Measurement of respiratory function: gas exchange and its clinical applications

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Abstract

Gas exchange is the main function of the lungs. Lungs have a large reserve for gas exchange. Oxygen and carbon dioxide diffuse along their partial pressure gradient across the alveolar–capillary membrane. Alveolar ventilation and pulmonary circulation are closely matched to provide efficient gas exchange in the lungs. Hypoxaemia often results from mismatch in ventilation–perfusion. Gas exchange can be impaired in various disease states. Measurement of the diffusing capacity for carbon monoxide (DLCO) provides estimation of the gas exchange function. A low DLCO indicates an impairment of oxygen transfer across the alveolar–capillary membrane. Based on the lung function tests one can assess the risks of perioperative pulmonary complications. Anaesthesia and surgery adversely affect pulmonary function, many of which adverse effects can be prevented.

Keywords Alveolar–capillary membrane; carbon dioxide; carbon monoxide; diffusing capacity; diffusion; gas exchange; general anaesthesia; oxygen; risks of perioperative pulmonary complications; ventilation–perfusion matching

Royal College of Anaesthetists CPD Matrix: 1A01

Learning objectives

After reading this article, you should understand the:
- physics of pulmonary gas exchange, including the factors affecting the rate of diffusion of gases
- functional histology of respiratory membrane and factors affecting its function
- diffusing capacity, how it is measured, and its clinical implications
- normal and abnormal distribution of ventilation and pulmonary circulation, and the zones of lung
- how to assess the risks of perioperative pulmonary complications
- effects of anaesthesia on the respiratory function

Precise physiological processes help to achieve the efficient gas exchange which is the primary function of the lungs. Gas exchange also occurs in the body tissues at the cellular level where O_2 and CO_2 diffuse into and out of the mitochondria. Our bodies maintain normal levels of O_2 and CO_2 through chemical and neural mechanisms of control of breathing. The level of CO_2 plays an important part in influencing the pH of the blood. Metabolic activity of the body determines the work load imposed upon the lungs. The earliest signs of respiratory impairment are noticed during exercise when respiratory reserves are used. This review article discusses the physiological processes involved in the gas exchange, including the physics of gas exchange, the alveolar–capillary membrane, the diffusing capacity, the pulmonary ventilation, the pulmonary circulation, the ventilation/perfusion and respiratory changes occurring with anaesthesia.

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Physics of gas exchange

Pulmonary gas exchange is a two-way diffusion process where oxygen (O_2) and carbon dioxide (CO_2) diffuse in opposite directions across the alveolar–capillary membrane driven by the gradients of their partial pressures. Being highly soluble in lipids, these physiologically important gases diffuse easily through the cell membranes. Diffusion of gas through the water in the alveolar lining is a limiting factor for the movement of gases. As such, diffusion of gases through the respiratory membrane and other tissues is almost equal to the diffusion of gases in water.

Factors affecting the rate of diffusion of gases

Some facts about the gas exchange are briefly listed in Box 1. According to Fick's law of diffusion, the rate of diffusion of gases in the fluids depends on various factors (Box 2) that are expressed in the formula:

$$D \propto \frac{\mathrm{P} \times \mathrm{A} \times \mathrm{S}}{\mathrm{d}\sqrt{\mathrm{MW}}}$$

The partial pressure difference (P) between the alveoli and the pulmonary capillary blood is a measure of the net tendency for the gas molecules to move across the membrane. For a given pressure difference, carbon dioxide diffuses about 20 times as rapidly as oxygen.

The surface area of the respiratory membrane (A) available for gas exchange may be reduced in certain conditions, e.g. pneumonectomy and emphysema. When the total surface area is decreased to about one-third to one-quarter of normal, gas exchange is significantly reduced even under resting conditions. While during sports and strenuous exercise, even the slightest decrease in surface area of the lungs can seriously decrease the gas exchange.

The rate of diffusion through the membrane is inversely proportional to the thickness of the membrane (d). When thickness of the respiratory membrane increases to more than two to three times the normal (e.g. in pulmonary oedema and

Some gas facts for the gas exchange

Dalton's law states that the partial pressure of a gas in a gas mixture is the pressure that this gas would exert if it alone occupied the total volume of the mixture. In the alveoli:

$$PT = PN_2 + PO_2 + PCO_2 + PH_2O$$

Gases flow from high pressure to low pressure areas and also along their molar concentration.

Graham's law states that the rate of diffusion of a gas is inversely proportional to the square root of its molecular weight.

Henry's law of solubility states that the amount of gas (O_2) physically dissolved in the water is proportional to its partial pressure in the gas phase.
Solubility and dissolved volumes of O_2 and CO_2 in alveoli.
O_2: Solubility =
0.225 ml/litre/kPaO_2
Dissolved volume =
0.225 X 13.33 = 3 ml.

CO_2: Solubility =
5.1 ml/litre/kPaCO_2
Dissolved volume =
5.1 X 5.33 = 27.2 ml.

Fick's law describes the rate of diffusion of O_2 and CO_2 from lungs to the pulmonary blood.

Box 1

fibrosis), it can significantly interfere with the normal exchange of gases.

The solubility (S) and molecular weight (MW), two characteristics of a gas itself, determine the diffusion coefficient of the gas. The rate of diffusion of a gas at a given partial pressure is proportional to its diffusion coefficient ($S/\sqrt{MW}$). It would be difficult for the larger molecules to pass easily through the cell membranes. Depending upon the molecular weights (O_2 is 32 and CO_2 is 44), one expects the diffusion of CO_2 to be slower than that of O_2. Actually CO_2 diffuses 20 times faster than O_2 and O_2 twice as rapidly as nitrogen. This is because CO_2 is 30 times more soluble in water than O_2, and taking the square root of these molecular weights reduces the difference between the gases. The diffusion coefficient of oxygen is considered as 1. The relative diffusion coefficient of other gases are: carbon dioxide 20.3; carbon monoxide 0.81; nitrogen 0.53 and helium 0.95.

Factors affecting the rate of diffusion of gas in a fluid

- Partial pressure gradient of the gas
- Surface area available
- Distance through which the gas must diffuse (thickness of alveolar–capillary membrane)
- Solubility of the gas in the fluid
- Molecular weight of the gas
- Temperature of the fluid (normally constant in the body).

Box 2

Alveolar–capillary membrane

The pulmonary gas exchange area is about the size of a tennis court packed into the two lungs. It is estimated that there are about 300×10^6 alveoli. The unit of gas exchange in the lungs is called the acinus. It consists of a group of alveoli with its respiratory bronchiole surrounded by pulmonary capillaries (Figure 1). The average diameter of an alveolus is 0.1–0.2 mm^3.

The alveoli are lined with two types of epithelial cells: type I and type II pneumocytes. The flat alveolar epithelial cells (type I pneumocytes) are the site of gas exchange, whereas type II pneumocytes are linked with surfactant production. The distance between the alveolar epithelium and the capillary basement membrane is 0.4 mm only. The mean diameter of the pulmonary capillaries is about 7 mm. This means that the red cells travel in

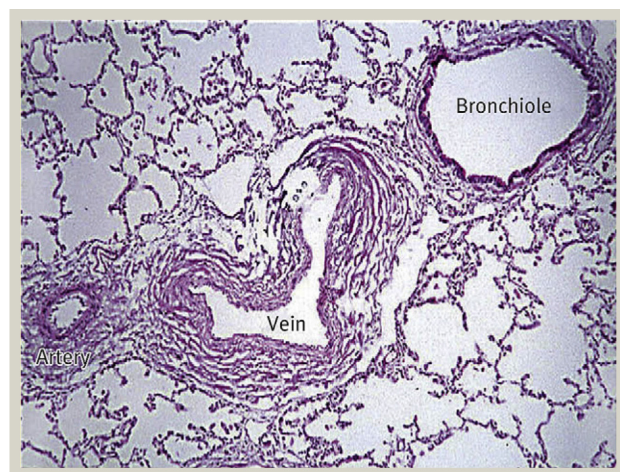

Figure 1 Microscopic view of normal lung tissue. Courtesy Dr A Hussain, Royal Victoria Hospital, Newcastle upon Tyne (UK).

Schematic representation of alveolar capillary membrane

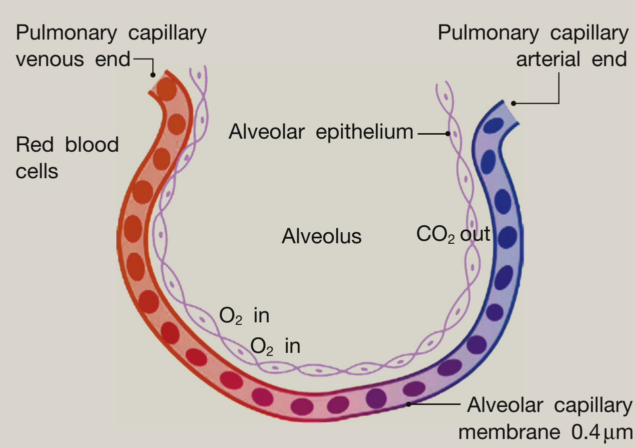

Figure 2