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One-Lung Ventilation

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Summary

One-lung ventilation is a major component of anaesthesiologic management for thoracic surgery and is achieved either by endobronchial placement of a double-lumen tube or through utilisation of a bronchus blocker. The indications for one-lung ventilation not only include lung surgery but also other surgical interventions involving thoracic structures or less common patient-specific factors. Double-lumen tubes and bronchus blockers constitute the technical basis of lung separation. The anaesthesiologist must have proven knowledge of the tracheobronchial anatomy including the segmental bronchi; routine use of flexible fibreoptic bronchoscopy is equally essential. This review article provides fundamental recommendations with respect to everyday clinical routine.

Introduction

Anaesthesia for thoracic surgery is characterised by the requirement for specialised knowledge, techniques and competency in airway management, one-lung ventilation and the handling of cardiopulmonary comorbidities. The high rate of postoperative pulmonary complications reinforces those prerequisites.

This manuscript aspires to present methods, provide practical assistance and illustrate specific recommendations aimed at ensuring patient safety.

Lung separation utilising one-lung or independent lung ventilation is indicated for most cases of **thoracic surgery,** but also for **surgery on thoracic structures** (e.g., the oesophagus, aorta or spine). Lung separation optimises surgical conditions by providing for unilateral **complete atelectasis.** In less common cases, separation is indicated to avoid aspiration of infectious material or blood from one lung to the other, or to enable adequate ventilation of the contralateral lung in the presence of large bronchopleural fistula (Tabl. 1).

The **pathophysiology of gas exchange during OLV** is determined in the same way as during normal bilateral ventilation by the proximity of blood and gaseous components required for diffusion. An efficient exchange of oxygen and carbon dioxide is dependent on the regional ratio of ventilation to perfusion (V/Q ratio). A large spectrum of principally "alveoli related" V/Q conditions exists at the extremes of the V/Q ratio, i.e., for dead space ventilation (approx. 2 ml/kg; V/Q ratio = ∞) and shunt (V/Q ratio = 0).

Which form of airway management is recommended and indicated for lung separation and OLV?

Modern double-lumen tubes (DLT) permit selective collapse of one lung and ventilation of the other. Separation can also be achieved using a bronchus blocker or Univent™ tube.

Table 1
Indications for one-lung ventilation.

surgical	patient-related
lung parenchyma: segmental resection, lobectomy, pneumonectomy, sleeve resection, lung transplantation	protection of the contra-lateral lung from infection (pulmonary abscess) or blood
intrathoracic surgery: thoracoscopy, oesophageal resection, anterior spinal surgery, thoracic aortic aneurysms, thymectomy, diaphragm surgery, pectus excavatum surgery	improvement on ventilation and oxygenation for bronchopleural fistulae and unilateral pulmonary pathology (bullae, cysts)

The asymmetry of the tracheobronchial anatomy is reflected in the design of right-sided and left-sided DLT. The DLT is forked and has both a bronchial and a tracheal lumen, with the latter opening distal to the tracheal cuff (Fig. 1). These tubes are offered by various companies in sizes 26 Fr, 28 Fr, 32 Fr, 35 Fr, 37 Fr, 39 Fr and 41 Fr (Fr = outer diameter in "French"; Tab. 2). The **left-sided DLT** is the most commonly used (Fig. 1, left), whilst the **right-sided DLT** incorporates an additional opening slot which permits for ventilation of the right upper lobe (Fig. 1, right). Placing the right-sided DLT is more difficult and use is reserved for special indications such as resections close to the hilum. With regard to correct positioning, the right-sided DLT is characterised by a reduced safety profile when compared directly to the left-sided DLT. The **DLT is also available with an optical sensor or integrated camera,** which aims to make for easier positioning and provide continuous visual monitoring of the correct position (Fig. 2, centre). The same model utilises a type of valve mechanism for achieving separation and atelectasis without clamping (Fig. 2, right). **Double-lumen tracheostomy tubes** are also available for use in patients who have previously undergone tracheostomy.

Figure 1

design of commercial left- and right-sided double-lumen tubes; the lower images depict (from left to right) the Medtronic® left and right bronchial tubes, and the Rüsch® left and right bronchial tubes (modified from [2]). Observe the colourcoding of the bronchial lumen. In general, DLT come pre-equipped with a flexible stylet which is withdrawn following successful laryngoscopy and passage through the vocal cords.

Verification of the correct position using flexible fibreoptic bronchoscopy is strictly required. Renewed verification must take place following positioning of the patient (Fig. 3).

In those cases where the patient requires post-operative ventilation, it is recommended that the DLT ist not be left in situ, but that the patient is instead reintubated with a standard single lumen tube.

A bronchus blocker may be passed through or next to an endotracheal tube and permits selective isolation of a main or lobar bronchus. 4 different models are available (Fig. 4 and Tab. 1): the **Arndt blocker, Cohen blocker, Uniblocker and EZ-blocker**. These differ in their materials, placement and lumina.

Indications for lung separation using a DLT or bronchus blocker are summarised in Table 1. The following general considerations are relevant when choosing specific airway devices:

- Is the intervention intrathoracic or extrathoracic?
- Which sections of the respiratory tract, and especially which proximal (tracheal or bronchial) sections may be involved in the intervention?
- If lung surgery is being performed, is it to be peripheral or central?
- Is surgery being undertaken on the left or the right hemithorax?
- What is the patient's size?
- Which relevant comorbidities does the patient suffer from?
- Have appropriate (functional pulmonary) evaluation and diagnostics (e.g., spirometry, stair-climbing test, spiroergometry, perfusion scintigraphic imaging) been performed and are the results complete?
- Is the airway difficult?
- Is use of a left-sided or right-sided tube intended?
- Which size of tube or bronchus blocker is appropriate?

Table 2

Size recommendations for double-lumen tubes [2].

females		males	
height in cm	**DLT in Fr**	**height in cm**	**DLT in Fr**
<150	32	<160	35–37
150–160	35	160–170	37
>160	35–37	>170	37–39
>180	39	>180	41
tracheal diameter measured in mm		**DLT in Fr**	
=12,5		32	
=14		35	
=15		35	
=16		37–39	
=18		39–41	

DLT: double-lumen; **Fr:** French.

Figure 2

Design of a double-lumen tube with an integrated optical sensor used to confirm positioning.

With regard to DLT and bronchus blockers there is no evidence for superiority of one or the other device when used for lung separation for thoracic surgery.

Criteria examined when comparing the devices were

- time required for and ease of placement,
- rate of dislocation,
- quality of atelectasis,
- extent of airway trauma and
- cost.

In many places, the DLT is considered to be the gold standard. In particular, dislocation during resections in close proximity to the bronchus, repeat transitions from atelectasis to ventilation to aid in the identification of parenchymal fistulae and secretion retention in patients with pulmonary disease are more easily and rapidly managed with a DLT. The utility of bronchus blockers as an alternative has, however, been demonstrated, even if these devices are not routinely used due to their high cost.

The **indications for bronchus blockers** are predominantly patient related. They are:

- children under the age of 8 years [1]
- emergencies, patients who are intubated, have undergone tracheostomy or are at risk of aspiration
- patients with a difficult airway

Absolute and relative **indications for the use of a right-sided DLT** are:

- left-sided pneumonectomy
- left-sided single-lung transplantation
- left-sided endobronchial pathologies (e.g., tumours, compression, rupture)
- left-sided upper lobe sleeve resection

When OLV cannot be established due to **failure of the lung to collapse**, the following steps should be undertaken:

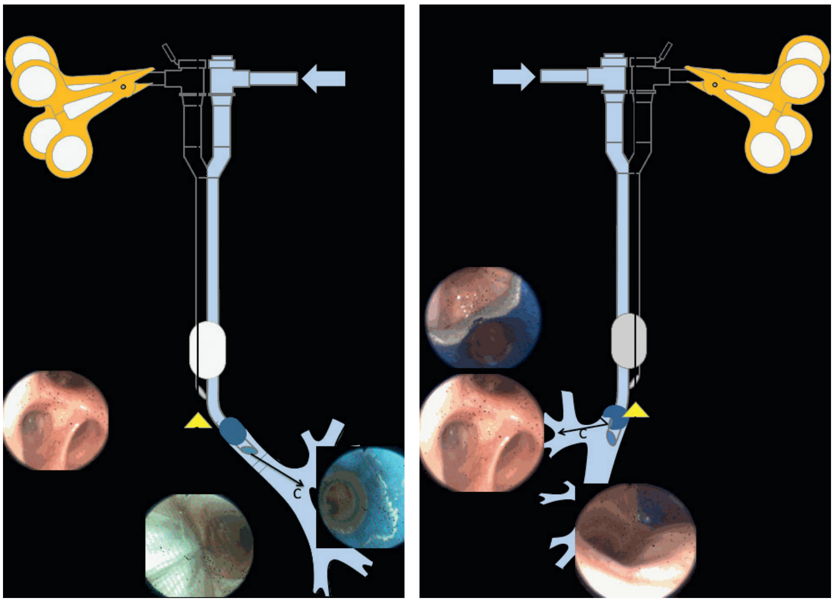
- fibreoptic verification of the position and repositioning of the DLT or bronchus blocker if required
- endobronchial suctioning of air and secretions from the non-ventilated lung
- if necessary, leaving suction in situ until pneumothorax has been established to avoid passive aspiration of nitrogenous ambient air and persistent expansion of the lung.

Which pathophysiologic changes take place during OLV?

Outline

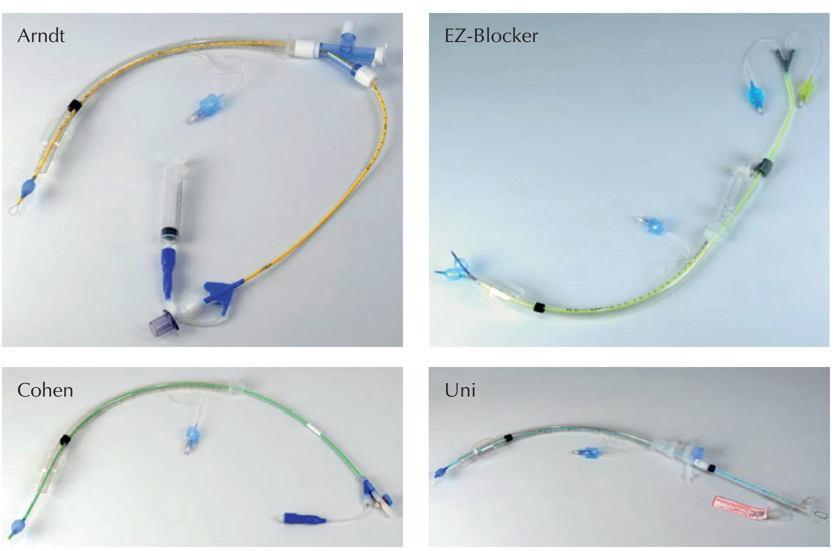
The risk of impaired gas exchange with an increased incidence of hypoxaemia during OLV has reached a level of below 5% [4]. Optimisation of the methods of lung separation (e.g., fibreoptic verification of correct positioning, design of DLTs, modified ventilation strategies etc.) and a better understanding of the pathophysiology of OLV have contributed to a declining incidence.

Figure 3



fibreoptic verification of the position of a left-sided (image left) and right-sided (image right) double-lumen tube.

Figure 4



Types of bronchus blockers (modified from [3]).

Conditions and factors influencing **gas exchange** during thoracic surgery and OLV are:

- intraoperative lateral position of the patient and gravity [5,6]
- (partial) opening of the thoracic cavity
- the side from which surgical access is gained (right-sided surgery) [7,8]
- ventilation of the dependent lung
- general anaesthesia with mechanical ventilation and paralysis [9]
- hypoxic pulmonary vasoconstriction [10]

The efficacy of normal gas exchange is substantially impaired by OLV. The partial pressure of oxygen p_aO_2 for an F_iO_2 of 1.0 decreases from over 400 mmHg to around 100 – 150 mmHg once OLV is established. This decrease is caused by an intrapulmonary shunt in the non-ventilated (main effect) and a **V/Q mismatch with shunting** in the ventilated lung. Due to **complete atelectasis** (ventilation = 0), any blood flow to the non-ventilated lung is rated as a shunt, albeit that the fraction of cardiac output to that lung is reduced from 50% to approx. 25% with a degree of individual variability. That reduction is mainly caused by **hypoxic pulmonary vasoconstriction** together with the effects of gravity and any impairments to perfusion caused by pathologies (e.g., tumours) [10]. Further factors influencing blood flow and with that shunting are surgical manipulation and pharmacologic substances. The aforementioned physiological changes lead to an **increase in perfusion** of the ventilated lung (approx. 75% of cardiac output) whilst the pulmonary arterial pressure remains unchanged. The V/Q ratio, however, is significantly heterogenic with some areas showing low V/Q ratios and shunting. Lateral position, anaesthesia, an elevated diaphragm and the weight of mediastinal organs all reduce the functional residual capacity (FRC) of the lungs, leading to an inclination to develop **dystelectasis** and **atelectasis** but also to **overdistention** of lung segments. The risk of atelectasis increases with higher F_iO_2. Other factors such as PEEP, recruitment manoeuvres, pre-existing pulmonary disease and ventilator settings all also influence the V/Q ratio [11].

What is the pathophysiologic mechanism behind hypoxic pulmonary vasoconstriction?

Hypoxic pulmonary vasoconstriction is a regional (pulmonary) change in blood flow in smaller sections of the pulmonary arterial vascular bed aimed at optimising the V/Q ratio and reducing shunt by up to 40% [10,12,13]. The change is primarily triggered by a low alveolar pO_2 whilst low mixed venous pO_2 is a secondary

Table 3
Bronchus blocker characteristics.

Characteristic	Arndt	Cohen	Uni	EZ
size in French (Fr)	5; 7; 9	9	5; 9	7
balloon	spherical	pear-shaped	spherical	globular
cuff volume in ml	5 Fr: 0.5–2 7 Fr: 2–6 9 Fr: 4–8	5–8	5 Fr: 0.5–2 9 Fr: 5–8	<10
cuff type	high volume low pressure	high volume low pressure	high volume low pressure	high volume low pressure
positioning mechanism	nylon loop	tip-deflecting wheel	pre-angled tip	distal Y-piece
minimum tube diameter in mm	5 Fr: 4.7 7 Fr: 7 9 Fr: 8	8	8	7.5
lumen in mm	5 Fr: 0,7 7 Fr, 9 Fr: 1.4	1,6	5 Fr: no lumen 9 Fr: 2.0	0.7

mechanism [10]. Systemic vasodilators (e.g., volatile anaesthetics) exert an unfavourable influence on hypoxic pulmonary vasoconstriction, which in turn is enhanced by vasoconstrictors.

How is respiratory gas exchange affected during OLV? [13]

A good number of factors and variables promote hypoxaemia during OLV. Patients suffering from relevant pulmonary pathology of the ventilated lung, such as

- pleural effusion,
- pneumonia,
- interstitial lung disease,
- oedema,
- bronchospasm or
- other restrictive changes

are at an increased risk of hypoxaemia during OLV. Right-sided surgical pulmonary interventions, high cardiac output and partial respiratory failure are further predictors of hypoxaemia. Conversely, overdistention caused by intrinsic PEEP puts patients with chronic obstructive lung disease at a lesser risk during OLV.

Which anaesthesiologic measures are helpful during OLV?

General considerations

Postoperative acute lung injury (ALI) following lung surgery has been described to occur at a rate of 4.3% and is associated with a significantly higher risk of mortality when compared with ALI following abdominal surgery [14].

Anaesthesiologic management during OLV should be based on strategies which both include **lung protective ventilation** (e.g., avoidance of volutrauma and barotrauma) and aim to **optimise oxygenation.** The following passages, Fig. 5 and Table 4 depict individual aspects in detail and summarise them.

If hypoxaemia occurs during OLV, a structured algorithm – which starts by considering and excluding the most common causes – should be triggered:

Stage 1:

- fibreoptic verification of the position of the DLT or bronchus blocker and correction if required
- bronchial toilet
- F_iO_2 of 1.0
- recruitment manoeuvre on the ventilated lung
- increase PEEP on ventilated lung

Stage 2:

- apply CPAP (continuous positive airway pressure) to non-ventilated lung
- establish ventilation of both lungs
- reduce blood flow in pulmonary artery by surgical means
- jet ventilation of non-ventilated lung.

Implementation of the individual steps is contingent on the severity of hypoxaemia, dynamics of the situation, and the individual patient's state. Establishing ventilation of both lungs (following communication with the surgeon) is the fastest concept for restoring normal oxygenation, but interrupts surgery. **Fibreoptic verification of the position of the DLT** is mandatory, as is **toilet bronchoscopy** of the ventilated lung. When correctly performed (e.g., 3–5 seconds of an inspiratory pressure of 25–35 cmH_2O), and whilst any resulting haemodynamic impairment is treated, **recruitment manoeuvres** are helpful [15].

Despite the risk of **resorption atelectasis** due to the wash-out effect on nitrogen, an F_iO_2 of 0.8 to 1.0 provides a high level of patient safety. F_iO_2 can typically be reduced to 0.5 once OLV has been established and conditions are stable. Hyperoxaemia leads to formation of oxygen radicals and is disadvantageous.

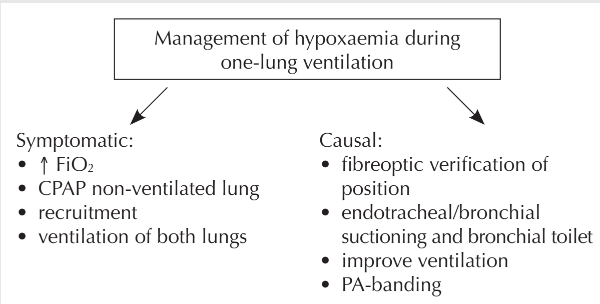
Applying CPAP to the non-ventilated lung has lost its clinical significance as the associated distension of the lung hampers surgical interventions – especially during video-assisted thoracoscopic surgery (VATS) – and could compromise the surgical outcome. Administration of pure oxygen following discreet recruitment via a CPAP system utilising a low pressure (3–8 cmH_2O) provides highly effective oxygenation. However, in the context of open **surgical decortication of the lung** for pleural empyema or in combination with pleurectomy, applying CPAP to the non-ventilated lung remains a mainstay, not only improving oxygenation in patients already suffering from poor gas exchange, but also aiding the surgeon in distinguishing between lung tissue, the pleura or pleural fibrosis.

Additional components of a lung-protective ventilation strategy

PEEP

Applying PEEP (positive end-expiratory pressure) to the ventilated lung can improve the V/Q ratio and oxygenation by preventing alveolar collapse and with that the occurrence of atelectasis. When

Figure 5



Structured algorithm for management of hypoxaemia during OLV.

CPAP: continuous positive airway pressure; **PA:** pulmonary artery.

Table 4

Anaesthesiologic lung-protective measures during OLV.

setting	rationale	open questions/problems
$F_iO_2 < 1.0$	atelectrauma ↓	critical value $F_iO_2 < 0.8$?
tidal volume < 6 ml/kg PBW or $P_{peak/plateau/driving}$ ↓	volutrauma/barotrauma ↓	ideal tidal volume?
PEEP ≥ 5 cmH_2O	oxygenation ↑	best-PEEP?
recruitment manoeuvre	oxygenation ↑	routine?
how?	Oxygenierung ↑	bei VATS schwierig
CPAP non-ventilated lung	oxygenation ↓	difficult during VATS
permissive hypercapnia	ALI ↓	critical value?
volatile anaesthetics	inflammation/ALI ↓	workplace exposure?

F_iO_2: fraction of inspired oxygen; **PBW:** predicted body weight; **PEEP:** positive end-expiratory pressure; **VATS:** video-assisted thoracoscopic surgery; **CPAP:** continuous positive airway pressure; **ALI:** acute lung injury.

the level of PEEP selected is too high, however, perfusion is redirected to the non-ventilated lung, increasing the shunt and impairing oxygenation. Optimum PEEP needs to be determined by titration on the basis of individual compliance of the respiratory system. As a rule, patients benefit from a PEEP > 5 cmH_2O to approximately 12 cmH_2O during OLV, especially in the presence of pre-existing restrictive pulmonary disease or obesity. Patients suffering from significant obstructive pulmonary disease, however, require lower levels of PEEP; the level of auto-PEEP should be detected to allow for complete expiration.

Combining low levels of PEEP (< 5 cmH_2O) with low tidal volumes (< 5 ml/kg) predisposes to poor aeration and development of atelectasis.

Tidal volume

A tidal volume of 5 – 6 ml/kg body weight during OLV, corresponding with the recommendations for lung-protective ventilation, generally results in sufficient ventilation and oxygenation [16]. It is perfectly feasible to practice **permissive hypercapnia** for a certain length of time during OLV. There are no explicit recommendations with regard to threshold values for pH or $paCO_2$ during permissive hypercapnia. The strategy should be avoided in patients requiring catecholamines or suffering from pulmonary hypertension.

Respiratory rate

The respiratory rate and ratio of inspiratory to expiratory time (I:E ratio) both also influence ventilation. High respiratory rates with a short expiratory phase entail a risk of **dynamic hyperinflation,** i.e., incomplete expiration through one lumen of the DLT. Patients suffering from obstructive pathology or undergoing left-sided ventilation via a left-sided DLT are at an increased risk.

Mode of ventilation

When selecting a ventilator mode for OLV, it is important to remember that **volume-controlled** ventilation (VCV) entails a pre-selected volume being applied at a constant flow. Conversely, **pressure-controlled ventilation** (PCV) involves a pre-selected pressure being applied with a decelerating flow and variable tidal volumes.

There is no evidence to suggest that VCV is superior to PCV. It has been shown, however, that oxygenation was better using PCV during OLV [17].

Advanced measures

Simple clamping of the pulmonary artery (or its divisions) by the surgeon reduces blood flow and with that shunting. Alternative methods, such as **high-frequency jet ventilation or insufflation of pure oxygen** via a catheter passed through the lumen of the DLT have effects and disadvantages comparable to use of a CPAP system.

Conclusion

The aim of one-lung ventilation necessitated by thoracic surgery is not only to provide for lung separation by means of advanced airway management, but also to prevent hypoxaemic events and ventilator-induced lung injury. Knowledge of lung-protective ventilation and its surrogate parameters tidal volume, F_iO_2, PEEP and respiratory rate helps expand the appreciation of the pathophysiology of OLV. Anaesthesiologists must master routine algorithms used in the management of hypoxaemic situations.

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