Blood Oxygenation Control by Vacuum Drawn Mixture of Room Air and Oxygen in a Membrane Oxygenator

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Purpose

Oxygen transfer function curves were created for the 1.5 m² Sci-Med Spiral membrane oxygenator* in a canine, left heart bypass preparation. The effects of altering the ventilating gas partial pressure of oxygen (VGpO₂) on blood oxygenation were quantitated at fixed values of oxygenator blood residence time (t), blood hemoglobin concentration (Hb) and venous blood %O₂ saturation of hemoglobin (SvO₂).

A clinical patient experience employing vacuum ventilation and altering the VGpO₂ to control PaO₂ in the Sci-Med Membrane system is reported.

Applying vacuum to the outlet of the gas path of a continuous membrane oxygenator has the following advantages: 1) the gas sweep rate may be increased to blow off more CO₂ when retention occurs without the sequelae of pressurizing the gas path, 2) the pressure gradient for gaseous microemboli to pass through pin hole leaks in the membrane is toward the gas path (viscous blood will not pass through pin hole leaks) and 3) the pressurization of the gas path above one atmosphere and increasing the partial pressure gradient for oxygenation does not occur aiding in avoiding high PaO₂’s.

Background

The volume of O₂ gas transported across an artificial membrane per unit time (VO₂) is determined by many variables including the solubility of O₂ in blood(s), the diffusibility of O₂ across the membrane material and in the blood (D), the venous O₂ partial pressure (PvO₂) and the distance O₂ must diffuse to reach the red blood cell (l).¹

\[ \dot{V}O_2 = \frac{[VGpO_2 - PvO_2] \times s \times D \times t}{1} \quad \text{Eq. 1} \]

The volume of O₂ per unit time that the tissue extract from the blood may be quantitated as:

\[ \dot{V}O_2 = \frac{[\{PaO_2 - PrO_2\} \times s] + \left[\frac{(SaO_2 - SvO_2)}{100}\right] \times 1.34 \times Hb}{100 \times C.O.} \quad \text{Eq. 2} \]

where: SaO₂ is the arterial % O₂ saturation of Hb
C.O. is the cardiac output in ml/min
1.34 is the volume of O₂ that 1 gram of Hb can carry

An equilibrium is reached during total heart lung bypass when the VO₂ extracted by the tissue is matched by the VO₂ delivered by the oxygenating device, hence:

\[ \frac{[\{PaO_2 - PrO_2\} \times s] + \left[\frac{(SaO_2 - SvO_2)}{100}\right] \times 1.34 \times Hb}{100 \times C.O.} = \frac{[VGpO_2 - PvO_2] \times s \times D \times t}{1} \quad \text{Eq. 3} \]

If the temperature is not altered and extreme changes in hematocrit are avoided, the solubility and diffusibility coefficients will not change and may be deleted

*Sci-Med Life Systems Inc., 13000 County Rd. 6 Minneapolis MN 55441

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Article available at [https://jetc.edpsciences.org](https://jetc.edpsciences.org) or [https://doi.org/10.1051/jetc/198012240]
along with the other constants to yield the following proportionality:

\[
\frac{[\text{VGpO}_2 - \text{PvO}_2] \times t}{\text{PaO}_2} = \frac{1}{\text{C.O.}} - \frac{[\text{SaO}_2 \times \text{Hb}]}{\text{C.O.}} + \frac{[\text{SvO}_2 \times \text{Hb}]}{\text{C.O.}} + \text{PvO}_2 \quad \text{Eq. 4}
\]

Equation four may be used to predict the direction of change in PaO\textsubscript{2} as alterations are made in the independent variables on the right side of the equation. For example, decreasing the SvO\textsubscript{2} and the PvO\textsubscript{2} will decrease the PaO\textsubscript{2} holding other variables constant. Increasing the forcing function for O\textsubscript{2} diffusion across the membrane, (VGpO\textsubscript{2} - PvO\textsubscript{2}) or the residence time in the oxygenating device will increase the PaO\textsubscript{2} holding all other variables equal. Increasing the cardiac output or distance that O\textsubscript{2} has to diffuse to reach a red cell or the hemoglobin concentration will decrease the PaO\textsubscript{2} if other variables do not change.

Equation five states the relationship between C.O. and t in seconds/m\textsuperscript{2} membrane surface area for one milliliter of blood.

\[
\text{blood residence time} = \frac{\text{oxygenator dynamic volume (ml)}}{\text{C.O. (ml/sec) \times \text{membrane surface area (m}^2)} \quad \text{Eq. 5}
\]

dynamic volume

\[
= \text{static volume} + (\text{compliance} \times \text{average membrane blood path pressure}) \quad \text{Eq. 6}
\]

Increasing C.O. decreases t. Employing an oxygenator with greater surface area and dynamic prime volume, increases t and the PaO\textsubscript{2}, holding the C.O. and the venous blood oxygen content constant.

If the effect of altering VGpO\textsubscript{2} - PvO\textsubscript{2} on the PaO\textsubscript{2} is examined, then the venous blood O\textsubscript{2} content, Hb concentration, t and I must be judiciously controlled and reported on the O\textsubscript{2} transfer curve.

The distance O\textsubscript{2} has to diffuse to reach a red blood cell (l) is difficult to control, however, the range of l may be minimized by not changing the hematocrit and maintaining the membrane blood path resistance (cross sectional area) constant. Alteration in the Sci-Med membrane blood path resistance occurs with changes in gas sweep flow, blood flow and blood path outlet pressure.

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**Protocol**

Normothermic left heart bypass was established from the left atrial appendage to the left femoral artery in a canine model. Right heart C.O. was assured by maintaining a normal right atrial filling pressure. The left ventricle ejected the remainder of the cardiac output that was not diverted to the extracorporeal circuit by the left atrial cannula. Blood return to the circuit’s collapsible reservoir was by gravity. Circuit blood was then pumped through a heat exchanger and a spiral-wound silicone membrane by a twin roller pump to the left femoral artery.

The pulmonary circuit was intact and was ventilated with a mixture of N\textsubscript{2}, CO\textsubscript{2} and O\textsubscript{2} to control the O\textsubscript{2} and CO\textsubscript{2} content of the left atrial blood to serve as a source of constant "venous" blood for the circuit and O\textsubscript{2} transfer studies.

The gas path of the membrane oxygenator was ventilated with a mixture of O\textsubscript{2} CO\textsubscript{2} and room air drawn by a vacuum source.

Figure One depicts the circuit and the instrumentation employed to retrieve the data in Table One. The VGpO\textsubscript{2} was dropped in 50 mmHg increments from 100% O\textsubscript{2} and measurements taken after equilibrium (5-10 minutes) at each value of VGpO\textsubscript{2}. Table Two lists the calculated variables.

The protocol isolates the effect of alterations in SvO\textsubscript{2}, Hct and t on the VGpO\textsubscript{2}, oxygenator function curve during vacuum ventilation. Four clinically simulated phases will be studied and are outlined in Table Three.

Blood residence times of 5.07 and 5.13 sec/m\textsuperscript{2} represent a C.O. = 1500 ml/min and, 6.56 and 7.14 sec/m\textsuperscript{2}, 2000 ml/min. SaO\textsubscript{2}, PaO\textsubscript{2}, and VO\textsubscript{2} plotted against ventilating gas pO\textsubscript{2} and % O\textsubscript{2} for each phase and the effect of different values of SvO\textsubscript{2}, t and hematocrit on O\textsubscript{2} transfer are evaluated.

**Results and Discussion**

Figures Two, Three and Four plot the affect of altering VGpO\textsubscript{2} and % O\textsubscript{2} on PaO\textsubscript{2}, SaO\textsubscript{2} and VO\textsubscript{2} respectively for each phase of the protocol (refer to Table Two).

In general, decreasing VGpO\textsubscript{2} decreased measurements of blood oxygenation in an exponential manner. The twelve function curves fit an exponential decay model with correlation coefficients ranging from .85 to .99. Although some point scattering is evident, the plotted lines are from the exponential equations derived.
CIRCUIT:
(Including manufacturer and specification references)

90% Nz, 10% CO2

Pulmonary Circuit

Systemic Vascular Circuit

90% Nz, 10% CO2

Left* Pulmonary

Right* Systemic

Circuit

Heart

Tissue

Pulmonary*

Right* Systemic

Circuit

Atrium

Ventricle

Room Air

Ventilator

Left Atrium

Left Ventricle

Blood Filter

Blood Pressure

Inlet Gas Path

Outlet Gas Path

Gas Metering

System

100% O2

100% CO2

Vacuum Trap

Calibrated

Vacuum Flow

Meter

Vacuum Trap

and Source Pressure

*Canine cannulation, left atrium, human cannulation, SVC & IVC.

FIGURE 1. In Vivo circuit employed to study vacuum ventilation mixture of room air and oxygen to control the PaO2.

from the linear regression of the VGP02 versus the natural logarithm of PaO2, SaO2 or V02.

Phases I and IV showed little difference in affecting the three function curves. C.O. and blood residence time were similar in Phase I and IV, therefore the drop in hematocrit from 34.5 to 23.4% from Phase I to IV and the increase in the SvO2 from 74.6 to 80.2% from Phase IV to I had equal offsetting effects on the O2 transfer curves.

Substantially less oxygen was transferred at each

FIGURE 2. The effect of altering ventilating gas O2 content on the PaO2 at various controlled operating parameters.

FIGURE 3. The effect of altering ventilating gas O2 content on the SaO2 at various controlled operating parameters.
TABLE I

Figure One manufacturer and parameter references and specifications.

<table>
<thead>
<tr>
<th>Figure One Reference</th>
<th>Device, Parameter or Specification</th>
<th>Device Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Respiratory rate</td>
<td>Harvard Animal Respirator, Harvard Apparatus Co., 150 E. Dover Road, Willimantic, CT 06226</td>
</tr>
<tr>
<td>2.</td>
<td>In line PaO₂, PaCO₂</td>
<td>Critikon Oximeter, Division of McNeil Laboratories, 2602 McGaw Avenue, Irvine, California 92614</td>
</tr>
<tr>
<td>3.</td>
<td>In SvO₂, 40-100% line</td>
<td>Industrial Inventions, Inc., Model 1400, BD2-463, 85 Route 1, Monmouth Junction, New Jersey 08852</td>
</tr>
<tr>
<td>5.</td>
<td>RV500-I Venous Reservoir</td>
<td>American Optics Oximeter, Model #10800, Eggert and Sugar Roads, Buffalo, NY 14215</td>
</tr>
<tr>
<td>6.</td>
<td>Cardiac Output (C.O.)</td>
<td>Sci-Med Life Systems, Inc., 1301 County Road, Minneapolis, MN 55441</td>
</tr>
<tr>
<td>7.</td>
<td>Omnitherm Heat Exchanger</td>
<td>Travenol Modular Calibrated Twin Roller Pump, Travenol Laboratories Inc., 1 Basset Pkwy, Deerfield, IL 60015</td>
</tr>
<tr>
<td>9.</td>
<td>Spiral Wound Silicon Membrane Oxygenator</td>
<td>Calibrated Hewlett-Packard strain gauge transducer, 175 Wyman Street, Waltham, Mass. 02154</td>
</tr>
<tr>
<td>10.</td>
<td>Negative pressure gauge 0 to -760 mmHg Membrane gas path pressure out (PMQ)</td>
<td>Sci-Med Life Systems, Inc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sarna, Inc., 6200 Jackson Road, Ann Arbor, MI 48103</td>
</tr>
<tr>
<td>11.</td>
<td>Ventilating Gas %O₂, 0-100% (VGpO₂)</td>
<td>Ohio Medical Products, Model 201, Arco Inc., Madison, WI 53701</td>
</tr>
<tr>
<td>12.</td>
<td>Ventilating gas %O₂, P-800 mmHg (VGpO₂)</td>
<td>Beckman Instruments, Model OM-15, Corporate, 2500 Harbor Drive, Fullerton, CA 92634</td>
</tr>
<tr>
<td>13.</td>
<td>Gas and blood line microfilters</td>
<td>Pall Corporation, Great Cove, NY 11542</td>
</tr>
<tr>
<td>15.</td>
<td>Vacuum Source and Trap, Set at -200 mmHg</td>
<td>Onequip, Inc., Chicago, IL 60658, Hackbeck Sales, Murray Hill, NJ 07974</td>
</tr>
</tbody>
</table>

VGpO₂ during Phase II than Phase III. Phases II and III had identical hematocrits and t values, yet the decreased SvO₂ in Phase II compromised the oxygenator's ability to attain acceptable PaO₂ and SaO₂ values at VGpO₂s less than 600 mmHg (82% O₂). Inadequate blood oxygenation would occur when values of SvO₂ became too low for the perfusionist selected variables of blood residence time and the ventilating gas O₂.

TABLE II

Equations for and units of measure of protocol calculated parameters.

<table>
<thead>
<tr>
<th>Calculated Parameter</th>
<th>Equation</th>
<th>Units of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane gas path resistance</td>
<td>(PMI-PMQ) / GQ</td>
<td>mmHg/L/min</td>
</tr>
<tr>
<td>Membrane blood path resistance</td>
<td>(PMI-PMQ) / C.O.</td>
<td>mmHg/ml/sec</td>
</tr>
<tr>
<td>V̇O₂</td>
<td>Equation 2 (text)</td>
<td>mlO₂/min</td>
</tr>
<tr>
<td>t</td>
<td>Equation 8 (text)</td>
<td>seconds</td>
</tr>
<tr>
<td>Average membrane blood path pressure</td>
<td>(PMI-PMQ) / 2</td>
<td>mmHg</td>
</tr>
</tbody>
</table>
TABLE III
Protocol phase control parameters of hematocrit, \( \text{SvO}_2 \), \( \text{PvO}_2 \), blood residence time and blood path resistance in the membrane oxygenator.

<table>
<thead>
<tr>
<th>CONTROL PARAMETERS</th>
<th>Residence Time</th>
<th>Venous % \text{O}_2</th>
<th>Venous \text{P}_{\text{O}_2}</th>
<th>Blood Path Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Hematocrit</td>
<td>\text{sec/M}^2</td>
<td>Saturation</td>
<td>\text{mmHg}</td>
</tr>
<tr>
<td>I mean</td>
<td>34.5</td>
<td>6.56</td>
<td>80.2</td>
<td>50.1</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.5</td>
<td></td>
<td>2.8</td>
<td>5.9</td>
</tr>
<tr>
<td>II mean</td>
<td>41.5</td>
<td>5.07</td>
<td>68.5</td>
<td>51.0</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.5</td>
<td></td>
<td>2.5</td>
<td>4.4</td>
</tr>
<tr>
<td>III mean</td>
<td>41.5</td>
<td>5.13</td>
<td>79.8</td>
<td>56.6</td>
</tr>
<tr>
<td>S.D.</td>
<td>1.9</td>
<td></td>
<td>1.9</td>
<td>2.8</td>
</tr>
<tr>
<td>IV mean</td>
<td>23.4</td>
<td>7.14</td>
<td>74.6</td>
<td>43.7</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.2</td>
<td></td>
<td>2.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

content. \( \text{CO}_2 \) transfer would be compromised if gas sweep rate were inadequate for the venous blood \( \text{CO}_2 \) content and blood residence time.

Phases I and III had higher values of hematocrit and similar \( \text{SvO}_2 \) yet the oxygenator was able to transfer substantially more \( \text{O}_2 \) at higher values of \( \text{VGP}_{\text{O}_2} \) in Phase I due to the increased blood residence time at the lower cardiac output through the 1.5 m\(^2\) membrane.

The greater the hematocrit and the lower the values of \( \text{t} \) and \( \text{SvO}_2 \), the greater the \( \text{VGpO}_2 \) needed to attain an arterial \( \text{pO}_2 \) and \( \text{SO}_2 \) acceptable for tissue perfusion. Conversely, lower hematocrits, longer values of \( \text{t} \) and high \( \text{SvO}_2 \) facilitate blood oxygenation at lower values of \( \text{VGpO}_2 \).

Clinical Example

Figure Five plots the bypass course for a 41 year old male redo coronary artery bypass graft patient. The circuit in Figure One was employed with a 3.5 m\(^2\) membrane.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{The bypass course for a 41 year old male, redo coronary bypass graft patient employing vacuum ventilation and a 3.5 m\(^2\) Sci-Med Membrane System.}
\end{figure}
Vacuum ventilation was employed to mix room air and 100% oxygen to vary V\( \text{GpO}_2 \) to control the PaO\(_2\). The vacuum flow rate was adjusted to alter the gas sweep rate to control the PaCO\(_2\).

The patient was cooled to 22°C esophageal. The \( \dot{V}O_2 \) reflects the decreased metabolism at 22°C and the resulting elevated SvO\(_2\) and PvO\(_2\) in the face of a Cardiac Index of 2.5 L/min/m\(^2\). The high venous O\(_2\) content allowed ventilation with 55% O\(_2\) in the sweep gas and the low production of CO\(_2\) by the patient facilitated the respiratory alkalosis experienced at a sweep rate of 2.7 to 4 L/min at 30–50 minutes into bypass. Efforts to decrease the sweep rate to retain CO\(_2\) were not successful until patient warming began. CO\(_2\) addition to the ventilating gas was justifiable at 0–40 minutes but not carried out.

Warming to 34°C brought a substantial increase in \( \dot{V}O_2 \) and concurrent drop in SvO\(_2\) and PvO\(_2\) despite the increase in C.O. at 100 minutes. The increase in CO\(_2\) production was not responded to by an increase in sweep rate before CO\(_2\) retention and an increase in total CO\(_2\) content of the blood was realized (respiratory acidosis). The gas sweep rate should have been increased at the beginning of warming (50 minutes) and to a greater magnitude at 35–38°C to blow off the CO\(_2\) accumulation with warming.

Blood oxygenation and PaO\(_2\) control were easily and safely controlled by altering the V\( \text{GpO}_2 \). CO\(_2\) control by altering the gas sweep rate in this example was tedious but a function of the perfusionist mastering the technique of predicting CO\(_2\) dynamics with rapid warming with the Sci-Med membrane in specific patient populations.

**Conclusions**

1. Blood oxygenation with a vacuum drawn mixture of room air and oxygen through the Sci-Med membrane is a safe and predictable clinical modality.
2. Arterial blood pO\(_2\) is adjusted by alterations in the \% O\(_2\) in the ventilating gas and arterial pCO\(_2\) is controlled by the total vacuum gas sweep rate.
3. Blood/membrane residence time, venous blood O\(_2\) content, hemoglobin concentration and membrane blood path thickness affect the oxygen transfer rate in the Sci-Med Membrane System. If the ventilating gas \% O\(_2\) is decreased, these variables and arterial blood gases must be carefully monitored to avoid O\(_2\) debts and CO\(_2\) retention in changing patient situations such as rapid warming.

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**Bibliography**