonly used flexible laryngotracheobronchoscopy systems and recommended minimum endotracheal tube size

	Neonatal/Infant		Pediatric		Teen	
Manufacturer	OD (mm)	ETT	OD (mm)	ETT	OD (mm)	ETT
Olympus	2.2 2.8 3.1	2.5 3.0[a] 3.5	3.8 4.1	4.0[a] 4.5	5.1	5.5
Karl Storz[b]	2.8 3.0	3.0[a] 3.5	3.7 4.0	4.0 4.5	5.2 5.5	5.5 6.0
Verathon[c]	Forthcoming		Forthcoming		5.0 5.8	6.0 6.5

Note: Ample lubrication is required to pass any scope through an ETT. We recommended silicon-based lubricants especially when the scope size approximates the ETT size. As scopes are used, the distal flexible sleeve will develop small folds over itself increasing the diameter and repaired insertion cords of the scope also tend to have a thicker distal end – both of these situations will limit the size of the ETT into which the scope will fit.

[a]Scope may not fit through if the 15mm circuit adapter is left on the ETT.

[b]Storz has disposable and reusable pediatric and adult fiberscopes and a picture in picture system in development.

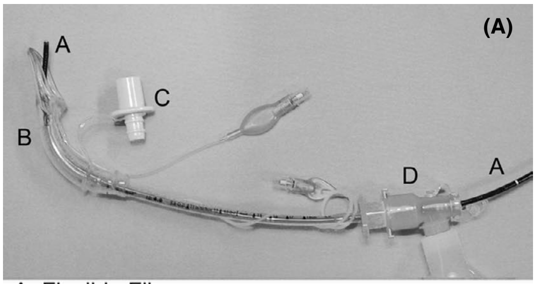
[c]Verathon has disposable and reusable adult fiberscopes and reusable pediatric fiberscopes with disposable pediatric fiberscopes forthcoming. Verathon has an adult size system that supports picture in picture for combining rigid video laryngoscope and flexible scope.

This technique has also been used successfully in children who are difficult to intubate.[15] It provides improved maneuverability and visualization over either technique alone; however, it does require multiple practitioners to operate the two devices and likely performs better in situations of anticipated difficulty rather than as a rescue technique. Flexible scopes may also be combined with traditional DL and nonangulated VL. The PeDI-R has an active protocol analyzing combined techniques, but randomized clinical trials are required to determine the situations for which this combined technique is best suited.

3.2 | Intubation via SGA with continuous oxygenation and ventilation

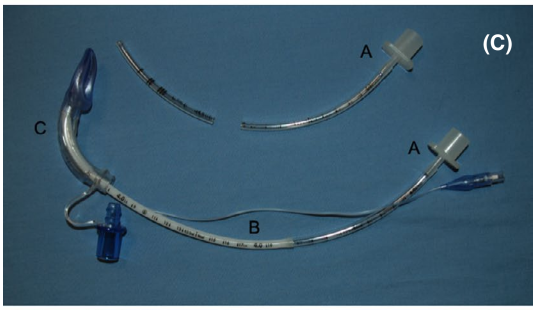
Another combination for management of difficult intubations is the use of a SGA as a conduit for intubation with a flexible scope. To maximize patient safety and success, this technique is best used with continuous oxygenation and ventilation during the intubation[16] as continuous ventilation during intubation via an SGA has been associated with decreased incidence of hypoxemia in young children with difficult direct laryngoscopies.[17] Intubation via an SGA may be used either as a planned approach to a difficult intubation or as a rescue technique in patients with an unanticipated difficult intubation. With placement of an SGA and resumption of oxygenation and ventilation following failed laryngoscopy, the practitioner has the necessary time to collect additional equipment and personnel to reattempt endotracheal intubation. Given the benefits highlighted above and supporting literature,[17] we believe that intubation via SGA with continuous oxygenation and ventilation may provide the optimal combination of success and patient stability.

The first step for this technique is successful placement of an SGA with confirmation of oxygenation and ventilation. When planned in advance, the SGA and ETT may be placed together as a single unit into the patient, or, when used as a rescue, the SGA may be placed first to reestablish oxygenation and ventilation, and then, the ETT may be inserted approximately halfway down into the SGA. If needed, the ETT cuff is inflated to make a seal within the SGA conduit. The ETT is connected to the anesthesia circuit, again reconfirming oxygenation and ventilation (Figure 1A). Following successful SGA placement, the provider may maintain spontaneous ventilation or choose to control ventilation with or without the use of neuromuscular blocking drugs as dictated by the clinical situation.[15] A triple port, swivel adapter is connected to the ETT, which, in turn, is connected to the anesthesia circuit to allow oxygenation and ventilation throughout the period of flexible laryngotracheobronchoscopy. The flexible scope is then introduced through the swivel adaptor and advanced through the ETT and SGA into the larynx and then the trachea. A key feature of this technique is that oxygenation and ventilation can continue throughout the manipulations of the flexible scope giving the provider an extended timeframe for airway management. In contrast to freehand flexible intubation where the user prefers to maximize the size of the scope relative to the size of the ETT to minimize the chance of entrapment of the ETT on anatomical structures, this technique requires enough space between the ETT and the flexible scope to allow oxygenation and ventilation. After the scope has been advanced into the trachea, the ETT is advanced over the scope and into the appropriate position as confirmed by the scope. Once the ETT has been successfully placed in the trachea, the flexible scope can be removed, and the patient is reassessed with attention to optimizing oxygenation, ventilation, and anesthetic depth. If subsequent removal of the SGA is preferred, ventilation



A: Flexible Fiberscope
B: Size 1 air-Q ILA™ containing cuffed ETT
C: 15-mm circuit connector from the air-Q ILA™
D: Triple port swivel adapter

A. Cuffed 4.0 ETT with 15-mm adapter removed
B. Size 1 airQ ILA
C. Laryngeal forceps



A. Stabilizing ETT - Uncuffed 4.0 ETT
B. Tracheal ETT - Cuffed 4.0 ETT with 15-mm adapter removed
C. Size 1 airQ ILA

FIGURE 1 Intubation via supraglottic airway with continuous oxygenation and ventilation and stabilization of endotracheal tube for removal of SGA. a, Intubation via supraglottic airway. Reprinted with permission.[16] b, Stabilization of endotracheal tube for removal of SGA. Stabilizing the ETT during removal of the SGA is a key aspect of the technique and if done incorrectly, can lead to dislodgement of the ETT from the trachea. Use of laryngeal forceps to stabilize ETT during SGA removal. c, Use of a second ETT to stabilize tracheal ETT during SGA removal. An advantage of this approach is that ventilation may continue as the SGA is initially removed. This decreases the time of unsupported ventilation. The second, stabilizing ETT should be cut so that the Murphy's eye is discarded. If the stabilizing ETT is trimmed such that the length of this ETT does extended past the length of the pilot balloon-cuff line, then the ETT does not need to be separated and only the ETT circuit connector is removed as the SGA is fully removed over the two ETTs. ETT, endotracheal tube; SGA, supraglottic airway

is briefly paused, while the ETT circuit connector is disconnected from the ETT leaving the connector attached to the anesthesia circuit via the swivel adapter to avoid misplacement. The SGA is now ready to be removed over the ETT, which is maintained in the trachea by a stabilization method. ETT position is reconfirmed, and oxygenation and ventilation are resumed.

Stabilizing the ETT during removal of the SGA is a key aspect of the technique and if done incorrectly, can lead to dislodgement of the ETT from the trachea. There are many potential ways to perform this step. The three basic methods are to use a tool such as laryngeal forceps, which grasp the tracheal ETT, add a second ETT into the tracheal ETT, or insert a commercial product into the ETT to prevent it from sliding (Figure 1B,C). There are commercial products that are specifically designed for this or one may improvise with other products such as an ETT stylet or an ETT exchange catheter that is large enough to be wedged into the top of the ETT without sliding through it. Whichever method is chosen, once the pilot balloon is about to enter the SGA airway conduit, the ETT is grasped in the oral cavity and the stabilization device must be disconnected from the tracheal ETT otherwise the tool and the pilot balloon will become stuck within the SGA airway conduit. An advantage of using a second, shortened ETT to stabilize the tracheal ETT is that ventilation may continue as the SGA is initially removed. This minimizes the time of unsupported ventilation.

Intubation via an SGA is particularly useful in very small infants and neonates in whom there are concerns regarding successful mask ventilation such as those with Robin sequence, as an SGA may be inserted in the awake infant, successful ventilation confirmed, and then induction of anesthesia undertaken.[18] We preferentially use an SGA in which the airway conduit is designed to accommodate a cuffed ETT and the pilot balloon (Table 3). While this technique does require multiple steps for successful completion, it offers the benefit of near-continuous oxygenation and ventilation throughout airway management, pausing respiratory support only during the time when the SGA is removed.

3.3 | Nonangulated rigid VL + video stylet

Combining a nonangulated videolaryngoscope with a video stylet allows the provider to use three techniques on a single attempt. In this combined technique, the video stylet acts as the ETT rigid stylet as well as either a verification of the ETT passage into the larynx or as the third method to intubate whether neither an adequate DL nor VL view is obtained. The provider starts with nonangulated VL using it as DL to position and assess the view of the airway. If the view is reasonable to proceed with an intubation attempt, the provider proceeds to pass the ETT under direct vision or may convert to video-assisted DL to confirm the passage of the ETT into the trachea. If instead, the view is not acceptable, the provider then uses the device as a videolaryngoscope and proceeds if an appropriate VL view is obtained. If neither DL nor VL view is reasonable to attempt an intubation, the video stylet becomes the primary visualization method of intubation by following its video view along the rigid videolaryngoscope toward and then into the larynx. Oxygen can be insufflated via the video stylet's oxygen adapter or a triple swivel adapter connected to the ETT while advancing the

TABLE 3 Commonly used pediatric supraglottic airways and suggested maximum cuffed ETT based on the ETT's internal diameter (mm)

	Neonatal/ Infant			Pediatric			Teen		
Supraglottic airway	**Wt**	**Size**	**ETT**	**Wt**	**Size**	**ETT**	**Wt**	**Size**	**ETT**
LMA Unique®	<5 kg 5-10 kg	1 1.5	3.0[a] 3.5[a]	10-20 kg 20-30 kg 30-50 kg	2 2.5 3	4.0[a] 5.0[b] 6.0	50-70 kg 70-100 kg	4 5	6.0 7.0
airQ® Intubating Laryngeal Airway	< 4 kg 4-7 kg	0.5[c] 1.0	4.0 4.5	7-17 kg 17-30 kg 30-50 kg	1.5 2.0 2.5	5.5 6.0 6.5	50-70 kg 70-100 kg	3.5 4.5	7.5 8.5
i-gel® supraglottic airway	2-5 kg 5-12 kg	1 1.5	3.0[a] 4.0[a]	10-25 kg 25-35 kg 35-60 kg	2 2.5 3	5.0[b] 5.0 [b] 6.0	50-90 kg >90 kg	4 5	7.0 8.0
Ambu® AuraGain™ Laryngeal Mask	<5 kg 5-10 kg	1 1.5	3.0[a] 3.5[a]	10-20 kg 20-30 kg 30-50 kg	2 2.5 3	4.5[a] 5.0 [b] 6.0	50-70 kg 70-100 kg >100 kg	4 5 6	6.0 7.0 7.5

Note: ETT sizes are for those ETT with a low profile cuff. As the airQ® is designed to allow pilot balloons to pass thought it, it will also allow larger ETT than would be routinely used for a child of the indicated weight.
[a]Pilot balloon will not fit through the SGA conduit.
[b]Pilot balloon may not fit through the SGA conduit.
[c]Only available as reusable product.

ETT and video stylet in the patient. The video stylet also can be used with hyperangulated VL without attempting a DL view. The preference is to use a malleable video stylet in which one can adjust the curvature as indicated by both the patient and the rigid blade (Table 4). Nonmalleable video stylets are feasible but do not provide the ability to customize the bend to the patient's anatomy, which may be especially problematic when used with a hyperangulated VL. In addition, adding a video adapter to the video stylet, which transfers the image to a visible screen within the operating room allows this technique to be employed by a single provider. The video adapter does add some heft to the ETT making it a more cumbersome but not absolutely limiting.

4 | OXYGEN DELIVERY

Maintaining adequate oxygen delivery to tissues to maintain homeostasis and cellular metabolism is essential in the perioperative period. Pediatric patients are known to have reduced safe apneic times compared to adults due to the inherent differences in their cardiopulmonary physiology including higher oxygen consumption and lower oxygen reserve, making techniques to prolong the period of time available for airway management vital for pediatric providers.[19]

4.1 | Passive oxygenation

Passive oxygenation or apneic oxygenation has long been known to increase safe apnea time in both children[20,21] and adults.[22] A small randomized controlled trial of healthy children age 1-8 years undergoing elective surgery demonstrated that children receiving 3 liters per minute (LPM) O_2 via nasal cannula during airway management had higher oxygen saturation compared with children assigned to standard of care.[23] Furthermore, in a cohort study of children from birth to age 8 years undergoing intubation by novices, the introduction of routine use of 5 LPM O_2 via nasal cannula during airway management was associated with an increase in the median time for pulse oximetry to fall below 95% from 158 seconds to greater

TABLE 4 Commonly used video stylets and recommended minimum endotracheal tube size

	Pediatric		Teen	
Manufacturer	**OD (mm)**	**ETT**	**OD (mm)**	**ETT**
Karl Storz	Bambrink 2.0 Bonfils 3.5	2.5 4.0	Bonfils 5.0 C-Mac 5.5	5.5 6.0
Clarus (Shikani)	Shikani 2.4	3.0	Shikani 5.1	5.5
UE video stylet	Small	3.0	Large	5.5
MPI MultiView Stylet Scope	Stylet Scope 2.5 Stylet Scope 3.5	3.0 4.0	Stylet Scope 5.0	5.5

Note: The Shikani stylets are malleable, allowing adjustment of the curvature as indicated by both the patient and the rigid blade.

than 277 seconds, and with a reduction in the incidence of hypoxemia during intubation with SpO_2 less than 90% from 31% in the no cannula group to 4% in the apneic oxygenation group.[24] A recent case report demonstrated the utility of apneic oxygenation with low flow nasal cannula in a premature dysmorphic neonate who tolerated three intubation attempts without hypoxemia or bradycardia.[25] Randomized trials in pediatric patients have shown that deep pharyngeal or laryngeal insufflation of oxygen via a laryngoscope results in slower rate of oxygen desaturation during laryngoscopy[26] and extends apneic time before the onset of hypoxemia.[27] In addition to the above techniques, the use of high flow, humidified oxygen via nasal cannula, as well as via simple nasal cannula at rates as low as 0.2 L/kg/min,[20] has been shown to extend safe apneic times in pediatric patients and is reviewed by Humphreys and Schibler elsewhere in this issue.

Multiple studies from pediatric emergency departments have demonstrated that in combination with other quality improvement measures, routine use of passive oxygenation during endotracheal intubation reduces the incidence of adverse events.[28-30] Given this evidence together with the known increases in safe apneic times, the PeDI Collaborative, which is the group behind the PeDI-R, has recommended the use of a difficult airway bundle checklist (Figure 2), which includes the use of supplemental oxygen during attempts at tracheal intubation. The bundle recommends using one of the following methods for providing supplemental oxygen during tracheal intubation: modified nasal trumpet connected to anesthesia circuit with 6 LPM flow O_2, oral RAE tube in the corner of the mouth, nasal cannula with at least 6 LPM flow O_2, or continuous ventilation through an SGA using a triple port swivel adapter. Adoption of routine apneic oxygenation, even in children who are predicted to have difficult intubations, has been challenging at the PeDI Collaborative institutions. Barriers to increased implementation of apneic oxygenation include concerns that nasal cannula may interfere with mask seal and therefore impair the effectiveness of mask ventilation as well as changing an individual's standard practice. We believe that, given the benefits highlighted above, apneic oxygenation should become routine, particularly for any infants, or children who are predicted to have difficult intubations.

4.2 | Modified RSI

Rapid sequence induction and intubation (RSI) has been traditionally advocated for patients at an increased risk of pulmonary aspiration such as those patients considered to have a full stomach. In a classic RSI, hypnotic agents are given for induction, neuromuscular blockade administered, and following onset of muscle relaxation, tracheal intubation is performed. Positive pressure ventilation is strictly avoided, due to concern for gastric insufflation and increased risk for pulmonary aspiration; however, surveys of American and British anesthesiologist have revealed that there are many clinical situations in which clinicians will opt for a modified technique, attempting to balance the risk of hypoxemia and the risk of pulmonary aspiration.[31,32] To minimize the risk of hypoxemia,

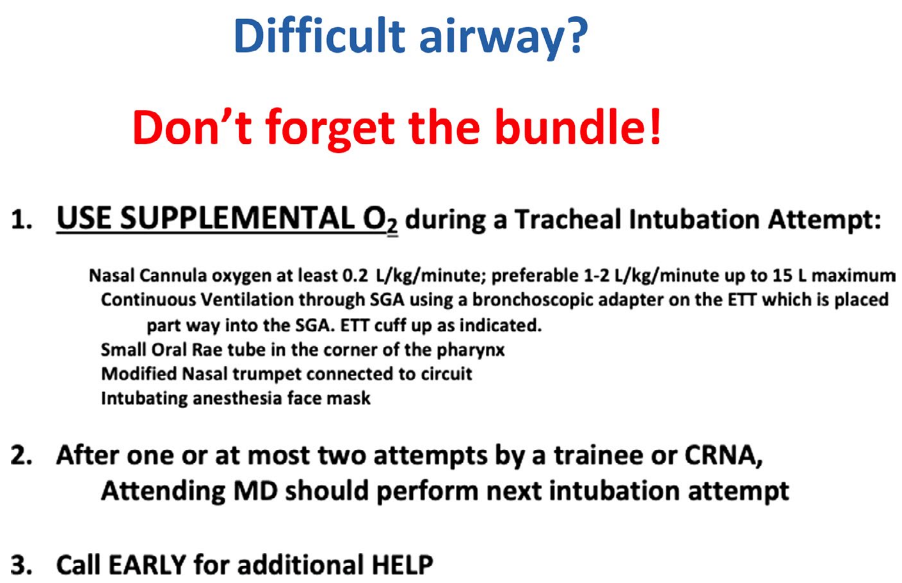


FIGURE 2 Pediatric Difficult Intubation (PeDI) collaborative difficult airway bundle. The bundle recommends using one of the following methods for providing supplemental oxygen during tracheal intubation: modified nasal trumpet connected to anesthesia circuit with 6 LPM flow O_2, oral RAE tube in the corner of the mouth, nasal cannula with at least 6 LPM flow O_2, or continuous ventilation through an SGA using a triple port swivel adapter. Other components of the bundle checklist include planning (1) who will perform first, second, and subsequent attempts at intubation; (2) induction method and medications; and (3) intubation method with primary and backup devices. The bundle also includes a rescue plan including who to call for assistance and a reminder "if anyone has a concern at any time during the procedure, please speak up." Finally, the bundle advises that after a 1st or, at most, a 2nd attempt by a trainee or CRNA an attending anesthesiologist should perform all subsequent techniques. LPM, liters per minute; SGA, supraglottic airway

many pediatric anesthesiologists prefer to utilize low-pressure, positive pressure ventilation following induction and prior to intubation, or a modified rapid sequence (mRSI) induction. However, the optimal technique for induction in pediatric patients considered at risk for regurgitation of gastric contents and subsequent pulmonary aspiration is an area of active debate. In a survey of Society for Pediatric Anesthesia members characterizing perioperative practice surrounding pyloromyotomy, though 86% of respondents reported utilizing a rapid induction, there was no clear consensus between RSI and mRSI.[33]

Current evidence, though limited, supports the safety of employing modified RSI to reduce hypoxemia with no indication that the risk of aspiration is increased. Neuhaus performed a retrospective cohort analysis of 1001 pediatric patients, including 107 patients younger than 2 years of age, having controlled rapid sequence that included low-pressure mask ventilation prior to intubation. Moderate hypoxemia (SpO_2 80%-89%) and severe hypoxemia (SpO_2 < 80%) occurred in 0.5% and 0.3% of patients, respectively.[34] Gencorelli et al analyzed 1070 patients having RSI. Compared with the Neuhaus study, despite including only patients older than 3 years of age, they observed higher rates of moderate and severe hypoxemia (1.7% and 0.8% of patients, respectively).[35] Both studies had comparable frequency of gastric regurgitation, 1/1001 and 1/1070, respectively, without evidence of pulmonary aspiration. Park et al compared the frequency of hypoxemia in 296 neonates and infants presenting for pyloromyotomy. Compared with rapid sequence induction, mRSI was associated with significantly less hypoxemia (17% vs 30%). Adjusted odds ratio (AOR) of hypoxemia for all patients having RSI vs mRSI was 2.8, and in subgroup analysis of neonatal patients, AOR was 6.5, indicating that younger, more vulnerable patients may derive even greater protective benefit from mRSI. Though pulmonary aspiration is a rare event, in the limited sample size of this study, there was again no indication that mRSI resulted in an observed increase in pulmonary aspiration.[12] We have made routine use of modified RSI with low-pressure positive pressure ventilation prior to intubation of infants with full stomach considerations part of our clinical practice.

Gastric ultrasound can provide noninvasive, quickly obtained information to more specifically guide clinical decisions regarding rapid sequence induction compared with clinical history and physical examination. Gagey et al prospectively observed 34 infants presenting for pyloromyotomy and performed gastric ultrasound prior to blind orogastric suctioning. In the majority of patients (91%, n = 31), adequate gastric imaging was obtained. Traditional management for this patient population assumes the potential for gastric residuals even after blind suctioning and therefore necessitates a rapid induction technique. In contrast, based on ultrasound findings, clinicians in this study proceeded with nonrapid induction or additional suctioning, and rapid induction was only performed in patients where imaging could not be obtained, or the stomach not fully emptied. There were no cases of pulmonary aspiration in this small cohort.[36] In a follow-up prospective cohort study of 143 children undergoing urgent surgery, gastric ultrasound obtained adequate images in 130 (90%) patients and resulted in a change in planned induction technique in 67 (47%) of patients. Gastric ultrasound resulted in the appropriate use of the indicated induction technique (RSI vs routine induction) in 85% of patients. The planned induction technique based on clinical assessment alone was consistent with postintubation findings following gastric suctioning (ie, RSI performed and gastric contents evacuated) in only 49% of patients.[37] Further studies are needed to develop risk estimates for patients with radiographic evidence of residual gastric contents, such as high-risk neonates or patients with difficult airways where it could be argued that the immediate risk of hypoxemia from strictly withholding ventilation may be greater than that of aspiration, as well as demonstrate actual risk reduction for pulmonary aspiration, which will be challenging, given aspiration is, fortunately, an infrequent event.

4.3 | Cannot intubate cannot oxygenate

Despite ensuring all clinically appropriate measures to minimize risk are employed, practitioners may be faced with a cannot intubate, cannot oxygenate scenario (CICO). In this potentially devastating circumstance, invasive airway access remains the only intervention that can potentially restore the ability to oxygenate and ventilate the patient and options include emergency front of neck access (eFONA) via a surgical approach or percutaneous cannula-based cricothyrotomy. Due to restrictions imposed by smaller anatomy, infants and neonates present unique challenges to surgical approaches. In particular, the outer diameter of the smallest neonatal ETT is larger than the average neonatal cricothyroid membrane,[38] severely compromising the ability to utilize a scalpel/bougie technique in this population. As a result, cannula-based techniques, where a small catheter is inserted through the cricothyroid membrane or trachea may be less traumatic, and a cannula-based cricothyrotomy are what is currently recommended by the Difficult Airway Society (DAS) in CICO scenarios when a surgeon capable of providing eFONA is not available, although documented success if quite limited.[39,40] Cannula-based techniques can be complicated by the inability to effectively ventilate patients, and limitations to air egress in patients with complete airway obstruction can lead to barotrauma. The Ventrain (Ventinova Medical, currently available in Europe) is a device that allows for oxygenation and ventilation through a small-bore catheter. Unlike other techniques such as jet-ventilation or oxygen flow modulators that rely on passive exhalation, Ventrain allows for active exhalation through a design that channels airflow to create subatmospheric pressure according to Bernoulli's principle providing, in effect, suctioning of the intrapulmonary air. With active exhalation, patients can be ventilated with inspiratory:expiratory (I:E) ratios close to 1:1, carbon dioxide can be effectively eliminated, and risk of barotrauma minimized. In addition, Ventrain is flow-regulated, which potentially limits the peak pressure during insufflation compared with other catheter-based oxygenation techniques.[41] In a porcine model of hypoxemia in the setting of a completely obstructed airway, Ventrain was effective in providing oxygenation and ventilation within one minute when used with an airway exchange catheter.[42] In a recent case report, Ventrain was used to restore ventilation and oxygenation in an infant who required reintubation with a 2-mm ETT following subglottic cyst resection. This child had persistent hypoxemia and increasing endtidal carbon dioxide despite a peak pressure of over 50 cm H2O peak using a standard ventilator.[43] Though these limited studies and reports support the potential for Ventrain to improve upon current existing modalities, further studies are needed to better establish safety and efficacy for its use.

4.4 | Oxygen reserve index

Novel equipment geared toward improving the clinicians' ability to more rapidly and accurately anticipate the impending onset of hypoxemia is currently available outside of the United States. There is a commonly recognized, clinically relevant delay in the time from beginning arterial oxygen desaturation to the time that standard pulse oximetry begins to decrease. The oxygen reserve index (ORi) is a unitless physiologic parameter ranging from 0.0 to 1.0 using measurements derived from a standard pulse oximeter. ORi is designed to detect changes in the arterial pressure of oxygen (PaO_2) in the range of 80-200 mm Hg, a range in which the hemoglobin oxygen saturation is generally 100%. Decreases in PaO_2 within this range may precede and thus predict the rapid onset of hypoxemia.[44,45] In a pilot study of 25 healthy children, ORi detected impending hypoxemia more than 30 seconds prior to noticeable decrease in pulse oximetry.[45] This advanced notice may give the clinician time to change strategies or intervene earlier in the onset of hypoxemia and potentially prevent associated hemodynamic consequences. In a recent case report of a 4-year-old undergoing tracheostomaplasty, a decrease in ORi to 0.0, consistent with a PaO_2 of approximately 100 mm Hg, was used as a trigger for interruption of surgery and resumption of ventilation; using this technique, pulse oximetry during the case had a nadir of 94%.[46]

If ORi is used during intubation, and attempts are interrupted due to impending desaturation, this may increase the number of attempts. As increased attempts are associated with increased complications, additional data are needed to ascertain, which factors play important roles in the rise of complications, the number of attempts or more prolonged attempts leading to loss of FRC and then complications as additional attempts are employed. ORi may become an added tool in the pediatric anesthesiologist's armamentarium, but further study is warranted to determine in what setting ORi may be useful.

5 | SUMMARY

At its core, the goal of pediatric airway management is to ensure oxygen delivery to tissues and maintain physiologic homeostasis for the child. Airway management in our youngest patients and those with difficult airways should be considered a critical event, and the gravity of such a designation must be fully understood and appropriately acted upon. A wide variety of techniques for such a critical event are reviewed above, but the technique for airway management in any given situation should be selected based on the provider's level of skill and experience to provide the best chance of optimizing oxygen delivery and minimizing physiologic disruptions. A method to ensure oxygen delivery to the child during airway management is essential, particularly in high-risk patients. Should one technique fail, an alternative approach should be undertaken in order to minimize overall attempts and to rapidly restore oxygenation and ventilation. As not one technique or device will be applicable to every case, providers must learn and continually practice a diverse set of advance airway techniques to be able to appropriately care for children in a variety of clinical situations.

REFLECTIVE QUESTIONS

1. What are the indications for video laryngoscopy with nonangulated and hyperangulated blades in your practice?
2. When faced with an anticipated difficult intubation, what are options for providing oxygen to the patient during airway management?
3. In your practice, how do you balance the risk of pulmonary aspiration and the risk of hypoxemia in a patient with indications for a rapid sequence induction and intubation?

DISCLOSURES

Dr Kovatsis is a medical advisor to Verathon. Dr Kovatsis is uncompensated in this role, and any compensation is provided to Boston Children's Hospital.

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