Management of One-Lung Anesthesia

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Traditionally, one-lung anesthesia has been used during thoracotomy for a variety of pulmonary surgical indications. These have been grouped into "absolute indications" (massive hemoptysis, lung abscess, empyema, bronchopleural fistula, etc.—"blood, pus, and air") and "relative indications" (surgical exposure). Recent advances in surgery, particularly the use of minimally invasive and robotic techniques for cardiac, esophageal, and pulmonary procedures inside the thorax have blurred this traditional division between types of indications for one-lung anesthesia (1). Many of these newer operations are completely dependent on the ability of the anesthesiologist to provide safe and reliable one-lung anesthesia.

The incidence of hypoxemia during one-lung anesthesia has declined from levels of 20%–25% in the 1970s (2) to <1% today (3). Two advances in thoracic anesthesia affect oxygenation. First, the routine use of fiberoptic bronchoscopy (FOB) for lung isolation to position double-lumen tubes (DLTs) and bronchial blockers. Second, the use of anesthetic techniques and ventilation strategies that optimize oxygenation during one-lung ventilation. This review will focus on these two main factors in one-lung anesthesia: lung isolation and management of one-lung ventilation (OLV).

Lung Isolation

There are three basic techniques for lung isolation that have persisted for the past 50 yr: single-lumen endobronchial tubes, bronchial blockers, and DLTs. Single-lumen endobronchial tubes have infrequent indications in adult surgery, usually for carinal resections or after a previous pneumonectomy. They are still useful in the younger pediatric population. The majority of lung isolation in adults and older children is performed with DLTs or bronchial blockers.

The original DLT of Carlens (4) has evolved to a tube specifically designed for intraoperative use (Robertshaw) (5) with larger, D-shaped, lumens and without a carinal hook. Current disposable polyvinyl chloride DLTs have incorporated high-volume low-pressure tracheal and bronchial cuffs. Recent DLT refinements have two major drawbacks: these tubes now require FOB for positioning (6) and a satisfactory right-sided DLT has not yet been designed to deal with the short (average 2 cm) and variable length of the right main-stem bronchus (7). Recently, there has been a revival of interest in bronchial blockers because of design advances such as the Univent tube (8) and WEB (Arndt) blocker (9) and Coopdech blocker (10). Also, this is a result of greater familiarity of anesthesiologists with FOB and the expanding indications for one-lung anesthesia (11). As one-lung anesthesia is more widely used, the need for lung isolation in patients with difficult airways arises more frequently. Double-lumen tubes are designed for patients with normal adult tracheobronchial anatomy. Bronchial blockers are far more adaptable to abnormal upper and lower airway anatomy.

Initial malpositioning of DLTs with blind placement can occur in more than 30% (12) of cases. Verification and adjustment with FOB before initiating OLV is mandatory because these tubes will migrate during patient repositioning (13). The trachea is usually intubated with the patient's head and cervical spine in the sniffing position. Then, after turning the patient to the side, the head is stabilized in the neutral position. This movement is responsible for much of the change in position of the DLT. It is useful to confirm the DLT position with the head in a neutral position. DLTs that migrate during patient repositioning are more likely to become malpositioned later in the case (14). Malpositioning after the start of OLV as a result of dislodgment is more of a problem with bronchial blockers than DLTs.

Whether it is a standard of practice always to use a FOB to position a DLT or bronchial blocker has been a source of debate. Although the FOB is not one of the ASA-mandated anesthetic monitors, informal surveys at large anesthesia meetings suggest that in North America most anesthesiologists are now routinely using a FOB to guide and monitor lung isolation. Anesthesiologists should consider what the majority of practitioners in their region do as a form of standard. Complications during thoracic anesthesia may not be defensible if a FOB is not used (15).

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Table 1. Tracheal and Bronchial Diameters and Recommended Double-lumen Tube Sizes

Tracheal width (mm)	Bronchial diameter (mm)	Size DLT (F)
>18	>12	41
>16	12	39
>15	11	37
>14	10	35
>12	<10	32

DLT = double-lumen tube.

Avoiding Airway Trauma

Iatrogenic injury has been estimated to occur in 0.5–2 of 1000 cases with DLTs (16). Common factors in many of these case reports are small stature, female sex, esophageal surgery, and previous radiotherapy (17). Patients with any combination of these risk factors are at increased risk for tracheobronchial trauma from DLTs.

1. The majority of difficult endobronchial tube placements can be predicted from viewing the chest radiograph (18) or computed tomographic scan (19) for evidence of abnormal anatomy. There is no substitute for the anesthesiologist assessing the film him/herself before induction.
2. Avoid nitrous oxide: nitrous oxide 70% can increase the bronchial cuff volume from 5 to 16 mL intraoperatively (20).
3. Inflate the bronchial cuff/blocker only to the minimal volume required for lung isolation and for the minimal time required. This volume is usually < 3 mL for endobronchial cuffs. Inflating the bronchial cuff does not stabilize the DLT position when the patient is turned to the lateral position (21).
4. Endobronchial intubation must be done gently and with fiberoptic guidance if resistance is met.
5. Use of an appropriate size tube. Too small a tube will make lung isolation difficult. Too large a tube is more likely to cause trauma. Tracheobronchial dimensions correlate with height (22). Useful guidelines for DLT sizes in adults are as follows:
   female, height <1.6 m (63 in): 35F;
   female ≥1.6 m: 37F;
   female <1.5 m (59 in), consider 32F;
   male <1.7m (67 in): 39F;
   male ≥1.7m: 41F;
   male <1.6m, consider 37F.
   Some authors advocate the measurement of the tracheal or bronchial diameters from the preoperative imaging and using these diameters to guide choice of double-lumen tube size (Table 1) (23). It is useful to appreciate the comparative diameters of single-lumen tubes and DLTs and to avoid using a DLT that exceeds the maximum size of a single-lumen tube which could be safely used in a given patient (Table 2) (24). One clinical problem with DLTs ≤32F is that the commonly available sizes of pediatric FOB (4 mm) will not pass through the lumens of these tubes (Table 2). Clinical judgment or infant FOBs are required to position these smaller double-lumen tubes.
6. Avoid passing a DLT as far as possible until resistance is met. This was the previous teaching with tubes such as Carlen's tube, which had a carinal hook. Modern DLTs will not meet resistance until the bronchial lumen is impacted in the lower lobe bronchus. The average depth at insertion, from the teeth, for a left-DLT is 29 cm in an adult and varies ±1 cm for each 10 cm of patient height ±170 cm (25). Tubes should be passed to an appropriate dept and then verified with FOB.

The airflow resistance from a 37F DLT exceeds that of a #9 Univent by <10%. These flow resistances are both less than a 7.5-mm ID endotracheal tube but exceed a 9.0 mm endotracheal tube. For short periods of postoperative ventilation and weaning, airflow resistance is not a problem with a modern DLT (26).

With modern bronchial blockers, lobar bronchial blockade has become a clinically useful technique in thoracic anesthesia. This technique can be used for isolation of a single lobe or lobes on the side of surgery in patients who have had previous contralateral pulmonary resections (27). A modification of lobar blockade is to use dual bronchial blockers for right-sided lung surgery: one in the right upper lobe and one in the bronchus intermedius (28). This overcomes the problem of instability of blockers in the right mainstem bronchus.

The new devices available for airway management and lung isolation have increased the options for achieving one-lung anesthesia in patients with difficult airways. A useful clinical plan is to initially place a single-lumen tube either with a fiberoptic bronchoscope or a video laryngoscope (29) before or after induction of anesthesia, depending on the case. Then, according to the clinical scenario, either to use a bronchial blocker through the single-lumen tube or to replace the single-lumen tube with a double-lumen tube using an airway exchange catheter. There are commercially available exchange catheters designed specifically for this purpose that have adequate length (100 cm) and a range of appropriate sizes (11F–14F). To avoid trauma, both to the patient and the tracheal cuff of the double-lumen tube, it is advisable to use a laryngoscope during this tube exchange to help align the normal oropharyngeal and tracheal axes. Many variations using single-lumen endobronchial tubes or the new bronchial blockers have been described to deal with specific abnormal upper or lower airway

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Table 2. Comparative Diameters of Single and Double-lumen Tubes

Single-lumen tubes		Double-lumen tubes		
ID (mm)	OD (mm)	French size (F)	OD (mm)	Bronchial lumen ID (mm)
6.5	8.9	26	8.7	3.5
7.0	9.5	28	9.3	3.2
8.0	10.8	32	10.7	3.4
8.5	11.4	35	11.7	4.3
9.0	12.1	37	12.3	4.5
9.5	12.8	39	13.0	4.9
10.0	13.5	41	13.7	5.4

ID = inner diameter; OD = outer diameter.

anatomy. The use of a bronchial blocker has even been described via a laryngeal mask airway (30).

The three techniques for lung isolation remain: single-lumen endobronchial tubes, DLTs, and bronchial blockers. The anesthesiologist must be comfortable with all three methods of lung isolation to provide adequate lung separation in the wide variety of patients and clinical situations for which lung separation is now indicated. The **ABC**'s of lung isolation will always apply: know the tracheobronchial **A**natomy, use the fiberoptic **B**ronchoscope, look at the **C**hest imaging (radiograph, computed tomography, and magnetic resonance imaging).

Anesthetic Technique

The major cause of hypoxemia during one-lung anesthesia is the shunt of deoxygenated blood through the non-ventilated lung. Factors that influence this shunt are hypoxic pulmonary vasoconstriction, gravity, the pressure differential between the thoraces, and lung volume. Hypoxic pulmonary vasoconstriction is a two-phase reflex with an initial rapid (minutes) onset and then a slower (hours) increase (31). Hypoxic pulmonary vasoconstriction is inhibited by essentially all volatile anesthetics; isoflurane/desflurane/sevoflurane are equivalent and less inhibitory than enflurane or halothane. Compared with the older volatile anesthetics, the newer agents, isoflurane/desflurane/sevoflurane, are very weak inhibitors of hypoxic pulmonary vasoconstriction (32). Clinically, oxygenation with $\leq$1 MAC isoflurane/desflurane/sevoflurane is equivalent to that seen during total IV anesthesia (33).

A third of the 35%–40% shunt commonly seen during OLV is attributable to ventilation-perfusion mismatch in the ventilated dependent lung. Factors under the control of the anesthesiologist can influence this dependent-lung shunt. An excess of IV crystalloids can rapidly cause desaturation of the pulmonary venous blood draining the dependent lung. Also, the use of nitrous oxide will lead to increased dependent-lung atelectasis because it causes greater instability of poorly ventilated lung regions than oxygen. A recruitment maneuver to the ventilated lung at the start of OLV improves oxygenation (34).

Several factors allow prediction of the risk of hypoxemia developing during OLV (Table 3) (35). First, the alveolar-arterial Po_2 gradient during two-lung ventilation. Second, the side of lung collapse during OLV (the mean Pao_2 level is 70 mm Hg higher for left versus right thoracotomies) (36). Third, patients with good preoperative spirometric pulmonary function tests tend to have lower Pao_2 values during OLV than patients with poor spirometry. This is related to auto-positive end-expiratory pressure in patients with poor spirometry.

Continuous positive airway pressure (CPAP) to the non-ventilated lung is the first line of defense and treatment for hypoxemia during OLV (37). Useful increases in oxygenation can be achieved with 1–2 cm H_2O CPAP applied to the inflated lung (38). Maintaining cardiac output during OLV increases Pao_2 via maintaining mixed venous oxygen content because these patients have a large shunt (20%–30%). Positive end-expiratory pressure to the ventilated lung decreases Pao_2 in the majority of patients during OLV. A minority of patients, usually those with normal (39) or supranormal (pulmonary fibrosis, obesity) lung elastic recoil benefit from dependent lung positive end-expiratory pressure (40). High frequency jet ventilation is useful for non-pulmonary intrathoracic surgery. An IV infusion of almitrine (a pulmonary vasoconstrictor) can restore Pao_2 during OLV to levels close to these seen during two-lung ventilation (41). Nitric oxide has not been found to increase oxygenation reliably during one-lung ventilation (42). The combination of nitric oxide to the ventilated lung and inflation of a pulmonary artery catheter balloon in the non-ventilated lung has been described to deal with problem hypoxemia during whole-lung lavage (43).

Accelerating collapse of the non-ventilated lung is useful to aid surgery, particularly in patients with COPD and in cases of video thoracoscopic surgery. Use of an air-oxygen mixture during two-lung ventilation before one-lung anesthesia delays the collapse

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Table 3. Factors Increasing the Risk of Hypoxemia During One-lung Ventilation

- High percentage of ventilation or perfusion to the operative lung on preoperative V/Q scan
- Poor Pao_2 during two-lung ventilation
- Right-sided surgery
- Good preoperative spirometry (FEV_1 or FVC)
- Supine (versus lateral) patient position

FEV_1 = forced expiratory volume in 1 s; FVC = functional vital capacity.

of the lung as a result of residual nitrogen in the hypoxic non-ventilated lung. Thorough denitrogenation of the lung on the surgical side speeds lung collapse and facilitates surgical access (44).

Ventilatory management during OLV needs to be individualized depending on the patient's underlying lung pathology. Initial strategies should now include: tidal volumes in the 5–7 mL/kg range, limiting plateau airway pressures to 25 cm H_2O and adding positive end-expiratory pressure 5 cm H_2O to patients without auto-positive end-expiratory pressure. Manipulating the ventilating pressures and tidal volumes during one-lung anesthesia can improve the oxygenation for individual patients. Patients with chronic obstructive pulmonary disease have better oxygenation during OLV with pressure-controlled versus volume-controlled ventilation (45).

Fluid Therapy During One-lung Ventilation

Postpneumonectomy pulmonary edema (Post Px-PE) is an infrequent but highly lethal postoperative complication. As other causes of post–lung resection mortality have decreased in frequency, the importance of Post Px-PE is now becoming more evident. Pulmonary edema may be responsible for 75% of post–lung resection in-hospital deaths (46). In 1984, Zeldin et al. identified three risk factors for Post Px-PE: right pneumonectomy, increased perioperative IV fluids, and increased postoperative urine output (47). The theory that intraoperative fluid administration is the sole cause of Post Px-PE was refuted in 1993 by Turnage and Lunn (48).

The known facts about Post Px-PE are as follows:

- Incidence of 2%–4% after pneumonectomy.
- Increased incidence in right pneumonectomies.
- Symptomatic onset at postoperative days 2–4 (radiographic onset precedes symptoms by 24 h).
- High mortality rates (>50%) and resistance to standard therapies for pulmonary edema.
- Association, albeit not clearly cause-effect, with fluid overload.
- Low pulmonary wedge pressures and high-protein edema fluid suggesting endothelial damage.

The cause of Post Px-PE must be multifactorial. Probable causes are fluid overload, lung lymphatic injury, increased pulmonary capillary pressure, and pulmonary endothelial damage. Possible causes are hyperinflation and right ventricular dysfunction. Questionable causes include cytokines and oxygen toxicity.

Excessive crystalloid administration to an anesthetized animal in the lateral position rapidly causes fluid accumulation and pulmonary venous desaturation in the dependent lung, leading to the dictum: "Don't drown the down lung" (49). However, extreme fluid restriction has not eliminated Post Px-PE.

Overinflation of the lungs causes capillary endothelial damage similar to that from excessive pulmonary vascular pressures. Prolonged elevated airway pressures during thoracic surgery have been shown to correlate with the development of postoperative lung injury (50).

Suggestions for fluid management for pneumonectomy are as follows (51):

- Total positive fluid balance in the first 24 h should not exceed 20 mL/kg.
- For an average adult patient, crystalloid administration should be limited to <3 L in the first 24 h (there is no "third space" in the chest).
- Urine output $>0.5\ mL \cdot kg^{-1} \cdot h^{-1}$ is unnecessary. If increased tissue perfusion is needed, it is preferable to use invasive monitoring and inotropes rather than cause fluid overload.

Other anesthetic management suggestions for pneumonectomy patients include the following:

- Avoid long periods with the residual lung in the dependent position postoperatively.
- Minimize factors likely to contribute to increased pulmonary vascular pressures: e.g., pain, hypercarbia, hypoxemia.
- Supplemental oxygen administration until the patient demonstrates maintenance of adequate saturation during both exercise and sleep.
- Avoid hyperinflation of the residual lung: during one-lung ventilation maintain peak airway pressure <35 cm H_2O and plateau end-inspiratory pressure <25 cm H_2O.
- Observe for overinflation of the lung postoperatively. Manage the chest drain, if one is placed, to minimize mediastinal shift.
- Nitric oxide may be useful as therapy for Post Px-PE (52).

Summary

One-lung anesthesia is requested for an increasing spectrum of surgical procedures. Strategies to improve clinical one-lung ventilation are summarized in Table 4. Recent advances in anesthetic equipment, monitoring, and pharmacology have increased the safety of one-lung anesthesia.

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Table 4. Strategies to Improve One-lung Anesthesia

• Always use a fiberoptic bronchoscope to position endobronchial tubes and blockers
• Judicious use of intravenous fluids
• Predict desaturation. Prophylactic nonventilated lung CPAP in patients likely to desaturate. Ventilated-lung PEEP in patients with no auto-PEEP (normal lung function)
• Recruitment maneuver to the ventilated-lung at the start of one-lung anesthesia
• Use FiO_2 1.0 during two-lung ventilation to accelerate subsequent collapse of nonventilated lung

CPAP = continuous positive airway pressures; PEEP = positive end-expiratory pressure.

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