Carbon dioxide transport

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Carbon dioxide is produced by cell metabolism in the mitochondria. The amount produced depends on the rate of metabolism and the relative amounts of carbohydrate, fat and protein metabolized. The amount is about 200 ml min^{-1} when at rest and eating a mixed diet; this utilises 80% of the oxygen consumed, giving a respiratory quotient of 0.8 (respiratory quotient = rate of carbon dioxide production divided by rate of oxygen consumption). A carbohydrate diet gives a quotient of 1 and a fat diet 0.7.

Carbon dioxide transport in the blood

Carbon dioxide is transported in the blood from the tissue to the lungs in three ways:[1] (i) dissolved in solution; (ii) buffered with water as carbonic acid; (iii) bound to proteins, particularly haemoglobin.

Approximately 75% of carbon dioxide is transport in the red blood cell and 25% in the plasma. The relatively small amount in plasma is attributable to a lack of carbonic anhydrase in plasma so association with water is slow; plasma plays little role in buffering and combination with plasma proteins is poor.

There is a difference between the percentage of the total carbon dioxide carried in each form and the percentage exhaled from them. For example, 5% of the total is in solution but 10% of exhaled carbon dioxide comes from this source; 10% is protein bound, particularly with haemoglobin, but this supplies 30% of the exhaled amount.

Dissolved carbon dioxide

Carbon dioxide is 20 times more soluble than oxygen; it obeys Henry's law, which states that the number of molecules in solution is proportional to the partial pressure at the liquid surface. The carbon dioxide solubility coefficient is 0.0308 mmol litre^{-1} mm Hg^{-1} or 0.231 mmol litre^{-1} kPa^{-1} at 37°C. (Solubility increases as the temperature falls.) This corresponds to 0.5 ml kPa^{-1} carbon dioxide in 100 ml blood at 37°C. The partial pressure of carbon dioxide is 5.3 pKa in arterial blood and 6.1 kPa in mixed venous blood; therefore, arterial blood will contain about 2.5 ml per 100 ml of dissolved carbon dioxide and venous blood 3 ml per 100 ml. A cardiac output of 5 litre min^{-1} will carry 150 ml of dissolved carbon dioxide to the lung, of which 25 ml will be exhaled. Because of this high solubility and diffusing capacity, carbon dioxide partial pressure of alveolar and pulmonary end-capillary blood are virtually the same. Even a large shunt of 50% will only cause an end-pulmonary capillary/arterial carbon dioxide gradient of about 0.4 kPa.

Carbonic acid

Carbon dioxide combines with water to form carbonic acid, a reaction accelerated by carbonic anhydrase. The carbonic acid then freely dissociates (Equation 1).

$$CO_2 + H_2O \overset{\text{carbonic anhydrase}}{\rightleftharpoons} H_2CO_3$$
$$\rightleftharpoons H^+ + HCO_3^- \quad (1)$$
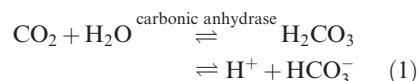
The enzyme carbonic anhydrase is present in a number of organs of the body including the eye, kidney and brain; however, for this purpose, it is the red blood cell carbonic anhydrase that is important. Once carbonic acid is formed it dissociates easily so that the ratio of H_2CO_3 to HCO_3^- is 1:20 (Equation 2).

$$\frac{CO_2}{H_2CO_3} = \frac{1000}{1}$$

$$\frac{H_2CO_3}{HCO_3^-} = \frac{1}{20} \quad (2)$$

Carbon dioxide and water diffuse freely into the red blood cell and are converted to carbonic acid, which dissociates into hydrogen and bicarbonate ions. Hydrogen ions do not pass through cell membranes but carbon dioxide passes readily. This situation cannot be sustained as the intracellular hydrogen ion and bicarbonate ion concentration, osmolarity and cell size will rise and rupture the cell. The

Key points

Carbon dioxide is transported in the blood in three ways: (i) dissolved in solution; (ii) buffered with water as carbonic acid; (iii) bound to proteins, particularly haemoglobin.

At a haemoglobin concentration of 15 g dl^{-1}, mixed venous P_{CO_2} 6.1 kPa contains 52 ml dl^{-1} of carbon dioxide; arterial blood P_{CO_2} 5.3 kPa contains 48 ml dl^{-1}.

The effects of carbon dioxide production in the tissues include: increased plasma Cl$^-$; increased red blood cell mean corpuscular volume; and haemoglobin becoming less acidotic than oxygenated haemoglobin.

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bicarbonate ion diffuses out to the plasma to be exchanged for chloride ions. This is known as the chloride shift (Gibbs–Donnan equilibrium or Hamburger effect). An ion exchange transporter protein in the cell membrane called Band 3 for $Cl^- HCO_3^-$ facilitates chloride shift.

A build up of hydrogen ion in the red blood cell would also prevent further conversion and production of bicarbonate ion. However, hydrogen ions bind easily to reduced haemoglobin, which is made available when oxygen is released; therefore, free hydrogen ions are removed from solution. Reduced haemoglobin is less acidic than oxygenated haemoglobin. This is another way of stating the Haldane effect, which explains that, at any given P_{CO_2}, the carbon dioxide content of deoxygenated blood is greater than that of oxygenated blood.

As a result of the shift of chloride ions into the red cell and the buffering of hydrogen ions onto reduced haemoglobin, the intercellular osmolarity increases slightly and water enters causing the cell to swell. This can be measured as an increase in mean corpuscular volume (MCV). The reverse process occurs as the red blood cell passes through the lung.

Bound to haemoglobin and other proteins

Carbon dioxide combines rapidly to the terminal uncharged amino groups (R-NH$_2$) to form carbamino compounds. (equation 3)

$$R\text{-}NH_2 + CO_2 \rightleftharpoons RNH - CO_2 + H^+ \qquad (3)$$
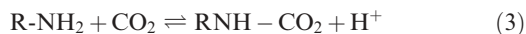
In most proteins, it is only the terminal amino acid group that combines with carbon dioxide. Haemoglobin is different when forming carbaminohaemoglobin. Reduced haemoglobin is the only effective protein buffer of hydrogen ion at physiological pH because of its high content of the amino acid histidine. Hydrogen ions attach to the imidazole group of the histidine. About 30% of exhaled carbon dioxide was combined with haemoglobin protein.

The amount of carbon dioxide held in blood in the carbamino form is small but it accounts a third of the difference between venous and arterial carbon dioxide content. The Haldane effect reflects the difference in carbon dioxide content between oxygenated and reduced haemoglobin at the same P_{CO_2}. This effect is partly attributable to the ability of haemoglobin to buffer hydrogen ions and partly due to the fact that reduced haemoglobin is 3.5 times more effective in combining with carbon dioxide than oxyhaemoglobin.

Different haemoglobins vary in their affinity for carbon dioxide, carbon monoxide and oxygen. Carbon dioxide combines readily with haemoglobin to form a carbamino bond at a lower partial pressure than oxygen, but haemoglobin carries less than a quarter of the amount of carbon dioxide compared with oxygen. By contrast, foetal haemoglobin, owing to the replacement of the β-chain with γ-chains, combines with oxygen at a lower partial pressure. Carbon monoxide has a greater affinity for haemoglobin and so displaces oxygen.
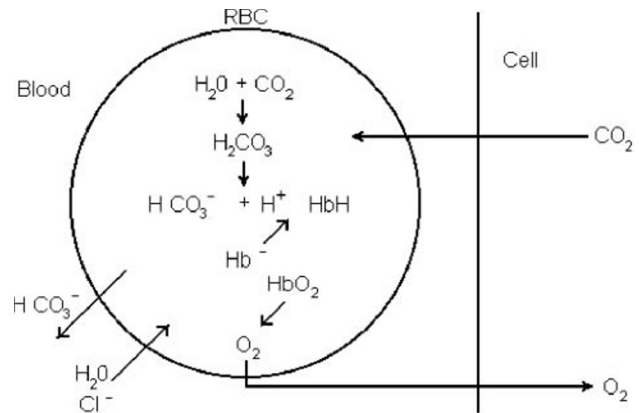

Fig. 1 Movement of gases at tissue level.

Carbon dioxide transport in the tissue

Carbon dioxide transport in the tissue is summarized in Figure 1. It combines with water to form carbonic acid. This reaction is very slow in plasma but fast within the red blood cell owing to the presence of the enzyme carbonic anhydrase. Carbonic acid (H_2CO_3) dissociates into H^+ and HCO_3^- ions; therefore, the concentration of both H^+ and HCO_3^- is increased in the red blood cell. HCO_3^- can diffuse out of the red blood cell into plasma whereas H^+ cannot. In order to maintain electrical neutrality, chloride ions diffuse into the red blood cell from the plasma as HCO_3^- diffuses out. Hydrogen ions are taken up by reduced haemoglobin. The imidazole group of the amino acid histidine gives haemoglobin a very significant buffering capacity, not present in other amino acids. This buffering capacity is made possible by the fact that each tetramer of haemoglobin contains 38 histidine residues and the dissociation constant of the imidazole groups of the four histidine residues, to which the haem groups are attached, is affected by the state of oxygenation of the haem. In the acidic state, the oxygen bond is weakened, while reduction of haemoglobin causes the imidazole group to become more basic. In the tissues, the acidic form of the imidazole group weakens the strength of the oxygen bond at the same time as hydrogen ions are being buffered by the more basic haemoglobin.

Carbon dioxide transport in the lungs

The combination of oxygen with haemoglobin is facilitated by the histidine group becoming more basic, which increases the affinity of the haem group for oxygen as the carbon dioxide is lost (Equation 4). This is one reason for the Bohr effect.

$$O_2 + HbH + HCO_3^- \leftrightarrow HbO_2 + H_2O + CO_2$$
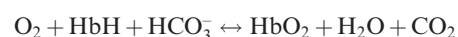
Release of H^+ shifts the equilibrium in favour of carbon dioxide formation and elimination. HCO_3^- concentration decreases as carbon dioxide is formed and eliminated (Fig. 2).
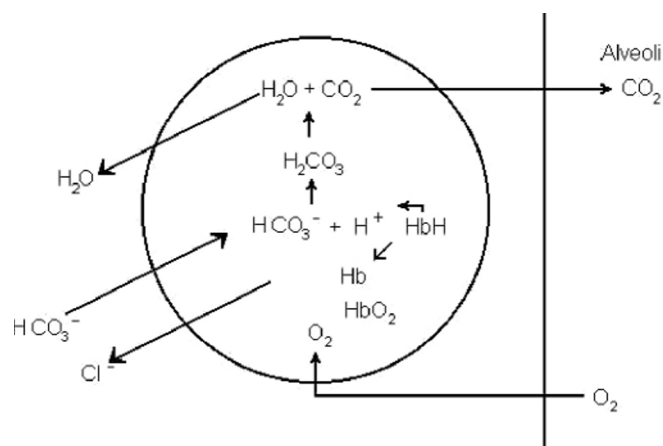
Fig. 2 Movement of gases at alveolar level.

Carbon dioxide dissociation curves

Carbon dioxide dissociation curves relate Pa_{CO_2} (kPa or mm Hg) to the amount of carbon dioxide (ml) carried in blood (Fig. 3). The amount of dissolved carbon dioxide and bicarbonate vary with P_{CO_2}, but are little affected by the state of haemoglobin. However, the amount of carbamino haemoglobin is much affected by the state of oxygenation of haemoglobin, less so by the P_{CO_2}.

In mixed venous blood, P_{CO_2} is 6.1 kPa (46 mm Hg) and in arterial blood P_{CO_2} is 5.3 kPa (40 mm Hg). Total carbon dioxide in venous blood is 52 ml per 100 ml and in arterial blood 48 ml per 100 ml. Consequently, the curve is more linear than the O_2Hb dissociation curve.

Figure 4 illustrates the difference between the content in blood of oxygen and carbon dioxide with change in partial pressure. It emphasizes that the carbon dioxide content rises throughout the increase in partial pressure. Oxygen content rises more steeply until a point at which the haemoglobin is fully saturated. After that, the increase is small because of the small increased amount in solution.

Differences between venous and arterial blood

The differences between arterial and venous blood are summarized in Figure 5 and Table 1. The high content of carbon dioxide in venous capillary blood reduces the affinity of haemoglobin for oxygen leading to release of oxygen to the tissues.[3] The oxygen dissociation curve shifts to the right (Bohr effect). Deoxygenated haemoglobin takes up more carbon dioxide than oxygenated haemoglobin (Haldane effect). Removal of oxygen from haemoglobin in the tissue capillaries causes the haemoglobin molecule to behave more like a base (better proton acceptor). Therefore, haemoglobin increases the amount of carbon dioxide that is carried in venous blood (Equation 4)

$$HbO_2 + CO_2 + H_2O \leftrightarrow HbH^+ + HCO_3^- + O_2 \qquad (4)$$

Each carbon dioxide molecule added to the red blood cell increases the intracellular osmotic pressure by an increase in either
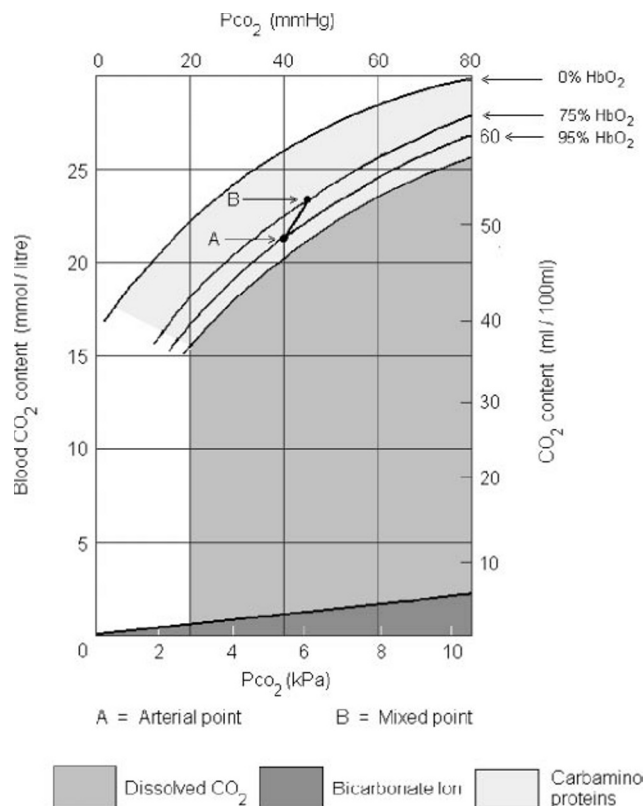

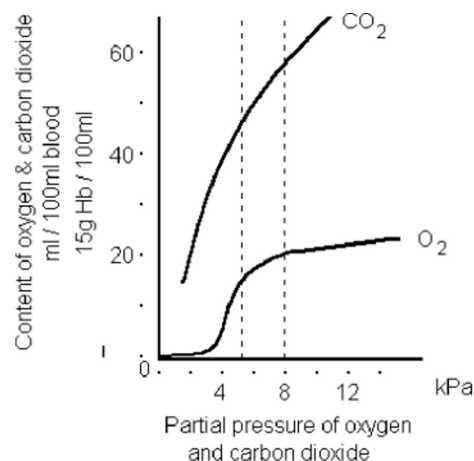Fig. 3 Total carbon dioxide transport in whole blood.

Fig. 4 Carbon dioxide transport in whole blood.

HCO_3^- or Cl^- ions. Therefore, the red blood cell increases in size and the haematocrit of venous blood is some 3% more than arterial blood. The plasma concentration of chloride ion is lower but bicarbonate ion concentration is greater.

pH of red blood cells

The total reduction of all haemoglobin would result in a rise in blood pH by 0.03. At 25% desaturation, the pH increases by 0.007 (at constant P_{CO_2}). If the P_{CO_2} rises by 0.8 kPa (6 mm Hg)

Table 1 Summary of normal values for pH and carbon dioxide carried in arterial and venous blood (1 mmol = 22.32 ml)[2]

	Arterial blood		Mixed venous blood		Arterial/venous difference	
Whole blood						
pH	7.4		7.36		−0.033	
P_{CO_2} kPa	5.3		6.1		+0.8	
Mm Hg	40		46		+6.0	
Total CO_2 mmol litre^{-1}	21.5		23.3		+1.8	
ml dl^{-1}	48		52		+4.0	
Plasma	mmol litre^{-1}	ml dl^{-1}	mmol litre^{-1}	ml dl^{-1}	mmol litre^{-1}	ml dl^{-1}
Dissolved carbon dioxide	1.2	2.5	1.4	3.0	+0.2	+0.5
Carbonic acid	0.0017		0.002		+0.0003	
Bicarbonate ion	24.4		26.2		+1.8	
Carbamino carbon dioxide	negligible		negligible		negligible	
Total	25.6		27.6		+2.0	
Erythrocyte fraction						
Dissolved carbon dioxide	0.44	1.0	0.51	1.2	+0.07	
Bicarbonate ion	5.88	13.0	5.92	13.2	+0.04	
Carbamino carbon dioxide	1.10	2.5	1.70	3.8	+0.6	+1.3
Plasma fraction						
Dissolves carbon dioxide	0.66	1.5	0.76	1.8	0.1	+0.3
Bicarbonate ion	13.42	30.0	14.41	32.0	0.99	+2.0
Total carbon dioxide in 1 litre of blood (mmol litre^{-1})	21.5	48	23.30	52	+1.8	+4.0
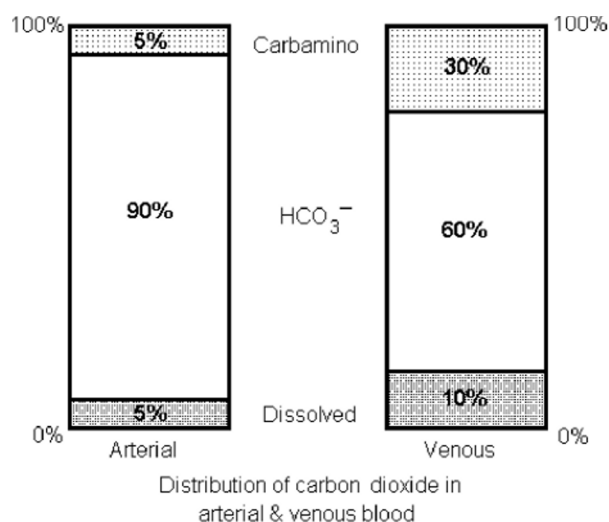
Fig. 5 Partial pressure of oxygen and carbon dioxide.

i.e. the difference between mixed venous and arterial blood, the pH will reduce by 0.04. The net effect is a fall in pH of 0.033 from 7.4 to 7.36.

Changes in red blood cells during passage through the lungs

In pulmonary capillary blood, the red blood cell releases carbon dioxide and the haemoglobin affinity for oxygen is increased. The oxygenated haemoglobin binds fewer hydrogen ions making it more acidic but the fall in P_{CO_2}, and the shift in chloride and bicarbonate ions, makes the red blood cell less acidic. The outward shift of water gives a smaller MCV and reduced haematocrit. The oxygen dissociation curve will shift to the left (Bohr effect). The plasma concentration of chloride ion is higher in arterial compared with venous blood; bicarbonate concentration is lower.

The role of carbon dioxide in acid elimination

Every minute, 200 ml of carbon dioxide is exhaled; this is the equivalent to 12–13 mol of hydrogen ions in 24 h.[1] Urine pH varies from 4.5 to 8.0. A pH of 4.0 represents 10^{-4} mol litre^{-1} of hydrogen ions. Therefore, the passage of 3 litres of urine accounts for a relatively small amount of hydrogen ion elimination in 24 h; however, this includes the phosphate and sulphate ions that cannot be converted to carbon dioxide.

Effect of apnoea

The total body content of carbon dioxide including bicarbonate ion is 120 litres or 100 times that of oxygen. If there is apnoea and all the carbon dioxide is retained in the body, P_{CO_2} will rise by 0.4 to 0.8 kPa min^{-1} (3–6 mm Hg). Alveolar gas will rapidly equate with venous blood, giving an alveolar P_{CO_2} rise from 5.3 to 6.1 kPa and a P_{O_2} fall from 14 to 5.3 kPa in 1 min. Therefore, the patient becomes rapidly hypoxaemic. If the patient is pre-oxygenated with oxygen 100%, the arterial oxygen tension will remain above 13 kPa and 100% saturation is maintained for several minutes as 250 ml min^{-1} of oxygen is used from a high partial pressure in the lung. However, Pa_{CO_2} will steadily rise; after 5 min, it will be approaching 10 kPa with an associated fall in pH.

References

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