Correlations Between the Pulmonary Circulation and Gas Exchange in Health and Disease

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The development of blood gas electrodes in the 1950s enabled laboratory analyses of respiratory gas exchange to be extended readily to patients. Extension of the three-compartment model of gas exchange (Riley and Cournand, 1949) ultimately led to the analysis of gas exchange (Hlastala, 1984) as a distribution of ventilation–perfusion ratios (V/Q model). This latter currently provides the most detailed practical conceptual framework, and has been limited in clinical practice only by the technical difficulty of the multiple inert gas excretion method that is used to derive the distributions. These difficulties have largely been solved by advances in micropore membrane inlet mass spectrometry (Baumgardner et al., 1997) and rapid, simple, real-time bedside derivations should soon expand the clinical and research applications of V/Q ratio distributions. There has been intuitive recognition from the beginning that blood flow was as important for gas exchange as was ventilation, but, because of the relative inaccessibility of the pulmonary circulation, knowledge of the role of blood flow remained limited and the pulmonary vascular bed was regarded simply as a passive conduit that permitted high flow at low pressures. Introduction of the balloon-tipped or flow-directed catheter has rapidly changed this view and has revealed the fundamental responsivity of the pulmonary circuit to exogenous and endogenous mediators, particularly to hypoxia. At the same time detailed information about the biodynamic properties of the pulmonary vascular bed have enabled the development of improved computer models (P/Q model) that represent the behavior of the pulmonary circulation more faithfully. With the availability of a method (Marshall et al., 1994) to combine V/Q and P/Q Models (V/Q–P/Q model) it is finally possible to analyze and understand quantitatively the complex interactions that blood flow regulation brings to gas exchange, and vice versa. Using this approach the present discussion addresses questions, such as: Under what circumstances of health and disease does a vasoconstrictor improve oxygenation? What are the mechanisms underlying improvement of oxy-
Ventilation–Perfusion Ratios: The V/Q Model of Gas Exchange

The pulmonary retention and elimination of an inert gas, infused in a steady state, can be represented by the arterial/mixed venous and the expired/mixed venous gas tension ratios. These ratios are simple functions of the total ventilation, total blood flow, solubility of the gas, and ventilation–perfusion ratio. If a mixture of six inert gases with widely different solubilities is administered, the pulmonary shunt, dead space, and distribution of V/Q ratios, expressed as means and log standard deviations (log SD) for ventilation and perfusion, can be derived using iterative computer routines (Wagner, Saltzman, and West, 1974). From the V/Q Model the values for normal lungs for the mean is approximately 0.8, and the upper limits of normal for the log SD is 0.6; for the physiological shunt, it is about 10%, and for anatomic dead space it is about 30% of the minute volume. With severe lung disease values for log SD exceeding 2.5 are observed, and the mean V/Q values vary widely, but shunt and dead space may exceed 80% of the cardiac output or ventilation, respectively. Exchange of the respiratory gases are accurately represented when calculated on the basis of these values for the V/Q Model and the impairment of oxygenation is correlated, particularly with shunt and broadening of the V/Q Ratio distribution for blood flow (West and Wagner, 1997).

Pressure–Flow Curves: The P/Q Model

When flow in the pulmonary vascular bed is increased from zero to above normal values, the pressure increase is related by a curve because the effective conductance (reciprocal resistance) of the bed progressively increases to some maximum that is thereafter constant. Although recruitment of vessels may account for some of the curvature at the lowest flows, measurement of the number, dimensions, and elastic properties of the entire pulmonary vascular tree have demonstrated a pattern of properties that support a generalized model (P/Q model) where the curvilinearity is entirely accounted for by the distension of vessels within specific transmural pressure limits (Fung, 1984). This model therefore accounts for the influence of pleural and alveolar gas pressures, left-atrial outflow pressures, and active and passive vasoconstriction on the position and shape of the pressure–flow curve.

Hypoxic pulmonary vasoconstriction (HPV) is the most unique property of pulmonary arteries to constrict in response to hypoxia. It is also the most obvious direct link between blood flow distribution and oxygen exchange. The stimulus (PsO₂) for HPV (Marshall et al., 1994) is the oxygen tension in the smooth muscle of small pulmonary arteries (with diameters <500 μm) and is determined by both alveolar (PaO₂) and mixed venous (PvO₂) oxygen tensions (PsO₂ = PaO₂^{0.6} × PvO₂^{0.4}). By stimulating HPV in hypoxic regions of the lung, blood flow is diverted to less hypoxic regions and oxygenation improved; however, severe systemic arterial hypoxemia (PaO₂ <50 mmHg) may be associated with inhibition of HPV (Brimioulle et al., 1994). This is probably because the vasa vasorum of the pulmonary arteries are from the systemic bronchial circulation and release dilator compounds when hypoxic (Marshall et al., 1991).