Section 1 Pre-operative considerations

1. Thoracic anatomy
DAVID MORRICE

2. Respiratory physiology
CAIT P. SEARL

3. Respiratory pharmacology
CAIT P. SEARL

4. Respiratory diseases
CAIT P. SEARL

5. Pre-operative assessment of the thoracic surgical patient
SION BARNARD AND DOUGLAS AITCHISON

6. Lung isolation
DAVID PLACE

7. Management of one-lung ventilation
LEENA PARDESHI AND IAN CONACHER

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Excerpt
More information

Chapter 1

Thoracic anatomy

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The knowledge of certain aspects of thoracic anatomical arrangements is of great importance to the thoracic anesthetist. It assists in the correct positioning of endobronchial tubes, the identification of diseased lobes, in an understanding of the proposed surgery and also the potential complications that might occur. The availability of computerized tomography (CT) also means that the anesthetist can utilize this to his/her advantage in predicting difficulties in major cases. However, to interpret these, an understanding of normal anatomy is a prerequisite.

Tracheal, bronchial, lobar division

The course and division of the airway is readily seen on flexible and rigid bronchoscopy.

Trachea

This conduit for air and exhaled gases arises from the lower border of the larynx at approximately the level of cervical vertebra C6. The trachea descends in line with the vertebra and moves slightly to the right and posteriorly in doing so. It consists of 16–20 C-shaped cartilaginous rings that provide a semi-rigid structure. Posteriorly the longitudinal trachealis muscle (non-striated) completes the tube structure. This muscle layer has the appearance of a flowing river and provides an easy landmark to orientation when performing a fiberoptic bronchoscopy. Bifurcation occurs at the level of thoracic vertebra T4. Thus the average length of the trachea in an adult male is 15 cm. The usual anterioposterior diameter is 20 mm.

Throughout its course the esophagus lies directly behind the trachea, with the recurrent laryngeal nerves lying in the groove in between. In the upper (extra thoracic) trachea, the isthmus of the thyroid overlies the trachea anteriorly with the thyroid lobes lying laterally. The relations of the trachea are shown in Figure 1.1. Moving down into the thoracic cavity the thymus overlies the trachea not far below the sternal notch, and below this are arterial vessels arising from the aorta below. These are from right to left, the brachiocephalic artery, left carotid, and below this the ascending aorta arches in front of the trachea, giving in addition to the above the left common carotid and subclavian arteries. During mediastinoscopy the brachiocephalic artery may be compressed by the rigid bronchoscope, affecting the blood supply to the right arm. The medial aspect of the right upper lobe lies against the trachea. The recurrent laryngeal nerves innervate the upper trachea.

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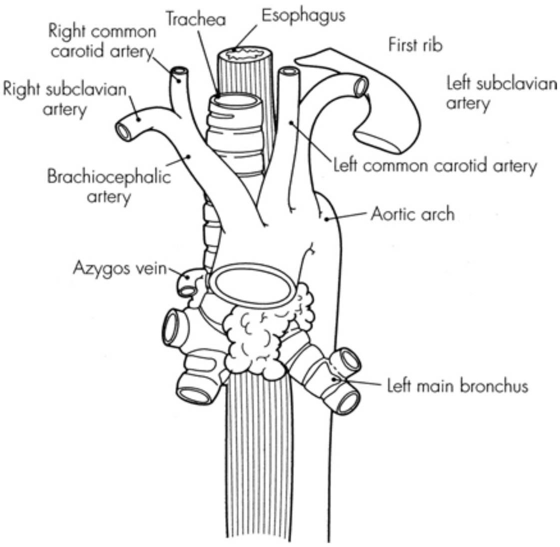

Figure 1.1 The relations of the trachea.

The bronchi and bronchial tree

The bronchial tree with its divisions is illustrated in Figure 1.2.

The carina and surrounding structures

The last tracheal ring is larger and wider than the others, forming a sharp sagittal ridge called the carina (Latin for the keel of a boat). The carina marks the bifurcation into right and left bronchi. Several important tracheobronchial lymph nodes lie within close proximity and tumor spread to these nodes may blunt the sharp edge of the carina. In addition mediastinoscopy to biopsy these nodes will reveal the intimate relations of the pulmonary artery, aorta and branches and superior vena cava. The pulmonary artery is particularly at risk of injury during this procedure.

Right and left bronchi

The right main bronchus compared to the left is shorter and descends more vertically, i.e. at 25° compared to 45°. This leads to a tendency for endobronchial tubes to favor entry to the right. It ends

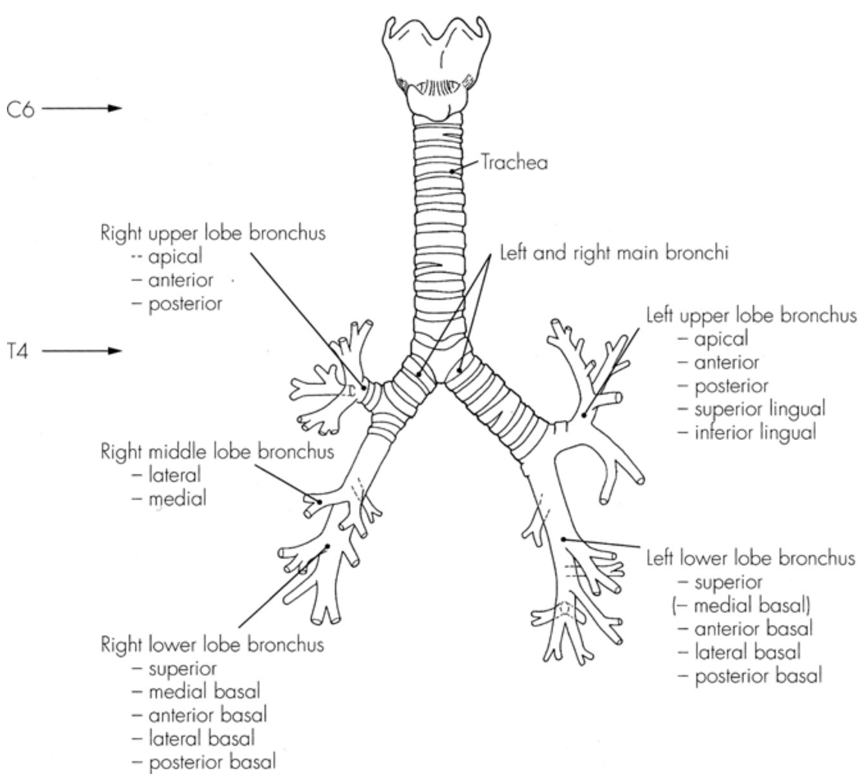

Figure 1.2 The bronchial tree.

when the right upper lobe orifice branches out after 2.5 cm. This lobe consists of three segments (apical, anterior and posterior).

The right upper lobe orifice is directed at 90° from the right main bronchus and may need some bronchoscopic maneuvering to visualize. The apical segment is directed vertically (the other two horizontally); hence on a "slice" of CT it appears as a small well-defined circle. This can be used to aid the localization of tumors within the lungs. Occasionally this lobe may arise higher, even from the trachea.

Following this first division the main bronchus continues as the bronchus intermedius for 3 cm until the middle lobe branches in a direction medially and downwards. Two segments are contained in the medial lobe (lateral and medial) which both project horizontally. This medial lobe is anteriorly placed and wedged between the anterior segment of the upper lobe and the anterior basal segment of the lower lobe.

Thereafter the main bronchus supplies the lower lobe. First to branch off horizontally, opposite the medial lobe orifice, is the apical segment of the lower lobe, worth mentioning because it is directed posteriorly. It is thus prone to collecting secretions in the supine patient. Four further branches are made in a downward direction, all to basal segments of the lower lobe. Thus the right medial lobe and apical portion of the right lower lobe divide at a similar level and appear as a row of three orifices, sometimes being referred to as the secondary carina.

On the **left side** the bronchial divisions supply the left upper lobe, lingula and lower lobe. At about 5 cm from the carina, the upper lobe bronchus branches to supply both the upper lobe and the lingula. The upper lobe bronchus is 1 cm long and supplies apical, anterior and posterior segments. The upper lobe is difficult to inspect due to its vertical take off and the anterior and posterior segments are also vertically orientated. The lingular orifice appears more in line with the left main bronchus (i.e. obliquely), and its bronchus is 2–3 cm long. It divides into two segments, superior and inferior, which also head in an oblique direction. In a similar fashion to the right middle lobe, the lingula is anteriorly placed and wedged between anterior segments of the left upper and lower lobes. The left lower lobe bronchus is directed downwards with division firstly into an apical segment arising from the posterior wall and directed horizontally. Below this the bronchus heads vertically downwards and divides into anterior, lateral and posterior basal branches.

Importance of bronchopulmonary segments

There are 20 segments as described above and each can be considered as being discrete physiologically functional units, as each segment has its own separate arterial supply, and venous and lymphatic drainage. The divisions are further illustrated in Figure 1.3. In the case of a lobectomy e.g. for neoplasia the surgeon will have to ensure correct isolation of each of these vessel types to avoid venous congestion or ischemia of other parts of the lung. As a rule each segment is pyramidal shaped and will receive a single branch of the pulmonary artery to perfuse the alveoli. These follow the course of the bronchi, and the division into bronchioles. The bronchus for each segment divides about 15 times into terminal bronchioles. Blood from each segment is drained by intersegmental veins that lie in the connective tissue around the segment, which generally leads to a single branch from each segment. However, the right upper lobe often has additional draining branches of the pulmonary vein. Lymphatics tend to closely follow the course of the bronchi. These drain into tracheobronchial lymph nodes located at the bifurcation of the larger bronchi.

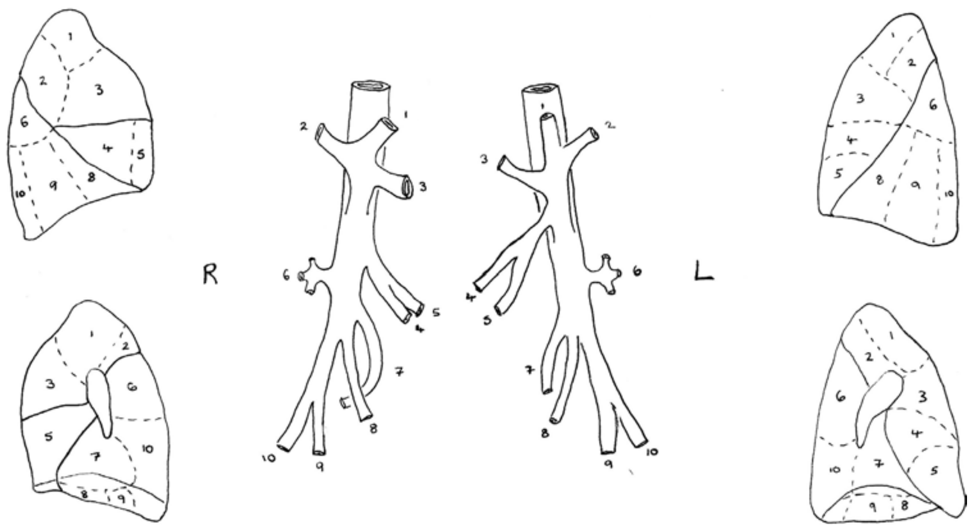

Figure 1.3 The bronchopulmonary segments.

Alveolar units

The terminal bronchioles further divide into respiratory bronchioles from which alveoli arise, finally ending in sacs of alveoli. Deoxygenated blood from the tissues is pumped forward from the right heart via the pulmonary arteries and intrasegmental branches to the fine capilliary beds around the alveolar sacs. Here, as described elsewhere, O_2 and CO_2 gas exchange occurs. Thereafter oxygenated blood drains into the pulmonary vein system, which collects in the intersegmental septa and drains ultimately into the left atrium.

Bronchial arteries

These smaller vessels supply the stroma of the lung including the bronchi, pleura and nodes. They follow the posterior aspect of the bronchi as they divide. There are usually two left bronchial arteries arising from the descending thoracic aorta and a right arising variably from the aorta or intercostal arteries. Bronchial veins drain only the more proximal bronchial divisions and may be susceptible to compression by edema as they cross the bronchial wall.

The hilum

The structures that enter the lung are the pulmonary arteries, veins, the primary bronchi, pulmonary nerve plexi and bronchial arteries. Where these structures enter and leave the lung is termed the hilum.

The pleura

Each pleural sac is a closed cavity lined by a serous membrane invaginated by a lung. The outer wall of the chest is lined by the parietal pleura while the visceral pleura cover the lung. The layers of pleura are continuous around the root of the lung. The parietal pleura lines the ribs, costal cartilages and the intercostal spaces, extending superiorly beyond the thoracic inlet to form the cervical dome of pleura. Inferiorly it forms a narrow gutter around the margin of the diaphragm, the costodiaphragmatic recess, and similarly anteriorly in front of the heart, the left costal and mediastinal surfaces are in contact forming the costomediastinal recess. The pleura is supplied by blood from the tissues it covers. The visceral pleura has no pain fibers but the parietal pleura has a rich nerve supply from nerves in adjacent tissues. The lymphatic drainage of the visceral pleura is to a superficial plexus in the lung and then to hilar nodes, and the parietal pleura drains to parasternal, diaphragmatic and posterior mediastinal nodes.

The paravertebral space

The borders of the thoracic paravertebral space are imprecise. It is a wedge-shaped space with its base being formed by the lateral surface of the vertebral body and intervertebral foramen. It is thought that the prevertebral fascia and anterior longitudinal ligament usually form a barrier to communication to the contralateral paravertebral space, breached only by lymphatic channels. The posterior wall is formed by the inner surface of the vertebral transverse process, the neck of the rib and the attached superior costotransverse ligament. The lateral boundary is formed by the ribs and internal intercostal muscles. The anterior wall is the parietal pleura.

The diaphragm

The diaphragm is a musculotendinous septum separating the thoracic and abdominal cavities. It consists of a peripheral muscular part attached to the edges of a central trilobed tendon (see Figure 1.4). The peripheral muscular part is divisible into three sections by its attachments:

1. Sternal part – from the back of the xiphoid process by two muscular slips.
2. Costal part – from the inner surfaces of the lower six ribs and costal cartilages, interdigitating with transverse abdominis.
3. Vertebral part – from the sides of the bodies of the upper lumbar vertebrae by two crura and from the medial and lateral arcuate ligaments on each side. The right crus is attached to the bodies of the first three vertebrae and the left crus to the first two. The larger right crus passes forwards and to the right surrounding the esophageal opening. The medial arcuate ligament is the thickened upper edge of the psoas fascia and passes from the body of the first lumbar vertebra to its transverse process. The lateral arcuate ligament is anterior to quadratus lumborum passing from the transverse process of the 1st lumbar vertebra to the 12th rib.

The two halves of the diaphragm are supplied by the corresponding phrenic nerves. The periphery also receives additional sensory branches from

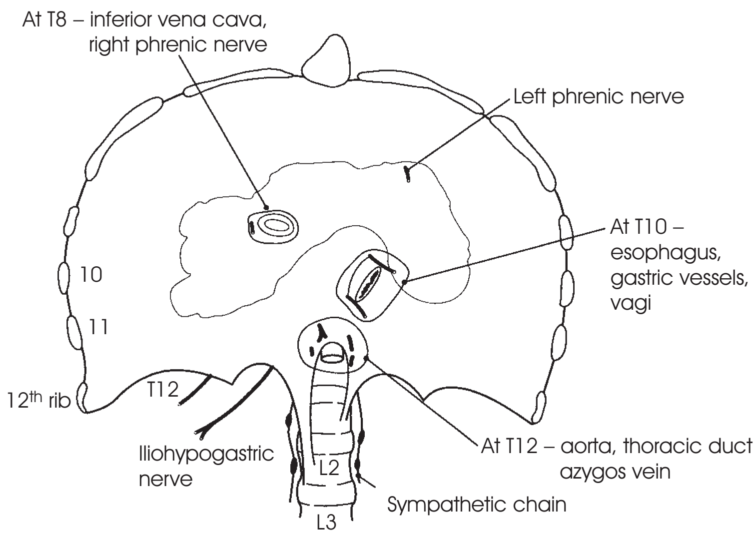

Figure 1.4 The diaphragm.

intercostal nerves. There are three large openings in the diaphragm from before forwards: for the inferior vena cava (with the right phrenic nerve) in the central tendon to the right of the midline at the level of the 8th thoracic vertebra; for the esophagus at the level of T10 as above (with branches of the vagus nerve and esophageal branches of the left gastric vessels); and for the aorta, between the crura of the diaphragm in front of T12. This also transmits the thoracic duct and azygous vein. The left phrenic nerve pierces the left dome of the diaphragm.

FURTHER READING

- Erdmann A. *Concise Anatomy for Anaesthetists*. Cambridge: Cambridge University Press, 2002.
- Cornley DM, Rosse C. *Interactive Atlas of Thoracic Viscera*. University of Washington, 1996, accessed at www9.biostr.washington-edu.

Chapter 2

Respiratory physiology

CAIT P. SEARL

The primary task of the lungs is respiration. Respiration is the exchange of gases between an organism and its environment with the utilization of O_2 and production of CO_2. In a multicellular organism such as man, diffusion pathways are too long for the rapid delivery of O_2 and removal of CO_2. The circulating blood provides a transport system to carry the respiratory gases between the lungs and the distant cells. Oxygen in the inspired air reaches the pulmonary alveoli (ventilation) where it diffuses into the blood whereas CO_2 diffuses in the opposite direction.

Respiratory mechanics

Bulk flow of air in and out of the lungs is achieved by pressure gradients between the mouth and alveoli. These pressure gradients are achieved by movement outward and inwards of the chest creating changes in pleural pressure and hence alveolar pressure changes. When the gas is stationary alveolar and mouth pressures are the same and at atmospheric pressure. Whether the air is flowing or not, the pleural pressure is affected by the inward elastic recoil of the lungs.

Inspiration is an active process: muscular contraction increases the volume of the chest, the lungs expand and the intrapulmonary pressure in the alveoli falls so that the air flows into the lungs. During expiration the lungs and chest recoil to the positions they occupied at the beginning of inspiration. Expiration is largely passive. During quiet breathing, the diaphragm accounts for around 75% of the lung volume change by its contraction during inspiration and relaxation during expiration. The diaphragm by itself or the scalene and external intercostal muscles alone can maintain adequate ventilation at rest. Expiration is achieved by passive recoil but can be assisted by contraction of the abdominal muscles and the internal intercostal muscles.

Respiratory volumes

The volume in the lungs at maximal inspiration is the total lung capacity (TLC; approximately 6 liters). Its subcomponents are inspiratory reserve volume (IRV), tidal volume, expiratory reserve volume (ERV) and residual volume (RV). The first three comprise the vital capacity (VC) and the latter two comprise the functional residual capacity (FRC) (see Table 2.1 and Figure 2.1). These volumes and capacities increase with body size and are smaller in females. There is a reduction in elastic recoil of the lungs and stiffening of the chest wall with aging. This leads to a gradual increase in RV and FRC and a fall in VC with little change in TLC.

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Table 2.1 Lung volumes and capacities.

Ventilatory volumes	
Tidal volume (TV)	Amplitude of the oscillation in lung volume during quiet respiration, usually about 400–500 ml
Inspiratory reserve volume (IRV)	Maximum volume of air which can be inspired in excess of normal inspiration
Expiratory reserve volume (ERV)	Maximum volume of air which can be expired in excess of normal expiration
Residual volume (RV)	The volume of air remaining in the lungs after maximal expiration; RV = FRC − ERV
Lung capacities	
Total lung capacity	Represents the sum of all the ventilatory volumes plus the residual volume
Vital capacity (VC)	The sum of the ventilatory volumes; the volume of gas that is expelled from the lungs from peak inspiration to peak expiration
Functional residual capacity (FRC)	Volume of gas left in the lungs at the end of quiet expiration
Inspiratory capacity	Equals tidal volume plus inspiratory reserve volume

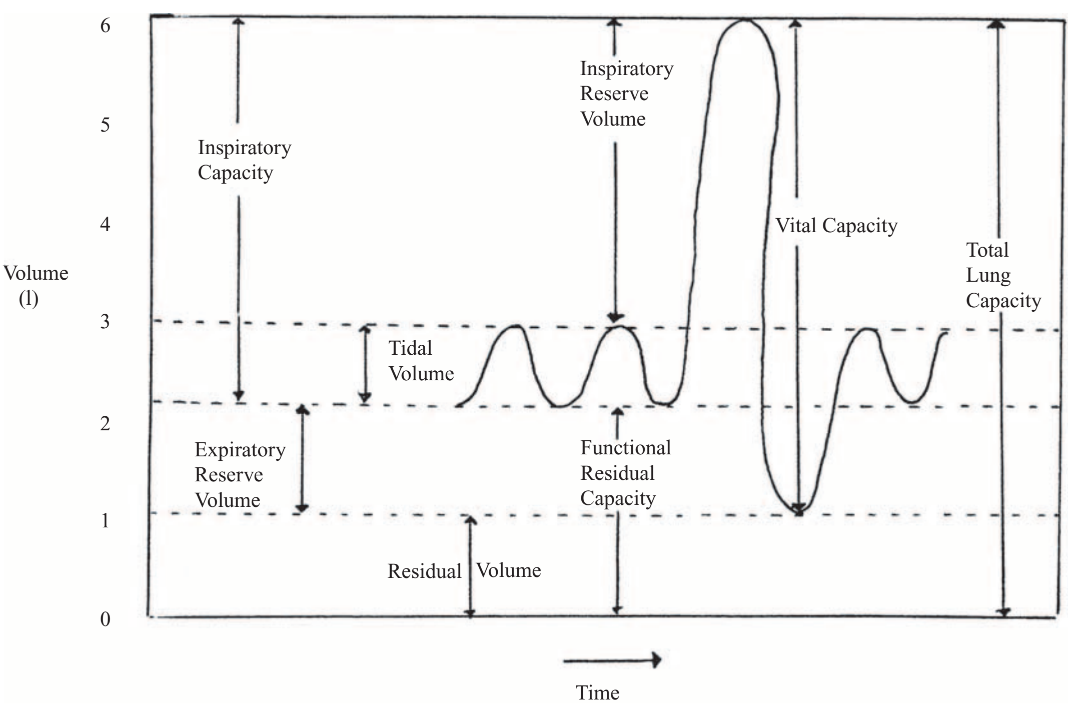

Figure 2.1 Lung volumes and capacities.

Lung compliance

Compliance is a measure of the difficulty of inflation of the lungs. It can be determined from the gradient of a plot of lung volume against distending pressure. This relationship demonstrates hysteresis but an average compliance can be determined using a linear interpolation (see Figure 2.2).

The most important physiological measure is the compliance of the intact respiratory system (i.e. the compliance of the lung and chest wall together). This is usually about 11 kPa^{-1} (100 ml/cm H_2O). This may be reduced by diseases of the lung such as pulmonary fibrosis or by abnormalities of the chest wall.

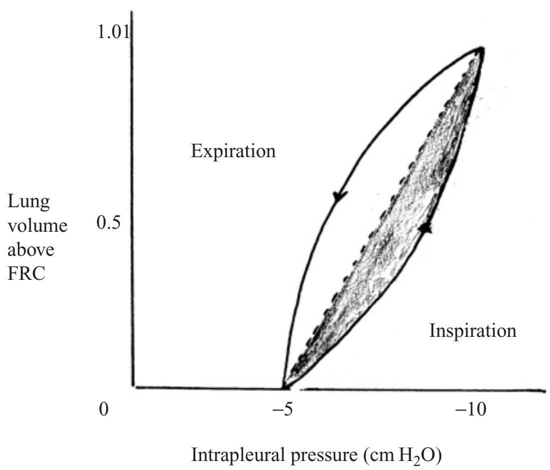

Figure 2.2 Compliance of the lungs.

Dead space

Gas exchange in the respiratory system only occurs in the alveoli. The part of the airway that does not participate in gas exchange is called the dead space. The total dead space consists of the "anatomical" dead space and the "physiological" dead space. The "anatomical" dead space consists of the mouth, nose, pharynx, trachea and main bronchi, and is equivalent to approximately 150 ml. The anatomical dead space functions as a conduit in which the air is filtered of dust particles, humidified and warmed. The functional dead space is normally equivalent to the anatomical dead space. If alveoli are ventilated but no gas exchange is taking place, then these contribute to the functional dead space. The volume of total dead space can be calculated from the CO_2 content of alveolar gas and the tidal volume using the Bohr equation (Box 2.1).

Box 2.1 The Bohr equation

$$V_D = \frac{V_T(F_{A}CO_2 - F_{E}CO_2)}{F_{A}CO_2}$$

Where

- V_D is the functional dead space
- V_T is the tidal volume
- F_ACO_2 is the fractional CO_2 concentration in the alveolar gas (can be determined from the terminal portion of air expired)
- F_ECO_2 is the fractional CO_2 concentration in the expired gas

Gas exchange in the lungs

The movement of O_2 and CO_2 in and out of the capillaries both in the lungs and in the peripheral tissues depends on gas diffusion. This in turn is affected by three main factors:

1. The partial pressure gradients of each gas.
2. The diffusion coefficient for each gas.
3. The physical properties of the tissues at the site of exchange (surface area, diffusion distances).

The lungs are well adapted for gas diffusion with a large alveolar surface area and a very thin layer of fluid and tissue separating alveolar gas from pulmonary blood.

Ventilation:perfusion ratio

Normal gas exchange requires both that the alveoli are adequately ventilated and that they are adequately perfused. This relationship is quantified by the alveolar:perfusion ratio, V/Q. V/Q = alveolar ventilation rate/pulmonary blood flow. When this deviates from normal, ventilation-perfusion mismatch occurs. If an area of the lung is inadequately ventilated but adequately perfused, V/Q will be reduced. Blood passing through such areas will be inadequately oxygenated reducing the partial pressure of O_2 in the systemic arterial blood: physiological shunting of blood. This is a major factor contributing to the abnormal blood gases seen in many respiratory diseases.

Pulmonary blood flow

Virtually all the cardiac output passes through the lungs, at arterial pressures of about one-sixth of systemic. The overall pulmonary blood volume is about 500 ml but only 80 ml is in the capillaries. Pulmonary vascular pressures are mainly influenced by gravity. When in the erect position,