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Thoughts and Progress

It is the goal of this section to publish material that provides information regarding specific issues, aspects of artificial organ application, approach, philosophy, suggestions, and/or thoughts for the future.

Sweep Gas Flowrate and CO_2 Exchange in Artificial Lungs

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Abstract: A simple analysis and graphic result are presented for characterizing the dependence of CO_2 exchange on the sweep gas (ventilating gas) flowrate in artificial lungs. The analysis requires no knowledge of the device-specific mass transfer characteristics of an artificial lung, nor does it require detailed mathematical modeling or computer simulation. Rather, it uses appropriate normalization to establish generic features of the gas flow dependency of CO_2 exchange that are applicable to all artificial lung devices. Principal results are that the transition from relatively gas flow-sensitive to gas flow-insensitive CO_2 exchange occurs at sweep gas flowrates of approximately 40–60 times the CO_2 exchange rate. Achieving a CO_2 exchange rate within 85% of maximal (for a given oxygenator and blood-side conditions) requires a sweep gas flowrate of no less than approximately 50 times the nominal CO_2 exchange rate. When the sweep gas flowrate is less than 20 times the CO_2 exchange rate, CO_2 exchange is highly gas flow dependent and less than one-half the maximal possible rate. **Key Words:** Artificial lungs—CO_2 exchange—Extracorporeal circulation.

The level of gas exchange within membrane-based artificial lung devices depends directly on the flowrate of the oxygen sweep gas (ventilating gas) through the device. This is the case because increasing the sweep gas flowrate reduces the accumulation of CO_2 along the sweep gas pathway. Therefore, the fractional concentration of CO_2 in the sweep gas is lowered while that for O_2 is raised, resulting in both cases in larger partial pressure gradients for diffusional exchange between blood and gas phases. The larger partial pressure gradients translate directly into larger gas exchange rates. The exchange rate for CO_2 is appreciably more sensitive to sweep gas flowrate than is that for O_2 because the nominal partial pressure gradient for CO_2 exchange is nearly 20 times less than that for O_2 exchange. Thus, a given increase in CO_2 along the sweep gas pathway produces a larger percentage loss in the P_{CO_2} exchange gradient compared with the percentage loss in the P_{O_2} exchange gradient.

This paper presents a simple analysis and graphic result for characterizing the effect of sweep gas flowrate on CO_2 exchange in artificial lungs. The analysis and its application require no detailed knowledge of the blood-side or membrane mass transfer characteristics of the artificial lung device nor of the gas flow or blood flow pathways through the device. Neither does it require detailed mathematical or computer modeling of the transport processes ongoing within the device. Rather, the analysis exploits a useful normalization to simply relate the CO_2 exchange rate within artificial lungs to the sweep gas flowrate, independent of device-specific flow and mass transfer complexities.

Simple analysis of CO_2 exchange and sweep gas flow

Consider an incremental (differential) area of exchange surface, dA, along the gas flow pathway within the artificial lung device. The rate of CO_2 exchange, $d\dot{V}_{CO_2}$ through dA is given by the following equation:

$$d\dot{V}_{CO_2} = K dA \, (P_{CO_2}{}^{b} - P_{CO_2}{}^{g}) \qquad (1)$$

where $P_{CO_2}{}^{b}$ and $P_{CO_2}{}^{g}$ are the CO_2 partial pressures in the blood and gas phases, respectively, that contact dA, and K is the mass transfer coefficient between these two phases. The value of K depends principally on CO_2 diffusion through blood-side boundary layers adjacent to the exchange surface and, to a lesser extent, on diffusion through the membrane itself (1). As a result, K depends on blood flowrate and blood flow patterns through the oxygenator as well as on fiber permeability and fiber orientation to the blood flow stream. Diffusion

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through the *gas phase* is sufficiently rapid, however, that K is essentially independent of gas flow and related gas phase indices (1). Integrating Eq. 1 over the entire exchange surface, A, of the artificial lung yields

$$\dot{V}_{CO_2} = KA(\bar{P}co_2{}^{b} - \bar{P}co_2{}^{g}) \quad (2)$$

where $\bar{P}co_2{}^{b}$ and $\bar{P}co_2{}^{g}$ are the *average* CO_2 tensions in the blood and gas phases, respectively.

For a given artificial lung device and blood-side operating conditions (that is, a given K and A), the maximum rate of CO_2 exchange, $\dot{V}^{max}_{CO_2}$, occurs when sweep gas flowrate is sufficiently high that CO_2 accumulation is negligible and $\bar{P}co_2{}^{g}$ equals 0. Thus $\dot{V}^{max}_{CO_2}$ equals $K\,A\,\bar{P}co_2{}^{b}$, and the CO_2 exchange rate at smaller sweep gas flowrate can be normalized to this rate to obtain:

$$\frac{\dot{V}_{CO_2}}{\dot{V}^{max}_{CO_2}} = 1 - \frac{\bar{P}co_2{}^{g}}{\bar{P}co_2{}^{b}} \quad (3)$$

The immediate utility of the normalization is that the device-specific parameters, K and A, are eliminated. The normalized rate of CO_2 exchange (Eq. 3) can be explicitly related to the sweep gas flowrate, Q_{gas}, by determining how $\bar{P}co_2{}^{g}$ is affected by Q_{gas}. The CO_2 partial pressure varies along the gas flow pathway from $Pco_2{}^{g} = 0$ at the sweep gas inlet (assuming a 100% O_2 sweep gas) to some value $P_{CO_2}{}^{o}$ at the gas phase outlet. Assuming a monotonic increase from 0 to $Pco_2{}^{o}$, a reasonable approximation for the average CO_2 partial pressure along the gas pathway is $\bar{P}co_2{}^{g} = \frac{1}{2}Pco_2{}^{o}$. In addition, an overall mass balance on CO_2 in the gas phase requires that $\dot{V}_{CO_2} = Q_{gas}\,(Pco_2{}^{o}/P_O)$ where P_O is the total gas pressure at the sweep gas outlet. Using these relations (to substitute for $\bar{P}co_2{}^{g}$), Eq. 3 can be rewritten as

$$\frac{\dot{V}_{CO_2}}{\dot{V}^{max}_{CO_2}} = 1 - \frac{P_O}{2\,\bar{P}co_2{}^{b}}\frac{1}{Q_{gas}/\dot{V}_{CO_2}} \quad (4)$$

Thus, a simple explicit relationship exists between the suitably normalized CO_2 exchange rate and sweep gas flowrate in an artificial lung. The relationship is essentially independent of the blood-side flow and mass transfer characteristics of the artificial lung device (Blood side characteristics do affect the average CO_2 partial pressure in blood. As $\bar{P}co_2{}^{b}$ is nominally much smaller than P_O, however, the typical resulting influence on normalized exchange rate is minor).

CO_2 exchange versus sweep gas flowrate

The predicted relationship between the normalized CO_2 exchange rate and sweep gas flowrate is graphically presented in Fig. 1. Here, conditions are chosen that are relevant to extracorporeal oxygenation in which the sweep gas exhausts at atmospheric pressure (that is, $P_O = P_{atm} = 760$ mm Hg). Curves are displayed for several relevant mean blood $\bar{P}co_2{}^{b}$ values of 40, 50, and 60 mm Hg. Several features of the predicted relationship are worth noting. Principally, a marked transition exists between relatively sweep flow-sensitive and sweep flow-insensitive CO_2 exchange. The transition occurs when the sweep gas flowrate is approximately 40–60 times the CO_2 exchange rate. The rate of CO_2 exchange essentially plateaus to within 85% of the maximal rate (all others factors being constant) when sweep gas flowrate is about 50 times the CO_2 exchange rate or higher. Conversely, when sweep gas flowrates fall below about 20 times the CO_2 exchange rate, the CO_2 exchange rate is less than one-half its maximal rate and depends sharply on sweep gas flowrate.

In application, the results of the analysis provide useful generic criteria for artificial lung design and operation. For example, if the determined rate of

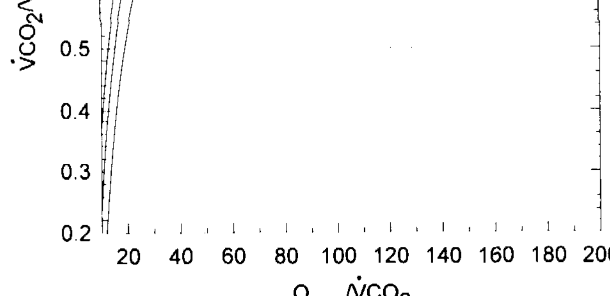

FIG. 1. The normalized CO_2 exchange rate versus normalized sweep gas flowrate is shown. Results are displayed for mean blood CO_2 tensions of 40, 50, and 60 mm Hg.

CO_2 exchange in an oxygenator is 200 ml/min, and the sweep gas flowrate used is 10 L/min, then, regardless of the device, the CO_2 exchange rate is close to maximal for the given blood-side conditions tested. Conversely, the same exchange rate for a sweep gas flowrate of 4 L/min indicates that CO_2 exchange is less than one-half maximal and could be adjusted by relatively small changes in the sweep gas flowrate. As another application, we are designing an intravenous artificial lung for supplemental respiratory support (2), which will require an ultimate CO_2 exchange rate of 130 ml/min. Our analysis tells us that the sweep gas flowpath should be designed to a minimum flow specification of 6.5 L/min to maximize the potential for accomplishing the requisite exchange.

In artificial lung practice it is customary to gauge appropriate sweep gas flowrates by some multiple of blood-side flowrate. The analysis and results given here indicate that additional insight into CO_2 exchange can be gained by gauging sweep gas flowrate to the nominal CO_2 exchange rate. The normalizations arising from the simple analysis allow important features of flow-dependent CO_2 exchange to be generically established without knowledge of the specific mass transfer characteristics of the particular artificial lung device under consideration.

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