The relationship between ventilation and perfusion determines the amount of gas exchange which occurs at the lung. This article reviews the physiological mechanisms of ventilation and perfusion. The author then presents types of disturbances present in pulmonary abnormalities resulting in hypoxemia, and calculations which are useful in estimating the extent of pulmonary pathology.

Disturbances in the relationship of ventilation and perfusion may result in hypoxemia, a deficiency of oxygen in the blood. The four major causes of hypoxemia are hypoventilation, alveolar-capillary diffusion impairment, shunt, and ventilation perfusion mismatch. In this article factors which determine ventilation and gas exchange will be identified and abnormalities leading to hypoxemia will be examined.

The alveolar $O_2$ tension ($PAO_2$) is determined by the balance between the addition of $O_2$ to the alveoli from ventilation and the removal of $O_2$ from the alveoli by pulmonary capillary blood. If alveolar ventilation is low, $PAO_2$ will decrease and $PACO_2$ will increase, resulting in hypoxemia and hypercarbia. This is known as hypoventilation. Causes of hypoventilation include anesthetics, narcotics, muscle relaxants, trauma to the chest wall, spinal cord injuries, and central nervous system depression. Arterial $O_2$ tension ($PaO_2$) can be maintained with increases in inspired oxygen while arterial $CO_2$ tension ($PaCO_2$) will always increase during hypoventilation.

The second cause of hypoxemia is impaired diffusion. With normal breathing, gas is transported through the airways to the alveoli by convective or bulk gas flow. At the alveolar capillary membrane the mechanism of gas transport is diffusion. When the alveolar-capillary membrane is thickened by disease, the difference between $O_2$ in the alveoli and $O_2$ in the end capillary blood may increase because of impaired diffusion. $CO_2$ diffuses 20 times more rapidly than oxygen, and elevation of $CO_2$ is not usually seen with impaired diffusion.

The third cause of hypoxemia is right to left shunt in which blood enters the arterial system...
without passing through the ventilated lung as shown in Figure 1. Normal anatomical shunt consists of blood from the bronchial veins and the coronary venous blood draining directly into the left ventricle through the thebesian veins. Capillary shunt occurs when blood traverses pulmonary capillaries adjacent to unventilated portions of the lung, as in acute atelectasis and consolidation.

Shunt can be calculated from the following equation:

\[
\frac{Q_s}{Q_t} = \frac{C_cO_2 - C_aO_2}{C_cO_2 - C_vO_2}
\]

where \( Q_s/Q_t \) is the shunt fraction, \( Q_s \) is the amount of shunted blood, \( Q_t \) is the total amount of blood flow or cardiac output, \( C_cO_2 \) is the oxygen content in pulmonary capillary blood, \( C_aO_2 \) is the oxygen content in the arterial blood, and \( C_vO_2 \) is the oxygen content in the mixed venous or pulmonary arterial blood. The calculation of oxygen content is shown in Table I. The \( PAO_2 \) used to estimate the oxygen content of the capillary blood can be calculated from the following ideal gas equation:

\[
PAO_2 = FiO_2 (BP - PH_2O) - PCO_2/RQ
\]

where \( PAO_2 \) is the alveolar partial pressure of oxygen, \( FiO_2 \) is the fraction of inspired oxygen, \( BP \) is the barometric pressure equal to 760 mmHg at sea level, \( PH_2O \) is the partial pressure of water vapor in the airways at 37° C and is equal to 47 mmHg, \( PCO_2 \) is the arterial \( CO_2 \) partial pressure in mmHg, and \( RQ \) is the respiratory quotient which is approximately 0.7 during general anesthesia.

Although shunted blood is rich in \( CO_2 \), an elevated \( PCO_2 \) does not usually result because the central chemoreceptors sense any elevation of arterial \( PCO_2 \) and respond by increasing ventilation. This maintains the \( PCO_2 \) at normal values. \( PCO_2 \) may be lower than normal if hypoxemia is significant enough to increase ventilation via the hypoxic respiratory drive. Figure 1 diagrammatically shows the difference between shunt and dead-space ventilation compared to a normal ventilation perfusion relationship.

The last cause of hypoxemia, ventilation-perfusion mismatch, is the most common yet the most difficult to understand. It has been referred to by various terms depending on the medical discipline and the author involved. Common terms are venous admixture, ventilation-perfusion inequality, V/Q inequality, and shunt-like effect (Figure 2). V/Q mismatch is actually a component, according to Shapiro, of physiological shunt.8 In any particular lung unit, when ventilation is not equal to perfusion the V/Q ratio will be something other than one. It is clinically important to know that this form of hypoxemia is responsive to oxygen therapy whereas true shunt is not. With ventilation-perfusion mismatch, small increases in inspired oxygen will result in dramatic increases in the amount of oxygen carried in blood (Figure 3).

Changes in the V/Q ratio will result in changes in gas exchange as measured by \( PaO_2 \) and \( PaCO_2 \). Lung units with no ventilation-perfusion inequality have normal alveolar partial pressures for \( O_2 \) and \( CO_2 \). As ventilation-perfusion inequality develops, the lung units acquire both low and high V/Q ratios. When this happens \( PaO_2 \) and \( PaCO_2 \) in the mixed capillary blood and alveoli will also diverge, resulting in abnormal arterial blood values.

### Table I

**Total blood oxygen content**

- \( Hb(GM\%) \times 1.34 \times O_2 \) Sat = \( O_2 \) attached to hemoglobin
- \( P_vO_2 \times 0.003 = O_2 \) dissolved in blood

**EXAMPLE:**

- \( P_vO_2 = 100 \) mmHg, \( O_2 \) Sat = 100%, \( Hb = 15 \) gm %
- \( C_vO_2 = (15 \times 1.34 \times 1) + (100 \times 0.003) = 20.40 \) cc \( O_2 \)/100 ml blood

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**Figure 2**

*Ventilation-perfusion abnormalities*

- V/Q Mismatch
- Venous Admixture
- Ventilation-Perfusion Inequality
- V/Q Inequality
- Shunt-like Effect

*ALL THESE TERMS ARE THE SAME*

**Figure 3**

*Shunt vs. V/Q mismatch*

- If \( FiO_2 \) is increased by 0.2
  - **Shunt** (Refractory Hypoxemia)
    - \( PaO_2 \) will increase less than 10 mmHg
  - **V/Q Mismatch** (Responsive Hypoxemia)
    - \( PaO_2 \) will increase more than 10 mmHg
There are regional differences in the ventilation-perfusion ratio in the upright normal lung. The PAO₂ is low at the bottom of the lung and there is increased perfusion relative to ventilation. At the apex of the lung PAO₂ is high and perfusion is low relative to ventilation. Because a greater fraction of cardiac output passes through the base of the lung, the arterial PO₂ is more reflective of the alveolar PO₂ at the base of the lung.

The gradient between the alveolar oxygen and arterial oxygen is calculated by subtracting the arterial oxygen from the alveolar oxygen, and is known as the (A-a) O₂ difference. The alveolar PO₂ can be calculated using the second equation shown in this article, and the PaO₂ can be measured directly. The (A-a) O₂ difference may occur because of the alveolar capillary tension gradient, lung units with low V/Q ratios or Qs/Qt or shunt.

Physiologic shunt can be increased by clinical factors which decrease the effectiveness of the hypoxic pulmonary vasoconstriction reflex (HPV). Vessels to lung units with PAO₂ less than 60 mmHg will normally constrict shunting blood away from the poorly oxygenated units to better oxygenated units, resulting in decreased shunt and increased arterial oxygen. Factors which decrease the effectiveness of this reflex are elevated pulmonary artery pressure (PAP), volatile anesthetics, vasopressors, hypothermia, hypocarbia and alkalosis (Figure 4).

General anesthesia for a patient in the supine position reduces functional residual capacity (FRC) by as much as 0.5-0.7L. Most reports indicate closing capacity remains unaltered. Airways may thus close above FRC more easily during general anesthesia. Also during general anesthesia pulmonary artery pressure may be decreased while alveolar pressure is increased, due to institution of positive pressure ventilation. These two factors will interfere with lung perfusion resulting in increased ventilation perfusion inequity. The anesthetic agent itself may also inhibit the HPV reflex, resulting in an increase in physiologic shunt. All these effects of general anesthesia will increase the likelihood of hypoxemia and are summarized in Figure 5.

To conclude, because the relationship between ventilation and perfusion determines whether oxygen is being adequately supplied, critical assessment of a patient's oxygenation status requires more than a measurement of PaO₂. To estimate the degree of hypoxemia, measurements of the (A-a) O₂ difference, Qs/Qt, and V/Q can be made. To measure the (A-a) O₂ difference, arterial PO₂ and the ideal gas equation are needed. This is the least invasive of the three tests. To measure Qs/Qt or the shunt fraction, mixed venous blood and cardiac output are required, which can only be obtained with a pulmonary artery catheter. The V/Q ratio can be measured using a test developed by West and Wagner called the multiple inert gas technique, which requires venous injection of several substances of different blood gas solubility and their measurement in the expired gas.

This technique is highly difficult and therefore is performed in very few clinical settings.

REFERENCES


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The opinions expressed in this article are those of the author alone and are not to be construed as reflecting the views of the U.S. Food and Drug Administration or the U.S. Public Health Service.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the Office of Graduate and Continuing Education, Uniformed Services University of the Health Sciences, Bethesda, Maryland, for assisting in the preparation of this paper.

This paper was presented at the Military Anesthesia Conference in Heidelberg, West Germany, December 9-12, 1985. The conference was sponsored by the Uniformed Services University of the Health Sciences, Bethesda, Maryland, and the 7th Medical Command, Heidelberg, Germany.