EXPERIMENTS ON GAS TRANSFER TO A FILM OF BLOOD THROUGH A MEMBRANE*

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The result of an increase in mean saturation of blood predicted by two mathematical models was verified by means of a series of experiments using cattle blood flowing in a 1.1 mm thick film, with flow rates ranging between 0.6 and 2.5 cc/min.

The use of the equation of O_2 transfer without taking into account the coupled CO_2 transfer leads to slightly conservative predictions, and experimental data fit the calculated values of saturation within an error of 5%. For very slow flow rates the deviations reach 10%.

The effectiveness of an artificial lung relies on the presence of a large interface between blood and oxygen. Such a surface may be created in different ways: (a) by dispersion of gas in a blood pool, as in the bubble artificial lung, (b) by spreading a blood film in a gas atmosphere, as in the film artificial lung and (c) by spreading the blood between gas-permeable membranes, as in the case of the membrane artificial lung.

This last one, the membrane artificial lung, seems to be the best perfusion equipment for preventing the lipoprotein denaturation that occurs at a free gas-blood interface during a time-consuming operation.

A mathematical model representing the process of transfer of oxygen to blood through a permeable membrane and carbon dioxide release from blood to the external gas atmosphere was obtained in terms of two coupled partial differential equations[3]

$$V_z \partial C_{O_2}/\partial z = D_{O_2} \partial^2 C_{O_2}/\partial x^2 \quad (1)$$

$$V_z \partial C_{CO_2}/\partial z = D_{CO_2} \partial^2 C_{CO_2}/\partial x^2 \quad (2)$$

A comparison was made between the numerical solution of the pair of mass-transfer equations and the solution of a single equation, assuming constant values of p_{CO_2} and pH. These solutions are referred to as cases 1 and 2, respectively.

A series of experiments was done to corroborate the results obtained from the mathematical models.

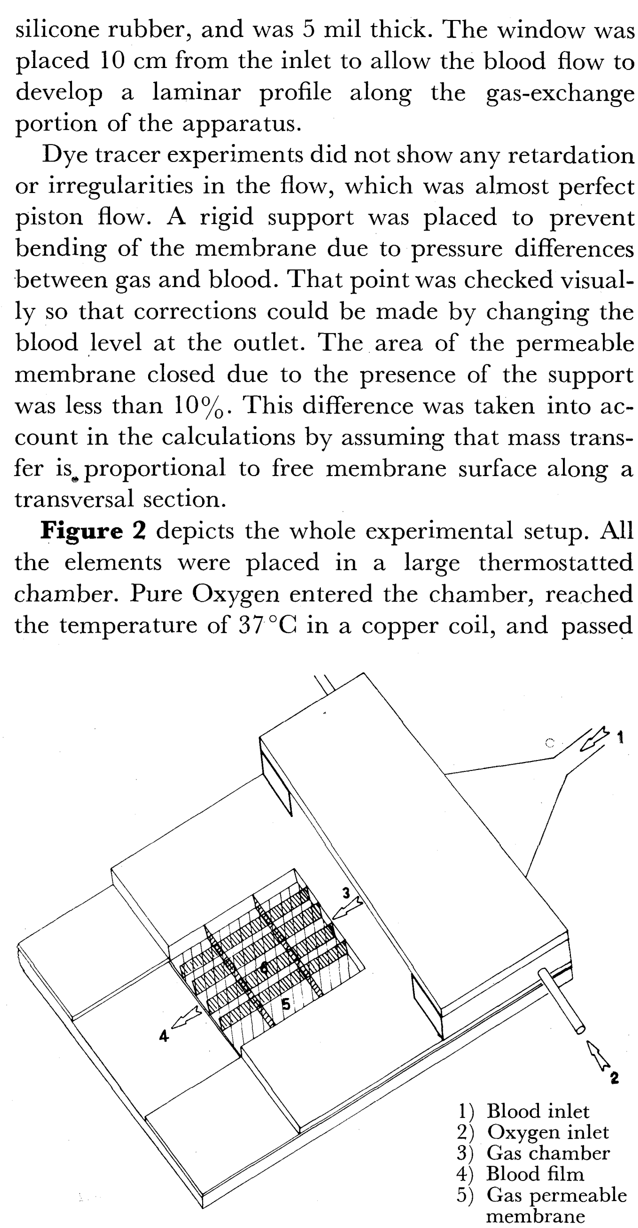
Experimental Apparatus

The transference unit shown in **Fig. 1** consisted of two chambers: a narrow 1.1 mm high chamber, within which the blood was flowing, and a larger chamber for the gas flow. A 15×6 cm window was drilled in the middle of the separation wall, and a gas-permeable membrane was placed there.

The membrane was made of Silastic Medical Grade silicone rubber, and was 5 mil thick. The window was placed 10 cm from the inlet to allow the blood flow to develop a laminar profile along the gas-exchange portion of the apparatus.

Dye tracer experiments did not show any retardation or irregularities in the flow, which was almost perfect piston flow. A rigid support was placed to prevent bending of the membrane due to pressure differences between gas and blood. That point was checked visually so that corrections could be made by changing the blood level at the outlet. The area of the permeable membrane closed due to the presence of the support was less than 10%. This difference was taken into account in the calculations by assuming that mass transfer is proportional to free membrane surface along a transversal section.

Figure 2 depicts the whole experimental setup. All the elements were placed in a large thermostatted chamber. Pure Oxygen entered the chamber, reached the temperature of 37°C in a copper coil, and passed



1) Blood inlet
2) Oxygen inlet
3) Gas chamber
4) Blood film
5) Gas permeable membrane
6) Membrane support

Fig. 1 Transference unit

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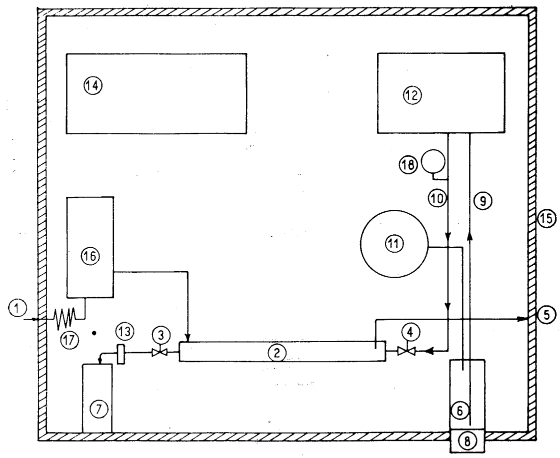


1) Oxygen inlet
2) Transference unit
3) Sampling point (outlet)
4) Sampling point (inlet)
5) Gas outlet
6) Blood reservoir
7) Processed blood
8) Magnetic stirrer
9) Blood to pump
10) Blood to transfer unit
11) Gas reservoir
12) Pump
13) Level control
14) Thermostatic system
15) Thermostated chamber
16) Oxygen-water bubbler
17) Copper coil
18) Capacitance

Fig. 2 Experimental setup

through a gas saturator before entering the transference unit. The gas flow rate was high enough to make CO_2 concentration negligible at the outlet of the chamber. Blood was stored in a flask where a magnetic stirrer prevented sedimentation of its components.

The gas over the blood in the reservoir was in equilibrium with it; thus, changes in the inlet conditions were due only to metabolic consumption of oxygen. Corrections in the calculations to account for these changes were small.

The blood was pumped with a peristaltic pump to the transference unit. Between the pump and the transference unit a capacitance was placed to attenuate the pulsations in the flow; at the low flow rates used, this was accomplished and tested by means of a dye-tracer experiment.

In order to prevent bending in the membrane, a special device was placed at the outlet of the transference unit to control the pressure in the blood chamber. Blood samples were taken at the inlet and outlet of the transference unit.

Experimental Procedure

Cattle blood, with heparin as anticoagulant, was used. The blood was drained from living oxen, thus obtaining venous conditions. Blood from killed oxen showed alterations in pH, perhaps due to stress effects and hypoventilation before decollation. Fresh blood, less than two days old, was always used.

The blood was preheated and then pumped at a steady rate through the transference unit. Before each run a volume of blood equal to three times the volume of the blood chamber was allowed to flow. A steady state was obtained both in flow profile and in mass transfer.

At the inlet and exit of the transference unit, samples were taken with hypodermic syringes. They were well shaken for homogenization and analyzed in a Type pHA 927b Radiometer, p_{O_2}, p_{CO_2}, and pH analyzer.

Once a day the hemoglobin content was evaluated by the Cianmetahemoglobin method, and the hematocrit was measured by centrifugation.

Twenty-one runs were carried out with whole blood, a typical value of hemoglobin concentration being $C_{Hb}=15$ gr%. Twenty-two runs were made adding Ringer solution to obtain $H=30$, that is, the value of hematocrit representative of the real conditions during usual surgical operations. A typical value of hemoglobin concentration in these runs was $C_{Hb}=9$ g/100 cc.

The flow rate varied from 0.5 to 2.5 cc/min and was measured volumetrically.

Results

The experimental results were expressed as mean saturation value; a comparison between cases 1 and 2 was made. The mean saturation is computed in the mathematical model in such a way that local supersaturation is allowed for, that is, that p_{O_2} may rise above the value needed for complete hemoglobin saturation. The mean saturation $\bar{s}$ has the property that when two equal volumes of blood are mixed, the resultant mean saturation is the arithmetic mean of the two original mean saturations. A mean saturation of 110% indicates that 100% of hemoglobin is saturated, and enough oxygen is dissolved in the plasma to cause 10% saturation of completely reduced blood[4].

In the calculations of the theoretical values of $\bar{s}$, the oxyhemoglobin-dissociation relationship for human blood was used, as described in ref. 3). The oxyhemoglobin dissociation relationship for cattle blood is slightly different but the results of gas transfer are almost the same. In general, results for any mammal should be similar, in the presence of a high oxygen-concentration gradient[4].

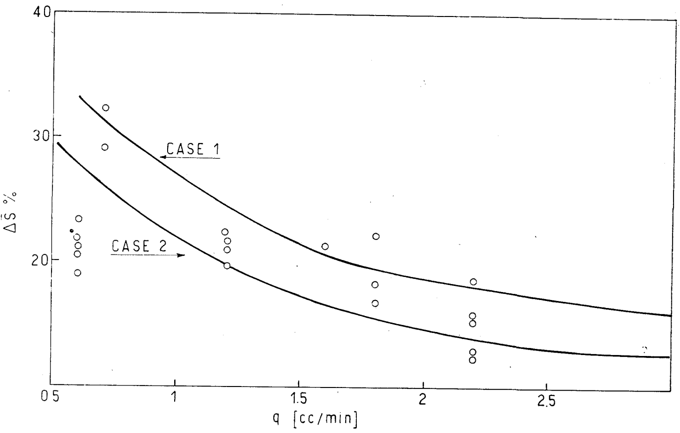
Such a gradient is present in this case, as can be seen in Figs. 3, 4 and 10 of ref. 3).

The values of oxygen and carbon dioxide diffusivities used for the calculation were obtained using Buckles'[1] ratio of diffusivity in blood to that in distilled water, and the data of solubility and diffusivity of carbon dioxide and oxygen from standard references[2].

Experimental Results

The saturation data are presented as $\bar{s}$, the increase in oxygen saturation, as a function of the blood flow rate for the values of hematocrit used: $H=42$% and 30%.

In **Fig. 3** the experimental data corresponding to $H=42$ with initial saturation $\bar{s}_0=58$% is plotted. In the same figure two theoretical lines were drawn for cases 1 and 2, respectively. In fact, the difference between cases 1 and 2 is small; about four units of saturation in cases where a representative value of $\bar{s}$ may be $\bar{s}=80$%. That means a difference of only 5%.



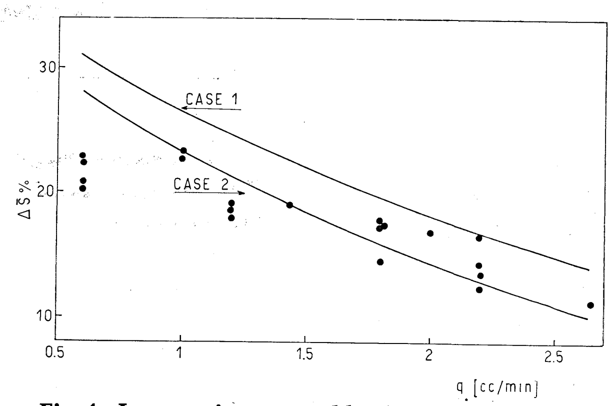


Fig. 4 Increase in average blood saturation $\bar{s}$ vs. blood flow rate, $H=30$

Fig. 3 Increase in average blood saturation $\bar{s}$ vs. blood flow rate, $H=42$

It may be seen that the data of saturation for low flow rates are well below the theoretical lines. That may be due to sedimentation of blood components at half a centimeter per minute blood velocity in some experiments. In that case, if the distribution of red cells is not homogeneous the mathematical model will fail.

In **Fig. 4** the experimental data corresponding to $H=30\%$ with initial saturation $\bar{s}_0=75\%$ is shown. As in Fig. 3, the data fit the theoretical predictions fairly well. Again a greater deviation is seen for low flow rates. In general, the experimental data fall between the two theoretical lines. Case 2 would give slightly conservative predictions of oxygen transfer. No influence of gas-phase mass transfer resistance was found, since gas flow rate did not change the oxygen uptake.

In **Fig. 5** all the experimental data are plotted against the predictions of case 2. Agreement is good within 5%. Some experimental points fall outside the 5% lines, but they correspond to very low flow rates. The largest deviation obtained in any case is 10%.

Conclusions

The basic process of oxygen and carbon dioxide transfer through a membrane to a film of blood was investigated. The results of increase in mean saturation of blood predicted by two mathematical models were verified by means of a series of experiments using cattle blood flowing in a 1.1 mm thick film, with flow rates ranging between 0.6 and 2.5 cc/min.

The use of the equation of oxygen transfer without taking into account the coupled carbon dioxide leads to slightly conservative predictions; and experimental data agree with the theoretical values within a 5% error for the average and a 10% error for very slow flow rates.

Acknowledgment

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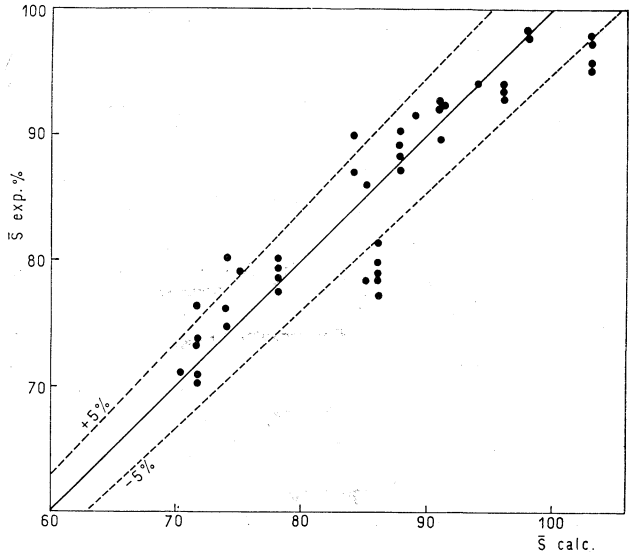

Fig. 5 Comparison between experimental data and $\bar{s}$ calculated with Eq.(1)

Nomenclature

C_{O_2}	= total oxygen conc.	[cc(STP)/cc]
C_{CO_2}	= total carbon dioxide conc.	[cc(STP)/cc]
C_{Hb}	= hemoglobin conc.	[gr/100cc]
D_{O_2}	= oxygen diffusivity	[cm²/sec]
D_{CO_2}	= carbon dioxide difusivity	[cm²/sec]
H	= hematocrit, the volume fraction of erythrocytes	
p_{O_2}	= partial pressure of oxygen	[mmHg]
p_{CO_2}	= partial pressure of carbon dioxide	
s	= percent saturation of hemoglobin	
s_0	= initial saturation	
s	= mean saturation	

Literature Cited

1) Buckles, R. G., E. W. Merrill and E. R. Gilliland: *AIChE J.*, **14**, 703 (1968)
2) Perry, J. H.: "Chem. Eng. Handbook", McGraw-Hill
3) Sosa, O. and J. C. Merchuk: *J. Chem. Eng. Japan*, **7**, 25 (1974)
4) Weissman, M. H. and Mockros: Proceedings of the American Society of Civil Eng., E. H. G., p. 225, Dec. 1967