EFFECT OF GAS CHANNEL HETEROGENEITY ON THE CARBON DIOXIDE OUTPUT RATE OF MEMBRANE OXYGENATORS

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Standard efficiency is an important functional parameters of membrane oxygenators. Standard efficiency of membrane oxygenators is determined, for example, by the AAMI Standard [5], and it is estimated by the amount of oxygen absorbed by blood or by the carbon dioxide removal from blood, whichever is the rate-limiting process. Study of processes both in individual gas channels and in the oxygenator as a whole [1, 2, 4] revealed that oxygen transport is the rate-limiting process in modern membrane oxygenators with continuous homogeneous high-permeability separating membranes. However, in experimental measurements of standard efficiency, carbon dioxide gas removal is sometimes a rate-limiting process. This discrepancy may be caused by inhomogeneous distribution of ventilation gas in parallel gas channels. The inhomogeneous distribution affects carbon dioxide gas removal more significantly than oxygen transport, because partial pressure bias between blood and gaseous phase for carbon dioxide is 15-20 times less than for oxygen. Therefore, the carbon dioxide gas removal is more sensitive to variation of ventilation parameters. It is shown below in this work that decreased carbon dioxide gas removal from inappropriately ventilated channels is not compensated by the increase of the carbon dioxide gas removal from the channels with ventilation rate higher than average.

Consider the carbon dioxide flow rate dependence on the flow rate g of the ventilation gas (or gas mixture) in one channel. The mass balance equation for the element dS of the mass-exchange surface of the gas channel can be written as:

$$g dP/P_0 = K(\bar{P} - P)dS, \tag{1}$$

where g is the oxygen (or gas mixture) flow rate in the channel; P is the partial pressure of carbon dioxide in the gas phase; P_0 is the total pressure in the channel (usually, atmospheric pressure); K is the mean coefficient of mass transfer of carbon dioxide, which takes into account the diffusion resistance of the blood layer, permeability of the membrane separating blood and gas, and gas phase resistance; $\bar{P}$ is the mean partial pressure of carbon dioxide gas averaged over the channel cross-section.

Because gas phase resistance is significantly less than diffusion resistance of the membrane and layer of blood, the value of K is virtually independent of the conditions of gas channel ventilation. Therefore, the effect of changes of g on the total flow of carbon dioxide is mediated by the changes of partial head $(\bar{P} - P)$ alone.

Under physiological conditions the value of $\bar{P}$ varies little along the mass-exchange surface (approximately from 40 to 45 mm Hg). Therefore, this value can be taken as constant. Therefore, if $P(0) = 0$, integration of Eq. (1) and calculation of carbon dioxide gas flow along the entire mass-exchange surface S gives:

$$J_{CO_2} = g[C(s) - C(0)] = g\frac{\bar{P}}{P_0}\left(1 - e^{-\frac{KSP_0}{g}}\right), \tag{2}$$

where $C = P/P_0$ is the CO_2 concentration in the gaseous phase.

It is seen from Eq. (2) that the outflow of CO_2 rises with g and tends to the limiting value $KS\bar{P}$. Therefore, $P \to 0$ and the difference $(\bar{P} - P)$ is maximal.

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Equations (1) and (2) are valid for a single gas channel. Consider carbon dioxide transfer from blood to a system of gas channels with similar or dissimilar hydraulic characteristics.

1. If all channels are similar and collector inhomogeneity is absent, the flow of ventilation gas is uniformly distributed over the gas channels and carbon dioxide gas outflow from the oxygenator is merely proportional to the number of channels N:

$$J_{CO_2} = NJ_{CO_2} = J_0.$$

2. Let n gas channels have hydraulic resistance ρ_1 and the other $N - n$ gas channels have hydraulic resistance ρ_2. Then, the total oxygen flow G is distributed between the channels of two types in the ratio ρ_1/ρ_2, i.e., $g_1/g_2 = \rho_1/\rho_2$, where g_1 and g_2 are the gas flows through the gas channels of corresponding type. In addition, the equation $g_1n + g_2(N - n) = G$ should be also observed. Therefore, the values of g_1 and g_2 can be calculated and Eq. (2) can be recast as:

$$\begin{gathered} J_{CO_2} = \frac{\bar{P}G}{P_0[\rho_2 n + \rho_1(N-n)]} \times \\ \times [\rho_1(N-n)(1 - e^{-\lambda/\rho_1}) + \rho_2 n(1 - e^{-\lambda/\rho_2})], \\ \lambda = \frac{KSP_0}{G}[n\rho_2 + (N-n)\rho_1]. \end{gathered} \tag{3}$$

The ratio of the calculated value of J_{CO_2} to the total flow of carbon dioxide gas J_0 under conditions of uniform distribution of ventilation gas over the gas channels is a characteristic of channel inhomogeneity effect[1]:

$$\begin{gathered} \lambda = \frac{J_{CO_2}}{J_0} = \frac{n_1[1 - e^{-\alpha(n_1 + \gamma n_2)}] + n_2\gamma[1 - e^{-\alpha(n_1/\gamma + n_2)}]}{(n_1 + \gamma n_2)(1 - e^{-\alpha})}, \\ \gamma = \rho_1/\rho_2,\ \alpha = KSP_0N/G,\ n_1 = n/N,\ n_2 = \frac{N-n}{N}. \end{gathered} \tag{4}$$

If the hydraulic resistance of one type of channels is high, e.g., $\rho_2 \to \infty$, $\gamma \to 0$, the channels are completely obstructed, and it follows from Eq. (4):

$$\lambda = \frac{1 - e^{-\alpha(n/N)}}{1 - e^{-\alpha}}.$$

If the flow rate of ventilation gas and ρ_2 increase coincidentally, i.e., $\gamma \to 0$, $\alpha \to 0$, it follows from Eq. (4):

$$\lambda = n_1 + \frac{n_2\gamma}{n_1\alpha}(1 - e^{-n_1\alpha/\gamma}). \tag{5}$$

Therefore, λ depends on the ratio of the increase of the ρ_2 and G values. If $\alpha/\gamma \to 0$, $\lambda = n_1 + n_2 = 1$. If $\alpha/\gamma \to \infty$, i.e., channels are obstructed virtually completely at high but finite change of G, $\lambda = n_1 = n/N$. If G is small, $\alpha \to \infty$, $\lambda \to 1$ (the values of α measured during the testing of the MOST-162 oxygenators vary from 0.3 to 0.5).

3. Assume that the oxygen flow through gas chambers obeys normal distribution. Then, the density of the channels with the flow rate g is $n(g) = Ae^{-(g - \bar{g})^2/2\sigma^2}$, where dispersion σ^2 is the characteristic of the curve $n(g)$ width. The total flow of carbon dioxide gas is:

$$J_{CO_2} = \int_0^\infty j(g)n(g)dg, \tag{6}$$

where $j(g)$ is defined by Eq. (2). The distribution parameters A and $\bar{g}$ can be obtained from the normalization condition:

$$\int_0^\infty n(g)dg = N,\ \int_0^\infty gn(g)dg = G.$$

[1]Channel inhomogeneity is defined as the spread of hydraulic resistance of the channels.

Therefore:

$$A = N\Big/\int_0^{\infty} e^{-(g-\bar{g})^2/2\sigma^2}dg,$$

$$\frac{N\int_0^{\infty} g e^{-(g-\bar{g})^2/2\sigma^2}dg}{\int_0^{\infty} e^{-(g-\bar{g})^2/2\sigma^2}dg} = G. \tag{7}$$

Then, Eq. (6) can be recast as:

$$J_{CO_2} = \frac{N\bar{P}g_0}{P_0\int_0^{\infty} R(x)\,dx}\cdot\int_0^{\infty} x(1-e^{-\alpha/x})R(x)\,dx,$$

where $x = g/g_0$; $R(x) = e^{-\frac{v^2}{2}\cdot(g_0x/\bar{g}-1)^2}$,

$$v = \bar{g}/\sigma,$$

and λ can be calculated from:

$$\lambda = \frac{\int_0^{\infty} x(1-e^{-\alpha/x})R(x)\,dx}{(1-e^{-\alpha/x})\int_0^{\infty} xR(x)\,dx}. \tag{8}$$

If the distribution function $n(g)$ is shifted sufficiently far to the right from the origin of coordinates (positive g), $g \to 0$, $n(g)$ is close to zero and limits of integration can be extended to $(-\infty, +\infty)$. This is also obviously valid if the dispersion is low and $n(g)$ rapidly declines to both directions from the maximum value at $g = \bar{g}$. In this case:

$$A = N\Big/\int_{-\infty}^{\infty} e^{-(g-\bar{g})^2/2\sigma^2}dg = N/\sqrt{2\pi}\sigma,$$

$$\frac{N}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty} g e^{-(g-\bar{g})^2/2\sigma^2}dg = N\bar{g} = G,\ \bar{g} = \frac{G}{N} = g_0. \tag{9}$$

Substitution of found values of A and g into Eq. (8) gives:

$$J_{CO_2} = \frac{Ng_0v}{\sqrt{2\pi}}\cdot\frac{\bar{P}}{P}\int_0^{\infty} x(1-e^{-\alpha/x})R(x)\,dx,$$

and the equation for λ is:

$$\lambda = \frac{v}{\sqrt{2\pi}}\int_0^{\infty} x(1-e^{-\alpha/x})R(x)\,dx/(1-e^{-\alpha}). \tag{10}$$

Estimate limiting values of λ. It follows from Eq. (10) that at $\alpha \to 0$ and $\alpha \to \infty$, $\lambda \to 1$. It was shown in [5] that if $\alpha \to \infty$, then:

$$\lambda \simeq 1 - 8e^{-v^2/2}\cdot\frac{ve^{-\alpha/2}}{\alpha\sqrt{2\pi}}.$$

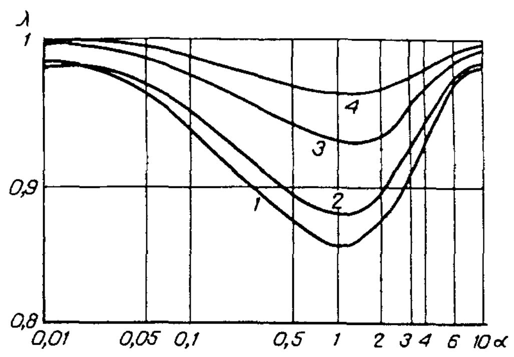

Fig. 1. Dependence of dimensionless flow of carbon dioxide gas λ on parameter α at different values of ν: 1) 0.5; 2) 1; 3) 2; 4) 3.

The results of numerical calculation of λ from Eq. (8) as a function of parameters α and ν are given in Fig. 1.

It is seen from Eqs. (8) and (10) that $\lambda < 1$ at any α. Therefore, possible heterogeneity of gas channels, resulting in nonuniform distribution of gas flow over the channels, may cause insufficient efficiency of carbon dioxide removal from oxygenators.

The derived equations allow the hydraulic resistance dispersion value of gas channels to be connected with the efficiency of carbon dioxide removal from oxygenators.

The effect of the heterogeneity of ventilation gas distribution over parallel gas channels on the efficiency of carbon dioxide removal from oxygenators was experimentally tested with the MOST oxygenators. Each gas channel in this case is formed by a gas chamber, the hydraulic characteristics of the chamber being specified before the assembly. Hydraulic resistance is an example of such hydraulic characteristic:

$$\rho = \Delta P/g,$$

where g is the flow rate of the ventilation gas through the channel; ΔP is the pressure drop in the channel at the flow rate g.

A distribution of ρ over the tested chambers was first found in these experiments, and the outflow of carbon dioxide from the oxygenator made from these chambers was then measured.

The chamber distribution over the ρ value was experimentally measured in a group of 150 chambers of the same technological lot. Special emphasis was placed on the similarity between the flushing conditions of the chambers before and after oxygenator assembly.

Because the efficiency of carbon dioxide removal from the oxygenator was assessed by the function of chamber distribution over the flow rate of ventilation gas, the ρ_i values should be converted into the g_i values of the gas flow rate through the ith chamber of the oxygenator.

The gas flow rate through the ith chamber is determined by the following equation:

$$g_i = \frac{G}{\rho_i \sum_1^N 1/\rho_K}, \tag{11}$$

where G is the total flow rate of ventilation gas through the oxygenator; N is the number of chambers of the oxygenator.

The values of N and G in oxygenators of different type differ, although the mean gas flow rate through one chamber $g = G/N$ is usually maintained constant.

Then, Eq. (11) can be recast as:

$$g_i = g \cdot \bar{\rho}/\rho_i, \tag{12}$$

where $1/\bar{\rho} = \frac{1}{N}\sum_1^N 1/\rho_i$ is calculated for the selected sample with $N = 150$.

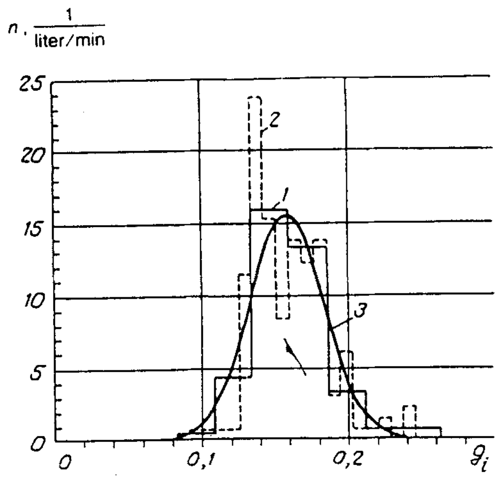

Fig. 2. Histogram of g_i for two divisions Δ: 1) $\Delta = \sigma/2$; 2) $\Delta = \sigma/6$; 3) normal distribution with $\bar{g}$ = 0.16 liter/min, σ = 0.0258 liter/min.

The calculations show that the mathematical expectation of the gas flow rate g in a sample of chambers and dispersion estimate are:

$$\bar{g} = \frac{1}{N}\sum_1^n g_i = 0.16 \text{ liter/min}, \qquad \sigma = \left[\frac{1}{N}\sum_1^N (g_i - \bar{g})^2\right]^{1/2} = 0.0258 \text{ liter/min},$$

respectively.

The histogram of g_i for two divisions (intervals on the gas flow rate axis of $\sigma/2$ and $\sigma/6$) are shown in Fig. 2. In case of smaller division length the pattern of density distribution is more complicated, because the technological factor is not random within a small sample of chambers.

The curve of the density of normal distribution with the calculated parameters $\bar{g}$, σ is plotted on the same frame of reference:

$$f(g) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(g-\bar{g})^2/2\sigma^2}.$$

The effect of inhomogeneity of gas channels on the carbon dioxide gas removal from oxygenators was experimentally tested with the MOST oxygenators. A gas mixture with the CO_2 content close to that in venous blood was supplied to the blood channel of the oxygenators. The gas channels of the oxygenators were flushed with oxygen, the oxygen flow rate being varied during the testing. Carbon dioxide transfer from liquid channels to gas channels through a membrane and further removal from the oxygenator was monitored by the CO_2 content in the liquid channels. The CO_2 content was measured by a capnograph. Total flow of carbon dioxide was calculated from

$$J_K = G_K(1 + C_{1K} + C_{2K})(C_{2K} - C_{1K}), \tag{13}$$

where G_K is the flow rate of oxygen (or another gas) flushed through the gas channels; $C_{1K,2K}$ is the carbon dioxide fraction at the input and output of the gas channel, respectively.

It is evident that the total amount of carbon dioxide removed from the oxygenator rises with oxygen flow rate G, and if $G \to \infty$, the value of J should corresponds to the rate of carbon dioxide removal from the oxygenator with homogeneous chambers J_∞ (uniform distribution of oxygen flow over gas channels). Comparison between J_∞ divided by the mean partial pressure bias between liquid and gas channels (i.e., mass transfer coefficient) and similar value measured under standard working conditions for each type of oxygenator allows the decrease of the oxygenator efficiency caused by gas channel heterogeneity to be determined.

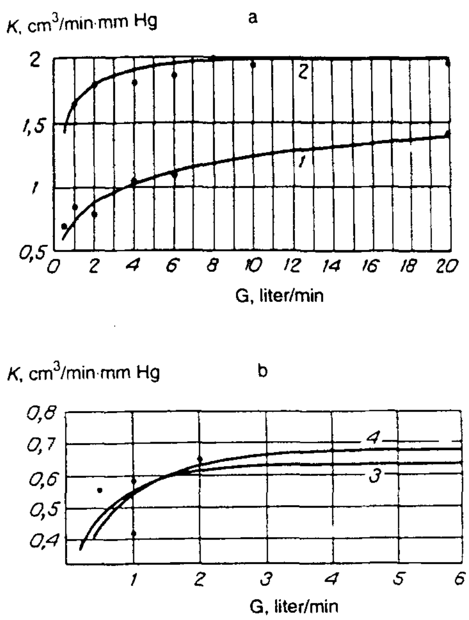

Fig. 3. Dependence of mass transfer coefficient $K = J_{CO_2}/\Delta P$ on ventilation oxygen flow rate G in oxygenators of two types: MOST-1903 oxygenator with 15 chambers (a, curves 1 and 2) and MOST-1801 pediatric oxygenator with 5 chambers (b, curves 3 and 4).

The mass transfer coefficients of carbon dioxide $K = J/P$ calculated for four different types of oxygenators as a function of oxygen flow rate G are shown in Fig. 3. The curves 1 and 2 in Fig. 3a show the dependences measured in the MOST-1903 oxygenators with 15 chambers. The curves 3 and 4 in Fig. 3b show the dependences measured in the MOST-1801 pediatric oxygenators with 5 chambers. The flow rate of the ventilation gas (oxygen) through the oxygenators was 2 and 1 liter/min, respectively.

It is seen that in the three considered cases (Fig. 3a, curve 2; Fig. 3b, curves 3 and 4) the value of K reaches its maximum at the highest tested values of gas flow rate G (20 and 6 liters/min for 15-chamber and 5-chamber oxygenators, respectively). The efficiency of the oxygenators under standard working conditions (ventilation rate 2 and 1 liter/min, respectively) is of about 85% of the maximum possible. These results and also the fact that the plateau of K is reached relatively rapidly are indicative of substantial homogeneity of the gas channels of the oxygenators. On the contrary, the value of K of curve 1 (see Fig. 3a) continuously rises over the whole range of G variation, and it does not yet reach a maximum even at G = 20 liters/min. Rather slow transition to the plateau and lower than in curve 2 value of K indicate low efficiency of the carbon dioxide removal from the oxygenator because of heterogeneity of its gas channels.

Conclusions

1. The dependence of efficiency of carbon dioxide removal from oxygenators on heterogeneity of gas channels was studies theoretically. It was shown that possible heterogeneity of ventilation gas (oxygen) distribution over the gas channels may decrease the efficiency of the oxygenators.

2. The hydraulic resistance of individual gas chambers was measured experimentally and the chamber distribution over the hydraulic resistance value was plotted. The distribution was shown to be adequately approximated by a normal distribution curve.

3. The technologically available homogeneity of the commercial MOST oxygenators was shown to be sufficient for effective removal of carbon dioxide.

4. It was shown in model experiments with the MOST oxygenators that the carbon dioxide removal efficiency can be improved by more uniform distribution of ventilation gas.

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