Review

Clinical review: Independent lung ventilation in critical care

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Abstract

Independent lung ventilation (ILV) can be classified into anatomical and physiological lung separation. It requires either endobronchial blockade or double-lumen endotracheal tube intubation. Endobronchial blockade or selective double-lumen tube ventilation may necessitate temporary one lung ventilation. Anatomical lung separation isolates a diseased lung from contaminating the non-diseased lung. Physiological lung separation ventilates each lung as an independent unit. There are some clear indications for ILV as a primary intervention and as a rescue ventilator strategy in both anatomical and physiological lung separation. Potential pitfalls are related to establishing and maintaining lung isolation. Nevertheless, ILV can be used in the intensive care setting safely with a good understanding of its limitations and potential complications.

Introduction

Indications for independent lung ventilation (ILV) in critical care medicine are poorly defined compared to their use in thoracic anaesthesia. Although first described in anaesthetic practice in 1931, it was only in 1976 that ILV was reported in an intensive care setting [1,2]. Specific primary indications such as whole lung lavage [3] and massive hemoptysis [4] have since been identified. There is also emerging data on ILV as a rescue ventilator strategy when conventional ventilator techniques fail [5].

Intubation alternatives for ILV include endobronchial blockers or double-lumen endotracheal tubes. Endobronchial blockers or selective double-lumen tube ventilation may limit respiratory support to one lung ventilation (OLV) temporarily. There are some ventilatory strategies adopted from thoracic anaesthesia that can be used to improve oxygenation in OLV. ILV can have several other variations including synchronous and asynchronous ventilation.

ILV can be classified as being used for either anatomical or physiological separation of the lungs [4]. Anatomical separation aims to isolate one lung from potentially injurious contaminants from the other diseased lung. Indications for anatomical lung separation include the management of massive hemoptysis and interbronchial aspiration of copious secretions [4], as well as whole lung lavage for pulmonary alveolar proteinosis [3] (Table 1). Anatomical isolation remains a short-term intervention and is not used for prolonged ventilation because infections cannot be reliably localised by blockers and hemoptysis can only be transiently tamponaded. It allows temporary ventilatory support while definitive treatment like surgery or embolisation is instituted.

In physiological lung separation, each lung is ventilated as an independent unit after isolating one side from the other. Different ventilator strategies can be used on each side because of asymmetric lung disease resulting in different airway resistance and lung compliance. Unilateral parenchymal lung diseases [4], post-operative complications of single lung transplants [1] and bronchopleural fistulas [6] are common indications for physiological separation (Table 1). ILV used as rescue ventilatory support in severe bilateral lung injury remains controversial [5].

The conundrum facing intensivists when confronted with new therapeutic options such as ILV is to separate what may work from that which can be tolerated by patients who are already dangerously ill and failing on established therapy [7]. Therefore, our focus will be on specifying ILV techniques for clearly defined indications while detailing the safety profiles of these techniques.

Endobronchial blockers

The range of endobronchial blockers that are available varies from balloon catheters, such as the Fogarty [8], Foley [9] or pulmonary artery catheters [4], to custom designed blockers that include the Arndt [10] wire-guided or Cohen [11] flexitip

COPD = chronic obstructive pulmonary disease; ILV = independent lung ventilation; OLV = one lung ventilation; PEEP = positive end-expiratory pressure.

Table 1

Indications for independent lung ventilation in critical care

Independent lung ventilation	Indication
Anatomical lung separation	Massive hemoptysis
	Whole lung lavage for pulmonary alveolar proteinosis
	Copious secretions (e.g. bronchiectasis, lung abscess)
Physiological lung separation	Unilateral parenchymal injury
	Aspiration
	Pulmonary contusion
	Pneumonia
	Unilateral pulmonary edema
	Single lung transplant (post operative complications)
	Bronchopleural fistula
	Unilateral bronchospasm
	Severe bilateral lung disease failing conventional ventilation[a]

[a]Controversial indication.

blockers. Fogarty blockers with smaller balloon catheters (0.5 to 3 ml) allow segmental lung isolation to be achieved [12].

Univent blockers are single-lumen endotracheal tubes with an anterior channel that houses a balloon catheter. The balloon catheter acts as a blocker and the Univent has been shown to be as effective as double-lumen tubes in OLV [13]. The central lumen of the balloon catheter allows a limited amount of suctioning of secretions. Oxygen can also be insufflated through this central lumen into the non-ventilated lung to improve oxygenation. Bronchial mucosal ischemia, bronchial rupture and pneumothorax are possible side effects of Univent blockers because of the high cuff pressures that can be generated [14].

Unlike double-lumen tubes, endobronchial blockers add no further complexity to intubation. They are introduced either along the side of a single-lumen endotracheal tube via direct laryngoscopy or into the lumen of the endotracheal tube after intubation. This offers a distinct advantage in the intubation of difficult upper airways; however, final placement to achieve adequate lung isolation may still take longer than double-lumen tube insertion and requires bronchoscopic guidance [15,16]. Endobronchial blockers also remain the only viable alternative in paediatric patients in whom the tracheobronchial size may not accommodate even the smallest double-lumen tube [17]. The comparative sizing of single-lumen, Univent and double-lumen tubes is shown in Table 2.

Table 2

Comparative sizing of single-lumen , Univent and double-lumen tubes [12]

Single-lumen endotracheal tubes (internal diameter in mm)	Univent tubes (internal diameter in mm)	Double-lumen tube (F)
12.5	9.0	41
12.0	8.5	39
11.0	8.0	37
9.5	7.5	35
9.0	7.0	33
8.0	6.0	28

Problems encountered with endobronchial blockers include tedious final placement after intubation. This is especially so when bronchoscopic visualisation is limited by massive hemoptysis. They cannot be used when the side of the bleeding is unknown. Dislodgement is also more common than in double-lumen tubes [18]. By blocking up the pathological side, it is impossible to monitor continued bleeding or secretions. In pulmonary hypertension, lobar rupture can potentially occur from continued bleeding on the isolated side [19].

Double-lumen endotracheal tube

The modern polyvinyl chloride double-lumen endotracheal tube has evolved from the rubber Carlens [20] and Robertshaw [21] tubes. Polyvinyl chloride double-lumen tubes have larger internal to external diameter ratios. They are also less irritative and more supple and so cause less trauma [4,18]. The Mallindrokodt double-lumen tubes have had further modifications for safety. These are a tighter curvature, inverted bronchial cuff shoulder and a square bronchial tip to reduce the risk of airway occlusion [22]. Polyvinyl chloride double-lumen tubes can be used for up to 10 days without evidence of tracheobronchial trauma [7].

Placement of double-lumen endotracheal tube

The shorter right main stem bronchus (1.5 cm) and early right upper lobe take-off increase the risk of inadvertent right upper lobe obstruction (89%) with 'blind' right-sided double-lumen tube intubation [23]. It is difficult to align the side ventilation slot of the bronchial lumen of a right-sided double-lumen tube with the orifice of the right upper lobe bronchus. Therefore, conventional recommendations are for the preference of a left-sided double-lumen tube unless bronchial stenosis, airway obstruction or airway deviation prevents its insertion [1,4,7].

Sizing the double-lumen endotracheal tube (Table 3) appropriately is important in order to obtain adequate functional

Table 3

Sizing polyvinyl chloride double-lumen tubes [63]

Tube size (F)	Circumference (mm)	Lumen diameter (mm)	Indication
35	38.0	5.0	Pediatrics
37	40.0	5.5	Small adults
39	44.0	6.0	Medium adults, usual female size
41	45.0	6.5	Large adults, usual male size

separation of the lungs, establish optimum access for suctioning and bronchoscopy, as well as prevent migration of the tube and consequent herniation of the bronchial cuff into the carina. Conversely, oversized tubes can cause excessive tracheobronchial trauma and are difficult to insert.

Direct laryngoscopy or bronchoscopic guidance can be used for left double-lumen tube insertion. When using direct laryngoscopy, the patient is first intubated, the double-lumen tube rotated through 90 degrees to the left and finally advanced into the left main stem bronchus until resistance is felt. Keeping the double-lumen tube stylet in place after intubation increases positioning accuracy from 17% to 60% [24]. If intubation is difficult, the patient can be intubated with a single-lumen endotracheal tube and the double-lumen tube inserted over a Cook exchange catheter [12]. Alternatively, bronchoscopic intubation can be attempted, which has the added benefit of precise placement and confirmation of position.

Confirming position and functional separation of lungs

After insertion, accurate anatomical position and adequate functional separation of the lungs needs to be ascertained. A 1.7 metre adult should have the double-lumen tube anchored at 28 to 32 cm, although height may be poorly correlated with tracheobronchial dimensions ($r < 0.5$) [25]. Alternatively, the distance between the cephalic edge of the sixth cervical vertebra to the carina [26] as well as three-dimensional reconstruction computer tomography of the trachea [25] have been proposed to predict placement depth and sizing of double-lumen tubes. Although these methods have been tried in pre-operative assessment, their practicality in critical care medicine is questionable. Chest X-rays are subsequently used to assess correct positioning post-intubation by identifying the radio-opaque strip on the double-lumen tube. Auscultation following sequential clamping of first the bronchial lumen to ventilate only the right lung and then the tracheal lumen to ventilate the left lung is unreliable. The auscultation method can result in incorrect positioning in 38% of cases, with wrong main stem intubated in 20.8% and double-lumen tube above the carina in 38.7% of these misplacements [27]. Therefore, bronchoscopic confirmation of placement is recommended and results in adjustment of double-lumen tube position in 48% to 83% of cases [28,29]. Bronchoscopy through the tracheal port should visualise the carina without any visible herniation of the bronchial cuff. The left upper lobe orifice should be seen through the bronchial port.

Functional separation of the lungs can be assessed by either the water bubble [30] or balloon inflation [31] technique. When using the water bubble technique, the tracheal port is placed under water while transiently maintaining a plateau pressure of 40 cm through the bronchial port. The appearance of bubbles at the tracheal port identifies a leak around the bronchial cuff [30]. The balloon inflation method substitutes a balloon for the underwater seal. Any inflation of the balloon at the tracheal port during positive pressure ventilation through the bronchial port identifies an air leak [31].

Precise monitoring of the position of an appropriately positioned double-lumen tube is necessary because displacement can occur in up to 32% of cases when the patient's position is changed [32]. Distal displacement is more common than proximal displacement. Movements of 16 to 19 mm of a left double-lumen tube and 8 mm of a right double-lumen tube can compromise functional lung separation [33]. Bronchoscopy is essential to exclude double-lumen tube displacement and to re-position it if necessary. Pulse oximetry, end-tidal capnography [34], peak and plateau pressures [35], as well as continuous spirometry [36] can be used for non-invasive monitoring, but cannot replace readily available bronchoscopy. The adequate sedation and sometimes paralysis needed for patients to tolerate ILV also help prevent double-lumen tube dislodgement by movement or coughing.

Potential complications

Complications specific to double-lumen tubes are related to the high pressures generated by bronchial cuffs. The polyvinyl chloride double-lumen tube cuffs can generate pressures of over 50 mmHg with an inflation of just 2 ml of air [37]. This is the estimated inflation required to generate a functional seal. Bronchial ischemia and stenosis, pneumothorax, pneumomediastinum, and subcutaneous emphysema have been reported as subsequent complications [38]. Deflating the cuff when moving the patient can further reduce these risks [7]. The risk of bronchial rupture is 0.5 to 2 per 1000 [39]. Risk factors increasing the likelihood of bronchial rupture include traumatic intubation, cuff over-inflation, over-sized double-lumen tubes and prolonged intubation. Patient-related risk factors for bronchial trauma are underlying malignancy, infection, chronic steroid use and prior tracheobronchial surgery [18].

One lung ventilation

OLV creates a shunt in the blocked lung. In thoracic anaesthesia, several strategies have been used to correct the

hypoxemia created by shunting in OLV. These include placing the ventilated lung in the lateral decubitus position and applying selective positive end-expiratory pressure (PEEP) to the ventilated side.

One lung ventilation strategies

Despite thromboxane A2 mediated hypoxic pulmonary arteriolar vasoconstriction in the non-ventilated lung [40], it still receives some perfusion, which can result in a shunting of up to 23% of cardiac output [41]. When the lateral decubitus position is employed in OLV, there is further gravitation dependent preferential perfusion to the dependent, ventilated lung. Selective PEEP complements this by recruiting alveoli in the ventilated lung. This may come at the expense of some diminished cardiac output (up to 17%) [42]. Oxygenation will only improve if the selective PEEP does not increase intrinsic PEEP and cause hyperinflation [43]. Risk factors for the development of intrinsic PEEP include high unilateral tidal volumes and increased airway resistance caused by either small calibre double-lumen tubes or underlying chronic obstructive lung disease (COPD) [44].

Other strategies to improve oxygenation in OLV include the use of continuous positive airway pressure or oxygen insufflation into the non-ventilated lung. Oxygenating blood that perfuses the non-ventilated lung reduces shunt. The use of inhaled nitric oxide [45], nebulised Nitro-L-arginine methyl ester (L-NAME, i.e. nitric oxide synthetase inhibitor) [46], intravenous almitrine [47] and selective perfusion of either prostoglandin E1 (ventilated lung) [48] or prostaglandin F2 alpha (non-ventilated lung) [49] have also been reported to improve ventilation-perfusion matching in OLV in an experimental setting.

Independent lung ventilation

ILV can be instituted synchronously with either one or two ventilator circuits. The alternative is asynchronous ventilation with two ventilators [50].

Synchronous independent lung ventilation

In synchronous ILV, the respiratory rate of both lungs is kept identical; however, the respiratory cycle can either be in phase or 180 degrees out of phase. Selective PEEP can also be added to either lung. The tidal volumes and inspiratory flow rates are set independently.

Synchronous ILV can be instituted using either a two-ventilator or a single ventilator system. Using two Servo 900 ventilators, a 'master' and a 'slave' ventilator are synchronised using an external cable [51]. A one-ventilator system employs a Y-piece with separate PEEP valves [6,52]. The airflow and tidal volume to each lung is then determined by the individual lung compliance and airway resistance.

Asynchronous independent lung ventilation

Asynchronous ventilation offers greater flexibility and is less complicated than synchronised ventilation. There is also no proven disadvantage compared to synchronized ILV [4]. Reported variations of asynchronous ventilation include: bilateral continuous mandatory ventilation [50]; continuous mandatory ventilation and synchronized intermittent mandatory ventilation [50]; continuous mandatory ventilation and high frequency jet ventilation [53]; as well as continuous mandatory ventilation and continuous positive airway pressure [54].

Anatomical lung separation

Anatomical lung isolation aims to isolate a relatively normal lung from harmful contaminants from the contra-lateral diseased lung. Massive hemoptysis [4] and whole lung lavage [3] are well-described indications. Prevention of inter-bronchial spillage of purulent secretions remains anecdotal and controversial.

Massive hemoptysis

ILV can be life saving in massive hemoptysis until definitive therapy like surgery, embolotherapy or interventional bronchoscopy can be instituted.

When the site of bleeding is unknown, double-lumen tubes should be used instead of endobronchial blockers. They offer the added advantage of permitting bronchial toilet and limited bronchoscopic therapy. Intubation may, however, be technically difficult in profuse hemoptysis [4].

Although it is easier to intubate with single-lumen endo-tracheal tubes and then deploy an endobronchial blocker, final placement of the blocker with bronchoscopic guidance may be challenging in the presence of copious blood in the airways. Furthermore, after deployment it is impossible to monitor continued bleeding distal to the blocker. After the bleed is isolated, the lungs should be ventilated with conventional volume and pressure targets and definitive treatment sought expeditiously.

Whole lung lavage

Sequential lung lavage is the recognised treatment of pulmonary alveolar proteinosis. The worse affected lung, if it can be identified, is lavaged first to minimise hypoxemia. A double-lumen tube is inserted under general anaesthesia and absolute functional lung separation needs to be ascertained. After pre-oxygenation, isotonic saline at body temperature is allowed to influx, 500 to 1000 ml at a time, and efflux is allowed immediately. Usually 40 to 50 l are lavaged over three hours until the efflux is clear. The procedure is repeated for the other lung after two to three days [3].

Leakage of fluid into the ventilated lung is a feared complication and is recognised by desaturation, fluid in the lumen of the ventilated lung and air bubbles in the lavage efflux. This mandates stopping lavage, placing the patient in the lateral decubitus position with the lavaged side down, suctioning out both lungs and rechecking double-lumen tube position.

Physiological lung separation

ILV has been used in a broad range of asymmetric lung diseases. Asymmetric parenchymal lung diseases [4,27,34], post-operative management of single lung transplant complications [1], bronchopleural fistulas [53,55] and unilateral bronchospasm following pleurodesis [56] are examples. Its role in acute bilateral lung injury remains unproven.

Asymmetric parenchymal lung disease

Asymmetric parenchymal lung diseases such as pulmonary contusion [34] and aspiration [4] change the compliance of one lung compared to the other. When supported with conventional ventilation, most of the tidal volume is diverted to the normal, more compliant lung, which will be disproportionately distended [57]. This can cause barotrauma and divert perfusion towards the abnormal side [58]. The application of bilateral PEEP with conventional ventilation may also be inadequate for alveolar recruitment in the diseased lung and, simultaneously, excessive in the normal lung, causing hyperinflation.

ILV allows independent ventilator strategies. Initial volumes of 4 to 5 ml/kg per lung can be used and this can then be adjusted according to target plateau pressures [34]. Furthermore, selective PEEP to improve recruitment in the diseased lung without overinflating the normal lung can be applied. Preferential PEEP can be adjusted to gas exchange parameters or mean airway pressures. ILV can eventually be discontinued safely when the tidal volumes and compliance of the lungs differ by less than 100 ml and 20% [34].

Single lung transplant

In single lung transplant, the management of pulmonary graft dysfunction, acute rejection, surgical pulmonary contusion and acute respiratory distress syndrome can all be managed with ILV rather than emergency re-transplantation [59]. Post-operative management of single lung transplant patients is similar to ventilating asymmetric parenchymal lung diseases because the compliance of the transplanted lung differs from the native lung. The relative compliance depends on both the insults to the transplanted lung as well as the underlying pulmonary pathology. Compliance of the native lung is higher in emphysema and lower in pulmonary fibrosis. ILV with selective PEEP to the transplanted lung will protect the native lung from hyperinflation. It is estimated that 12% of single lung transplants for COPD may have indications for ILV post-operatively [1]. Risk factors that may predict need for ILV post-single lung transplant for COPD include severity of underlying airway obstruction, peri-operative injury to the donor lung and size of donor lung [60].

Bronchopleural fistula

Intercostal drainage with an adequate suction device prevents tension pneumothorax development in bronchopleural fistulas. Subsequently, positive pressure ventilation and negative pressure from the chest tube suction will delay healing of the fistula site [4]. Decreasing the fistula air leak and maintaining adequate oxygenation are the conflicting needs of conventional ventilation. When this fails, ILV is a therapeutic alternative [4,6,55]. After double-lumen tube intubation, the fistula side is ventilated with the lowest possible tidal volume, respiratory rate, PEEP and inspiratory time to minimise air leak [55]. An alternative is to use high frequency jet ventilation on the fistula side with conventional ventilation on the normal side [53].

Unilateral airway obstruction

When ILV is employed in unilateral obstructive airway diseases, the affected side is ventilated with a low respiratory rate, low tidal volume and prolonged expiratory time to prevent the accumulation of intrinsic PEEP while the unaffected side is supported with conventional ventilator settings [56].

Acute bilateral lung disease

Acute bilateral lung disease remains a controversial indication for the use of ILV. Successful use has been reported in acute respiratory distress syndrome [5]. ILV can be combined with placement of the patient in the lateral decubitus position and application of selective PEEP to the dependent side. Preferential PEEP should recruit alveoli in the better-perfused dependent side while diverting perfusion to the better-ventilated non-dependent side. Although there are some data on improvement in gas exchange with ILV in bilateral lung disease, outcome data are still lacking [61,62].

Conclusion

ILV is usually instituted as rescue therapy when the fraction of inspired oxygen and PEEP have been already optimised in conventional ventilation without success in asymmetric or unilateral lung disease. Prevention of contamination of the unaffected lung by secretions or blood may involve endobronchial blockade or selective double-lumen tube ventilation. Physiological lung separation is used when mechanics and ventilation/perfusion ratios are very different between the two lungs. In such instances, application of uniform ventilatory support, such as PEEP, inspiratory flow rate, respiratory rate and tidal volume, may be injurious to one lung even if beneficial to the other.

The limitation of the current data is that they are confined to case reports and series with no prospective, systematic investigations in the intensive care unit available. Positive outcome bias is the concern with this retrospective data. The more extensive thoracic anaesthesia experience suggests that despite its potential complications, OLV can be safely instituted on a short term basis. There is also evidence to show that gas exchange and ventilatory targets can be met with ILV. Outcome and mortality data are lacking, however, and this remains an area for future clinical research.

Any decision to institute ILV must account for the expertise required in double-lumen tube/endobronchial blocker

insertion, skilled and intensive nursing, specialised monitoring and ready availability of fibreoptic bronchoscopy [4]. Complications associated with ILV are usually related to either double-lumen tube intubation or endobronchial blocker placement or the inadvertent loss of functional separation. These technical requirements and potential complications must be carefully weighed against any perceived benefits before proceeding with ILV.

Competing interests

The author(s) declare that they have no competing interests.

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