
Prediction of Minimal Ventilation Requirements for Oxygenation in a Bubble and Membrane Blood Oxygenator During Cardiopulmonary Bypass

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Abstract

2300 Optiflo II and 80 Sci-Med blood oxygenator cardiopulmonary operative records were studied to define the semilogarithmic relationship between the PaO₂ and the gas-to-blood flow ratio or the percent FIO₂ respectively. A mathematical model was developed to consider the linear effects of oxygenator blood residence time, temperature, hematocrit and the continuously monitored venous inlet % O₂ saturation of hemoglobin on the slope and Y-intercept of the device semilog PaO₂ function curve.

The ventilation of five Optiflo II patient circuits (37 blood gas determinations) and five Sci-Med patient circuits (40 blood gases) ventilation was controlled by intrabypass evaluation of a mathematical statement as each of the four continuously monitored independent variables were altered. The formulae were solved to generate gas-to-blood flow ratios and FIO₂'s to yield PaO₂'s of 150 mmHg. The average resulting PaO₂ in the Optiflo II group = 158 ± 55 mmHg (mean ± 1 S.D.), the PaO₂ falling within 150 ± 60 mmHg 70.3% of the time. The average resulting PaO₂ in the Sci-Med group = 180 ± 59 mmHg, the PaO₂ falling within 150 ± 60 mmHg 67.5% of the time.

The minimal ventilation requirements to achieve blood oxygenation were quantitated, formulated, and tested with success.

Background

The four major determinants for *in vitro* blood oxygenator ventilation requirements are the blood oxygen carrying capability, the blood residence time in the artificial oxygenator, the venous inlet oxygen content, and the temperature at which the reaction is completed. (1-5) Hypothetically, the continuous knowledge of parameters reflecting change in the four determinants would allow prediction of minimal ventilation requirements for *in vitro* blood oxygenation. The results of intermittently sampling the percent hematocrit, blood flow, venous percent oxygen saturation of hemoglobin, patient nasopharyngeal temperature, and total gas flow on 2300 Optiflo II* or percent oxygen mixture on eighty Sci-Med** blood oxygenators were employed to construct a multivariant exponential model to predict the minimal oxygenation ventilation requirements.

Previously, the oxygenation ventilation requirements of various extracorporeal oxygenators could not be quantitated clinically. The patient's oxygen consumption rate never exactly equals the oxygen transfer rate of the extracorporeal oxygenator. Hence, the arterial blood oxygen content rarely stabilizes to allow clinical quantitation of oxygenator function by intermittent sampling. Retrospective study of a large oxy-

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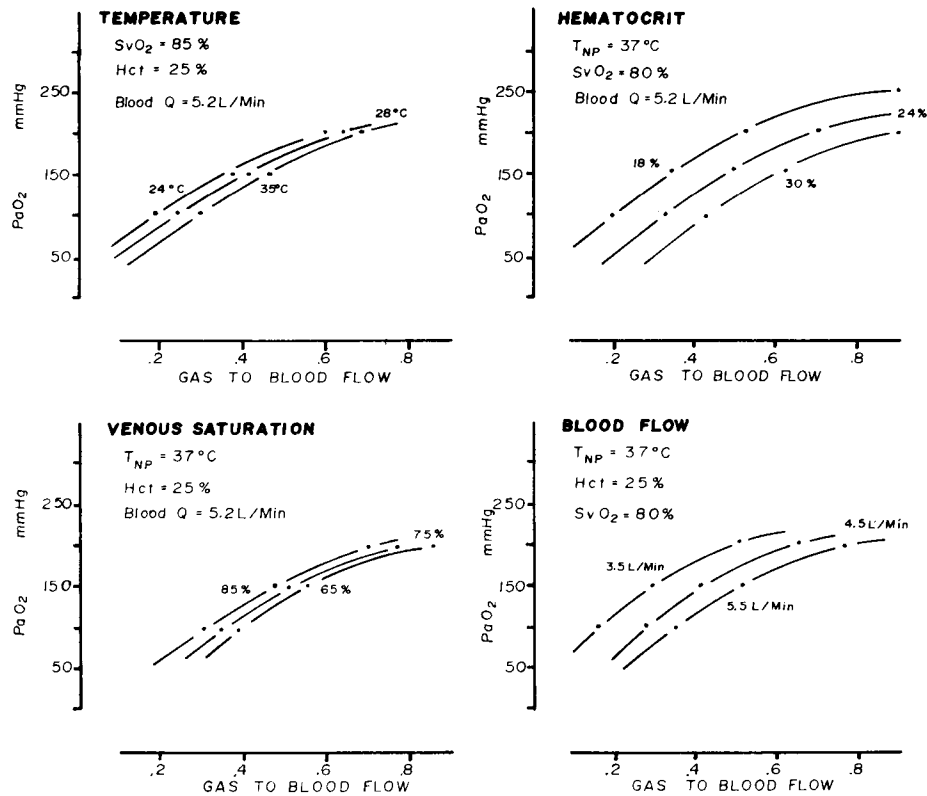


FIGURE 1. Optiflo II determinant isobars are plotted to demonstrate the effect of each variable on the bubbler gas-to-blood flow ratio versus PaO₂ function curve as evaluated by the hand held calculator predicting formula.

generator/device population allows the construction of function curves. Continuous monitoring of the four determinants of oxygenator ventilation requirement allows the prediction of a gas-to-blood flow ratio or FIO₂ necessary to achieve an adequate arterial blood PaO₂. The recent availability of the blood Oxy-Sat meter*** allows the continuous monitoring of the venous inlet percent oxygen saturation of hemoglobin.

Method

The oxygenator patient population data was collected. The arterial blood flow was used as an indicator of blood residence time in the bubble oxygenator. The blood flow rate was normalized to the membrane surface area in the Sci-Med group to account for oxygenator model differences. The arterial pO₂ was temperature corrected to the nasopharyngeal temperature which also served as the reference for the predicting

formula. (6) The venous blood pO₂ was used to calculate the venous percent oxygen saturation of hemoglobin to construct the equations. (7) The FIO₂ or gas-to-blood flow ratio and resulting PaO₂ were organized with the four main determinants data.

The data was organized to isolate the effects of a single determinant variable holding the other three determinants constant. The semilog family of curves for each single determinant's effect on the PaO₂ versus the FIO₂ to gas or blood flow ratio was quantitated. The effect of a single determinant variable change on the slope and Y-intercept of the PaO₂ function curve was also quantitated.

A formula following an exponential model was written to compile the singular effects of each determinant variable on the primary PaO₂ function curve for both devices. The formulae were entered into a hand-held calculator program format to predict the gas-to-blood flow ratio or FIO₂ necessary to yield a PaO₂ equal to 150 mmHg given specific entry values of the four ventilation requirement determinants. Figure One plots the formula isobars for each determinant's effect on the bubbler PaO₂ function curve. Some determinant

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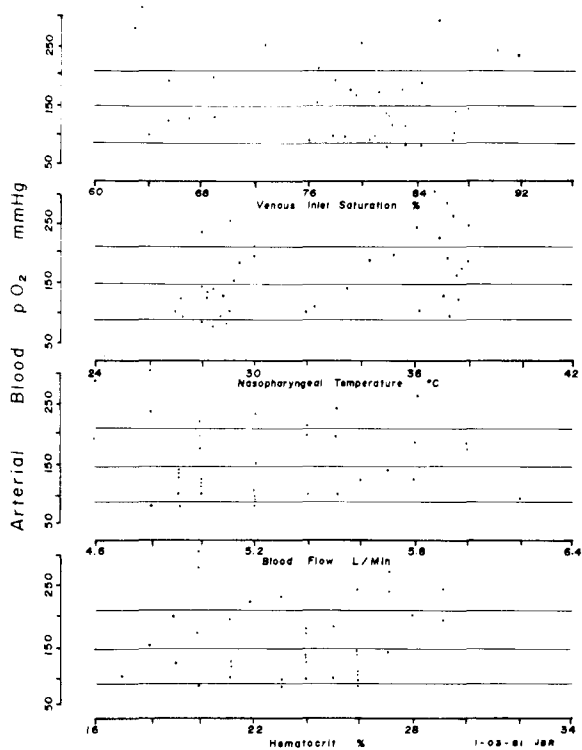


FIGURE 2. The resulting PaO₂'s (N = 37) by the gas-to-blood flow predicting formula for the Optiflo II blood oxygenator group are plotted against the specific values of the determinant variables employed in the test.

membrane oxygenator have been published previously (3,8).

The results of the predicting formulae were compared with patient oxygenator data used to construct them. The comparison yielded correlation coefficients

ranging from .62 to .81 with average predicted PaO₂ deviations of ± 35 to 45 mmHg.

Bypass was initiated slowly and continuous predictions of the gas-to-blood flow ratio or FIO₂ necessary to achieve a PaO₂ equal to 150 mmHg were made as the four determinant variables were continuously monitored and changed. The initial bypass hematocrit was predicted with a dilutional formula from the immediate prebypass hematocrit and entered into the predicting formula. Hematocrit was monitored every fifteen minutes and updated in the predicting formula. The ventilation rate or FIO₂ was readily updated with the slightest change in the four determinants since a minimal ventilation rate was being predicted and possible oxygenator hypoventilation was a constant sequela. The formulae were expected to yield PaO₂'s equal to 150 ± 50 mmHg on at least 60 percent of the trials based on the construct correlation coefficients. Human, computer unassisted, oxygenator ventilation yielded PaO₂'s of 150 ± 50 mmHg on approximately 40 percent of the data base trials.

Results and Discussion

Optiflo II Group: Figure Two plots the 37 sample data points that resulted from formula prediction of the minimal gas-to-blood flow ratio during total bypass in the Optiflo II Group listed in Table One. No attempt was made to control patient selection since patient morphology-related ventilation requirements should be accounted for in the four basic determinants. The

TABLE I
Patient group, procedure, and morphology information are listed including the immediate prebypass hematocrit (Hct) and the coldest temperature (Cold Temp.) attained during hypothermia.

Patient Initials	Surgical Procedure	Bypass Min.	Age Years	Weight Kg.	B.S.A. M2	Sex M/F	Hct %	Cold Temp.
Optiflo II Group:								
G.F.C.	CABG × 4	89	62	77	1.96	M	38	28
M.D.W.	CABG × 7	170	71	77	1.8	F	35	28
A.R.C.	CABG × 4	80	52	80	1.86	F	38	28
C.V.P.	CABG × 4	140	75	74	1.94	M	39	28
A.K.F.	CABG × 4	86	56	75	1.98	M	38	28
Sci-Med Group:								
L.D.M.	AVR, MVR, TVR	210	33	57	1.74	M	36	25
R.E.K.	AVR, MVR	183	36	51	1.5	F	33	25
E.P.K.	CABG × 4, AVR	180	73	79	2.0	M	40	28
D.L.G.	MVR	74	64	64	1.44	F	29	27
G.M.F.	Redo MVR	126	56	72	1.78	F	36	28

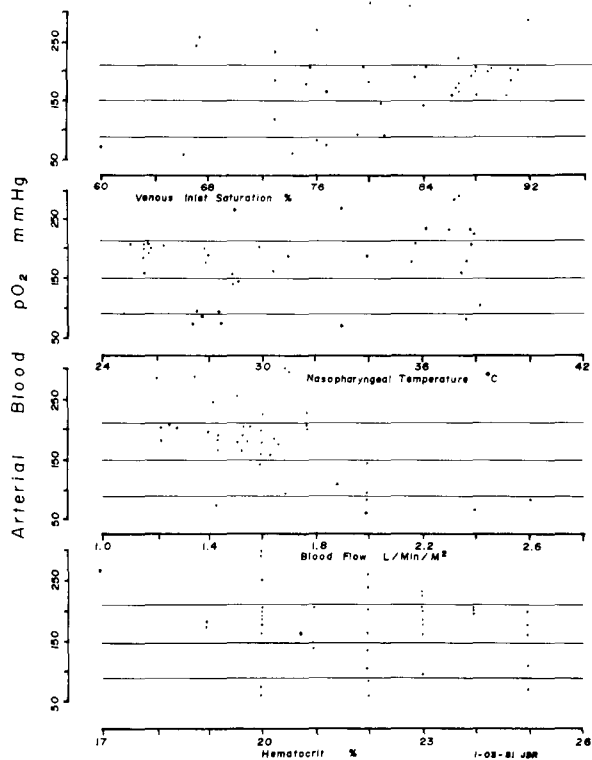


FIGURE 3. The resulting PaO₂'s (N = 40) by the FIO₂ predicting formula for the Sci-Med blood oxygenator group are plotted against the specific values of the determinant variables employed in the test.

resulting PaO₂'s were plotted against each determinant to graphically display predicting formula weakness.

The average resulting PaO₂ was 158 ± 55 mmHg (one S.D.). Figure Two depicts a temperature effect in the predicting ability of the test formula where the process tended to evaluate higher than necessary gas-to-blood flow ratios at higher hematocrits and conversely at low hematocrits. The resulting 55 mmHg standard deviation was consistent with the data base deviation and correlation coefficients. The final formula was adjusted to compensate for the observed predicting error.

Sci-Med Group: Figure Three plots the 40 sample PaO₂'s that resulted from formula prediction of the minimal FIO₂ required during total bypass in the Sci-Med test group listed in Table One. No attempt was made to control patient selection.

The average resulting PaO₂ in the Sci-Med trial was 180 ± 59 mmHg (one S.D.). Two determinant effects are apparent. The predicting formula tended to evaluate higher than necessary FIO₂'s at lower hematocrits

and evaluate lower than necessary FIO₂'s at higher membrane blood flow rates. Optimal formula control of the PaO₂ was experienced at membrane blood flow rates of 1.0 to 1.8 L/Min/M². The higher resulting average PaO₂ in the Sci-Med group and slightly larger standard deviation than that in the Optiflo II group was probably due to the smaller construct data based. The final FIO₂ predicting formula was adjusted to compensate for the observed predicting error.

Carbon Dioxide Removal: Control of the arterial blood pCO₂ was accomplished with ease. Average temperature corrected PaCO₂'s of 40 ± 3.3 mmHg (one S.D., N = 37) in the Optiflo II group were accomplished employing a FICO₂ = 2.4 ± 1% (one S.D., N = 15) at 28°C hypothermia and an FICO₂ = 0 at normothermia with the formula predicted gas-to-blood flow ratios in this method.

Average PaCO₂'s of 39 ± 4.2 mmHg (one S.D., N = 40) were accomplished in the Sci-Med group employing FICO₂'s equal to 1.9 ± .8% and 1.3 ± .9% (one S.D., N = 15) at 25°C and 28°C hypothermia respectively with gas sweep to blood flow ratios of .4:1. FICO₂'s equal to 0 and gas sweep to blood flow ratios of .85:1 were required during normothermia employing the vacuum ventilation technique previously described (8).

Possible hypoventilation and concurrent carbon dioxide retention are constant sequelae to this minimal ventilation prediction technique. The deviation in the resulting PaO₂'s from the prediction formula is contributed to by the operator's potential for negligence in updating the ventilation prediction with the slightest change in one of the four determinant variables.

In the bubble oxygenator, the buffer for oxygen and carbon dioxide exchange is removed when minimal ventilation techniques are employed. If the patient enters an accelerated oxygen consumption bypass situation, the perfusionist must respond by increasing the ventilation rate and/or decreasing the FICO₂. The bubble oxygenator's inherent respiratory quotient and the magnitude of the blood carbon dioxide content attained during hypothermia determine the PaCO₂ during warming when minimal ventilation techniques are employed with FICO₂'s equal to 0. The operator often has to settle for elevated PaO₂'s during warming in the face of greater than necessary gas-to-blood flow ratios for oxygenation to rid the blood of excess carbon dioxide retained during hypothermia.

Summary

1. 2300 Cobe Laboratory Optiflo II and Sci-Med Life System blood oxygenator/patient cardiopulmonary bypass records were studied to formulate an equation that predicted the minimal, adequate gas-to-blood flow ratio or FIO_2 respectively necessary for blood oxygenation.

2. The mathematical models requiring the current values of the blood flow rate, hematocrit, temperature, and venous inlet % oxygen saturation of hemoglobin were employed to predict the ventilation rates of the two oxygenators during cardiopulmonary bypass. The hand-held calculator formulae were solved to yield PaO_2 's = 150 mmHg.

3. The average resulting PaO_2 from the formula prediction of the gas-to-blood flow ratio of the Optiflo II group was 158 ± 55 mmHg (mean \pm 1 S.D.).

4. The average resulting PaO_2 from the formula prediction of the FIO_2 in the Sci-Med group was 180 ± 59 mmHg (mean \pm 1 S.D.).

5. The final versions of the formulae were adjusted to correct for the observed predicting weaknesses discovered in this method.

6. Carbon dioxide control was accomplished by varying the $FICO_2$ in the bubbler group when the predicted gas-to-blood flow ratio required for oxy-

genation was inadequate for the carbon dioxide retention or a higher than necessary gas-to-blood flow ratio for oxygenation was employed to remove CO_2 . Carbon dioxide control was accomplished in the membrane group by varying the $FICO_2$ and gas sweep rate independent of the FIO_2 in a vacuum ventilation model.

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