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Arterial Oxygenation and Management of Hypoxemia During VATS

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Abstract The volume and complexity of thoracic procedures performed with a thoracoscopic approach are steadily increasing. Surgical exposure is paramount for thoracoscopic procedures and requires meticulous lung isolation. In this review, the physiological adaptive mechanisms that occur during one-lung ventilation (OLV) are discussed. Factors that predict the occurrence of hypoxemia during OLV and a structured approach to the treatment of hypoxemia are outlined. Hypoxemia management is formulated in an escalating fashion, from basic solutions to common problems, all the way to advanced manipulations of shunt fraction and partial ventilation techniques.

Keywords Hypoxemia · Thoracoscopy · VATS · One-lung ventilation · Thoracic surgery · Thoracic anesthesiology · Lung isolation · Hypoxic pulmonary vasoconstriction · Oxygenation · Shunt · Cerebral desaturation · Protective ventilation

Introduction

Thoracoscopy was first described over a century ago, but its use surged in the 1990s following developments in fibreoptic technology and minimally invasive surgical techniques. Video-assisted thoracoscopic surgery (VATS) approaches have since been described for all types of thoracic procedures [1]. At present, there is a high rate of adoption of VATS lobectomies in academic institutions in the USA [2]. The reported clinical benefits of VATS procedures include a reduction in intraoperative blood loss, hospital length of stay, duration of chest tube drainage and postoperative pain [3•, 4]. Early concerns about oncological outcomes after lobectomies are being allayed by recent results suggesting VATS to be equivalent if not superior to open approaches [3•].

There are key differences in the anesthetic considerations between thoracotomy and VATS approaches. The thoracic cavity remains partially closed during thoracoscopic surgery, as surgical ports and instruments in effect seal the incision sites. This is the main reason for the slower lung collapse that is typical of thoracoscopic surgery. CO_2 insufflation into the closed thoracic cavity to improve visualization may therefore also result in tamponade physiology [5]. Optimum surgical exposure with meticulous lung isolation is key to successful VATS. The dependence on lung isolation is in contrast to open thoracotomy procedures, where it is desirable but not essential, and substantially impacts the approach to managing hypoxemia for VATS, as partial lung re-inflation is relatively contraindicated considering its impact on surgical exposure [6].

Incidence and Prediction of Hypoxemia During Thoracoscopic Surgery

Hypoxemia during one-lung ventilation (OLV) is now occurring in about 5 % of cases when defined as a decrease in arterial oxygen saturation to less than 90 % [7, 8••, 9],

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which is a dramatic decrease from a reported 27 % in the 1970s [10]. More reliable lung isolation due to routine bronchoscopy and the lesser effects of the newer volatile anesthetics on hypoxic pulmonary vasoconstriction (HPV) are felt to be responsible for this change [6].

A number of patient and procedural factors have been described that are predictive of OLV hypoxemia [11, 12]. Increased perfusion of the operative lung predictably increases the shunt fraction during OLV and therefore the risk of hypoxemia. This explains the increased risk of desaturation with right-sided surgery and procedures after contralateral resections [13]. Similarly, supine positioning prevents gravity redistribution of pulmonary blood flow resulting in increased shunt flow [13]. Perfusion abnormalities can be determined preoperatively with ventilation–perfusion (V/Q) scanning or intraoperatively by determining the end-tidal CO_2 gradient between the lungs in the lateral position [14]. Moreover, intrapulmonary admixture of venous blood is increased by insufficient oxygenation of blood in atelectatic and poorly ventilated regions of the dependent ventilated lung [15].

Normal lung function tests, in particular a normal FEV_1, indicate a higher risk for desaturation. This is felt to be due to the high elastic recoil in normal lung tissue, which predisposes to lung collapse in the ventilated lung. In contrast, intrinsic PEEP in the patient with obstructive lung disease is likely to be protective against atelectasis formation in both the ventilated and non-ventilated lung [6]. Assuming homogenous lung disease, poor arterial oxygenation during two-lung ventilation (TLV) is predictive of hypoxemia during OLV [6]. Conversely, significant unilateral pathology or tumor load in the operative lung may be protective, as perfusion has already been shifted toward the contralateral non-operative lung [9, 16].

Oxygenation During One-Lung Ventilation

Adequate oxygenation during OLV is dependent on optimal ventilation of the non-operative lung and minimizing the shunt through the operative lung. Modifiable factors influencing these will be discussed in turn.

The shunt fraction during OLV is estimated to be in the order of 20–30 % of the cardiac output [13]. In the absence of HPV, the non-ventilated lung would receive half of the pulmonary blood flow during OLV, resulting in a shunt fraction of 50 % and an oxygen saturation below 90 %. HPV is a physiological mechanism that optimizes V/Q matching in the normal and diseased lung. During OLV, HPV minimizes the shunt fraction by restricting blood flow to the operative lung. HPV is a core principle in the understanding of oxygenation during OLV. The concept that alveolar hypoxia causes pulmonary vasoconstriction was first acknowledged about a century ago [17••]. HPV occurs throughout the pulmonary vasculature including capillaries, venules and non-muscular arterioles; however, the main site appears to be the pulmonary arterioles [15, 18]. Mitochondria of the pulmonary artery smooth muscle cell, which produce reactive oxygen species in response to hypoxemia, are thought to be the primary sensor for HPV [16]. The precise transduction pathway remains to be fully elucidated. HPV is a triphasic response [19, 20], with initial rapid vasoconstriction that is maximal at 15–30 min. This is followed by gradual sustained vasoconstriction at 30–120 min. Finally, there is a further increase when the period of regional hypoxia extends beyond 120 min. In animal studies the threshold pAO_2 (alveolar $p0_2$) for the onset of HPV is approximately 80 mmHg [21], while the maximal response is reached at a pAO_2 of 25 mmHg.

Anesthesiologists control several factors that will impact the HPV response. Volatile anesthetic agents are known to inhibit HPV; however, the impact is minimal at less than 1 MAC and negligible with newer agents [22]. A recent Cochrane review of intravenous versus inhalational anesthesia for OLV concluded that there was very little evidence from randomized controlled trials to suggest differences in patient outcomes between groups [23•]. However, given that oxygenation is equivalent at low MAC values and volatiles demonstrate anti-inflammatory benefits during OLV [24•], intravenous anesthesia is likely rarely warranted.

Cardiac output needs to be maintained for adequate oxygenation because of the negative effect of low mixed venous oxygen tensions on oxygen delivery in the setting of high shunt fractions. Supra-normal cardiac output is detrimental because of inhibition of HPV by any of increased pulmonary artery pressures, increased mixed venous oxygen tensions or directly by adrenergic agents [25, 26].

Whether arterial oxygenation is the most appropriate monitor to judge oxygen delivery has recently been called into question by studies demonstrating cerebral oxygen desaturations in the absence of arterial hypoxemia [27]. In particular, the suggestion of a potential association with postoperative complications is concerning [28], but further research is required to define the underlying mechanism and delineate its significance.

The ventilator management of patients during OLV has changed significantly because of the realization that OLV predisposes patients to acute lung injury (ALI) in the ventilated lung [6]. Protective OLV is well established and consists of low-tidal volumes (4–6 ml/kg), routine PEEP, lower FiO_2 and permissive hypercapnea ($paCO_2$ 40–60 mmHg). While beneficial from an ALI prevention perspective, there is some controversy as to whether this approach may predispose to more hypoxemia [29, 30]. Large tidal volumes produce more tidal recruitment than small tidal volumes [31••], which is the reason that tidal volumes of 10 ml/kg were traditionally recommended for OLV to optimize oxygenation [32]. However, the increased tidal recruitment is likely responsible for the increased lung injury seen with high tidal volumes. Given the reduced amount of tidal recruitment with protective ventilation, optimal PEEP selection is crucial to prevent atelectasis formation.

Management of Hypoxemia During VATS

OLV hypoxemia requires a structured assessment and treatment approach (Fig. 1). The urgency of the situation will vary depending on the degree of hypoxemia and patient risk factors. Increasing the FiO_2 is a simple and effective maneuver that should be employed early, as it affords more time to search for the cause of hypoxemia. The single most effective way to improve oxygenation is to resume TLV. Except for the most peripheral lung lesions, however, this will completely obscure the surgical field and make surgery impossible. If the situation allows, other management steps should therefore be considered first, unless the hypoxemia is severe and resulting in end-organ dysfunction (e.g., myocardial ischemia). Dislodgement of the airway device, be it a double-lumen tube (DLT) or bronchial blocker, must be ruled out early in the course of management. Aside from direct visualization with a fiber-optic bronchoscope, changes in ventilation pressure and volume measurements may be helpful in making this diagnosis. Lung de-recruitment is common and may be due to a multitude of reasons, including hypoventilation,

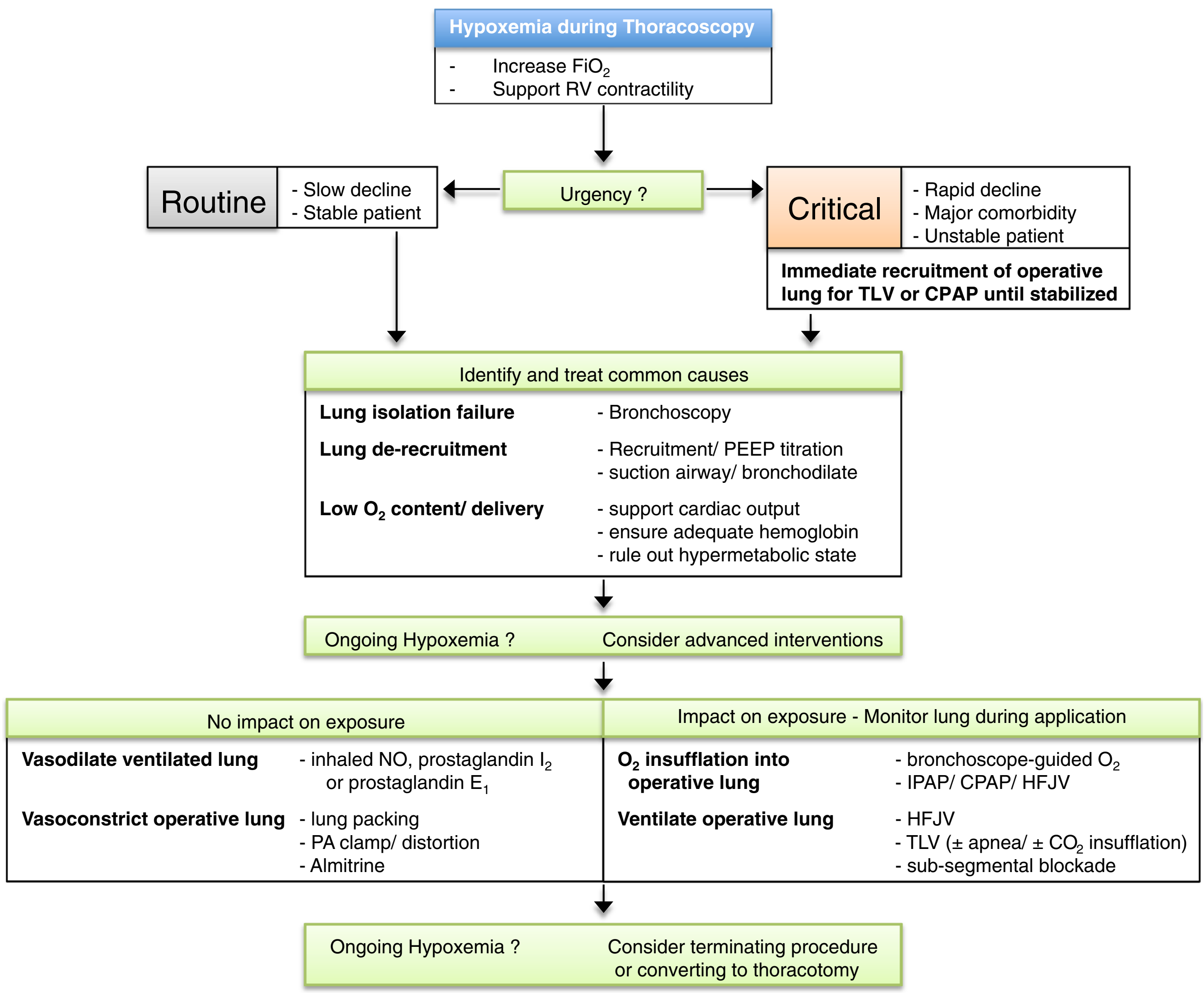

Fig. 1 OLV hypoxemia treatment pathway adapted to thoracoscopic surgery. See text for details. *FiO_2* fractional inspired oxygen, *CPAP* continuous positive airway pressure, *TLV* two-lung ventilation, *IPAP* intermittent positive airway pressure, *NO* nitric oxide, *PEEP* positive end-expiratory pressure, *RV* right ventricular, *HFJV* high-frequency jet ventilation. Modified from [11], with permission from Elsevier

inadequate PEEP or bronchial obstruction from airway malposition, blood or secretions. Early use of bronchoscopy will confirm patency of the airway and bronchus. Derecruitment of the ventilated lung is common, but easily correctable with lung recruitment. Recruitment maneuvers have been shown to result in marked improvements in oxygenation and ventilation. Both vital capacity maneuvers (30–40 cmH_2O for 10–40 s) and cycling maneuvers with stepwise increases in Ppeak and PEEP have been reported [33]. If successful in recruiting lung, as evidenced by improved oxygenation, a recruitment maneuver should be followed by an increase in the PEEP applied.

Low cardiac output is detrimental to oxygenation because of the reduction of mixed venous oxygen content, which is harder to overcome in the setting of a high shunt fraction. Treatment should be directed at the most likely culprit, whether it is hypovolemia, sympathectomy or myocardial depression. Adrenergic agents (e.g., ephedrine, norepinephrine) will increase cardiac index and oxygen delivery, and have a beneficial effect on the pulmonary to systemic pressure ratio in patients with pre-existing pulmonary hypertension, which is in contrast to vasoconstrictors (e.g., phenylephrine) [34]. Fluid should be used sparingly so as not to contribute to postoperative ALI [35]. Blood transfusions will rarely be necessary, but can be considered in cases of symptomatic anemia. If hypoxemia persists despite optimal perfusion and ventilation of the dependent lung, advanced interventions will have to be considered.

The shunt fraction is the biggest determinant of oxygenation during OLV. Interventions that increase pulmonary blood flow in the ventilated lung, and therefore decrease the shunt through the operative lung, may therefore significantly improve oxygenation. The pulmonary vasculature has a large capacity for recruitment [36]. Selective vasodilatation of the pulmonary vascular bed in the ventilated lung can be achieved with inhalational agents. Inhaled nitric oxide (iNO), alprostadil (PGE1) and prostacyclin (PGI2, also known as epoprostenol or Flolan®) have all been studied in the setting of OLV. Nitric oxide diffuses rapidly across the alveolar–capillary membrane into the pulmonary vascular smooth muscle, where it activates guanylate cyclase and increases intracellular concentrations of cGMP, resulting in smooth muscle relaxation [37]. In addition to its pulmonary vasodilating effects, inhaled NO also has bronchodilating and anti-inflammatory effects [38, 39]. At doses of 20–40 ppm, it has been demonstrated to cause a significant reduction in pulmonary arterial pressure [40] and improved oxygenation in patients with pulmonary hypertension and severe hypoxemia undergoing OLV [41]. Prostacyclin has been shown to be an effective alternative in inducing pulmonary vasodilatation [42, 43]. Alprostadil has also been shown to reduce pulmonary vascular resistance and improve oxygenation in patients undergoing lung transplantation [44]. All of these agents are expensive and require specialized delivery systems, meaning that none of them can be considered a readily available treatment for hypoxemia. They rather represent an advanced intervention in the anticipated borderline patient.

Potentiating HPV in the operative lung may further reduce the shunt fraction. Almitrine, a respiratory stimulant, acts as a selective pulmonary vasoconstrictor and has been demonstrated to increase HPV and decrease the shunt fraction [6]. An intravenous infusion of 8 μg/kg/min of almitrine has been shown to significantly improve oxygenation during OLV, while the combination of almitrine and iNO was found to have even more profound effects on oxygenation [45]. Unfortunately, almitrine is not commercially available in North America and its safety in patients with pulmonary hypertension not fully established. In a small trial, phenylephrine was shown to have some ability in strengthening HPV, however only in half of all patients and always associated with systemic vasoconstriction [46]. Mechanical restriction of pulmonary blood flow is also a possibility. Clamping of the operative pulmonary artery has been described during VATS surgery [47, 48]. If hilar exposure is not available, physical distortion of the lung anatomy can reduce pulmonary blood flow, but may be associated with decreases in the cardiac index because of increased right ventricular afterload [49]. Caution must therefore be exercised depending on the baseline right ventricular function and the hemodynamic response to PA manipulation.

Partial ventilation of the operative lung, or apneic oxygenation with continuous positive airway pressure (CPAP), is highly effective in improving oxygenation as it converts the shunt to lung tissue participating in gas exchange. Success of this technique requires alveolar recruitment, as application of oxygen to completely collapsed lung tissue does not improve oxygenation [50]. While being highly effective in improving oxygenation and commonly used during thoracotomy procedures, lung recruitment and CPAP are considered contraindicated during VATS surgery because of their negative impact on surgical exposure [6]. However, there is evidence that CPAP can be used during thoracoscopy. CPAP of 2 cmH_2O following a recruitment maneuver to the operative lung during thoracoscopy resulted in a significant improvement in oxygenation, with only a minimal decrease in surgical exposure and surgeon satisfaction scores of nine out of ten [51••]. While recruitment is essential for any CPAP technique, it clearly has to be restricted to only partial recruitment and therefore should be guided by real-time visual inspection of the lung on the surgical monitors. Modified techniques for the application of CPAP have been described. These include intermittent positive airway pressure (IPAP) of the operative lung, applied to either the entire lung [52] or a subsegment [53]. Application of IPAP to the entire operative lung has been described by attaching oxygen tubing with flows of 2 l/min to a bacteriostatic filter on the non-ventilated lumen of the DLT, with intermittent occlusion of the filter delivering short oxygen bursts. Subsegmental IPAP has been described by positioning the tip of the fiberoptic bronchoscope into a broncho-pulmonary segment distal to the site of surgery. With the oxygen source attached to the suction port, oxygen can be delivered upon depressing the suction trigger while observing the targeted subsegment on the monitors to avoid impaired surgical exposure and over-distention. On rare occasions, ventilation of a lobe of the operative lung may be possible by selective lobar bronchial blockade using a bronchial blocker [54]. Lastly, high-frequency jet ventilation (HFJV) of the operative lung is known to be a highly effective CPAP alternative; however, it has also been anecdotally described as an alternative to lung isolation for operative lung ventilation during VATS with minimal impact on surgical exposure [55•]. Another option to consider, in consultation with the surgeon, is institution of TLV with concomitant CO_2 insufflation to protect surgical exposure. As previously stated, this comes with the caveats that due to the moving lung it is more suited to peripheral or non-lung surgery and that tamponade physiology is likely.

Should intractable hypoxemia persist despite intervention, conversion to an open thoracotomy should be considered as it allows for more aggressive application of CPAP, IPAP and partial ventilation techniques.

Conclusion

There has been a large increase in the volume of thoracoscopic cases performed in the last decade. While hypoxemia has become less frequent, its management is more difficult during VATS procedures. All of the interventions known to improve oxygenation during OLV can be applied with some adjustments in technique. Partial ventilation or oxygen insufflation techniques require delicate application and good communication with the surgical team to minimize the impact on surgical exposure.

Compliance with Ethics Guidelines

Conflict of Interest Abigail M. Walsh and Jens Lohser declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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