Chapter 1

Basic physiology for thoracic anaesthesia

Abnormalities in the distribution of Q and V, diffusion of gases and hypoxic pulmonary vasoconstriction
Normal pulmonary ventilation and perfusion
One lung ventilation and the lateral decubitus position
Abnormalities in the distribution of Q and V, diffusion of gases and hypoxic pulmonary vasoconstriction

Introduction

- Much of the physiological effects of OLV are due to changes in ventilation and perfusion matching.
- The ratio of pulmonary ventilation to pulmonary blood flow (V/Q) for the whole lung at rest is about 0.8:
  - Alveolar ventilation 4 L/min; pulmonary blood flow 5l/min.
- There are regional differences in the ventilation-perfusion ratio within the normal lung parenchyma.
- Differences can largely be explained by the effect of gravity on blood flow and alveolar compliance.
- V/Q mismatching leads to impairment in the transfer of gases between alveolar space and blood stream within the lung.
- Local changes in the V/Q ratio are very common in disease states.
- Although hypoventilation, diffusion abnormalities and shunts can all contribute to the development of hypoxemia in patients ventilated via one lung, understanding V/Q mismatching is central to the understanding of hypoxaemia and the necessary steps to correct it.

Factors affecting V/Q ratio in thoracic anaesthesia

- One lung ventilation.
- Lateral decubitus position.
- Hypoxic pulmonary vasoconstriction (HPV).
- Attenuation of HPV response by volatile agents.
- Ventilation strategies during OLV.
- Cardiac output.
- Surgical technique.
- Chest wall compliance.
- Lung disease.

Clinical relevance

- One-lung ventilation should still provide the ability to oxygenate the entire cardiac output.
- The role of the thoracic anaesthetist is to identify factors contributing to the impaired gas exchange and then corrected them in a stepwise manner from major to more minor.
ABNORMALITIES IN THE DISTRIBUTION OF Q AND V

One lung ventilation

The non ventilated lung
- The non-ventilated lung is perfused but, obviously, not ventilated.
- Surgical manipulation and hypoxic pulmonary vasoconstriction reduce what might otherwise be a substantial right-to-left shunt.

The ventilated lung
- In the lateral position, gravity usually ensures preferential perfusion of the dependent lung. (Increased shunt seen during OLV in the supine position as this gravity effect is not present).
- The alveolar compliance curve is shifted down and to the left for alveolar in the dependent lung. Abnormal V/Q ratios result. Alveolar collapse results in atelectasis.
- Without an increase in FiO₂ hypoxaemia will occur.
- Due to greater solubility of carbon dioxide and its more linear dissociation curve, PaCO₂ is less affected by V/Q mismatch.

Lateral positioning of the patient
Upper lung now lies on the steep part of the compliance curve and the lower lung on the flatter part.

The non-dependent lung
- The upper lung receives a smaller percentage of the blood flow as a result of gravity.
- The upper lung now lies on the steep part of the compliance curve and thus receives a greater percentage of the ventilation.

The dependent lung
- The lower lung receives a greater percentage of the cardiac output as a result of gravity.
- The lower lung now lies on flat part of the compliance curve and thus receives a lower percentage of the ventilation.
- Malpositioning of a DLT in the dependent lung can further impair gas exchange eg misplaced right DLT resulting in the exclusion of the right upper lobe from ventilation.

Hypoxic pulmonary vasoconstriction (HPV)
- This important regulatory mechanism diverts blood flow away from hypoxic to better oxygenated areas of the lung.
- When changing from two-lung ventilation to OLV, HPV diverts blood flow from the non-ventilated to the ventilated lung, thereby reducing venous admixture and ameliorating the decrease in PaO₂.
- It involves the constriction of small arterioles (and to a lesser degree, venules and capillaries) in response to alveolar hypoxia.
- HPV occurs with seconds, reaches an initial plateau after 15 minutes but the maximum effect only occurs after about 4 hours.
- Alveolar (PaO₂) is the primary stimulus (80%) to HPV although mixed venous PvO₂ also exerts an effect (See Table 1.1 for other factors).
- The effect occurs in the physiological range (PaO₂ 5.5–13kPa) and is mediated in part via inhibition of nitric oxide synthesis.
CHAPTER 1  Physiology for thoracic anaesthesia

- HPV reduces the blood flow through the non ventilated lung by about 40%, some blood flow remains.
  - This is why insufflation of 100% O₂ into this lung via a catheter/CPAP circuit is effective in reducing hypoxia.
- HPV is more efficient if pulmonary artery pressure and mixed venous oxygen saturation are normal; very high and very low values greatly reduce the effect of HPV.
- Hypocapnia reduces HPV, potentially leading to an increase in shunt.

Volatile anaesthetic agents

- HPV is inhibited by all volatile anesthetics.
- In theory this would allow a right to left shunt causing venous admixture and hypoxaemia. However, clinically this does not happen because:
  - Degree of HPV is inversely proportional to cardiac output. Volatile agents inhibit HPV directly but also indirectly augment it by decreasing cardiac output.
  - Inhalational agents are bronchodilators. This will cause more uniform ventilation in the dependent lung and improve V/Q matching.
  - Haemodynamic stability and ventilation strategies are far more important than choice of anaesthetic to maintain oxygenation.
  - The relative effect in humans in vivo is: Halothane > enflurane > isoflurane and sevoflurane > desflurane.
  - IV anesthetic techniques have not been shown to provide better oxygenation than the newer volatile anesthetics in <1MAC concentrations.
- Reduction in HPV may occur due to the direct vasodilatory effects of volatiles.
- Glyceryl trinitrate, sodium nitroprusside, isoprenaline, dobutamine and nitric oxide have also been shown to inhibit HPV.
ABNORMALITIES IN THE DISTRIBUTION OF Q AND V

Ventilation strategies during OLV

- Applying high peak inspiratory pressure and high end-expiratory pressure pressures to the ventilated lung can increase pulmonary vascular resistance, divert blood flow to the non-ventilated lung and decrease the cardiac output. Oxygen delivery may be impaired.
- In contrast, particularly in the relatively normal lung, modest PEEP can improve the compliance of the dependent lung, improve oxygenation and improve oxygen delivery.
- There is the potential, particularly in patients with severe COPD for PEEP, excessive ventilation or short expiratory times to lead to incomplete expiration with the "breath stacking" causing increased airway pressure. It may be necessary to accept a degree of hypoventilation in some patients with severe COPD.

### Table 1.1 Factors affecting HPV

<table>
<thead>
<tr>
<th>Category</th>
<th>Effect</th>
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<tbody>
<tr>
<td><strong>Anaesthetic agents—inhaled</strong></td>
<td>All inhaled agents inhibit HPV but have a minimal clinical effect at levels of 1 MAC.</td>
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<tr>
<td></td>
<td>1 MAC of isoflurane reduces HPV by 21%, increasing the shunt fraction from 20% to 24%.</td>
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<tr>
<td></td>
<td>N2O reduces HPV by approximately 10%.</td>
</tr>
<tr>
<td><strong>Anaesthetic agents—intravenous</strong></td>
<td>Propofol, Thiopentone, Fentanyl, Remifentanil &amp; Ketamine have no effect on HPV.</td>
</tr>
<tr>
<td><strong>Anaesthesia—regional</strong></td>
<td>Thoracic epidural anaesthesia has no significant effect on PVR and may enhance HPV.</td>
</tr>
<tr>
<td><strong>Vasodilators</strong></td>
<td>GTN, β agonists, nitroprusside, nitric oxide, calcium channel antagonists, prostacyclin &amp; dobutamine all inhibit HPV.</td>
</tr>
<tr>
<td></td>
<td>Aminophylline and hydralazine have only minimal effects.</td>
</tr>
<tr>
<td><strong>Vasoconstrictors</strong></td>
<td>Norepinephrine, epinephrine and phenylephrine constrict blood vessels in the ventilated lung, diverting blood flow to the non-ventilated lung, thereby having a HPV inhibiting effect.</td>
</tr>
<tr>
<td><strong>Oxygen</strong></td>
<td>Increasing the inspired oxygen concentration to the dependent lung decreases pulmonary vascular resistance and increases pulmonary blood flow to the ventilated lung.</td>
</tr>
<tr>
<td></td>
<td>HPV is maximal when the percentage of the lung that is hypoxic is between 30–70%.</td>
</tr>
<tr>
<td><strong>Carbon dioxide</strong></td>
<td>Hypercapnia during OLV tends to increase PVR by acting as a direct vasoconstrictor, thereby diverting blood flow to the non-ventilated lung. Hypocapnia directly inhibits HPV, through the development of a respiratory alkalosis.</td>
</tr>
<tr>
<td><strong>Acid-base balance</strong></td>
<td>Acute respiratory or metabolic alkalosis reduces the effect of HPV, whilst metabolic acidosis enhances HPV.</td>
</tr>
</tbody>
</table>
CHAPTER 1 Physiology for thoracic anaesthesia

- But the increases in PaCO₂ and decreases in pH may increase pulmonary artery pressure and thus potentially increase the V/Q mismatch.
- Pressure controlled ventilation is often the mode of choice during OLV.
- 5–7 ml/kg tidal volume, (ideal body weight), with inspiratory airway pressure limited to 25cm H₂O are useful initial parameters for OLV in the majority of patients.
- The high solubility of nitrous oxide may lead to increased dependent lung atelectasis.

Cardiac output
- A reduction in cardiac output will decrease the mixed venous PvO₂ and in the presence of a significant shunt decrease the PaO₂.
- Reduced perfusion to the dependent (ventilated) lung may increase V/Q mismatching in this lung.
- Overzealous infusion of crystalloids to improve the cardiac output may lead to impaired gas exchange in the ventilated lung (pulmonary oedema).
- Cardiac failure and RV dysfunction is common post-pneumonectomy (particularly after R pneumonectomy).
  - 2" to 1RV afterload as a result of size of pulmonary vasculature
  - DO₂ and/or PacO₂ further increases pulmonary arterial pressure via HPV.

Surgical technique
- Early ligation of the appropriate branch of the pulmonary artery to the operated lobe or lung will reduce/stop the shunt through the operated lung and improve oxygenation.
- Surgical manipulation can reduce venous return, cardiac contractility and cardiac output and thus impair oxygenation and oxygen delivery.
- Uncorrected bleeding may lead to impaired cardiac output, oxygenation and thus oxygen delivery.

Increased chest wall compliance
- Poor chest wall compliance will require an increase P_{insp} to achieve the necessary tidal volume.
- High P_{insp} may lead to an increased V/Q mismatch.
- Muscle relaxation results in upward movement of the abdominal contents, reducing the FRC of the ventilated lung.
- Conversely, poor muscle relaxation may lead to high airway pressures by a patient as the patient ‘fights’ the ventilator. Bronchospasm may be induced.

Lung disease
- The pathology of the patient may be a contributor to V/Q mismatch.
- Pathology (e.g. tumour) in the non-dependent lung may limit the perfusion to this lung. Thus paradoxically the shunt may be larger in patients without lung pathology undergoing OLV.
- Pulmonary fibrosis
- Oxygenation may be difficult due to a reduced diffusion capacity in the dependent lung.
- PE (discussed at length, see Pulmonary embolism, p. 664).

**Further reading**
Normal pulmonary ventilation and perfusion

Introduction

The thoracic anaesthesit requires a working knowledge of pulmonary ventilation and perfusion in order to anticipate, prevent and when necessary treat hypoxaemia during one lung anaesthesia. Thoracic surgery and anaesthesia alter normal pulmonary mechanics and perfusion in several ways:

- Lateral decubitus position.
- The open chest.
- One-lung ventilation.

Normal pulmonary ventilation (V)
- Ventilation—process by which gas reaches the alveoli with each breath.
- May be quantified as alveolar minute ventilation (VA ml/min). Thus:

\[ VA = (VT - VD) \times RR = \alpha \frac{VCO_2}{PaCO_2} \]

\[ VT = \text{Tidal volume (ml)} \]
\[ VD = \text{Dead Space (ml)} \]
\[ RR = \text{Respiratory rate (breaths/min)} \]
\[ VCO_2 = \text{CO}_2 \text{ production} \]

For example PaCO_2 will double if VA is halved and VCO_2 remains constant.

Regional differences in pulmonary ventilation
- Distribution of ventilation is affected by gravity and the resting volume of alveolar in different regions of the lung.

Table 1.2 Effect of patient position during spontaneous ventilation (in an awake subject), on the distribution of alveolar ventilation in a normal lung

<table>
<thead>
<tr>
<th>Patient position</th>
<th>Greater ventilation</th>
<th>Lesser ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>Lung base</td>
<td>Lung apex</td>
</tr>
<tr>
<td>Supine</td>
<td>Posterior lung</td>
<td>Anterior lung</td>
</tr>
<tr>
<td>Lateral decubitus</td>
<td>Dependent lung</td>
<td>Non-dependent lung</td>
</tr>
</tbody>
</table>


CHAPTER 1 **Physiology for thoracic anaesthesia**
Factors that impact on pulmonary ventilation

Dead space

- 2 ml/kg.
- Anatomical:
  - Measured using Fowler technique i.e. measurement of expired N₂.
  - Essentially measures volume of the conducting airways.
- Physiological:
  - Measured using Bohr equation:
    \[ \frac{V_\text{D}}{V_\text{T}} = \frac{P_\text{aCO}_2 - P_\text{ECO}_2}{P_\text{aCO}_2} \]
  - Essentially measures the volume of lung not involved in gas exchange i.e. does not eliminate CO₂.
- In normal subjects, anatomical and physiological dead spaces are almost identical.
- In lung disease, physiological dead space may be greatly increased e.g. chronic obstructive lung disease. \( V_A \) will be decreased.

Respiratory system compliance

\[ \frac{8V}{6P} \]

- Represented by the slope of the p-v curve for the respiratory system.
- Two components:
  - Lung compliance (C_L).
  - Chest wall compliance (C_W).
- Respiratory system compliance (C_R):
  \[ \frac{1}{C_R} = \frac{1}{C_L} + \frac{1}{C_W} = 100 \text{ ml/100 cm H}_2\text{O} \]
- At the extremes of the p-v curve. Thus greater pressures are required for alveolar ventilation.
- \( \uparrow \) in:
  - Pulmonary emphysema.
  - Non-dependent lung during one-lung ventilation.
CHAPTER 1 Physiology for thoracic anaesthesia

- Decreased in:
  - Dependent lung during one-lung ventilation,
  - Elderly patient,
  - Reduced surfactant,
  - Pulmonary fibrosis,
  - Pulmonary oedema,
  - Pulmonary atelectasis e.g. 2nd hypoventilation,
  - ARDS.

Airway resistance
- Predominantly occurs at the medium-sized bronchi.
- As resistance increases, greater pressures are required to ventilate the alveoli.
  - Resistance:
    - Low lung volumes e.g. dependent lung during one-lung ventilation.
    - Bronchospasm.
    - Upper & lower airway obstruction e.g. foreign body/tumour/extrinsic compression.
    - Anaesthesia i.e. decreased FRC.

Normal pulmonary perfusion (Q)
- Low pressure and resistance system.
- ~80% lower than pressures within the systemic circulation.
- Pulmonary artery pressure (PAP) = 25/8 mmHg.
- Mean PAP = 15 mmHg.
- Two components:
  - Pulmonary arteries perfuse the parenchyma distal to the respiratory bronchiole i.e. the alveolar involved in gas exchange.
  - Bronchial arteries (1% of CO) perfuse the lung tissue proximal to the respiratory bronchiole (conducting airways). Their origin is variable but usually from the aorta or intercostal arteries. Contributes to anatomical shunt.
- R output slightly less than L output due to bronchial circulation.

Factors that impact on pulmonary circulation
Pulmonary vascular resistance (PVR)
- 10 times less than systemic vascular resistance.
- 1.7 mmHg/L/min.
- Pulmonary factors that alter PVR:
  - Recruitment of closed or underperfused pulmonary capillaries with rising arterial or venous pressure decreases PVR.
  - Distension of perfused pulmonary capillaries with rising arterial or venous pressure decreases PVR.
NORMAL PULMONARY VENTILATION AND PERFUSION

- At low or high lung volumes PVR increases due to collapse of extra-alveolar vessels and stretching of pulmonary capillaries respectively.
- Acute or chronic lung disease may cause raised PVR and resultant right ventricular failure.
- Positive pressure ventilation may increase PVR when alveolar pressure exceeds that within the pulmonary capillaries, causing them to collapse.
- Low pH raises PVR.
- Drugs that alter PVR:
  - Prostacyclin & nitric oxide both reduce PVR.
  - Vasodilators e.g. serotonin, norepinephrine, histamine all reduce regional pulmonary vascular resistance in normoxic lung.

Distribution of pulmonary blood flow
- Blood flow is increased to dependent areas of lung, e.g. basal flow is greater than apical flow in the upright lung.
- This is explained by considering the upright lung as 3 zones:
  - Apical zone: $PA > Pa > PV$, blood flow is absent. Under normal conditions this does not occur. However, it may occur in severe hemorrhage or during positive pressure ventilation.
  - Mid zone: $Pa > PA > PV$, blood flow is dependent on the arterio-alveolar pressure difference.
  - Basal zone: $Pa > PV > PA$, blood flow is dependent on the usual arterio-venous pressure difference.
- In the basal zone, increases in blood flow occur by recruitment and distension of pulmonary capillaries.
- At low lung volumes, collapse of extra-alveolar vessels due to atelectasis causes a reduction in blood flow.
- During exercise, the mid and apical zones behave more like the basal zone.

Hypoxic pulmonary vasoconstriction
(See Abnormalities of Q and V, the diffusion of gases and hypoxic pulmonary vasoconstriction, p. 2).

Ventilation-perfusion matching (V/Q)
To ensure adequate gas exchange it is important to match perfusion and ventilation in the alveoli. (See Fig. 1.1).
The ideal V/Q relationship equally matches ventilation and perfusion.

- V/Q increases towards the lung apex.
  - ↑ V/Q = High $P_{a}O_{2}$ & low $P_{a}CO_{2}$ (apex).
  - ↓ V/Q = Low $P_{a}O_{2}$ & high $P_{a}CO_{2}$ (base).
- Note that the change in $P_{a}CO_{2}$ associated with changes in V/Q matching is much less than the change in $P_{a}O_{2}$.
- The regional differences in V/Q matching give rise to an alveolar-arterial $O_{2}$ difference = 4 mm Hg in normality.
- Increased V/Q mismatch in disease may give rise to:
  - Hypoxaemia and/or hypercarbia.
  - Increased alveolar-arterial difference.
  - Increased shunt fraction.
  - Increased physiological dead space.

Further reading
CHAPTER 1  Physiology for thoracic anaesthesia

One lung ventilation and the lateral decubitus position

Upon moving the anaesthetized patient from the supine to the lateral decubitus position there are numerous changes to the ventilation and perfusion of both lungs, both before and after the thoracic cavity is opened.

Closed chest

Ventilation

- After induction of general anaesthesia both lungs take up lower positions on the pressure-volume curve (See Fig. 1.1).
- The dependent (bottom) lung falls onto the lower, flatter portion of the pressure-volume curve, with a subsequent decrease in FRC and compliance. This is caused by compression of the dependent lung by:
  - Cephalic movements of the abdominal contents, pushing on the paralysed hemi-diaphragm,
  - The weight of the mediastinal contents,
  - Placing the patient in a jack-knife or flexed position.
- The non-dependent (top) lung is now on the steep part of the pressure-volume curve, with an improved FRC and compliance, and is therefore preferentially ventilated.
- Gravity has no effect on the distribution of ventilation during IPPV.

Perfusion

- In the lateral decubitus position, blood flow is primarily determined by gravity with 60% going to the dependent lung.
- The net result is the production of a V/Q mismatch.

Open chest

Ventilation

- Upon opening the thoracic cavity, the differential ventilation between the lungs becomes more pronounced.
- As the non-dependent lung is no longer restricted by the chest wall, its compliance increases. This results in a further increase in ventilation of the non-dependent lung at the expense of the dependent lung.
- Compression of the dependent lung also results in areas of atelectasis, producing a degree of shunt.

Perfusion

- Blood flow remains unchanged with the majority still going to the dependent lung.
- This results in the dependent lung being poorly ventilated but well perfused, and the non-dependent lung, well ventilated but poorly perfused.
- This combination of V/Q mismatching and shunt produces an increase in the alveolar-arterial oxygen gradient and impaired oxygenation.
ONE LUNG VENTILATION AND THE LATERAL DECUBITUS POSITION

Collapse of the non-dependent lung

Ventilation
- After the institution of one lung ventilation (OLV), the non-dependent lung is no longer directly ventilated.
- This produces an obligatory shunt through this lung, in addition to any existing shunt in the dependent lung.
- A tidal ventilation of approximately 150 ml does occur in the non-dependent lung as a result of the transmitted pressure changes from the ventilated hemithorax.
- The compliance of this lung however, is markedly reduced due to direct pressure from surgical retraction and handling.

During OLV PaCO$_2$ is affected to a lesser extent than PaO$_2$. Blood flowing through the non-ventilated lung will carry a larger amount of CO$_2$. Due to the linear shape of the CO$_2$ dissociation curve, this is offset by the blood flowing through ventilated alveoli releasing a greater amount of CO$_2$. This compensation is not complete and a gradual increase in end-tidal CO$_2$ occurs.

Perfusion
- The collapse of the non-dependent lung would be expected to produce a shunt fraction of 40–60% (depending on whether it is the left or right lung that is collapsed), which could not be rectified by an increase in the FiO$_2$.
- Blood flow however is reduced in the non-dependent lung by several mechanisms, thereby reducing the degree of shunt (discussed below).

Pulmonary vascular resistance (PVR)

Hypoxic pulmonary vasoconstriction (HPV) (See Abnormalities of Q and V, the diffusion of gases and hypoxic pulmonary vasoconstriction, p. 2).

PEEP
- + The addition of positive end expiratory pressure to the dependent, ventilated lung results in an increase in the pulmonary vascular resistance of the lung
- + The addition of PEEP may improve lung compliance and prevent atelectasis thereby preventing increases in PVR in the dependent lung
- - This may result in the diversion of blood to the non-ventilated lung and may worsen the shunt.
CHAPTER 1 Physiology for thoracic anaesthesia

Lung volumes
- During positive pressure ventilation PVR is lowest at FRC.
- At lung volumes above FRC, PVR increases due to the excess stretching of the capillaries and at low lung volumes PVR increases due to the loss of traction holding capillaries open.
- Thus ventilation of the dependent lung with high airway pressures may increase PVR and divert blood flow to the non-ventilated lung.

Cardiac output
Variations in cardiac output either affect HPV via changes in the pulmonary artery pressure or mixed venous oxygen saturation.
- High cardiac output—may attenuate HPV via directly increasing pulmonary artery pressure and increasing blood flow to the non-ventilated lung, or by an increase in mixed venous oxygen saturation inhibiting PVR by reverse diffusion of oxygen.
- Low cardiac output—will also attenuate HPV. Low cardiac outputs produce a decrease in the mixed venous oxygen partial pressure and thus a decrease in the alveolar oxygen tension in the dependent lung. This results in an increase in HPV in the dependent lung that offsets the HPV in the non-dependent lung. The net result is that less blood flow is diverted away from the more hypoxic collapsed lung.
- Balanced anaesthesia (usually consisting of general and epidural anaesthesia) can result in lower than normal cardiac output. In this situation, increasing the cardiac output back to normal levels will result in an improvement in the mixed venous oxygen saturation, thereby improving arterial oxygen saturations. This occurs despite a small increase in the amount of blood diverted to the non-ventilated lung by the increased pulmonary artery pressure.

Non-dependent lung effects
- The collapse of the non-dependent lung, in tandem with surgical handling, retraction and vessel ligation, causes a direct mechanical obstruction to blood flow through the lung.
- In addition, the underlying pathology of the operative lung may have already caused a reduction in lung blood flow prior to the collapse of the lung.