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Single-lung ventilation in infants and children

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Summary

During the past decade, the use of video-assisted thoracoscopic surgery (VATS) has dramatically increased in children as well as adults. Although VATS can be performed while both lungs are being ventilated, single-lung ventilation (SLV) is desirable during VATS. In addition, anaesthesiologists are performing (and paediatric surgeons are requesting) SLV more frequently for open thoracotomies in infants and children.

Keywords: video-assisted thoracoscopic surgery; child; single-lung ventilation; open thoracotomy; thoracic surgery

Introduction

Prior to 1995, nearly all thoracic surgery in children was performed by thoracotomy. In the majority of cases, anaesthesiologists ventilated both lungs with a conventional tracheal tube and surgeons retracted the operative lung to gain exposure to the surgical field. During the past decade, the use of video-assisted thoracoscopic surgery (VATS) has dramatically increased in adults and children, and recent advances in surgical technique and instrumentation (such as high-resolution microchip cameras and smaller endoscopic instruments) have facilitated the use of VATS in smaller patients. VATS is now being used extensively for pleural debridement in patients with empyema, lung biopsy to diagnose interstitial lung disease and mediastinal masses, and wedge resection to treat metastatic lesions. More extensive pulmonary resections, including segmentectomy and lobectomy, have been performed to treat lung abscess, bullous disease, sequestrations, lobar emphysema, cystic adenomatoid malformations, and neoplasms. In certain centres, more advanced procedures have been performed by VATS, including closure of patent ductus arteriosus, repair of hiatal hernias, and anterior spinal fusion.

The VATS can be performed while both lungs are being ventilated using CO_2 insufflation and placement of a retractor to displace lung tissue in the operative field. However, single-lung ventilation (SLV) is extremely desirable during VATS. In addition, anaesthesiologists are performing (and paediatric surgeons are requesting) SLV more frequently even for open thoracotomies in infants and children.

Ventilation/perfusion during thoracic surgery

Ventilation is normally distributed preferentially to dependent regions of the lung, so that there is a gradient of increasing ventilation from the most nondependent to the most dependent lung segments. Because of gravitational effects, perfusion normally follows a similar distribution, with increased blood flow to dependent lung segments.

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Therefore, ventilation and perfusion are normally well-matched.

During thoracic surgery, several factors act to increase ventilation/perfusion (V/Q) mismatch. General anaesthesia, neuromuscular blockade, and mechanical ventilation cause a decrease in functional residual capacity of both lungs. Compression of the dependent lung in the lateral decubitus position may cause atelectasis. Surgical retraction and/or SLV result in collapse of the operative lung. Hypoxic pulmonary vasoconstriction (HPV), which acts to divert blood flow away from underventilated lung, thereby minimizing V/Q mismatch, may be diminished by inhalational anaesthetic agents and other vasodilating drugs. These factors apply equally to infants, children, and adults. The overall effect of the lateral decubitus position on V/Q mismatch, however, is different in infants compared with older children and adults.

In adults with unilateral lung disease, oxygenation is optimal when the patient is placed in the lateral decubitus position with the healthy lung dependent (down) and the diseased lung nondependent (up) (1). Presumably, this is related to an increase in blood flow to the dependent, healthy lung and a decrease in blood flow to the nondependent, diseased lung because of the hydrostatic pressure (or gravitational) gradient between the two lungs. This phenomenon favours the adult patient undergoing thoracic surgery in the lateral decubitus position.

In infants with unilateral disease, however, oxygenation is improved with the healthy lung 'up' (2). Several factors account for this discrepancy between adults and infants. Infants have a soft, easily compressible rib cage that cannot fully support the underlying lung. Therefore, the infant's functional residual capacity is closer to residual volume, making airway closure likely to occur in the dependent lung even during tidal breathing (3). When the adult lung is placed in the lateral decubitus position, the dependent diaphragm has a mechanical advantage because it is 'loaded' by the abdominal hydrostatic pressure gradient. This pressure gradient is reduced in infants, thus also reducing the functional advantage of the dependent diaphragm. Finally the infant's small size results in a reduced hydrostatic pressure gradient between the nondependent and dependent lungs. Consequently, the favourable increase in perfusion to the dependent, ventilated lung is reduced in infants. All of these factors put infants at increased risk of significant oxygen desaturation during surgery in the lateral decubitus position. For this reason, techniques used for SLV in infants and young children should include the option of providing oxygen to the operative lung.

Techniques SLV in infants and children

Techniques for SLV in infants and children include use of a single-lumen endotracheal tube (ETT), balloon-tipped bronchial blockers, a Univent tube, or a double-lumen tube (DLT).

Single-lumen endotracheal tube

The simplest means of providing SLV is to intentionally intubate the ipsilateral mainstem bronchus with a conventional ETT (4). When the left bronchus is to be intubated, the bevel of the ETT is rotated 180° and the patient's head is turned to the right (5). The ETT is advanced into the bronchus until breath sounds on the operative side disappear. A fibreoptic bronchoscope may be passed through the ETT to confirm or guide placement. When a cuffed ETT is used, the distance from the tip of the tube to the proximal cuff must be shorter than the length of the bronchus so that the cuff is entirely within the bronchus and the upper lobe bronchial orifice is unobstructed (6).

This SLV technique is simple and requires no special equipment other than a fibreoptic bronchoscope. Accordingly, this may be the preferred technique for SLV in emergency situations such as airway haemorrhage or contralateral tension pneumothorax.

Problems can occur when using a single-lumen ETT for SLV. These include failure to provide an adequate seal of the tube in the bronchus, especially if a smaller, uncuffed ETT is used. This may prevent the operated lung from adequately collapsing or fail to protect the healthy, ventilated lung from contamination by purulent material in the contralateral lung. One is unable to suction the operative lung when a single-lumen ETT is used. Also, hypoxemia may occur because of obstruction of the upper lobe bronchus, especially when the short right mainstem bronchus is intubated.

Variations of this technique have been described, including intubation of both bronchi independently with small ETTs (7–10). With this variation, one mainstem bronchus is initially intubated with an ETT, after which another ETT is advanced over a fibreoptic bronchoscope into the opposite bronchus.

Balloon-tipped bronchial blockers

A technique for SLV has been described in which an end-hole, balloon wedge catheter is used as a bronchial blocker (11,12). The bronchus on the operative side is initially intubated with an ETT. A guidewire is then advanced into that bronchus through the ETT. The ETT is removed and the blocker is advanced over the guidewire into the bronchus. An ETT is then reinserted into the trachea alongside the blocker catheter. The catheter balloon is positioned in the proximal mainstem bronchus under fibreoptic visual guidance, or a Fogarty embolectomy catheter may be placed with or without bronchoscopic guidance (13–15). With an inflated blocker balloon the airway is completely sealed, providing more predictable lung collapse and better operating conditions than with an ETT in the bronchus.

A potential problem with this technique is dislodgement of the blocker balloon into the trachea. The inflated balloon will then block ventilation to both lungs and/or prevent collapse of the operated lung. A second possible problem is that the balloons of most catheters currently used for bronchial blockade have low-volume, high-pressure properties and overdistension can damage or even rupture the airway (16), although a recent report suggested that bronchial blocker cuffs produced lower 'cuff-to-tracheal' pressures than double lumen tubes (17). Lastly, when closed-tip bronchial blockers are used, it is not possible to suction or provide continuous positive airway pressure (CPAP) to the operated lung.

Recently, adapters have been used that facilitate administration of oxygen and ventilation during placement of a bronchial blocker through an indwelling ETT (18,19). The risk of hypoxaemia during blocker placement is diminished, and repositioning of the blocker may be performed with fibreoptic guidance during surgery. Takahashi and colleagues described a double-access-port ETT for SLV in paediatric patients (18). This tube is constructed by combining two ETTs, one of which is shortened and perforated to facilitate cannulation with the other, smaller tube. A fibreoptic bronchoscope is passed through the smaller tube and a bronchial blocker is advanced through the outer tube.

Arndt and colleagues. have described the use of a wire-guided endobronchial blocker (WEB, Cook Critical Care, Bloomington, IN, USA) placed through a multiport adapter for SLV in adults (19). The WEB is placed coaxially through the blocker port of the adapter, which also has a port for passage of a fibreoptic bronchoscope and ports for connection to the anaesthesia breathing circuit and ETT. The fibreoptic bronchoscope port has a plastic sealing cap, and the blocker port has a Tuohy–Borst connector that locks the catheter in place and maintains an airtight seal.

The first Cook WEB catheter is 9 Fr in diameter, limiting its use to adolescents and adults in whom an ETT at least 7.5 mm in internal diameter (ID) can be placed. The new Cook 5 Fr WEB catheter has a maximal outer diameter of 2.5 mm (including the deflated balloon), a central lumen with a diameter of 0.7 mm, and a distal balloon with a capacity of 3 mL (12). The low-pressure, high-volume balloon is elliptical and conforms to the bronchial lumen when inflated. The balloon has a length of 1.0 cm, corresponding to the length of the right mainstem bronchus in children approximately 2 years of age (20). This allows the catheter to be placed so that the balloon is entirely within the mainstem bronchus, i.e. not obstructing the upper lobe bronchus, even when the shorter right mainstem bronchus is catheterized in young children. The balloon is blue in colour to facilitate visualization in the airway.

Because placement of the 5 Fr endobronchial catheter is guided by fibreoptic bronchoscopy, both the catheter and the fibreoptic bronchoscope must pass through the indwelling ETT. As the catheter (with the balloon deflated) has a diameter of 2.5 mm, the smallest ETT through which the catheter and fibreoptic bronchoscope can be placed is determined by adding 2.5 mm to the outer diameter of the fibreoptic bronchoscope. The endobronchial catheter and a fibreoptic bronchoscope 2.5 mm in diameter may be inserted through an ETT as small as 5.0 mm ID. For children with an indwelling 4.5-mm ID ETT, a fibreoptic bronchoscope with a diameter of 2.0 mm may be used. This technique is generally limited, therefore, to children over the age of 1 year. If the indwelling ETT is too small to accommodate the smallest available fibreoptic bronchoscope and endobronchial catheter, this new catheter may be placed outside the ETT using a technique described previously (21).

Univent tube

The Univent tube (Fuji Systems Corporation, Tokyo, Japan) is a conventional ETT with a second lumen containing a small tube that can be advanced into a bronchus (22–24). A balloon located at the distal end of this small tube serves as a bronchial blocker. Univent tubes require use of fibreoptic bronchoscopy for successful placement. Univent tubes are now available in sizes as small as 3.5 and 4.5 mm ID for use in children as young as 6 years of age (25).

Because the blocker tube is firmly attached to the main ETT, displacement of the Univent blocker balloon is less likely than when other blocker techniques are used. The 4.5 mm ID (but not the 3.5 mmID) Univent tube blocker tube has a small lumen that allows egress of gas and can be used to insufflate oxygen or suction the operated lung.

A disadvantage of the Univent tube is the large amount of cross-sectional area occupied by the blocker channel, especially in the smaller tubes. The smaller Univent tubes have a disproportionately high resistance to gas flow (26). In addition, the Univent tube's blocker balloon has low-volume, high-pressure characteristics, so mucosal injury can occur during normal inflation (27, 28).

Double-lumen tubes

All DLTs are essentially two tubes of unequal length moulded together. The shorter tube ends in the trachea and the longer tube in the bronchus. Marrarro described a bilumen tube for infants that consists of two separate uncuffed tracheal tubes of different lengths attached longitudinally (29). However, this tube is not available in the USA.

The DLTs available in the USA include conventional plastic cuffed tubes in adult sizes (35, 37, 39, and 41 Fr), in sizes 28 and 32 Fr (Mallinckrodt Medical, Inc., St Louis, MO, USA) for children as young as 10 years, and as small as 26 Fr (Rusch, Duluth, GA, USA) for children as young as 8 years old. These DLTs have cuffs located on the tracheal and bronchial lumens. The tracheal cuff, when inflated, allows positive-pressure ventilation. Inflation of the bronchial cuff allows ventilation to be diverted to either or both lungs, protecting each lung from contamination from the contralateral side.

In children, the DLT is inserted using the same technique as in adults (30). If fibreoptic bronchoscopy is to be used to confirm tube placement, a bronchoscope with a small diameter and sufficient length must be available (31). The tip of the tube is advanced until it is just past the vocal cords and then the stylet is withdrawn. The tube is rotated 90° to the appropriate side and then advanced into the bronchus. In adults, the depth to which the tube should be inserted is directly related to the height of the patient. No equivalent measurements have yet been established in children.

A DLT offers the advantages of ease of insertion, ability to suction and oxygenate the operated lung with CPAP, and ability to visualize the operative lung. Left DLTs are preferred to right because of the shorter length of the right main bronchus (32). Right DLTs are more difficult to position accurately because of the greater risk of right upper lobe obstruction.

The DLTs are relatively safe and easy to use, as evidenced by very few reports of airway damage from DLTs in adults and none in children (33). The high-volume, low-pressure cuffs of these tubes

Table 1
Tube selection for single-lung ventilation in children and teens (34)

Age (years)	*ETT (ID in mm)*	*BB (Fr)*	*Univent®*	*DLT (Fr)*
0.5–1	3.5–4.0	5		
1–2	4.0–4.5	5		
2–4	4.5–5.0	5		
4–6	5.0–5.5	5		
6–8	5.5–6	5	3.5	
8–10	6.0 cuffed	5	3.5	26
10–12	6.5 cuffed	5	4.5	26–28
12–14	6.5–7.0 cuffed	5	4.5	32
14–16	7.0 cuffed	5	6.0	35
16–18	7.0–8.0 cuffed	5 or 9	7.0	35

BB, bronchial blockade (Cook Critical Care, Inc., Bloomington, IN, USA); DLT, double-lumen tube (26 Fr = Rusch, Duluth, GA, USA; 28–35 Fr = Mallinckrodt Medical, Inc., St Louis, MO, USA); ETT, endotracheal tube (Sheridan® Tracheal Tubes; Kendall Healthcare, Mansfield, MA, USA); Fr, French size; ID, internal diameter; Univent (Fuji Systems Corporation, Tokyo, Japan).

should not damage the airway if they are not overinflated with air or distended with nitrous oxide while in place.

Tube selection for SLV in children

Guidelines for selecting the appropriate tube (or catheter) for SLV in children of various ages are shown in Table 1 (34). Children of the same age, especially during adolescence, vary significantly in overall size and the dimensions of the airway. The recommendations in Table 1 are based on average values for airway dimensions in each age group. Larger DLTs may safely be used in large teenagers.

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