Recent developments in airway management of the paediatric patient

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Purpose of the review

During the last two years, several studies have enhanced our knowledge about the influence of pharmacological agents and routine airway management manoeuvres on the airway of paediatric patients. New supraglottic airway devices have been introduced into routine paediatric anaesthesia practice, and the design of paediatric endotracheal tubes has been modified. This review summarizes the most recent and relevant scientific developments in paediatric airway management.

Recent findings

Strong evidence has been gained that the lateral position is the best to ensure a clear airway in anaesthetized or sedated spontaneously breathing children. Remifentanil has emerged as an appealing drug for airway management in anaesthetized or sedated children. The paediatric ProSeal™-Laryngeal mask airway offers important advantages over the Classic™-Laryngeal mask airway for supraglottic airway management. The newly designed Microcuff™ paediatric endotracheal tube offers an improved age-appropriate design.

Summary

Remifentanil has found a place in airway management in paediatric patients. Recent improvements in the design of paediatric supraglottic airway devices and endotracheal tubes are promising. Further research is needed to consolidate their role in improving the perioperative outcome in paediatric patients.

Keywords

airway, children, endotracheal tube, laryngeal mask airway, remifentanil

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Abbreviations

CLMA	Classic™-Laryngeal mask airway
ETI	endotracheal intubation
ETT	endotracheal tube
FOB	fibreoptic bronchoscope
LMA	laryngeal mask airway
PLMA	ProSeal™-Laryngeal mask airway

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Introduction

Airway management is one of the key areas of paediatric anaesthesia practice. It has long been known that respiratory adverse events account for the largest proportion of perioperative critical events in paediatric patients [1,2]. Recent studies confirm that this is still true, despite the routine use of pulse oximetry and capnography [3,4]. This review discusses the most recent developments and scientific findings in paediatric airway management.

Impact of anaesthesia and simple manoeuvres on airway patency

Due to anatomical differences children are more prone to upper airway obstruction under sedation and general anaesthesia than adults [5]. In addition, they have a much higher oxygen consumption than adults and consequently develop hypoxemia much faster when their airway obstructs or when they become apnoeic [6]. It is crucial for paediatric anaesthesiologists to be aware of the implications of these differences and of the impact of simple manual manoeuvres to ensure the patency of the upper airway. Certain strategies to avoid airway obstruction, such as extubation in the lateral position, are standard practice in many paediatric institutions. In the past 2 years, several studies have enhanced our understanding of the underlying reasons for airway obstruction in children, as well as the ability to improve upper airway patency with simple manoeuvres.

Changes in upper airway dimensions under sedation

Evans *et al.* [7] studied the effect of increasing depth of propofol anaesthesia on airway dimensions in healthy children aged between 2 and 6 years using magnetic resonance imaging. Airway narrowing occurred throughout the entire upper airway, but was most pronounced in the hypopharynx at the level of the epiglottis. Arens *et al.* [8••] studied children with obstructive sleep apnoea syndrome aged 4 ± 2 years under light pentobarbital sedation and matched these patients with healthy controls using magnetic resonance imaging. The cross-sectional area in obstructive sleep apnoea patients was smaller. Airway narrowing during inspiration and airway dilatation during expiration was significantly more pronounced, shown by fluctuation of cross-sectional area during tidal breathing of between 300 and 900% and only 15–24% in controls. The authors suggested that the most likely reason was increased resistive pressure-

loading due to increased upper airway resistance, i.e. a more negative inspiratory pressure load on inspiration and a more positive expiratory pressure load on expiration. They speculated that increased airway compliance might also be a contributory factor in these patients. Both studies made a great contribution to understanding how and why the airways of healthy children and children with airway pathology obstruct under sedation.

Lateral positioning, chin lift, and jaw thrust

Another study demonstrated the mechanism of improving airway patency in sedated children by lateral positioning [9••]. In children aged 2–12 years, it was shown by magnetic resonance imaging that the total airway volume increased significantly from the supine position to the lateral position, and that the greatest relative increase in size occurred between the tip of the epiglottis and the vocal cords. Arai *et al.* [10] investigated the combined effect of lateral positioning and the chin-lift and jaw-thrust manoeuvres in spontaneously breathing children with adenotonsillar hypertrophy aged 1–11 years under 5% sevoflurane anaesthesia. In a later study [11••] they were able to demonstrate endoscopically that every single manoeuvre improved airway dimensions. Lateral positioning in combination with any manual manoeuvre enhanced the effects of each manoeuvre that, on its own, was not effective enough to provide a clear airway. In conclusion, these studies scientifically support what many paediatric anaesthesiologists practise routinely. However, despite proven value in the majority of patients, it must be borne in mind that such manoeuvres might not be of benefit in every child, as was described by von Ungern-Sternberg *et al.* [12] in a recent report on two children with cervical masses in whom upper airway obstruction deteriorated on using the jaw-thrust manoeuvre.

Remifentanil

Remifentanil, an ultra-short-acting opioid, has been used in routine anaesthesia for a decade [13,14]. Until recently, little information on its use in infants and children was available [15,16]. During the last 2 years, however, it has been studied extensively in paediatric patients. With respect to airway management, the focus of most studies was its use for endotracheal intubation (ETI) to avoid the use of succinylcholine, and its use in combination with propofol to preserve spontaneous ventilation.

Remifentanil for endotracheal intubation

The use of remifentanil for ETI without neuromuscular blockade in children was suggested some years ago. While Robinson *et al.* [17] stated that remifentanil does not appear to offer any advantage over alfentanil for routine use, Klemola and Hiller [18] concluded that remifentanil provided excellent to good intubation conditions. Very different doses of remifentanil had, however, been used. Recently, two different groups [19,20••] investigated the optimal dose of remifentanil in combination with propofol (3 and 4 mg kg^{-1}, respectively) for ETI in children and infants using doses of remifentanil of 1–3 μg kg^{-1}. Both groups compared different remifentanil doses with the use of a neuromuscular blocking agent. Blair *et al.* [19] studied a group of school-aged children and Crawford *et al.* [20••] studied both small children aged 4 years and infants aged less than 1 year. Blair *et al.* found that both 2 and 3 μg kg^{-1} remifentanil provided better intubating conditions than 1 μg kg^{-1}, but only with 3 μg kg^{-1} there was no difference from the control group (mivacurium). Since resumption of spontaneous respiration occurred significantly later in subjects given 3 μg kg^{-1} remifentanil but not in subjects given 2 μg kg^{-1}, they suggested that the latter regimen may provide all the advantages of an opioid for induction and ETI with rapid return of respiration. The study may be criticized for using mivacurium as reference. Crawford *et al.* first confirmed that the dose-response of remifentanil for ETI is similar in infants and children. They found that the effective remifentanil dose in 50% (ED_{50}) and 98% (ED_{98}) of patients was 1.7 ± 1 and 2.9 ± 0.5 μg kg^{-1}, respectively. In a second study, they found that the intubating conditions and apnoea time after 3 μg kg^{-1} remifentanil were similar to those after 2 mg kg^{-1} succinylcholine, the gold-standard of neuromuscular blockade for ETI. In both studies, 3 μg kg^{-1} remifentanil provided haemodynamic stability and attenuated the pressure response to ETI; however, patients had been pretreated with either atropine or glycopyrolate. In conclusion, these studies show that the combination of 3 μg kg^{-1} remifentanil and 3 mg kg^{-1} (children)–4 mg kg^{-1} (infants) propofol provides clinically acceptable intubating conditions and haemodynamic stability as well as a rapid return of spontaneous respiration. This technique can therefore be recommended for ETI in children undergoing brief surgical procedures or in children in whom the use of neuromuscular blocking agents is contraindicated. If return of spontaneous respiration is crucial, it might be sensible to reduce the dose of remifentanil to 2–2.5 μg kg^{-1} and to add a small dose of lidocaine.

Remifentanil titrated to preserve spontaneous respiration

Remifentanil's pharmacokinetics mean that it is ideal for any procedure that requires precise titration to omit or preserve spontaneous respiration. Of special interest for the paediatric anaesthesiologist is its use as an infusion in children who require airway management under spontaneous respiration such as patients with an anticipated difficult airway. Although no studies have investigated

the use of remifentanil for fibreoptic intubation under preserved spontaneous respiration, some studies do provide useful information on this area of application. Berkenbosch *et al.* [21] used a remifentanil–propofol mixture for flexible fibreoptic bronchoscopy in 15 patients aged 9 ± 5 years. They prepared a mixture of both drugs by adding remifentanil to undiluted propofol yielding a mixture of 10 mg mL^{-1} propofol and 15–20 μg mL^{-1} remifentanil. Sedation was induced with 0.1 mL kg^{-1} of this mixture (1 mg kg^{-1} propofol + 1.5–2 μg kg^{-1} remifentanil) administered over 5 min, maintained after this by titration, giving a mean maintenance dose of 4.1 ± 1.8 mg kg^{-1} h^{-1} propofol and 0.13 ± 0.06 μg kg^{-1} min^{-1} remifentanil. Apart from one patient who experienced a short episode of apnoea, all patients were breathing spontaneously with a respiratory rate of 6 ± 5 breaths min^{-1} and an SpO_2 of 95 ± 3%. The authors concluded that this technique is appealing for this kind of procedure, as discontinuation of both drugs allows rapid recovery if clinically significant respiratory depression occurs. Although the author of this review shares this opinion, he prefers to use two separate infusion pumps for fibreoptic intubation to enable independent up- and down-regulation of each drug, in a dose range similar to that reported by Berkenbosch. Ansermino *et al.* [22••] provide useful information for administration of remifentanil in spontaneously breathing children using 1% end-tidal sevoflurane in a nitrous oxide–oxygen mixture. In a dose-finding study, they found a large variation in the dose of remifentanil tolerated by spontaneously breathing children aged 2–7 years with a median dose of 0.127 μg kg^{-1} min^{-1} (range 0.053–0.3 μg kg^{-1} min^{-1}). A dose of 0.05 μg kg^{-1} min^{-1} allows spontaneous respiration in >90% of children, and a dose of 0.3 μg kg^{-1} min^{-1} prevents spontaneous respiration in >90% of children. Paediatric anaesthesiologists who wish to use this drug for fibreoptic intubation under conscious sedation in children must be aware of the wide variation in dose and the need for careful titration to avoid unwanted episodes of apnoea. Although Ansermino *et al.* state that a respiratory rate of <10 breath min^{-1} appears to be the best predictor of the maximum tolerated dose, they also concluded that increased tidal volume variability might be a better marker of opioid-induced respiratory depression in an article published in a different journal on the same subject and study [23]. It is the author's opinion that continuous respiratory rate monitoring provides a reliable way to avoid episodes of apnoea in most clinical circumstances when remifantanil is used for sedation.

Laryngeal mask airway

During the last two decades, the Classic™-Laryngeal mask airway (CLMA, Laryngeal Mask Company, Henley-on-Thames, UK) has become one of the cornerstones of airway management. In contrast to the face mask, the CLMA bypasses all potential pharyngeal obstacles and forms an airtight seal around the larynx, thereby making it a more effective supraglottic ventilating device than the face mask [24,25]. In contrast to the ETT, it does not enter the easily irritated and vulnerable tracheobronchial tree of the child. Both aspects have made the CLMA a very popular airway device for paediatric anaesthesiologists and have led to its widespread use. Although many studies have shown an advantage of the CLMA over the face mask or the ETT in various surgical procedures, there are still some areas where the CLMA is widely used but the scientific evidence of benefit for the patient is rather weak. For two of those applications — flexible bronchoscopy and neonatal resuscitation — valuable scientific evidence that supports its use has been published recently.

Bronchoscopy

Use of the CLMA for flexible bronchoscopy in children has been advocated by various authors [26–28]. Its use simplifies the procedure compared to the use of a modified face mask and its larger internal diameter compared with the ETT permits use of relatively larger FOBs. Reports so far, however, have covered only a small number of patients. A recent retrospective study by Naguib *et al.* [29••] over 15 years and 1947 procedures in 1548 patients with a mean age of 4.9 ± 5.6 years demonstrated for the first time that use of the CLMA results in a lower rate of procedure-related complications than the nasal route or the ETT. In addition, its use helped to reduce procedure and anaesthesia time.

Neonatal resuscitation

The LMA was recognized some time ago as a valuable tool in neonatal resuscitation [30,31] and this led to its inclusion in the 2000 and the 2005 Resuscitation Council Guidelines for Resuscitation [32,33]. Despite this, it has not yet become a routine technique in neonatal resuscitation. In a recent retrospective analysis, Trevisanuto *et al.* [34] reported on a further large series of cases in which the CLMA was successfully used for neonatal resuscitation. The outcome in neonates resuscitated using the CLMA was not different from the outcome in neonates matched for gestational age and mode of delivery who were resuscitated using a face mask. In addition, the CLMA provided effective ventilation in four neonates in whom bag-mask ventilation had failed. The same group was able to collect some data providing a possible explanation for the low utilization rate of the LMA for neonatal resuscitation [35]. LMA availability, LMA user competence and perceived value were much lower in paediatric departments than in anaesthesia departments. However, neonatal resuscitation remains the domain of paediatricians. Consequently, in order to

overcome the underuse of the LMA for neonatal resuscitation, the LMA needs to be provided more readily by paediatric departments, and paediatricians need to be trained better in its use. Gandini and Brimacombe [36] recently showed that this can easily and successfully be accomplished by simple manikin training.

ProSeal™- Laryngeal mask airway

Although in widespread use, the CLMA has well known limitations, such as its low pressure seal and the lack of protection against aspiration [37]. This led to the development of the ProSeal™- Laryngeal mask airway (PLMA, Laryngeal Mask Company, Henley-on-Thames, UK) – a new LMA with a gastric drainage tube and a modified cuff [38]. The first paediatric size PLMA – size 2 – became available in 2003, and a year later the sizes 1½ and 2½ were added. They differ from the adult size PLMAs in that they do not contain an additional dorsal cuff. Five comparative studies [39–41,42••,43] have shown that the paediatric PLMAs form a better seal than the CLMA and allow reliable gastric-tube placement. The size 3 PLMA – the smallest adult size, which can be used in adolescents – has also been compared with the CLMA in paediatric patients [43,44]. It was found that the paediatric-sized PLMA and the size 3 PLMA provide a much better seal than the CLMA, as indicated by a 20–30% higher mean airway leak pressure. No difference in airway leak pressure between the PLMA and CLMA was found in only 1 study [39]. In addition, reliable functional separation of the respiratory and digestive tract with the correctly positioned PLMA – achieved by the double-tube design – was evident in two important findings: (1) Gastric insufflation did not happen in any patient with the PLMA but occurred in 6–27% with the CLMA; (2) Gastric tube placement was possible in all but one patient within 2 attempts; gastric tube placement was not possible in only one newborn in whom a size 1½ was apparently too large [42••]. Evidence that the paediatric PLMAs can provide protection against pulmonary aspiration in the case of unexpected passive gastric regurgitation came from 2 case reports [45,46•]. One of the cases of regurgitation occurred in a crossover study comparing the PLMA with the CLMA, demonstrating the advantage of the PLMA over the CLMA in such a case [46•]. Despite similar anatomic positioning of both masks, the PLMA provided a substantially higher airway leak pressure (PLMA *vs.* CLMA: 31 cm H_2O *vs.* 21 cm H_2O) and offered an escape route for gastric fluid through the drainage tube.

Two further studies [47••,48••] examined whether the improved airway seal of the paediatric PLMAs enables the anaesthesiologist to ventilate children with two different modes of ventilation that are not routinely used with the CLMA because of its low pressure seal: pressure-support ventilation and pressure-controlled ventilation combined with positive end-expiratory pressure. Both studies confirmed increased PLMA airway leak pressures of previous PLMA–CLMA crossover investigations of 25 ± 4 and 23 ± 5 cm H_2O, respectively. Pressure-support ventilation reduced work of breathing and improved gas exchange compared with its continuous positive airway pressure ventilation, but mild hypercarbia was present [47••]. Pressure-controlled ventilation led to normocarbia in all patients and application of positive end-expiratory pressure improved oxygenation compared to zero end-expiratory pressure [48••]. Neither gastric insufflation nor any other adverse events related to the mode of ventilation were reported in any patients in either study.

In adults, the PLMA has proved more difficult to position than the CLMA, but this has not been the case in children. The anatomical position is also similar or – in infants – even better for the PLMA. Together with the fact that the CLMA needed to be repositioned more often than the PLMA, this indicates, in the author's opinion, that the different cuff design for the paediatric PLMAs helped to create an age-appropriate paediatric version of this new supraglottic airway device. In the author's opinion, the PLMA offers features that make it a better device for controlled ventilation in children than the CLMA. The higher airway leak pressure and functional separation of the respiratory and digestive tract with the correctly positioned PLMA could be the basis upon which the use of supraglottic airway management in paediatric patients could be expanded, for instance in patients with low lung compliance and high airway resistance requiring high peak airway pressures during controlled ventilation. Further scientific data need to be gathered to demonstrate that patients would benefit from such an expansion of use. Particularly, randomized controlled trails comparing the PLMA and ETT are required. Primary outcome parameters must be laryngotracheal morbidity and incidence of respiratory adverse events.

Endotracheal intubation

Only uncuffed ETTs have traditionally been used in children younger than 6–8 years for perioperative ventilation, mainly for two reasons. First, for a long time, it was not possible to manufacture small, age-appropriate, cuffed paediatric ETTs below 5 mm without a significant reduction of the internal diameter. Second, in children, the narrowest part of the trachea is at the level of the cricoid cartilage. As this part of the trachea has a round cross-section, an appropriate sized uncuffed ETT usually seals the trachea at this site without excessive air leakage at an airway pressure of 20–25 cm H_2O

[49]. Despite cautious selection of an appropriate sized ETT, laryngotracheal damage can be caused by an uncuffed ETT. It is, however, well known that cuffed ETTs pose a particular risk of laryngotracheal damage to infants and children. For this reason some experts strongly believe that they must not be used in this age group [50,51].

Shortcomings of paediatric ETTs

During the last two years, a number of studies have shed some light on the underlying reasons for laryngotracheal damage caused by cuffed ETTs. It has emerged that many commercially available paediatric ETTs are poorly designed and that this might be one of the most important sources of morbidity associated with the use of cuffed ETTs in children [52]. It was found that the outer diameters varied markedly for a given internal diameter, both between ETTs from different manufacturers and between cuffed and uncuffed ETTs from the same manufacturer. Probably the most important findings were that the upper border of the ETT cuff generally corresponded to the position of the depth marking of the next larger sized (+0.5 mm) uncuffed ETT from the same manufacturer and that most depth markings were positioned too high. As a result, for most of the ETTs, the cuffs would lie in the subglottic larynx or between the vocal cords if the ETT tip was placed in the mid trachea according to radiological criteria or, if inserted by the depth markings or the upper border of the cuff just lying below the lower border of the cricoid cartilage, the ETT tip would lie dangerously near the carina. Indeed, Dillier *et al.* [53] recently published a case report showing that the inappropriate design of a cuffed ETT led to severe laryngeal damage in a 13-month-old child.

The Microcuff™ ETT

Much effort was put into the development of a new paediatric ETT with a high-volume–low-pressure cuff [54]: The new Microcuff™ ETT (Microcuff GmbH, Weinheim, Germany) has anatomically based depth markings, a cuff-free subglottic shaft and a short high-volume-low-pressure cuff with an ultrathin cuff membrane. In various studies, it was shown that the design of the Microcuff™ ETT is more age appropriate and therefore superior to the design of most other commercially available paediatric ETTs. The tracheal sealing characteristics of the Microcuff™ ETT allow effective sealing of the trachea at low cuff pressures [55] and the anatomically based intubation depth markings allow safe placement with a cuff-free laryngeal zone without the risk of endobronchial intubation [56•]. In a study in 500 patients, the results of the preliminary study were confirmed. In all patients, tracheal sealing was achieved with a cuff pressure ≤20 cm H_2O (mean sealing pressure: 9.7 cm [4–20] H_2O) [57••]. In 8 patients (1.6%), the selected ETT was too large and had to be replaced by an ETT one size smaller ETT. In nine patients (1.8%), signs of mild to moderate postintubation stridor were noticed, requiring epinephrine inhalation in two patients.

Cuff pressure monitoring

Cuff overinflation is an important factor contributing to laryngotracheal morbidity caused by the use of cuffed ETTs. Bernet *et al.* [58•] demonstrated that even small amounts of inflated air led to a rapid increase in cuff pressure and volume resulting in an increase in outer cuff diameter up to 2–2.5 times the age-corresponding internal tracheal diameter. If not already considered mandatory, this underlines why cuff pressure monitoring must be part of standard perioperative monitoring if cuffed ETTs are used. To avoid cuff overinflation, the anaesthesiologist must check and deflate the cuff to a preset cuff pressure at regular intervals. A more sophisticated way would be to use a newly designed reusable cuff pressure pop-off valve (Microcuff GmbH, Weinheim, Germany) that continuously prevents cuff overinflation. Dullenkopf *et al.* [59] were able to show in a preliminary *in-vitro* study that this device reliably prevents the cuff pressure from exceeding a pre-set pressure of 20 cm H_2O in case of inadvertent cuff inflation or nitrous oxide exposure. However, a similar device was evaluated *in vivo* by the same group, confirming the *in-vitro* findings [60].

Cuffed ETTs in critically ill children

Cuffed ETTs are increasingly being used in some paediatric centres [61,62]. Newth *et al.* [63] recently published their experience with cuffed ETTs in 210 critically ill children comparing it with patients in whom an uncuffed ETT had been used. The frequency of epinephrine inhalation for postextubation croup and the rate of successful extubation did not differ between the two groups. The authors concluded that the traditional dictum that cuffed ETTs should not be used in children younger than 8 years should be reviewed, to offer children the benefits of modern low-pressure cuffed ETTs during critical illness. Considering the results of investigations into the use of the Microcuff™ ETT, it might be concluded that the Microcuff ETT is the best cuffed ETT for use in critically ill children. Without doubt, the results of studies investigating its use in children are promising; however, evidence that it is associated with a lower laryngotracheal morbidity than uncuffed ETTs is lacking. Also, the incidence of 1.8% postintubation croup in Dullenkopf's study is higher than that of 1% reported by Koka *et al.* [64] in a study in almost 8000 patients managed with an uncuffed ETT. Therefore, the author believes that the practice of routine use of uncuffed ETTs in children under the age of 8 years should only be changed if there is clear

evidence of an improved perioperative outcome in children with cuffed ETTs, i.e. reduced laryngotracheal morbidity. An adequately powered randomized study comparing the Microcuff™ ETT with uncuffed ETTs is required, with a primary outcome parameter of visible signs of laryngotracheal injury rather than surrogates such as epinephrine inhalation or others.

Conclusion

Respiratory adverse events continue to be the leading reason for perioperative critical events in children. Although the latest trends and developments, such as the use of remifentanil, the paediatric ProSeal™-Laryngeal mask airway, and the paediatric Microcuff™ endotracheal tube, have the potential of improving perioperative anaesthesia-related outcomes in paediatric patients, this still needs to be demonstrated by future research. Of uppermost importance for the safe perioperative care of children is a thorough understanding of the impact of anaesthesia on the unique anatomy and physiology of children. One such example is the impact of anaesthesia and simple airway management manoeuvres on airway patency. New developments in airway management in paediatric patients can only improve perioperative outcome if children are cared for by anaesthesiologists who are fully acquainted with these fundamental aspects of paediatric anaesthesia.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:
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Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 349).

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