Chapter 1

Physiology of ventilation and gas exchange

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Among its many functions, the lung has two major ones: it must harvest oxygen to fuel aerobic respiration and it must vent acid-forming carbon dioxide. This chapter will offer a brief overview of how the lung fulfills these functions. It will also discuss some of the mechanisms through which adequate oxygenation can fail. A secure understanding of these principles allows an insight into the way in which mechanical ventilation strategies can be altered in order to enhance oxygenation and carbon dioxide clearance.

Functional anatomy of the lung

The airways

During inspiration, air is drawn into the oropharynx through either the mouth or the nasal airway. Nasal breathing is preferred, as it is associated with enhanced particle removal (by nasal hairs and mucus-laden turbinates) and humidification. However, this route is associated with a fall in pharyngeal pressure. Just as Ohm's law dictates that voltage is the product of current and resistance, so pharyngeal pressure is the product of gas flow and pharyngeal resistance. A 'fat apron' around the pharynx because of obesity may lead to increased pharyngeal compliance, and thus increase the risk of dynamic pharyngeal collapse in such patients. In adults, when pharyngeal flows exceed 30 to 40 litres per minute, the work of breathing becomes high and the fall in pharyngeal pressure too great for the adequate intake of air: the mouth then becomes the preferred route for breathing.

The larynx remains a protector of the airway, with aryepiglottic and arytenoid muscles able to draw the laryngeal entrance closed like a purse-string and the epiglottis pulled down from above like a trap door. In addition, the arytenoid cartilages can swing inwards to appose the vocal cords themselves, thus offering an effective seal to the entry of particles or gases to the airway beneath. Meanwhile, tight occlusion can be achieved during swallowing or to 'fix' the thorax during heavy lifting, allowing the larynx to resist internal pressures of some 120 cm H_2O. Laryngeal sensitivity to irritation, causing a cough, makes the larynx effective at limiting entry of noxious gases or larger particles, while more intense chemoreceptor stimulation can cause severe laryngeal spasm, preventing any meaningful gas flow. In the anaesthetic room, this can be life-threatening.

When air enters the trachea, it is supported by anterior horse-shoes of cartilage (Figure 1.1). However, these are compliant, and tracheal collapse occurs with extrinsic pressures of only 40 cm H_2O. Ciliated columnar epithelium yields an upward-moving mucus 'escalator'. The trachea then divides into the right and left main bronchi (generation 1 airways), and then into lobar and

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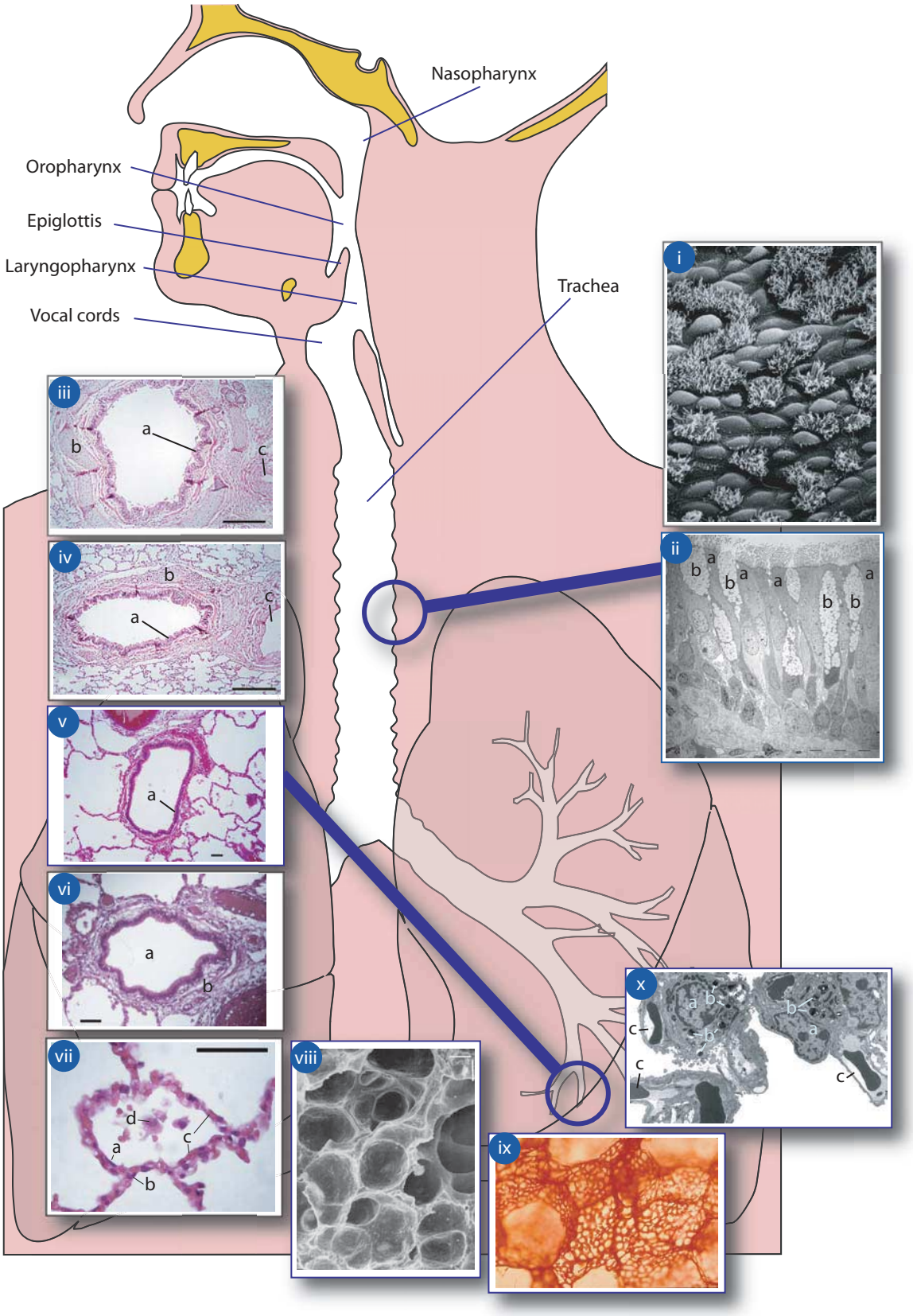

segmental bronchi (generations 2–4). The right main bronchus is wider and more vertical than the left, and is thus the 'preferred' path for inhaled foreign bodies. Cartilaginous horse-shoe supports in the upper airways give way to plates of cartilage lower down, but all will collapse when exposed to intrathoracic pressures of >50 cm H_2O (or less in situations in which the walls are diseased, such as in chronic obstructive pulmonary disease or bronchomalacia).

Successive division of bronchi (generations 5–11) yield ever-smaller airways (to about 1 mm diameter), all of which are surrounded by lymphatic and pulmonary arterial branch vessels. They are supported by their cartilaginous plates and rarely collapse because intra-bronchial pressure is nearly always positive. So long as there is patency between alveoli and bronchi, even forced expiration allows sufficient gas flow to maintain intra-bronchial pressures to a level above intrathoracic pressures.

Bronchioles (generations 12–16) lack cartilaginous support, but are held open by the elastic recoil of the attached lung parenchyma, making airway collapse more likely at lower lung volumes. The cross-sectional area of these very small distal airways, and their very thin walls, makes airway resistance at this level almost nil in the absence of contraction (bronchoconstriction) of the wall's smooth muscle cells. Subsequent respiratory bronchioles (generations 17–19) have increasing numbers of gas-exchanging alveolar sacs in their walls; these bronchioles are anchored open under tension from surrounding parenchyma. Each of 150 000 or so 'primary lobules' represents the distal airway subtended by a respiratory bronchiole. Distally (generation 20–22), alveolar duct walls give rise to some

Figure 1.1 Gross and microscopic anatomy of the respiratory tract.

Inset i: Conventional microscopy view of the surface of the ciliated epithelium of the trachea showing cells bearing cilia adjacent to cells which appear flat, but which in fact bear microvilli. Photomicrograph courtesy of the Ernest Orlando Lawrence Berkeley National Laboratory, California.

Inset ii: Transmission electron microscope image of a thin section cut through the bronchiolar epithelium of the lung showing ciliated columnar cells (a) interspersed by non-ciliated mucous-secreting (goblet) cells (b). Slide courtesy of Dr Susan Wilson, Histochemistry Research Unit, University of Southampton.

Inset iii: Section of bronchus lined with pseudo-stratified columnar epithelium (a), and surrounded by a ring of hyaline cartilage (b). The presence of sero-mucous glands (c) differentiates this from a bronchiole. This section also contains an arteriole (d). Bar = 250 microns. Slide reproduced with permission. Copyright © Department of Anatomy and Cell Biology, University of Kansas.

Inset iv: Tiny islands of hyaline cartilage (a) confirm that this is bronchus rather than bronchiole, and adjacent is a pulmonary vein (b). Bar = 250 microns. Slide reproduced with permission. Copyright © Department of Anatomy and Cell Biology, University of Kansas.

Inset v: The absence of cartilage and sero-mucous glands means that this is a bronchiole, with a surrounding cuff of smooth muscle (a). Bar = 25 microns. Slide courtesy of Dr Susan Wilson, Histochemistry Research Unit, University of Southampton.

Inset vi: A small bronchiole (a) surrounded by smooth muscle (b). Bar = 25 microns. Slide courtesy of Dr Susan Wilson, Histochemistry Research Unit, University of Southampton.

Inset vii: An alveolus lined by thin flat type I pneumocytes (a) and cuboidal, surfactant-secreting type II pneumocytes (b), with an integral network of fine capillaries (c) embedded within the alveolar walls. The lumen of the alveolus contains a large alveolar macrophage (d). Bar = 25 microns. Slide courtesy of Dr Susan Wilson, Histochemistry Research Unit, University of Southampton.

Inset viii: Scanning electron microscope image of the alveolar honeycomb. Photomicrograph courtesy of the Ernest Orlando Lawrence Berkeley National Laboratory, California.

Inset ix: This photomicrograph shows the fine network of capillaries that enmesh the alveoli.

Inset x: Transmission electron microscopic image of alveolar cells, showing large cuboidal type II pneumocytes (a) packed with vesicles containing surfactant (b). Nearby alveolar capillaries containing red blood cells can be seen (c). Photomicrograph courtesy of the Rippel Electron Microscope Facility, Dartmouth College, New Hampshire.

20 alveolar sacs, containing one third of all alveolar gas. The terminal alveolar sacs (generation 23) are blind-ending.

The Alveoli and Their Blood Supply

Each lung may contain up to half a billion alveoli, which are compressed by the weight of overlying lung and are thus progressively smaller in a vertical gradient. Alveolar gas can pass between adjacent alveoli through small holes called 'the pores of Kohn'. The pulmonary capillaries form a rich network enveloping the alveoli, with the alveolar epithelium closely apposed to the capillary endothelium. The other surface of the capillary is embedded in the septal matrix.

Blood delivered into the pulmonary arteries from the right ventricle flows at a pressure less than 20% of that of the systemic circulation. With near identical blood flows, one can infer that pulmonary vascular resistance is correspondingly five- to sixfold lower than systemic. Working at lower pressure, the pulmonary arterial wall is correspondingly thinner, while the pulmonary arteriolar wall contains virtually no smooth muscle cells at all. Capillaries in dependent areas of the lung tend to be better filled than areas higher up (due again to gravitational effects), while lung inflation compresses the capillary bed and increases effective resistance to blood flow. Blood flows across several alveolar units before passing into pulmonary venules and thence to the pulmonary veins.

Pulmonary mechanics

Air enters the lung in response to the generation of a negative[1] intrathoracic pressure (in normal ventilation, or in negative pressure and cuirass mechanical ventilation), or to the application of a positive airway pressure (in positive pressure ventilation modes). Work is thus performed in overcoming both resistance to gas flow and elastic tension in the lung tissue during the thoracic expansion of inspiration. A small quantity of energy is also dissipated in overcoming lung inertia and by the friction of lung deformation.

Elasticity and the lung

The lung's elasticity derives from elastin fibres of the lung parenchyma, which accounts for perhaps one third of elastic recoil, and from the surface tension of the fluid film lining the alveoli. When fully collapsed,[2] the resting volume of the lung is considerably smaller than the volume it occupies when fully expanded in the chest cavity. Fully expanded, the elasticity of the lungs generates a subatmospheric pressure in the pleural space of about -5.5 cm H_2O (Figure 1.2). At peak inspiration, when the thoracic cage is maximally expanded, this pressure may fall to nearly -30 cm H_2O.

It is worth giving some thought to the issue of surface tension forces within the lung. The pressure within a truly spherical alveolus (P_A) would normally be calculated as twice the surface tension (T_s) divided by the alveolar radius (r):

$$P_A = \frac{2 \times T_s}{r}. \qquad (1.1)$$

This equation tells us that if surface tension were constant, the alveolar pressure would be inversely proportional to the alveolar radius. In other words, alveolar pressure would be higher in alveoli with a smaller radius (Figure 1.3). If this were the case, it would mean that smaller alveoli would rapidly empty their gaseous content into larger adjacent alveoli and collapse. Taken to its logical conclusion, all of the alveoli in a lung would empty into one huge alveolus.

Fortunately, surface tension is *not* constant because of the presence of a mixture of phospholipids[3] and proteins[4] that floats on the surface of

[1] Also referred to as *subatmospheric*.

[2] For example, when removed from the chest at autopsy.

[3] Mainly phosphatidylcholine, commonly referred to as *lecithin*.

[4] Surfactant proteins A to D, often referred to as *SP-A*, *SP-B*, etc.

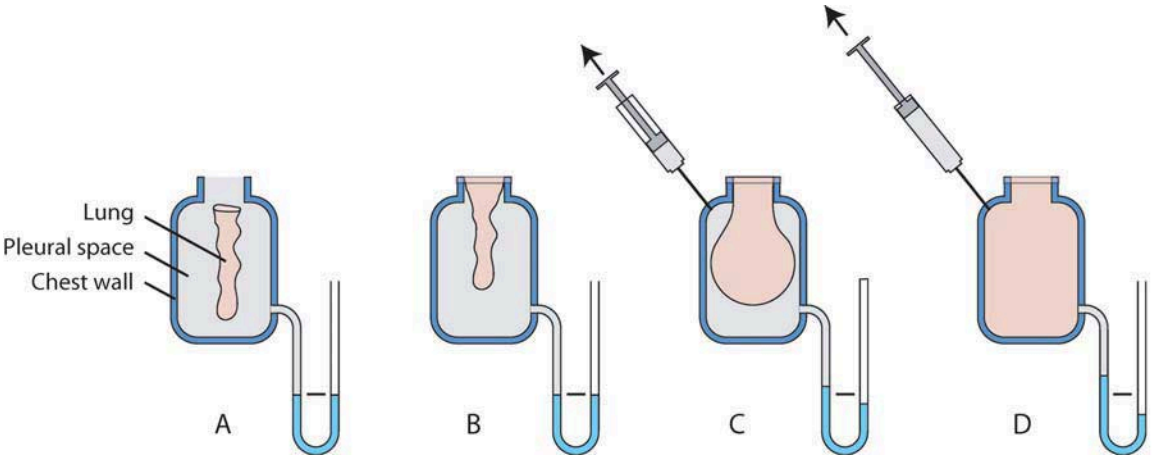

Figure 1.2 Negative pleural pressure.

A: The respiratory system can be compared to a rubber balloon (the lungs) placed inside a glass jar (the chest cavity) with the space between the outside of the balloon and the inside of the jar representing the pleural space.

B: The opening of the glass jar is sealed over by the rubber balloon, sealing the space between the outside of the balloon and the inside of the jar from the atmosphere.

C: As residual gas in this space is evacuated the pressure in the 'pleural space' drops below atmospheric and the balloon expands.

D: Once all the gas in the 'pleural space' is evacuated the 'lung' is completely expanded to fill the 'chest cavity'. The pressure inside the 'lung' remains atmospheric while the pressure in the pleural space is subatmospheric (negative).

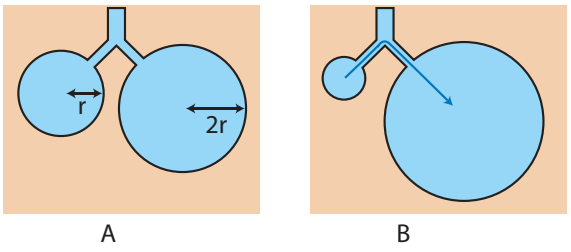

Figure 1.3 Alveolar instability with constant surface tension.

A: With constant surface tension (T_s), the alveolar pressure in the smaller alveolus is $\frac{2\times T_s}{r}$ and the pressure in the larger alveolus is $\frac{2\times T_s}{2r}$, which means that whatever the values of T_s and r, the pressure is only half that in the larger alveolus.

B: Under these circumstances, gas flows from the smaller alveolus (higher pressure) to the larger alveolus (lower pressure).

the fluid lining the alveoli (the surfactant; see Figure 1.4), which reduces the surface tension *in proportion to the change in the surface area*: the smaller the surface area of the alveolus, the greater the reduction in surface tension. This means that gas in fact tends to flow from larger to smaller alveoli, producing homogeneity of alveolar volume and stabilizing the lung. One other major advantage of this effect on fluid surface tension is that the lung's compliance is significantly increased, reducing the negative pressure generated by the lung in the pleural space. This consequently reduces the hydrostatic pressure gradient between the inside of the pulmonary capillaries and the pulmonary interstitium, minimizing the rate at which intravascular fluid is drawn from the capillaries. Lack of surfactant, for instance in intensive care patients with acute lung injury, thus tends to cause alveolar collapse and reduce lung compliance, which substantially increases the work of breathing.

As the chest expands during inspiration, intra-alveolar pressure falls to little more than −1 cm H_2O, causing the air to flow down a pressure gradient from the nose and mouth to the alveoli. It is notable just how modest the intra-alveolar pressures have to be to cause gas to flow in and

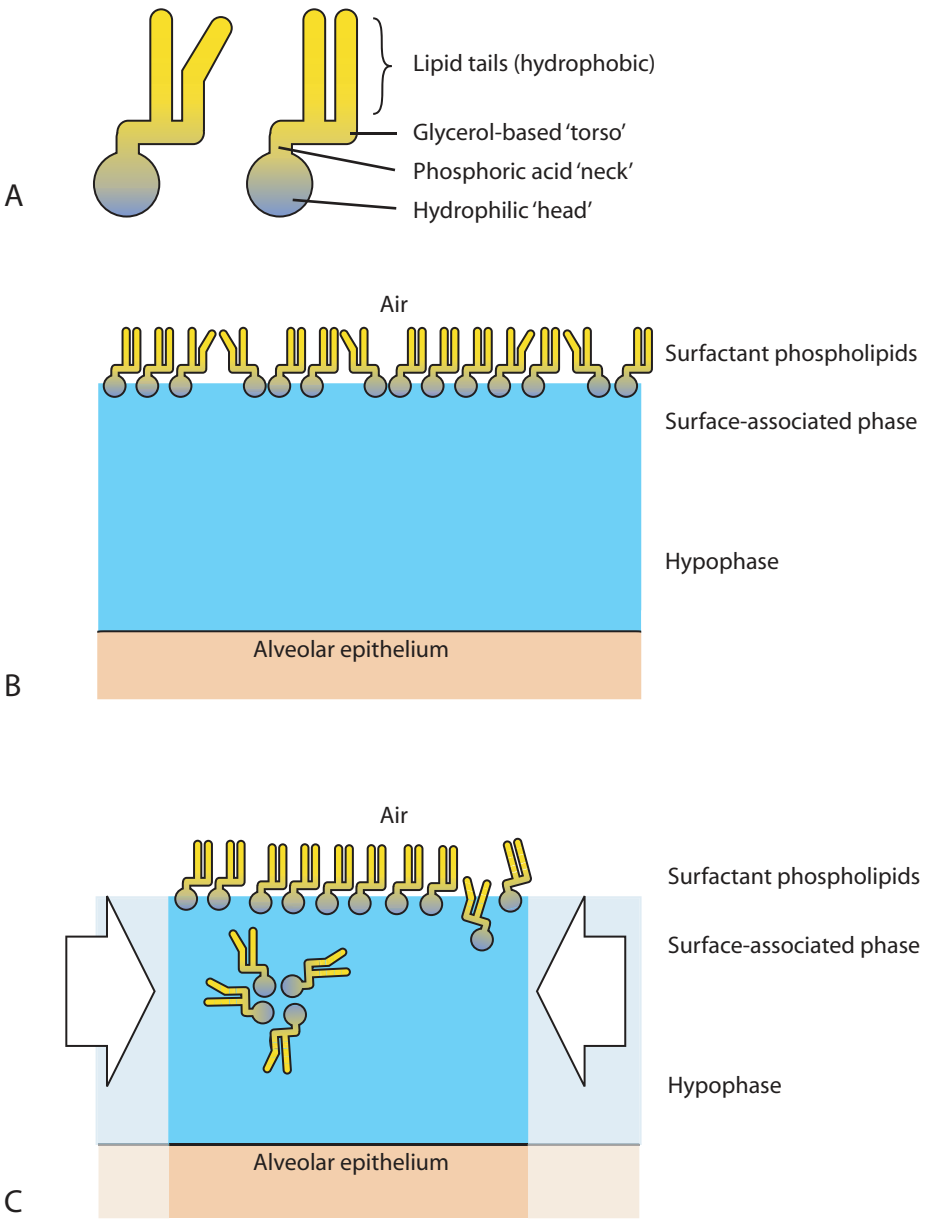

Figure 1.4 Surfactant.

A: Surfactant phospholipids are composed of two hydrophobic fatty acid tails joined to a hydrophilic head via glycerol and phosphoric acid. The most common phospholipid in surfactant is phosphatidylcholine, while the hydrophilic head is choline. Fatty acids in which all the bonds between adjacent carbon atoms are single are said to be 'saturated', and are physically flexible, allowing the molecule to pack in closely to its neighbour. Fatty acids in which one or more of the carbon–carbon bonds are double are said to be 'unsaturated'. These double bonds impart an inflexible angulation to the molecule, which prevents it from packing closely. The most effective phosphatidylcholine molecules are ones in which both fatty acid tails are saturated ('di-saturated'), such as dipalmitoyl-phosphatidylcholine.

B: The surfactant phospholipids float on the surface of the fluid lining the alveoli, with their hydrophilic heads in contact with the aqueous phase and their hydrophobic tails sticking in the air.

C: Expiration reduces the surface area of the alveolus, squeezing the bulkier and less effective phospholipids into the surface-associated phase. The remaining phospholipids, being predominantly disaturated, are more effective at reducing the surface tension and, as their concentration is increased, the surface tension is reduced further.

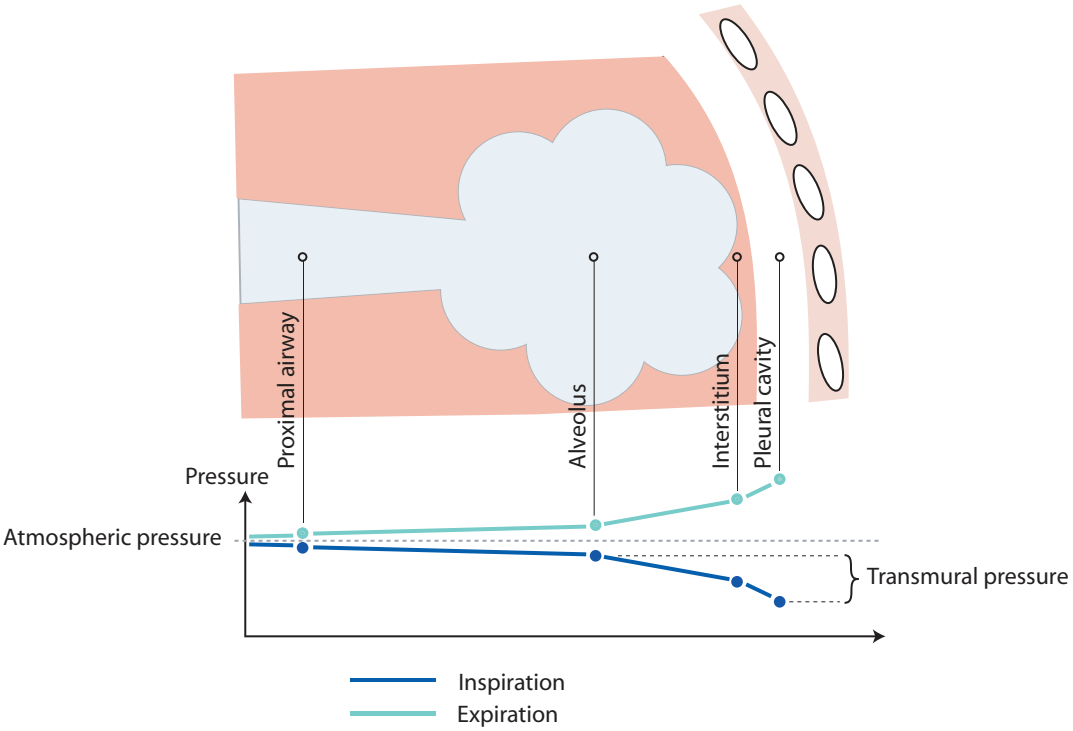

Figure 1.5 Absolute pressures along the airway during inspiration (blue) and expiration (green). During inspiration (blue) there is a pressure gradient between the proximal airway that is at atmospheric pressure at the mouth and the pleural space that is reversed during expiration.

out of the lung during normal breathing, a factor to be considered when comparison is made with mechanical modes of ventilation. Of course, much higher pressures *can* be achieved. Straining against a closed glottis, for example, can raise alveolar pressure to 190 cm H_2O, while maximal inspiratory effort can reduce pressure to as low as -140 cm H_2O.

Transmural pressure is defined as the difference between the pressure in the pleural cavity and that in the alveolus (Figure 1.5). To remain open, alveolar pressure must be greater than that of the surrounding tissue. During inspiration, intra-pleural pressure falls to a greater degree than alveolar pressure, and the transmural pressure gradient thus increases. Over the range of a normal breath, the relationship between transmural pressure gradient and lung volume is almost linear. This relationship holds true for the alveoli, but the lower down in the lung the alveoli are, the more the distending transmural pressure gradient is counteracted by the weight of lung tissue compressing the alveolus from above. For this reason, dependent alveoli tend to have a smaller radius and are more likely to collapse.

The 'expandability' of the lung is known as its compliance. A high compliance means that the lung expands easily. The compliance of the normal respiratory system (lungs and thoracic cage) in upright humans is about 130 mL.cm H_2O^{-1}, while that of the lungs alone is roughly twice that value, demonstrating that half of the work of breathing during health simply goes into expanding the rib cage. When a positive pressure is applied to the respiratory system, such as during positive pressure ventilation, gas immediately starts to flow into the lungs, which then expand. However, while gas is flowing,

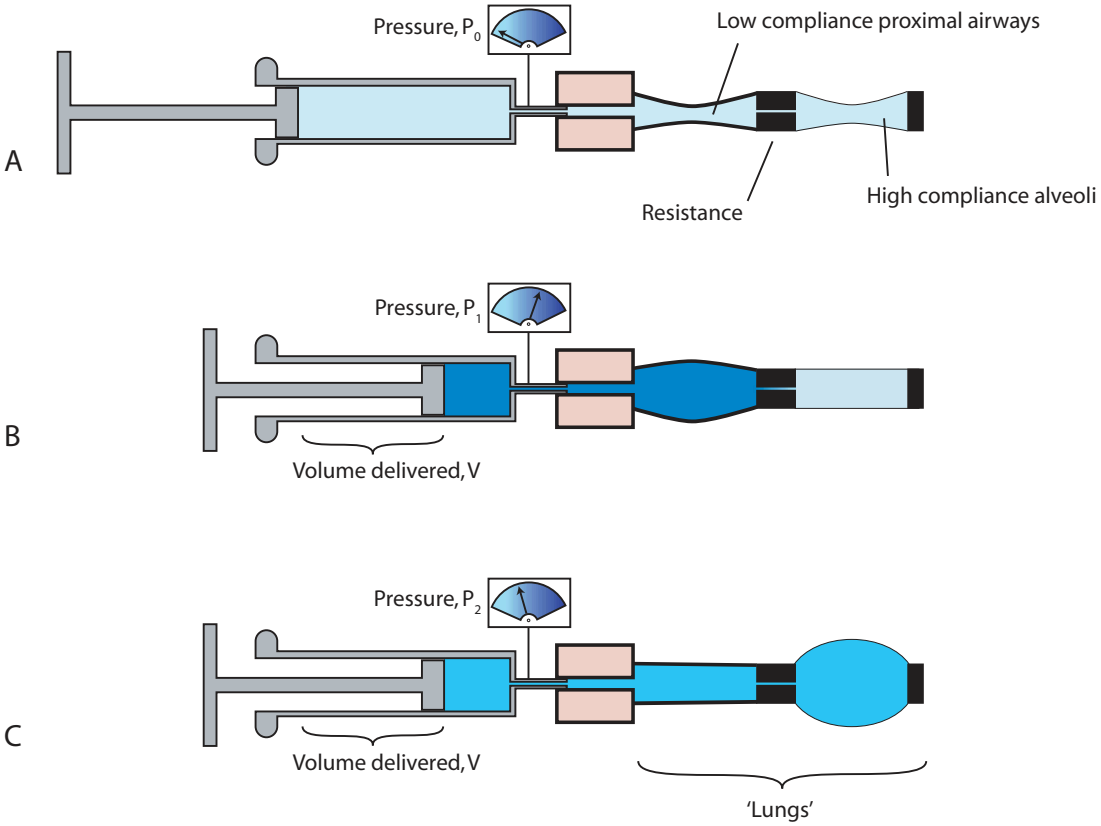

Figure 1.6 Two-compartment model of static and dynamic compliance.

A: In this model the ventilator is represented by the syringe, which is attached to the two-compartment lung model that consists of a low-compliance proximal chamber (the proximal airways) separated from a high-compliance distal chamber (the alveoli) by a fixed resistance. Prior to the onset of gas delivery (inspiration), the whole system is at the same pressure: P_0.

B: Gas is delivered to the lung model with a moderate increase in gas pressure in the syringe (the ventilator) and proximal chamber (the large airways) but with only a small increase in pressure in the distal chamber (the alveoli) as gas seeps through the resistance. Compliance measured just prior to the end of inspiration would be given by V/P_1.

C: Without the delivery of any further gas from the ventilator, the volume of the distal chamber continues to increase until the pressure in both chambers becomes the same. As gas redistributes from the high-pressure proximal chamber to the low-pressure distal chamber, the gas also expands slightly. At equilibrium, the compliance is given by V/P_2, which is larger than that calculated in B because $P_2 < P_1$.

the proximal airway pressure *must* be higher than alveolar pressure,[5] and the steepness of this pressure gradient will depend on the *resistance* to gas flow. Therefore, during inflation the ratio of volume change to inflating pressure (known as *dynamic* compliance) is lowered by the effect of resistance to gas flow (Figure 1.6). At the end of inspiration, the proximal airway pressure immediately falls as gas delivery ceases (and with it, the resistive contribution to airway pressure) and then falls a little further as gas is redistributed from low-compliance proximal airways to high-compliance alveoli. There is also an associated small increase in total lung volume. The percentage of *total* change in lung volume

[5] Otherwise gas would not flow.

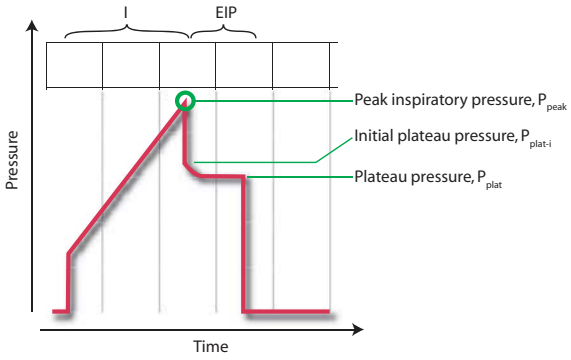

Figure 1.7 A pressure and time profile during volume-targeted constant flow mechanical ventilation.

For a delivered tidal volume of V mL, *dynamic* compliance is given by V/P_{peak} and *static* compliance is given by V/P_{plat}. The difference between P_{peak} and P_{plat-i} is due to airways resistance, while the difference between P_{plat-i} and P_{plat} is due to inter-alveolar gas redistribution (pendelluft) and hysteresis.

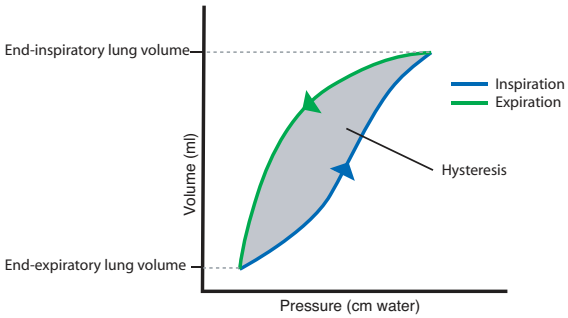

Figure 1.8 Inspiratory and expiratory volume/pressure loop during positive pressure inflation showing the phenomenon of hysteresis.

During inspiration (blue) of the lung, both pressure (x-axis) and volume (y-axis) increase, but this is non-linear. During expiration, the volume/pressure curve traces a different path. The area subtended by the inspiratory and expiratory paths represents the energy consumed by hysteresis.

when held at a set pressure is known as the lung's *static* compliance. Put another way, if a set volume of air is used to inflate a lung, pressure will rise accordingly, but (with lung volume held) will then gradually fall by some 25% or so (Figure 1.7). This effect is one of the contributing factors to a phenomenon known as *hysteresis* in which the lung traces a different path on an expiratory plot of lung pressure (x-axis) against volume (y-axis) than it does during inflation (Figure 1.8). Other contributors to hysteresis include the opening of previously collapsed alveoli during inflation,[6] displacement of lung blood at higher lung volumes, 'stress relaxation' of lung elastic fibres, and perhaps most importantly, the surface-area-dependent effect of surfactant in reducing surface tension. In practice, what this means is that at any given inflation pressure, lung volume will be greater during expiration than inspiration because the lungs are resistant to accepting a new higher volume, and then resistant to giving it up again.

[6] Commonly referred to as alveolar 'recruitment'.

LUNG VOLUMES

Total lung capacity (TLC) is the volume of intrapulmonary gas at the end of a maximal inspiration. Functional residual capacity (FRC) is the volume remaining in the lungs at the end of normal expiration that rises with body size (as determined by height) and on assumption of the upright posture. In mechanically ventilated subjects, FRC is also known as the end-expiratory lung volume (EELV). FRC is reduced when the lung is extrinsically compressed (from pleural fluid or abdominal distension), when lung elastic recoil is increased, or when the lungs are fibrosed.

Gas exchange

OXYGEN UPTAKE

Oxygenation is accomplished through the diffusion of oxygen down its partial pressure gradient (Box 1.1) from the alveolus, across the alveolar epithelium, and thence across the closely apposed capillary endothelium to the capillary blood, a distance of <0.3 μm. The capacity to transfer oxygen from alveolus to red blood cell is determined by (1) the surface area for diffusion and (2) the ratio

Box 1.1 Diffusion and partial pressures

Diffusion describes the passive movement of a substance from an area of high concentration to one of low concentration. Diffusion also applies to gases, but in this case the motive force is the differential *partial pressure* of the gas. Partial pressure simply refers to the proportion of the total gas pressure that is attributable to the gas in question. As an example, if you have a 1-litre flask containing 800 mL of helium and 200 mL of oxygen at atmospheric pressure (101 kPa), the partial pressure of oxygen in the flask will be

$$\frac{200}{800+200} \times 101 = 20.2 \text{ kPa}.$$

between the speed of diffusion and the alveolar contact time, which is the length of time the red cell remains in contact with the alveolus (Figure 1.9).

The *speed* of diffusion is determined by the partial pressure gradient of oxygen between alveolar gas and capillary blood, the thickness of the barrier between alveolus and capillary, and the solubility of oxygen in this barrier. Because there are no factors that influence oxygen's solubility under physiological conditions, the only sources of variation in the speed of diffusion are the partial pressure gradient of oxygen and the barrier thickness.

The partial pressure of oxygen in alveolar gas is not the same as the partial pressure of oxygen in inspired gas because alveolar gas contains two other constituents: carbon dioxide and water vapour. Therefore, breathing air at sea level, the alveolus contains four gases: nitrogen, oxygen, carbon dioxide and water vapour. The total pressure of these gases must equal atmospheric pressure (101 kPa):

$$P_{A_{N_2}} + P_{A_{O_2}} + P_{A_{CO_2}} + P_{A_{H_2O}} = 101\,kPa. \quad (1.2)$$

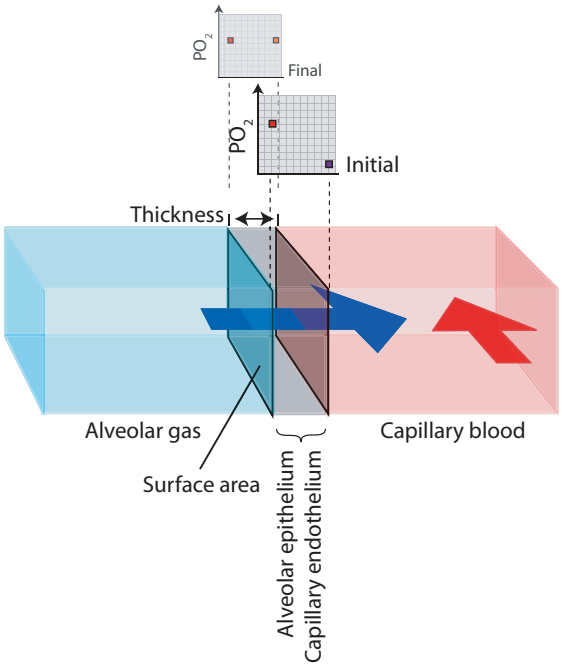

Figure 1.9 Factors that determine the capacity to transfer oxygen from alveolar gas to capillary blood. Oxygen diffusion (blue arrow) proceeds from alveolar gas (shown on the left) to capillary blood (shown on the right) across the intervening barrier of the alveolar epithelium and capillary endothelium, with capillary blood shown flowing away from the observer (red arrow). The capacity to transfer oxygen to red blood cells depends on the surface area for diffusion, and the ratio between the speed of diffusion and the length of time that the red cells spend in contact with the alveolus (referred to as the 'contact time').

The *speed* of diffusion is determined by the (1) initial partial pressure gradient of oxygen between alveolar gas and capillary blood; (2) the thickness of the barrier constituted by the alveolar epithelium, capillary endothelium and any other intervening tissue; and (3) the solubility of oxygen in this barrier.

The contact time is inversely proportional to the cardiac output and at rest is normally 0.75 seconds. Breathing air at sea level, red cells passing the alveolus are normally fully saturated after only 0.25 seconds, leaving a 'reserve' of 0.5 seconds. Diffusion limitation to oxygen transfer is therefore only seen with conditions that reduce the speed of diffusion (low alveolar partial pressure of oxygen or increased barrier thickness), reduce the contact time, or both. In trained athletes at maximum exertion the contact time falls to just over 0.25 seconds.