Chapter 11

Equipment and Monitoring in Paediatric Anaesthesia

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Introduction

It is important that correct equipment and monitoring are available to provide safe anaesthesia for children. Equipment and monitoring specifications need to consider the anatomical and physiological differences between adults and children, particularly in relation to infants and young children. It is also imperative to conduct inventory checks at regular intervals to ensure the whole range of sizes is available for use. Recent developments have amplified the role of mobile platforms to deliver remote assessments and point-of-care interventions.

Airway Equipment

Face Masks

Inhalational induction of anaesthesia is commonly performed in paediatric practice. It is important that face masks are acceptable to the child. Ideally, they should be constructed from clear plastic and have a soft rim. Some manufacturers produce scented masks to make them more attractive to children (applying scented lip balms to the inside of masks will have a similar effect).

Paediatric face masks exist in a range of sizes. The appropriate size should be used so that the face mask sits comfortably over the mouth and nose, pressure on the eyes is avoided and there is a good seal and minimal dead space. Commonly used masks are teardrop-shaped with inflatable seals; round masks are often useful for infants and neonates due to their relative micrognathia. A well-designed face mask facilitates the appropriate technique for maintaining the airway ('chin lift' or 'jaw thrust').

Oropharyngeal Airways

Infants and young children have a relatively large tongue, and airway obstruction tends to occur early during induction of anaesthesia as airway tone is lost. This may be overcome with simple manoeuvres such as the application of continuous positive airway pressure (CPAP) via the breathing circuit, by a jaw thrust manoeuvre or by the insertion of an oropharyngeal airway once anaesthesia has been deepened. Oropharyngeal airways are available in sizes 000 to 4. The correct size is selected by placing the airway against the side of the mouth; the airway should reach from the angle of the mandible to the centre of the incisors or from the tragus of the ear to the corner of the mouth (see Figure 11.1). Too large an airway will protrude from the mouth and be ineffective; one that is too small may cause obstruction by pushing the tongue back or from the tragus of the ear to the corner of the mouth.

Nasopharyngeal Airways

Nasopharyngeal airways (NPA) are well tolerated in the awake child and may be useful in a variety of circumstances:

- Children with congenital abnormalities associated with midface hypoplasia (e.g. Apert and Crouzon syndrome) or severe micrognathia (e.g. Pierre Robin sequence)
- Airway management under anaesthesia, such as to avoid problems with poor mouth opening or loose teeth and to aid fibreoptic intubation (FOI)
- Postoperatively to relieve obstruction at the palato-pharyngeal junction, such as posttonsillectomy in children with severe obstructive sleep apnoea (OSA) or palate repair in children with severe micrognathia

The length of the NPA should be such that it can be fixed securely to the face whilst the tip should just protrude from behind the soft palate. Nasopharyngeal airways are commercially available for all ages but have the disadvantage of being of fixed length. Alternatively, an NPA of specific length can be constructed from a cut tracheal tube

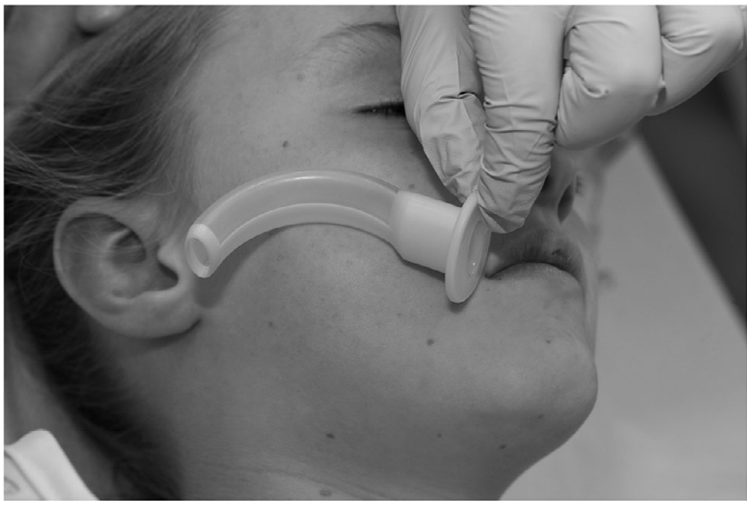


Figure 11.1 Sizing an oral airway – from the tragus of the ear to the corner of the mouth.

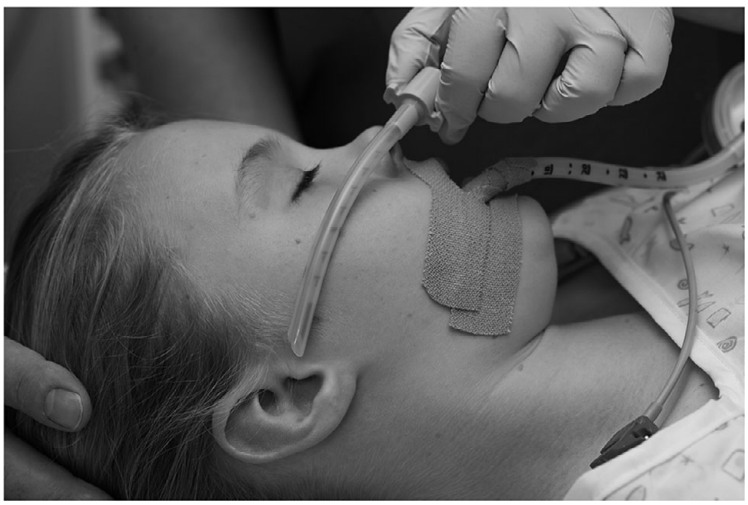


Figure 11.2 Sizing a nasopharyngeal airway – from the tip of the nose to the tragus of the ear.

(TT), the same size or one size smaller than the age-appropriate TT for intubation. Ideally, a flanged TT connector is used to secure the NPA to the face. It is important that the NPA is neither too long, as it will protrude from the nose or cause laryngeal irritation and coughing, nor too short, as it will be ineffective in relieving airway obstruction at the palato-pharyngeal junction. The length should be approximately the distance from the tip of the nose to the tragus of the ear (see Figure 11.2). For some patients, the NPA can be cut to length under direct vision at the end of surgery. It is important that the length of the NPA is recorded and that the NPA is suctioned to this depth regularly, particularly in postoperative patients. For children needing an NPA to maintain patent upper airway, a spare NPA should be immediately available at the bedside in case of blockage with secretions or blood.

Supraglottic Airways

Paediatric supraglottic airways (SGAs) are sized according to patient weight (see Table 11.1). The classic paediatric laryngeal mask airway (LMA) was not specifically designed for use in children but is merely a scaled-down version of the adult LMA. This has implications for its use in the paediatric population.

Single-use SGAs are used widely and are available in paediatric sizes 1–3. There is a learning curve when using the SGA in children. The complication rate is inversely proportional to patient size; displacement and airway obstruction occur

Table 11.1 Supraglottic airway sizes

Supraglottic airway size	Patient weight (kg)
1	<5
1.5	5–10
2	10–20
2.5	20–30
3	30–50

most frequently with the size 1 and 1.5 SGAs. The SGA has an important role in the management of the difficult paediatric airway (see Chapter 22), and the size 1 SGA has a role in neonatal resuscitation. In infants, airway obstruction may occur if the SGA pushes the large floppy epiglottis down to obstruct the laryngeal inlet. Difficulty can be encountered when using the traditional adult technique for SGA insertion in children. This may be due to adenotonsillar hypertrophy in older children or due to the epiglottis impinging on the SGA grille. Different techniques for SGA insertion and removal have been described. The SGA can be inserted partially inflated against the lateral side of the tongue and gently advanced until resistance from the tonsil is met, and then moved back into the midline. Alternatively, a rotational technique may be used where the SGA is inserted 'back-to-front', with the cuff facing the palate and turned through 180° once the hypopharynx is reached. The rotational and lateral techniques are both associated with high success rates for insertion in children less than six years of age.

Cuff inflation after insertion of SGAs may be according to the manufacturer's guidelines for volume and cuff pressure (<60 cmH2O) or by clinical endpoints such as forward movement of the SGA and ability to ventilate with a good seal. The use of a cuff pressure monitor has been recommended to avoid hyperinflation of the cuff and improve the overall positioning of the SGA (often at lower cuff inflation volumes than suggested by manufacturers). There is no consensus for the optimal timing for removal of SGAs in children. However, young children have reactive airways and show rapid emergence from anaesthesia. They may be more liable to develop laryngospasm if removal is delayed, and many practitioners prefer to remove the SGA whilst the patient is still deeply anaesthetised.

Flexible SGAs are available in size 2 and above. They have a non-kinking flexometallic tube that is longer and has a smaller internal diameter than in the standard LMA. This increases airway resistance and may increase the work of breathing if used with spontaneous breathing in longer cases. Flexible and preformed SGAs (e.g. AMBU®) permit the breathing circuit to be connected away from the operative area on the face (e.g. ophthalmic, dental, facial procedures).

The Pro-Seal LMA™ is available from size 1.5. It has a modified cuff that has been specifically designed for children. The LMA has an additional lumen running from the tip in parallel with the main airway that acts as an oesophageal drainage tube. This allows passive drainage of gastric contents and minimises gastric insufflation during positive pressure ventilation. The drainage tube also provides a route for nasogastric tube insertion and may prevent the epiglottis from obstructing the mask aperture. There is a high success rate for first insertion and overall high success rate for insertion in children. iGel® and LMA Supreme® have shown similar efficacy and ease of use in paediatric patients.

Whichever type of supraglottic device is used, displacement is common in children, particularly during patient transfer. The risk of displacement may be reduced by robust fixation of the device using an adhesive tape together with disconnection from the anaesthetic circuit during patient positioning.

Tracheal Tubes

The traditional teaching to use uncuffed TTs in children under the age of 8 years stems from a conical model of the subglottic airway; the narrowest part of the airway was thought to be at the level of cricoid cartilage, which is the only cartilage forming a complete ring around the airway. This concept has evolved as more imaging data have become available. The paediatric airway is now believed to be ellipsoidal in the subglottic area, with the anteroposterior diameter larger than the transverse. This shape becomes circular at the level of cricoid cartilage.

This realisation coupled with improvements in TT technology have made cuffed tubes desirable for the following reasons:

- Better likelihood of selection of the correct size tube at the first intubation; avoids potential trauma associated with multiple intubations
- Reduces risk of aspiration

Table 11.2 Uncuffed tracheal tube sizes

Age	Internal diameter (mm)	Fixation length (cm)	
		Oral ETT	Nasal ETT
Neonate (3 kg)	3.0–3.5	10–10.5	12
6 months (6 kg)	4.0	11.5–12.5	13
1 year (10 kg)	4.5	13–13.5	15
> 1 year	(Age in years/4) + 4.5	(Age in years/2) + 12	(Age in years/2) + 15

- Allows accurate measurement of $ETCO_2$; facilitates low-flow anaesthesia and reduces environmental pollution and costs
- More effective ventilation in children with poor lung compliance

However, in the absence of an international standard for tracheal tube marking or for the position or length of the cuff of a tracheal tube, there is great variability between manufacturers in the design of cuffed paediatric TTs. Ideally a TT with a high-volume, low-pressure cuff should be used, and care should be taken that the correct size TT is chosen; that the cuff is inflated in the mid-trachea, not in the subglottic region or between the vocal cords (nor to obstruct the right-upper lobe bronchus); and that the minimum cuff inflation pressure is used to seal the TT. The cuff pressure should be monitored and should not exceed 20 cmH_2O.

The ideal size of TT is one that will fit snugly to allow ventilation without excessive leak and prevent aspiration whilst avoiding pressure on the tracheal mucosa, particularly in the vulnerable subglottic area. Traditionally, this has been achieved by ensuring that there is a small audible leak around the TT at 20 cmH_2O inflation pressure. Damage to the underlying mucosa can result in airway oedema and post-extubation stridor or, in the most serious cases, mucosal ulceration and necrosis leading to acquired subglottic stenosis. The formula for the selection of the correct size and length of TTs is based on age. These formulae are merely a guide, and TTs half a size smaller and larger than the tube selected should always be available. The formulae are less reliable in children under the age of one year (see Table 11.2). The formula for sizing cuffed TTs is shown in Table 11.3.

Careful selection and placement of an appropriate TT, whether cuffed or not, is important in minimising airway injury. It should be remembered that all TTs can be associated with airway trauma. It is our practice to use uncut TTs so that the tube connector can be seen, and the head can be placed to one side so that the TT will not kink. Some practitioners place an oropharyngeal airway along the side of the TT to provide some stability to the smaller TTs, which are more liable to kink. Once in place, it is important that the TT is fixed securely in position. There are many suitable methods. We use two pieces of adhesive tape cut into a 'trouser shape' to secure the TT. One 'trouser leg' of each piece should be attached to the TT, with the other 'leg' attached to the upper or lower lip (see Figure 11.3). It is important to make sure the tape is clear of the lip mucosa. Various proprietary tube holders/tube fixation devices are available for neonates. The reader must become familiar with the recommended method of securing and releasing tracheal tubes from the specific device used in their workplace.

Table 11.3 Cuffed tracheal tube sizes

Age	Internal diameter of ETT (mm)
Neonate (3 kg)	2.5–3.0
6 months (6 kg)	3.0–3.5
1 year (10 kg)	3.5–4.0
>1 years	(Age in years/4) + 3.5

Polar (RAE) Tracheal Tube

RAE tubes are useful in head and neck surgery, and are named after their inventors, Ring, Adair and Elwin. They are manufactured in a preformed shape, either 'south facing' for oral intubation for cleft surgery or tonsillectomy, or 'north facing' for nasal intubation for dental or maxillofacial surgery. The lengths of the intraoral or intranasal

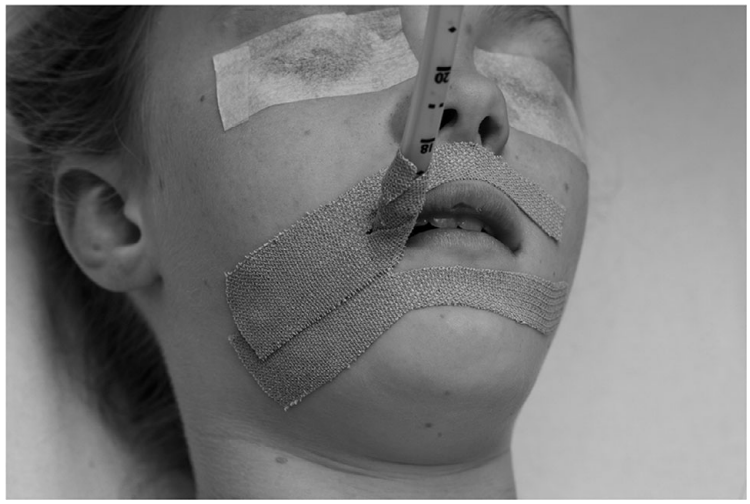


Figure 11.3 Fixation of a tracheal tube. Two pieces of adhesive tape cut into a 'trouser shape'. One 'trouser leg' is attached to either the upper lip or the lower lip and the other end to the TT. An oropharyngeal airway can be inserted along the side of the TT to improve stability.

sections are fixed. If these proportions are too long, there is a risk of endobronchial intubation. There is currently no international standard for the length of preformed tracheal tubes, and different manufacturers produce tubes of different lengths. Difficulties may also be encountered in a child with failure to thrive where the larynx will be the age-appropriate size, but the child will be small for their age. The length of preformed tubes should therefore be checked after insertion by careful auscultation for bilateral breath sounds, and if necessary, the tube should be withdrawn. If using an oral preformed tube, a dental roll taped to the chin under the curve of the tube may be useful to fix the tube at the correct length. Note that extension of the head and neck reduces the length of the tube in the trachea; flexion of the neck will push the tube down towards the carina. Whatever design of tube is used, the position of the tube should be checked carefully after intubation, and again after repositioning for surgery.

Armoured Tracheal Tubes

These tubes are indicated in neurosurgery, for surgery in the prone position and in cases where the head position is changed during surgery. A metallic spiral in the wall of the tube provides increased flexibility and reduces the chance of kinking. This increased flexibility may necessitate the use of an introducer or stylet for intubation. They have a greater external diameter than standard TTs, and a tube size half a size smaller than anticipated should be used. Although these tubes do not kink on bending, irreversible narrowing of internal diameter may occur if the patient bites on them, as may happen during reversal. Adequate depth of anaesthesia should be ensured to prevent this situation, or a bite block may be considered whilst waking the patient up.

Cole Tracheal Tube

These tubes have a wide intraoral section that narrows to the appropriate size distally to pass through the vocal cords. The wider portion affords them more stability than the equivalent size of TT and makes them easier to manipulate. They are popular in neonatal units and are useful in airway rescue when inducing infants with suspected subglottic pathology. The shouldered portion sits against the vocal cords thus reducing the risk of endobronchial intubation. However, the wide portion of the Cole TT must not be allowed to move against or through the vocal cords, as this may lead to vocal cord injury or subglottic stenosis, and for this reason they are not recommended for prolonged periods of intubation.

Double-Lumen Tracheal Tubes (DLT)

DLTs are used in adults to facilitate single-lung ventilation for a variety of thoracic procedures, including video-assisted thoracoscopic surgery. The smallest commercially available DLTs are 26 Fr gauge, which is roughly equivalent in external diameter to a size 6.5 mm TT. DLTs are therefore only suitable for children from the age of 8–10 years upwards. They are available as left- or right-sided DLTs, referring to which main

bronchus is intubated. When used, left-sided DLTs are preferred to avoid the bronchial cuff occluding the right upper lobe bronchus.

If one lung ventilation is required in smaller children, infants or neonates, an appropriate-size TT may be advanced into the main bronchus. Alternatively, a bronchial blocker or Fogarty catheter is placed by the side of a single lumen TT. Cuff position is ascertained with bronchoscopy before inflating it. Utmost care needs to be taken to avoid displacement and overinflation of bronchial cuff.

Tracheostomy Tubes

Paediatric tracheostomy tubes are available from various manufacturers, with each detailing unique features with respect to material, dimensions, MRI compatibility, extensions, cuff variations, ergonomics, flange shapes, adjustable flange, etc (see Table 11.4). It is vital to ensure that spare tracheostomy tubes (of same make/size and of a size smaller) and adjuncts (suction apparatus with catheters, tracheal dilator, tube securing kit, scissors) are immediately available at all times. The reason for tracheostomy, upper airway patency and emergency care notes should be made clearly visible at the patient's bedspace. Surgeons often place stay sutures in paediatric trachea during first tracheostomy insertion to facilitate quick re-insertion of a new tube in case of accidental extubation. Other adjuncts include heat and humidity exchangers and speaking valves.

Laryngoscopes and Blades

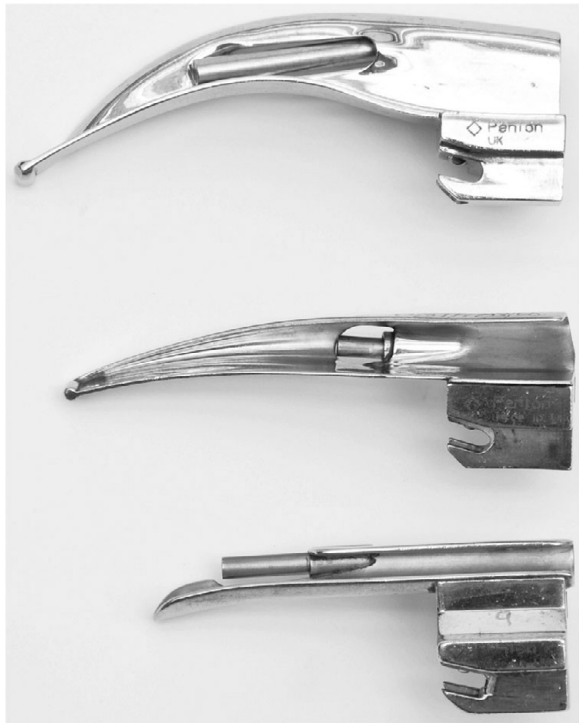
Straight Laryngoscope Blades

Straight laryngoscope blades are useful in infants up to about six months of age. Infants have a relatively large tongue, the larynx is relatively cephalad and the epiglottis is long and floppy and may be angled into the lumen of the airway to cover the laryngeal inlet. This combination of factors may make it difficult to visualise the laryngeal inlet by conventional laryngoscopy (i.e. indirect elevation of the epiglottis with the tip of the laryngoscope blade placed in the vallecula above the epiglottis). The straight blade takes up less space in the mouth and allows the epiglottis to be lifted directly to reveal the glottic opening. Two different techniques have been described to visualise the larynx in infants: the laryngoscope blade is slid underneath the epiglottis and the tip of the blade lifted so that the glottis is exposed; or the laryngoscope blade is deliberately advanced into the oesophagus and then, with the tip lifted anteriorly, withdrawn slowly until the larynx drops into view. Both techniques bring the blade into direct contact with the undersurface of the epiglottis, which may cause intense vagal stimulation.

Table 11.4 Paediatric tracheostomy tubes used in the United Kingdom

	Variants	Material	ID (mm)	Cuff features	MRI compatibility	Notes
Portex Bivona®	Neonatal (smaller shaft) Paediatric (longer shaft)	Siliconised PVC with wire coil	2.5–5.5	Uncuffed and cuffed: Aire-Cuf® (air) TTS™ (water) Fome-Cuf® (foam)	Incompatible (MRI conditional version available)	Available in V & straight flanges; Flextend™ offers long external shaft
	Hyperflex™ (adjustable flange)	Stainless steel coil			Incompatible	Replace with customised fixed flange tube ASAP
Shiley™	Neonatal (Neo) Standard Paediatric (Ped) Paediatric Long (PDL)	Opaque thermosensitive PVC	3.0–4.5 3.0–5.5 5.0–6.5	Uncuffed only Uncuffed and cuffed (standard and long lengths)	Compatible	PVC is stiffer & easier to railroad over suction catheters

Notes: ID: internal diameter; MRI: magnetic resonance imaging; PVC: polyvinyl chloride.



(a) Macintosh

(b) Robertshaw

(c) Miller

Figure 11.4 Selection of laryngoscope blades used in paediatric anaesthesia.

There are several different straight blade laryngoscopes available (see Figure 11.4). The type selected is often based on personal preference. The Robertshaw and Seward blades have an open cross-section profile that allows for easier intraoral manipulation of the TT. The Miller laryngoscope blade is C-shaped in cross-section, which reduces the ease of such manipulation but the extended curve at the tip of the blade facilitates anterior lifting of the epiglottis.

Curved Laryngoscope Blade (Macintosh Blade)

These are used from about the age of six months. The conventional technique for laryngoscopy should be employed. There are five sizes available: small infant size 0, infant size 1, child size 2, adult size 3 and large adult size 4. Polio blades and short-handled laryngoscopes may be useful.

Specialised LARYNGOSCOPES

The McCoy Blade

This is a standard Macintosh blade with a hinged tip that is useful for elevating the epiglottis if it is obstructing the view of the laryngeal inlet.

Videolaryngoscopy

This traditionally describes the transmission of the view from the tip of the blade via a fibreoptic endoscope to a video display. Newer videolaryngoscopes use an image-sensing microchip camera with LED light source at the distal end; optical data are then transmitted electronically to a display system. This eliminates the fragility of fibreoptic bundles and provides a wider, clearer field of vision. Videolaryngoscopes are available in sizes suitable for all ages and are useful teaching aids when learning the techniques of paediatric intubation. Some such as the Glidescope® and D blade of CMAC® provide an angulated view of the larynx and may be useful in difficult intubation.

A combination of videolaryngoscope and flexible bougie or fibrescope (with TT railroaded) may be used for particularly challenging airway anatomy (see Chapter 22 regarding difficult airway in children).

Other videolaryngoscopes such as McGrath® and AirTraq® are portable and disposable or allow convenient disinfection after use.

Aids to Intubation

Bougies and stylets are available in paediatric sizes. The smaller-sized bougies are rigid and often

difficult to manipulate, and care must be taken to avoid trauma to the distal airway. A well-described technique in infants is a 'two-person' technique, where the first operator obtains the best possible laryngeal view during laryngoscopy using external pressure to the larynx, and a second anaesthetist passes the bougie. Stylets are useful for the introduction of flexible tubes. Care must be taken not to allow the hard tip of the stylet to protrude beyond the end of the TT to avoid trauma to the airway.

Magill's Forceps

These are shaped anatomically to allow an object in the oropharynx to be gripped whilst staying away from the field of view. It is most commonly used to direct TT into the glottis, position the throat pack and assist in the retrieval of objects from the oropharynx. Adult as well as paediatric sizes should be available.

Atomiser Devices

Nasal atomisers (MAD Nasal™) are used for transnasal administration of drugs like vasoconstrictors, local anaesthetics and premedication (dexmedetomidine). Laryngo-tracheal spray of local anaesthetic is used to anaesthetise the mucosa for diagnostic and therapeutic airway procedures. Devices with malleable stylet (MADgic®) are available in paediatric and adult sizes for this purpose.

Airway Exchange Catheters

Airway exchange catheters, for example those manufactured by Cook®, are useful when employing fibreoptic techniques to manage a difficult airway. Their hollow central channel allows insufflation of oxygen and monitoring of end-tidal carbon dioxide ($ETCO_2$). The smallest size available is an 8 Fr catheter, which can be used to exchange a size 3 TT (see Table 11.5).

Table 11.5 Airway exchange catheters

Catheter gauge (French)	Catheter internal diameter (mm)	For replacing a TT with internal diameter (mm)
8	1.6	$\geq$ 3.0
111	2.3	$\geq$ 4.0
4	3.0	$\geq$ 5.0

Suction Catheters

Suction catheters are available in a range of sizes. The following formula describes the relationship between the size of suction catheter and TT:

> Suction catheter (French size) = 2 × internal diameter (in mm) of TT

Closed system suction catheters allow repeated suctioning without disconnections, thereby maintaining positive end expiratory pressure (PEEP), reducing wastage and preventing aerosolisation associated with disconnections.

Breathing Systems

The ideal paediatric breathing system should have minimal functional or apparatus dead space, be either valveless or fitted with very low resistance valves and be constructed in such a way as to minimise gas turbulence and subsequent flow resistance.

Mapleson classified breathing systems into five types (A to E) according to their efficiency in eliminating carbon dioxide during spontaneous ventilation. Mapleson D, E and F systems are the most commonly used in paediatric practice as they most closely meet the criteria for an ideal paediatric system. However, the use of the circle system as the sole circuit for all age groups is increasingly common practice.

The Jackson Rees Modification of the Ayre's T-Piece

The Mapleson E system is the Ayre's T-piece. This is a valveless breathing system used for children up to 25–30 kg. It consists of a T-shaped tubing with three opening ports: one port receives fresh gas from the anaesthetic machine; the second port leads to the patient's mask, LMA or TT; and the third port leads to reservoir tubing (see Figure 11.5). Mapleson F describes the Jackson Rees modification of system E by the addition of the open-ended reservoir bag to the end of the reservoir tubing.

The system requires a fresh gas flow (FGF) of 2.5–3 times the minute volume to prevent rebreathing with a minimum FGF flow of 4 l min^{-1}. The open-ended bag has a number of functions: it acts as a visual monitor during spontaneous ventilation, it can be used to provide CPAP during spontaneous ventilation and it can be used to

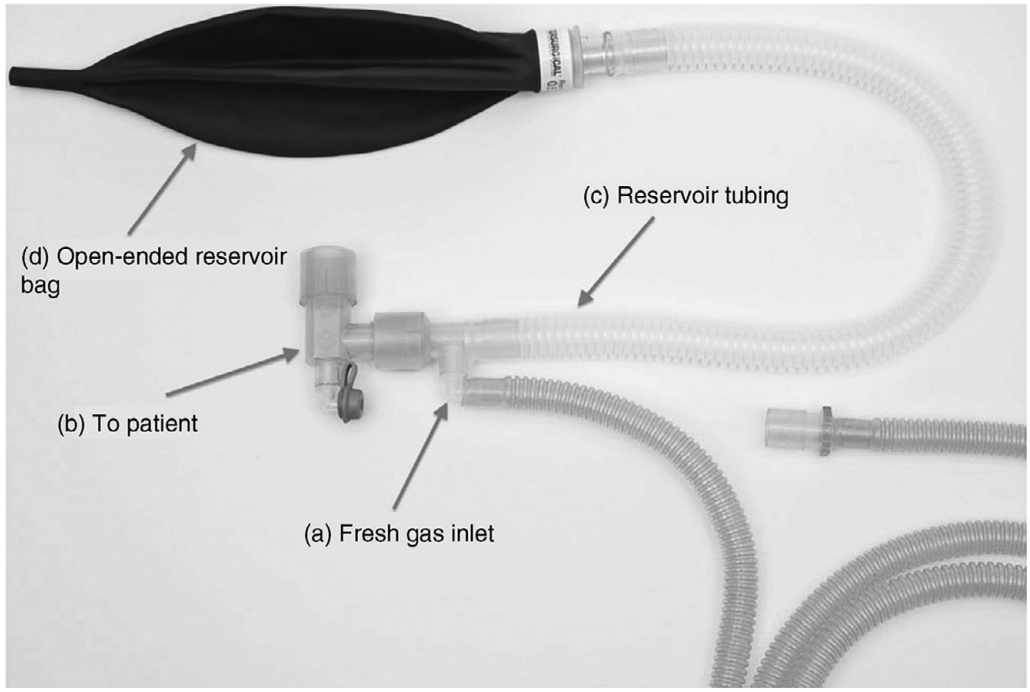


Figure 11.5 The Ayre's T-piece with the Jackson Rees modification.

provide controlled ventilation, although experience is required to master the technique. The T-piece is not ideal for use in resuscitation for this reason.

The Bain System

This is the coaxial version of the Mapleson D system. It may be used during induction of anaesthesia in children over 25–30 kg (although most practitioners now use the circle system for this purpose). The fresh gas flow to prevent rebreathing during spontaneous ventilation is 1.5–2 times the minute volume. Thus, a flow rate of 100–200 ml $kg^{-1}min^{-1}$ is required. During controlled ventilation, a fresh gas flow rate of 70–100 ml kg^{-1} min^{-1} is required.

The Circle System

In this breathing system, soda lime is used to absorb the patient's exhaled carbon dioxide. The paediatric circle consists of lightweight 15 mm diameter tubing and a small 500 ml reservoir bag; 1 L bags are available for bigger children and adult tubing and reservoir bags (2 L) should be used in patients over 50 kg. The circle system/low-flow anaesthesia allows for improved preservation of heat and moisture, greater economy with less volatile agent used and reduced environmental pollution compared with the non-absorber systems. It is important to be vigilant if an uncuffed tube with a significant leak is used and very low-flow rates are employed.

Self-inflating resuscitating bags should be immediately available in adult, paediatric and infant sizes along with reservoir bags and supplemental oxygen connectors.

Humidification

Humidification of inspired gases is important to prevent damage from dry gases and to minimise heat loss via the respiratory tract. The heat moisture exchanger (HME) is available in a range of sizes (volumes 7.8–100 ml) and is inserted at the point of connection of the airway device to the breathing circuit. The HME conserves approximately 50% of the water normally lost via the respiratory tract and prevents corresponding heat loss. This is of particular importance in neonates and small infants, who lose heat more rapidly than older children and adults because their ratio of minute volume to body surface area is higher. In addition, the HME protects against the inhalation of infective or hazardous particles and

prevents cross-contamination between patients if re-usable breathing circuits are used. The HME is most efficient with smaller tidal volumes and higher respiratory rates and so is well suited to paediatric practice.

Ventilators

The majority of children can be ventilated using modern adult circle ventilators provided:

- The ventilator can deliver high respiratory rates using pressure or volume-controlled ventilation.
- It allows adjustment of the I:E ratio.
- Lightweight 15 mm paediatric tubing is used.

Pressure-controlled ventilation is the preferred mode of ventilation in children as it can be adjusted more easily to compensate for leaks in the breathing circuit and minimises the risk of barotrauma.

Ventilation for term and preterm neonates can be challenging on conventional anaesthesia ventilators due to the requirement of accurate, small volume breaths delivered at a high rate with minimal dead-space/wasted ventilation. There are proprietary ventilators available for this niche requirement.

Jet Ventilation

Low-frequency jet ventilation (LFJV) is a useful modality for laryngo-bronchoscopy (usually through a wide, short tube attached to the endoscope) and in 'can't intubate, can't ventilate' (CICV) situations (through a cricothyroidotomy cannula). Sanders injector or Manujet III are widely used hand-triggered devices. Particular attention should be paid to prevent disconnections, allow adequate time for exhalation and avoid barotrauma.

CPAP and BiPAP machines

Children with obstructive airways, respiratory pathology or neuromuscular diseases may be supported with home ventilation and/or oxygen supplementation. These ventilators vary widely in their features, settings and emergency usage. Detailed discussion of these devices is beyond the scope of this text; however, anaesthetists should ensure they gain adequate understanding of their functioning, as children are likely to need this support whilst recovering from surgery and anaesthesia.

High-Flow Nasal Oxygen Therapy (HFNOT)

Various devices are commercially available (e.g. OptiFlow™, Airvo™, Vapotherm, AquaVENT®, HI-Flow Star, AcuCare™, etc.) and are increasingly used to provide respiratory support in ward and ICU settings. These are open system devices that deliver heated (33–43°C), humidified (95–100%) oxygen at titratable FiO_2 and constant high flows (40–60 L/min). This combination allows improved oxygenation and patient compliance whilst reducing moisture loss and anatomical dead space. Attachments are available to adapt usage to tracheostomy tubes as well as nebulisers. Devices use different mechanisms to generate high flows (oxygen-air blender/entrainment system/built-in flow generator) and consequently differ in their operational characteristics. These devices have been used in various clinical settings:

- Supporting respiration in respiratory compromise when invasive ventilation is not indicated
- As an apnoeic oxygenation device during intubation or airway procedures
- Postoperative respiratory support to bridge transition to spontaneous ventilation

All the contraindications for non-invasive ventilation also apply to HFNOT, along with conditions like epistaxis or facial injury.

Equipment for Vascular Access

Intravenous Access

A range of sizes of cannula should be available. A 22-gauge cannula will suffice for the administration of drugs and fluid in most young children and infants. A 24-gauge, or even 26-gauge cannula, may be more appropriate in premature infants or those with difficult venous access. Larger-gauge cannulae are indicated for cases where significant blood loss is anticipated.

Specialised equipment is available for central venous access in children; catheters vary in length and size. A 4 Fr catheter is suitable for infants under 5 kg, 7 Fr for adolescents and 5 Fr catheters for all other ages. Ultrasound guidance should be used with a strict aseptic technique for the

placement of central venous catheters in children, commonly via the internal jugular route or via the femoral vein.

Finding and cannulating paediatric veins can be challenging. This can be aided by 'vein finder' devices using principles of infrared light projection, transillumination or high-frequency ultrasound scanning.

Intraosseous Access

Intraosseous (IO) access provides rapid, safe and effective vascular access in situations when intravenous access is difficult, for example during resuscitation. Various purpose made needles are available in 18G (0–6 months), 16G and 14G sizes. They possess a trocar that prevents bone from plugging the lumen of the needle. Traditional intraosseous needles (Cook®-type) are placed manually, the site, force required and depth of insertion being determined by the operator. Since 2006, a second type of device has been used in adult and paediatric practice. The EZ- IO® (Vidacare) has a battery-powered drill handle that powers needle insertion. Three different needle lengths are available, suitable for patients from 3 kg upwards.

Any drug or solution that can be given intravenously can be given by the IO route. Manual injection rather than passive infusion of fluid is required because of increased resistance. The resistance felt during injection is similar to that encountered during injection via an epidural catheter.

There is insufficient evidence to support use of IO samples for blood testing, and it should be reserved for when no other option is available. Results should be interpreted with caution and in the context of the clinical situation. Testing is invariably not calibrated for IO samples (samples may also be haemolysed or inadequate) and particulate matter can damage automated analysers.

Equipment for Fluid Administration

It is important that intraoperative administration of fluids is carefully controlled and documented. Intravenous giving sets should incorporate a burette in smaller patients in order that accurately measured aliquots of fluid can be administered. A standard burette dispenses fluid at 20 drops per ml, and a microdrop burette dispenses fluid at 60 drops per ml. Blood and blood products should be infused using a system with an integral 170–200 mm filter.

Fluid warmers should be used in cases where large volumes of fluid or blood transfusion are anticipated. Many of the systems used in adult practice are not appropriate for use in the paediatric setting owing to cooling along the length of the IV tubing and relatively slow infusion rates in children. This problem is overcome by the use of counter-current warming systems (e.g. Hotline®) where warm water circulates around the entire length of the delivery line up to the point of administration to the patient.

Drug Administration

Drug doses in paediatric practice are based on patient weight. Often only very small volumes of standard formulations of drug are required. Smaller-sized ampoules or paediatric formulations are available for some drugs, which help to reduce waste. It is important that a range of syringes from 1 ml upwards is available in order that dosing is accurate. Equipment to measure accurate weight and height must be available for all ages from preterm neonate to a teenager.

While using total intravenous anaesthesia (TIVA), appropriate paediatric-specific models should be loaded and used in syringe pumps.

Equipment for Regional Anaesthesia

Epidural kits containing 19/20G Touhy needles are available with catheters ranging from 21G to 24G. These have 0.5 cm markings and are available in 50 or 80 mm length. Catheters can be multi-orifice or open-ended single orifice.

Temperature Maintenance

Infants and small children are at particular risk of developing hypothermia owing to their large body surface area to volume ratio. It is important to avoid hypothermia as it increases postoperative oxygen consumption, affects recovery from anaesthetic drugs, impairs coagulation, may depress ventilation and can result in arrhythmias.

The ambient temperature in the operating theatre may be raised, which will help reduce heat loss due to radiation. However, the theatre should not be heated to such an extent as to compromise infection control policies and staff comfort. The ideal theatre temperature is between 19°C and 21°

C, and it should not exceed 23°C. Blankets, sheets, gauze pads and fluids are often warmed in a warming cabinet to prevent rapid cooling of an infant or small child.

Care should be taken during induction of anaesthesia to avoid unnecessary exposure of the child. It is important to remember to keep infants' heads covered. Intraoperatively, forced-air warming devices are most widely used. In smaller patients, most benefit is derived if the device is placed under the patient. Humidification of anaesthetic gases and fluid warmers should be used routinely, as discussed in the 'Humification' section. Clear plastic drapes are highly effective at reducing heat loss and prevent pooling of liquids which evaporate and further cool the patient. In conditions where forced-air warming is not feasible (transport, MRI suite, etc.), disposable transport warming mattresses can provide effective underbody warming (TransWarmer®); activation of the gel starts an exothermic reaction which provides warming for up to two hours without the need for a power source.

Monitoring Equipment

Most monitors have been developed for adult practice and adapted for use in children. Essential monitoring is mandatory in all anaesthetised patients, but monitors are not a substitute for the presence of a vigilant anaesthetist, who should combine the information provided by the monitors with their own observations in order to direct the management of the patient. Essential monitoring for anaesthesia includes:

- Oximetry
- ECG
- Non-invasive blood pressure
- Capnography
- Airway pressure

Pulse Oximetry

This provides a non-invasive measurement of peripheral saturation of arterial blood (SpO_2). It enables the detection of incipient and unsuspected arterial hypoxaemia, allowing early intervention before tissue damage occurs.

The 'peg-like' probes used in adult practice are suitable for use in children over 10 kg. A more reliable device for use in younger children is a wraparound probe in an adhesive strip. The strip can be attached to a digit, palm of a hand or sole of a foot, the site depending on the size of the patient. The sensors should be protected from interference from outside light sources. Motion artefact can also be a significant problem in the awake patient.

The presence of foetal haemoglobin or hyperbilirubinaemia in young infants has no clinical effect on the detection of hypoxaemia by the pulse oximeter. In patients with cyanotic congenital heart disease, the oximeter tends to overestimate readings at lower saturations. It should be remembered that in neonates with duct-dependent systemic circulation, the saturation measured may be appreciably different depending on the site of the probe; shunting of deoxygenated blood through a patent ductus arteriosus will result in lower saturations in the left hand and lower body.

Electrocardiography

The electrocardiogram (ECG) provides a monitor of heart rate and rhythm and can indicate myocardial ischaemia. Neonates and young children display right-ventricular dominance on their ECG. This gradually declines with age; the QRS axis becomes similar to that of an adult by the age of five years. Neonatal and paediatric electrodes are available for babies and small infants.

Infants and young children are at risk of bradycardia during anaesthesia and surgery. Continuous ECG monitoring allows prompt intervention. Infants and young children desaturate rapidly and develop a bradycardia in response to hypoxia. Many practitioners advocate leaving both the pulse oximeter and ECG in place during emergence from anaesthesia; if technical problems or artefacts are encountered with the saturation probe and its accuracy is questioned, a slowing of heart rate will alert the practitioner to a 'patient' rather than 'equipment' problem.

Capnography

Gases with molecules that contain at least two dissimilar atoms absorb radiation in the infrared region of the spectrum. This property forms the basis of capnography and the measurement of expired carbon dioxide concentration throughout the respiratory cycle. Capnography is an invaluable aid to detect oesophageal intubation, disconnection of the breathing circuit, rebreathing and hypoventilation and is a useful monitor to indicate low cardiac output.

The capnograph sampling chamber can be either positioned within the patient's gas stream (mainstream sampling) or connected to the distal end of the breathing system via a sampling tube (side-stream sampling). The latter is the most common arrangement in theatres. However, both systems have their drawbacks. With side-stream analysis, the $ETCO_2$ may be underestimated when the tidal volumes are very small (standard rate of sampling 150–200 ml min^{-1}). Mainstream (or inline) analysis is more accurate, but the sample cell is heavy and bulky and risks kinking the TT. Mainstream analysers are widely used in ICU and for monitoring during the transfer of intubated patients. The measurement of $ETCO_2$ levels in children may also be inaccurate if respiration is rapid or shallow, if there is a leak around the TT or when there is a large volume of apparatus dead space. In patients with cyanotic congenital heart disease, the $ETCO_2$ readings will be lower than arterial $PaCO_2$, sometimes by 2 kPa.

Transcutaneous Carbon Dioxide Measurement

Arterial CO_2 tension can also be estimated from the continuous measurement of transcutaneous CO_2 ($TcCO_2$). This is a useful tool in the PICU but is of limited use in anaesthesia as calibration of the apparatus takes 10 minutes for each patient, and it requires good and constant skin perfusion. It may be useful in situations where $ETCO_2$ measurement is inaccurate, for instance during laparoscopic surgery in neonates. The position of the heated sensor (43–44°C) must be changed every three to four hours to avoid thermal injury.

Non-invasive Blood Pressure Measurement

An appropriately sized blood pressure cuff is one that occupies two-thirds of the upper arm. A width of 4 cm is recommended in full-term neonates. If the cuff is too small, it overestimates blood pressure; if it is too large, readings are falsely low.

Invasive Blood Pressure Measurement

An arterial line provides direct measurement of blood pressure and allows for intermittent blood sampling. The radial or the femoral arteries are the most common sites that are cannulated. The axillary artery can be used as an alternative, but the brachial route should be avoided as it has poor collateral vessels. A 22-gauge cannula is suitable for most infants and small children, a 24-gauge cannula should be used in neonates and preterm babies if the radial site is accessed. A cannula in the femoral artery can compromise blood flow to the leg, especially in infants of less than 3 kg, and placement of a cannula in this site should have a strong indication in these patients. Likewise, blood flow to the leg should be monitored when combined femoral venous and arterial access is used in older infants. Ultrasound is a useful tool for locating and confirming patency of arteries and with practice can be used to guide cannula insertion in peripheral sites even in very small babies. It is imperative that an arterial cannula does not possess an injection port and is clearly labelled. The transducer systems are the same as those used in adult practice and incorporate a column of bubble-free (heparinised) saline at a pressure of 300 mmHg. Care should be taken with the volume of fluid administered by the arterial flush system, and for this reason, an infusion pump delivering 1 ml $hour^{-1}$ is commonly used in the ICU setting.

Monitoring Cardiac Output in Children

Monitoring cardiac output (CO) is technically challenging in children, and most paediatric anaesthetists monitor surrogates of flow such as pressure (arterial, central venous), capillary refill or markers of tissue oxygen delivery (base excess, lactate, central venous oxygen saturation). Technology is improving, though, and several techniques used in adults can now be applied to infants and children to provide accurate measurements of cardiac output:

- Thermal dilution – catheters limited to children >5 kg
- Lithium dilution (LiDCO)
- Transoesophageal, transthoracic echocardiography
- Transoesophageal doppler – probes limited to children >3 kg
- Pulse contour analysis (PiCCO)
- Venous oximetry
- Near-infrared spectroscopy (NIRS)

Transoesophageal Doppler

Transoesophageal Doppler is used to measure the flow velocity in the descending aorta to estimate cardiac output. Aortic diameter may be measured

directly or may be derived from an inbuilt nomogram by entering age, height and weight. Placement in the oesophagus is operator dependent, and CO values show reasonable correlation with those obtained by thermal dilution. Probes suitable for children >3 kg are now available.

Pulse Contour Analysis

CO may be derived from arterial waveform analysis, and there are a number of different techniques available that measure real-time CO. Most depend on complex mathematical and physiological calculations, and few studies have validated these in children. These techniques may be useful during stable conditions, but monitors require recalibration and may have limited accuracy when vascular tone changes or with rapidly changing haemodynamics during surgery.

Near-Infrared Spectroscopy

NIRS is a non-invasive optical method for continuous measurement of tissue oxygenation and has been used as a measure of cerebral and somatic perfusion in adults and children, particularly during cardiac surgery and intensive care. It relies on the principle that haemoglobin absorbs infrared light close to the visual spectrum, and that the absorption of light depends on the oxygenation status of haemoglobin, as most other biological tissues do not absorb light of this wavelength. Whereas pulse oximetry requires a pulsatile flow and provides a measure of arterial saturation, tissue oximetry does not require a pulsatile flow, and the value is mainly determined by venous oxygen saturation, haemoglobin and blood flow. Provided oxygen extraction and haemoglobin remain constant, the NIRS value becomes a surrogate measure of flow. The precise design of the equipment and the algorithms used to determine tissue oxygenation vary between manufacturers. Probes, including infant probes, are specifically designed for different tissue areas (cerebral, abdominal, renal, muscle) and will give inaccurate results if not used according to the manufacturer's instructions. The sensitivity and specificity of NIRS-derived measurements of low perfusion compared with invasive measurements of cardiac output are improved by monitoring at multiple sites. The technology is improving, but absolute values vary between manufacturers, and the upper and lower NIRS values are not clearly defined. The probes are expensive, and controversy remains about the value of NIRS in improving outcomes. However, NIRS does appear to have a role in monitoring trends in tissue perfusion, particularly as an early warning of low cardiac output or to detect catastrophic events, for instance during aortic cannulation in cardiac surgery.

Depth of Anaesthesia Monitors

Traditionally, clinical signs (breathing pattern, pupillary size and reactivity, eye movement) and physiological response to surgical stimulation have been used to assess depth of anaesthesia. Several monitors have been developed by different manufacturers to assess depth of anaesthesia based on analysis of the EEG using information derived from adult EEG data. The Bispectral Index (BIS) has been studied extensively, but other monitors include the Narcotrend™, Cerebral State Monitor™, AEP/2 and M-entropy monitor. These monitors help to avoid awareness in high-risk patients and also, by avoiding unnecessarily deep anaesthesia, may improve recovery from anaesthesia. These monitors are affected by the use of neuromuscular blocking agents, some specific anaesthetic agents used (BIS is unaffected by nitrous oxide and high-dose opioids) and there may be paradoxical changes during sevoflurane anaesthesia (increased EEG activity associated with deep sevoflurane anaesthesia results in higher BIS values). The EEG changes during a child's development, and since they have been developed using adult data, depth of anaesthesia monitors may not be reliable in infants and younger children.

Temperature Monitoring

Temperature monitoring is essential to detect both hypothermia and inadvertent hyperthermia in children undergoing general anaesthesia. Temperature is usually monitored in the nasopharynx, oesophagus or rectum or at a peripheral site. Oesophageal temperatures should be recorded in the lower third of the oesophagus to avoid falsely low readings caused by a leak around the tracheal tube. Rectal probes can cause perforation in neonates and should not be used in neutropenic patients.

Urine Output

This should be monitored in all cases of major surgery or when significant blood loss is anticipated. Silastic catheters are used. The smaller

catheters have a stylet, which should be removed prior to insertion to avoid creating a false passage. The smallest balloon catheter available is 6 Fr; this has a 1.5 ml balloon which is appropriate for most term neonates onwards. If a balloon catheter cannot be passed, then a 6 Fr feeding tube should be used (this is stiffer and smaller than the 6 Fr Foley as it does not have the extra thickness at the balloon). The balloon should always be inflated with water, not saline (and only after urine has been identified), as saline may crystallise, which can then block the channel and prevent balloon deflation. The same catheters are used for girls and boys. In male infants, the preputial orifice overlies the glandular meatus and thus the prepuce does not need to be fully retracted during catheter insertion. Once inserted, the catheter should be connected to a urometer that can collect and measure small volumes of urine.

Point-of-Care Ultrasound

Ultrasonography (USG) is a useful bedside tool, assisting vascular access, regional anaesthesia, echocardiography, lung ultrasound and newer applications, including determination of gastric residual volume/contents, delineating tracheal anatomy and TT cuff localisation. The hockey-stick probe (7–10 MHz) has the smallest footprint and is most versatile, though a range of probes should be available for different applications. Bedside use of USG may become more commonplace with availability of portable and handheld units which interact via app-based interfaces on various devices. Apart from smaller structures, paediatric patients may have greater anatomical variations and mobile vasculature. Interventions with ultrasound require a motionless field, and general anaesthesia is often required to achieve the best conditions. Frequent practice and an understanding of USG principles and drawbacks, including reverberation artefacts, mistaking the shaft of the needle for the tip and acoustic shadowing, are vital to benefit from the use of USG.

Anaesthetic Record and Configuration of Monitors

A clear record of all drugs and the doses administered should be part of the information recorded on the anaesthetic chart. The chart should also record the method of induction, airway management, monitoring equipment used and patient position in addition to documenting the physiological parameters measured throughout the procedure. Any problems encountered should be clearly documented as they may act as an alert for future anaesthetists. Electronic patient recordkeeping systems are being incorporated into many hospitals. These include anaesthetic charts for preassesment and intra- and postoperative care documentation. Staff should receive adequate training to use these systems. Where autopopulated data are incorrect, annotations may need to be made to improve accuracy. Various systems can be configured to allow secure communication with patients through apps and video conferencing, thereby making remote preassessments more routine. This may partly be aided by the evolution of medical grade remote monitors and wearable devices.

The presence of monitoring is not a substitute for an anaesthetist. Age-appropriate alarm limits should be set for each physiological variable to increase vigilance. The information provided by the monitors must be integrated with the anaesthetist's own observations so that appropriate interventions are made. It is worth noting that not all monitoring devices have established clinical testing standards for paediatric patients, and data may be extrapolated from adult counterparts.

Distraction Technologies

Various distraction methods are available to help manage procedural anxiety and reduce stress in children. Toys, audio-visual stimulation and storytelling are often useful for infants and toddlers. Tablets, mobile phones, music players and gaming devices and virtual reality systems are available for older children. Pictures, videos and virtual reality simulations have been used preoperatively to familiarise children with specific hospital environments to help reduce anxiety.

Key Points

- It is imperative that the correct equipment and monitoring are available to provide safe anaesthesia for children.
- Supraglottic airway size selection is based on patient weight; tracheal tube size selection is based on patient age.
- Most children can be ventilated using modern adult circle ventilators, as long as the appropriate settings are selected.

- Temperature monitoring and heat conservation techniques are important as infants and small children are at particular risk of developing hypothermia.
- Increasingly sophisticated monitors have been developed that are suitable for use in children, but no monitor is a substitute for the presence and vigilance of the anaesthetist.

Further Reading

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