A multicompartment analysis of the lung*

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Abstract—Intravascular inert-gas tracers have been employed in a multicompartment lung model to measure the anatomic shunt. This includes blood flow to atelectatic areas, to regions with closed nonventilated airspaces and to regions where there are diffusion blocks to tracer passage. The volume of perfused airspaces without diffusion-block distal to bronchial obstruction has been determined. The gases xenon 133 and krypton 85 were used to measure shunting. Data indicate that this shunt is 30–50% less than that calculated with 100% oxygen breathing. This is related to the effects of low \( \dot{V}_a/Q \) ratios in the shunt calculations using 100% oxygen. A system employing two compartments is analysed, and a graphical technique is presented which allows calculation of the ventilation, perfusion and alveolar volume of each compartment. Comparisons are made between single- and 2-compartment analyses, and it is shown that the single-compartment model will underestimate the true \( \dot{V}_a/Q \) ratio except in very special cases. Where possible, the results for 2-compartment systems are extended to \( N \) compartments. Clinical application of the methods described is facilitated by establishing a steady-state tracer distribution with a constant tracer infusion. Such an equilibrium condition is not required, but reduces the number of tracer sample measurements to four.

Keywords—Multicompartment analysis of the lung

Symbol definitions—Multicompartment analysis of the lung

\( C_b = \text{concentration of tracer in blood, amount/ml, amount/g} \)
\( M = \text{amount of tracer injected, g, cpm, ml, etc.} \)
\( \dot{Q} = \text{blood flow, ml/s} \)
\( r = \text{fractional recovery of tracer (dimensionless)} \)
\( t = \text{time, s} \)
\( i = \text{transit time, s} \)
\( T = \text{time of one complete respiratory cycle, s} \)
\( V = \text{gas volume within the control surface, ml} \)
\( \dot{V}_a = \text{alveolar ventilation, ml/s} \)
\( V_B = \text{gas volume at end expiration within the control surface, ml} \)
\( \bar{V}_B = \text{average gas volume during breathing within the control surface, ml} \)
\( V_E = \text{gas volume expired during one respiratory cycle, ml} \)
\( V_H = \text{gas volume within the control surface during breath holding, ml} \)
\( \lambda_b = \text{gas (tracer) partition coefficient between blood and air} \)

Subscripts
\( A = \text{alveolus, alveolar gas} \)
\( Kr = \text{krypton 85} \)
\( S = \text{shunt} \)
\( Xe = \text{xenon 133} \)
\( o = \text{output from control volume} \)

1 Introduction

Previous work has described the use of intravascular tracers (indocyanine green, iodoantipyrine, and xenon 133) for estimating alveolar ventilation and volume in a single-compartment lung model with a uniform ventilation/perfusion ratio (REID and HECHTMAN, 1973).

However, it is well known that even in normal lungs this model is not strictly correct (WEST, 1962). This paper extends the applicability of our previous results to cases of anatomic shunts. Such shunts include blood flow to areas of atelectasis, to alveoli which are air filled but not ventilated, such as might occur distal to bronchial obstruction, and to ventilated lung elements with diffusion block. A 2-compartment system is also presented and extended to \( N \) compartments. Measurements of anatomic shunt or ventilation and perfusion and alveolar volume for each region in the 2-compartment system are described for xenon and krypton tracers.

2. General comments

Our previous work with intravascular tracers in single-compartment lung models yielded the following results (REID and HECHTMAN, 1973):

Nonventilated (breath-holding) lung without diffusion:

\[
V_H \simeq \lambda_b \dot{Q} i 
\]

(1)
Constant (nonpulsatile) air flow without diffusion:

\[ \dot{V}_A \simeq \lambda_b \dot{Q} \left( \frac{1}{r} - 1 \right) \]  

\[ \dot{P}_b \simeq \lambda_b \dot{Q} \frac{i}{r} \]  

Oscillatory (period \( T \) seconds) air flow without diffusion:

\[ \dot{V}_A = \frac{V_E}{T} = \lambda_b \dot{Q} \left( \frac{1}{r} - 1 \right) \]  

\[ \dot{V}_b \simeq \lambda_b \dot{Q} \left( i - \frac{T}{2} \right) \left( \frac{1}{r} - 1 \right) \]  

\( V_H \) correlates with functional residual capacity. \( \dot{V}_A \) and \( \dot{V}_b \) correlate with alveolar ventilation and lung gas volume distal to, and including, respiratory bronchioles, respectively. The fractional recovery of tracer, \( r \), following a bolus injection of tracer of mass \( M \) into the right heart is the ratio of the total mass of tracer recovered at the aorta (without recirculation) to \( M \). Alternatively, a constant infusion of tracer can be used to establish a steady-state tracer distribution during ventilation, in which case \( r \) is the ratio of the concentrations of tracer in a systemic artery to that in the right heart. Tracer is removed from the lung only by ventilation and perfusion. Any loss by diffusion through lung tissue is neglected to simplify the results presented.

Transit time \( i \) is defined by

\[ i = \int_{\infty}^{\infty} \frac{C_b \dot{Q} t dt}{C_b \dot{Q} dt} \]  

where \( C_b \) is the tracer concentration at the systemic arterial sampling site, and \( \dot{Q} \) is the total pulmonary blood flow. The effects of vessel transit delays may be cancelled by substituting \( \Delta t = i - \text{(indocyanine green mean transit time)} \) for \( i \) wherever applicable. The principle of mass conservation governs the distribution of tracer.

Lung blood and tissue volumes are neglected in eqns. 1, 3 and 5 to simplify subsequent results, although there is no theoretical requirement for this. In addition, anatomic and physiologic respiratory dead space are not measured by eqns. 2-5. These effects are therefore neglected. Justification for these approximations is discussed in a companion paper (Reid and Hechtman, 1974a).

Perfect mixing of intravascularly injected tracer with blood is assumed so that the tracer mass is distributed among the vascular paths in the multi-compartment system in proportion to the path flow rates. Total blood flow \( \dot{Q} \) is measured using standard dye-dilution techniques.

3 Anatomic shunt

Fig. 1 is the model to be analysed. Tracer is injected at \( i' \) and sampled at \( o' \), and a solution for \( \dot{V}_A \) and \( \dot{Q}_s \) is sought. The necessary equations follow from eqn. 4, the fact that a compartment with a pure anatomic shunt will have full tracer recovery and the principle of mass conservation:

\[ \dot{Q} = \dot{Q}_A + \dot{Q}_S \]  

\[ r_s = 1 \]  

Combining these equations leads to

\[ r = \frac{\dot{Q} - \dot{Q}_A}{\dot{Q}} \left( \frac{\dot{V}_A \lambda_b \dot{Q}_A}{1 + \dot{V}_A \lambda_b \dot{Q}_A} \right) + \frac{1}{1 + \dot{V}_A \lambda_b \dot{Q}_A} \]