FELLOWSHIP AWARD:

Oxygen Consumption Plateauing: A Better Method of Achieving Optimum Perfusion

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ABSTRACT

A method of conducting perfusion, by which the patient’s oxygen consumption ($V\dot{O}_2$) is always being maximized, is presented. The endpoint of good perfusion is argued to occur when $V\dot{O}_2$ plateaus despite further increases in cardiac index, hemoglobin concentration, arterial oxygen delivery, or pharmacological intervention. Thus, this method quickly assesses the patient’s varying oxygen demands, reduces metabolic acidosis, and enhances oxygen distribution.

Determination of $\dot{V}O_2$ was done with in-line oxygen sensors (Critikon) and a handheld programmable calculator (Texas Instruments Model 59). No nomograms or tables are necessary and the time required is less than 80 seconds.

Exemplary cases demonstrate the value, cost effectiveness, and simplicity of the $\dot{V}O_2$ plateauing method. The dependence upon conventionally used perfusion parameters such as venous saturations, flows, pressures, and urinary output are refuted.

INTRODUCTION

The primary goal of the heart-lung machine operator is to meet the patient’s total oxygen requirements and to facilitate oxygen distribution to all tissues. However, even though clinical heart-lung bypass is in its third decade; reliable, quick, simple, and cost effective methods of determining the adequacy of oxygen supply to all tissue beds are not yet available. It is possible for the perfusionist to easily ascertain the performance of artificial gas transfer devices, but it is not yet possible to quickly monitor the adequacy of total body perfusion. The result, more often than not, is a metabolic acidosis. Thus, administration of any sodium bicarbonate to the patient during or immediately after cardiopulmonary bypass documents less than adequate artificial perfusion.

Current practices for determining “adequate” perfusion include monitoring arterial and mixed venous blood gases, pressures, flows, and electrolytes. Perfusion is usually conducted to maintain these parameters within normal ranges or as directed by individual surgeons. On the other hand, some merely pump blood on the basis of “rule of thumb” flows, which were empirically determined from early laboratory or clinical case studies.

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MATHEMATICAL MODEL OXYGEN DISSOCIATION CURVE *

\[
\text{SO}_2 = 100 \left[ \frac{a_1 + a_2 x^2 + a_3 x^3 + x^4}{a_4 + a_5 x + a_6 x^2 + a_7 x^3 + x^4} \right]
\]

WHERE: 
\[x = \text{PO}_2 \text{ meas.} \times 10^{(0.024 \times (37 - \text{temp}) + 0.40 \times (\text{pH} - 7.40) + 0.06 \times (\log \text{PCO}_2) - 10} \]

\[a_1 = -8.5322299 \times 10^3 \]
\[a_2 = 2.1214010 \times 10^3 \]
\[a_3 = -6.7073989 \times 10^1 \]
\[a_4 = 9.3596087 \times 10^5 \]
\[a_5 = -3.1346258 \times 10^4 \]
\[a_6 = 2.3961674 \times 10^3 \]
\[a_7 = -6.104406 \times 10^1 \]

* from Kelman, G. Richard * J. Appl. Physiol. 21 (4) : 1375, 1966

Figure 1. The mathematical model used to calculate oxygen saturation. Note that the measured oxygen tension is corrected for changes in temperature, carbon dioxide tension, and pH.

Consequently, variables such as; changes in anesthetic level, hemoglobin concentration, temperature, vasomotor tone, and metabolic rate, are not considerations. Since local tissue hypoxia cannot be monitored, only a metabolic acidosis can be detected. However, this is too late. Thus, the perfusionist pumps by the seat of his pants (or her skirt). Unfortunately, no reliable methodology has been developed to determine the real time status of the patients’ metabolic requirements (oxygen need) and tissue perfusion (oxygen distribution). This paper suggests a simple, rapid and cost effective method of meeting the varying oxygen needs of the patient while preventing the consequences of overperfusion. The goal of this method is to conduct perfusion to continuously maximize the patient’s oxygen consumption during any given situation or condition. The oxygen consumption is quickly and easily calculated with a programmable handheld calculator, while real time venous and arterial oxygen tensions are being measured by in-line sensors.

MATERIALS AND METHODS

The patient’s resting, pre-induction oxygen consumption/m² (\(\dot{V}O_2/m^2\)) is estimated using the non-invasive method developed by LaFarge and Miettinen:³

For males:

\[
\dot{V}O_2/m^2 = \left[ 138.1 - 11.49 \log_{10}(\text{age}) + 0.378 \text{ (heart rate)} \right]
\]  \quad \text{Eq. 1}

For females:

\[
\dot{V}O_2/m^2 = \left[ 138.1 - 17.04 \log_{10}(\text{age}) + 0.378 \text{ (heart rate)} \right]
\]  \quad \text{Eq. 2}
TABLE I
An example calculation of oxygen consumption ($\dot{V}O_2$), arterial-venous oxygen content difference ($CO_2 - CV_2$) and base excess (BE) when a hypothetical patient's values are: $PaO_2$meas = 138 mmHg, $PvO_2$meas = 43, temperature 28°C, pH 7.35, $pCO_2$ = 46 mmHg, hemoglobin (Hb) = 9 mg/dL, and pump blood flow 6.2 L/min. Note the total time of operation to obtain the displays is 79 seconds.

**EXAMPLE CALCULATIONS**

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>MINIMUM REQUIRED TIME FOR OPERATION (SEC)</th>
<th>DISPLAY</th>
<th>CUMMULATIVE TIME (SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ENTER $pH$, $pCO_2$, Hb, $PaO_2$meas and flow</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>2. CALCULATE $PaO_2$vir</td>
<td>3</td>
<td>214.9</td>
<td>28</td>
</tr>
<tr>
<td>3. ENTER $PaO_2$vir</td>
<td>5</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>4. CALCULATE $SaO_2$</td>
<td>7</td>
<td>0.9936</td>
<td>40</td>
</tr>
<tr>
<td>5. ENTER $SaO_2$</td>
<td>3</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>6. ENTER $PvO_2$meas</td>
<td>7</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>7. CALCULATE $PvO_2$vir</td>
<td>3</td>
<td>66.96</td>
<td>53</td>
</tr>
<tr>
<td>8. ENTER $PvO_2$vir</td>
<td>3</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>9. CALCULATE $SvO_2$</td>
<td>7</td>
<td>0.9328</td>
<td>63</td>
</tr>
<tr>
<td>10. ENTER $SvO_2$</td>
<td>3</td>
<td></td>
<td>66</td>
</tr>
<tr>
<td>11. CALCULATE A-VO$_2$ diff</td>
<td>3</td>
<td>1.249</td>
<td>69</td>
</tr>
<tr>
<td>12. CALCULATE $\dot{V}O_2$</td>
<td>5</td>
<td>77.443</td>
<td>74</td>
</tr>
<tr>
<td>13. CALCULATE BE</td>
<td>5</td>
<td>0.49</td>
<td>79</td>
</tr>
</tbody>
</table>

The estimated resting value is then used as a basis of comparison of the patient's cardiopulmonary bypass values.

Oxygen tension sensors are placed in the arterial and venous lines of the extracorporeal circuit to provide continuous analysis.* Frequent blood gas/pH and hematocrit determinations were also made. Arterial and venous blood temperatures were measured adjacent to the respective oxygen sensors.

A Texas Instruments, Model 59, programmable handheld calculator was used to determine body surface area, blood volume, cardiac index, systemic vascular resistance, oxygen consumption, arterial-venous oxygen content differences, arterial and venous oxyhemoglobin saturations, base excess, and total body base/acid corrections. The

* Critikon, Oxytrak Model 630, Div. McNeil Lab., Irvine, CA 92714.
Figure 2. Oxygen consumption increases with arterial oxygen supply until the former plateaus. Increased metabolism and increased oxygen needs result in an increased consumption; whereas, decreased metabolism and reduced oxygen needs result in a decreased consumption. Point A represents the point of optimum perfusion, B hypoperfusion, and C overperfusion. Rapid calculation of VO₂ enables the perfusionist to individualize perfusion for each patient to point A.

Because temperature, carbon dioxide tension, and hydrogen ion concentration affect the oxyhemoglobin dissociation curve; the oxygen tension (pO₂ meas) as measured by the in-line sensors requires correction to conform to a standard tension at 37°C, pH 7.40, and a 40 pCO₂. Consequently, the virtual oxygen tension (pO₂ vir) is calculated using the following equation of Kelman:

\[
pO2_{\text{vir}} = pO2_{\text{meas}} \times 10 \left[0.024(37 - \text{temp}) + 0.40(pH - 7.40) + 0.06(\log 40 - \log pCO2)\right] \quad \text{Eq. 3}
\]

where temp. is the patient's blood temperature in °C and pH is the patient's blood pH and pCO₂ is the blood carbon dioxide tension.

The pO₂ vir is then used to determine the saturation from the standard oxyhemoglobin dissociation curve (pH 7.40, 40 pCO₂, 37°C) according to a mathematical model (Fig. 1). Thus, once the calculator is programmed, blood gases/pH and temperature can be entered and oxygen consumption by the Fick Equation, base excess, and arterial-venous oxygen differences can be calculated. Time for data entry and calculation of outputs is easily less than 90 seconds (Table 1). Moreover, no tables, charts, or nomograms are
required. Therefore, the perfusionist can still easily and simultaneously direct the necessary attention to the operation of the extracorporeal circuit.

Perfusion is conducted until the oxygen consumption is maximized for the exact conditions of bypass. Since oxygen consumption varies with oxygen supply until the former plateaus (Fig. 2); flows, arterial and venous blood pressures, the patient’s vasomotor state, and the arterial carbon dioxide tension are altered until oxygen consumption plateaus. Thus, continuous calculation of oxygen consumption enables the perfusionist to construct an individualized oxygen supply-consumption curve which is responsive to changes in metabolic rate, vasomotor state, hemodilution, temperature, oxygen tensions, and anesthetic levels. In short, the variables affecting metabolic rate are accounted for by simply entering a few numbers into the calculator.

RESULTS

Figure 3 summarizes a typical case using the oxygen consumptions plateauing method. It depicts \( \dot{V}O_2 \) changes in a 79 Kg male undergoing total cardiopulmonary bypass for a multiple coronary artery revascularization. During the period of stable hypothermia (1–3 hours bypass time), the \( \dot{V}O_2 \) was made to plateau by controlling the cardiac index. Vasodilators were given when the patient became vasoconstricted. The venous saturation

![Figure 3. The changes in \( \dot{V}O_2 \) are summarized in this typical bypass case. See text for discussion.](image-url)
was never less than 72% during the bypass period. Note the greatly reduced $\text{VO}_2$, shortly after the onset of total bypass despite a $S_c\text{O}_2$ of 82%. This patient required 24 mEq HCO$_3$/hour of bypass to maintain the base deficit at zero.

DISCUSSION

Clark logically described the ideal flowrate in terms of basal oxygen consumption. However, the perfusionist cannot predict or even assume that the oxygen requirement of the anesthetized patient will be less than basal conditions. In fact, a greater oxygen consumption on bypass than predicted basal oxygen consumption is not uncommon. Since the oxygen consumption changes because of changes in hemodilution, hypothermia, vasomotor states, pharmacological effects of anesthesia, and aortic cross clamping; it is impossible to predict the patient's oxygen requirements for any given situation on bypass. Thus, adherence to a rigid method of calculating an optimal perfusion flow-rate; for example, 2.4 liters/minute/m$^2$, does not insure that the patient's metabolic needs will be met. Pre-calculated flows do not consider the total oxygen carrying capacity of the blood or the patient's varying oxygen needs.

Since metabolic acidosis is inversely related to the perfusion flowrate (oxygen supply), some perfusion techniques employ high flows. However, there are disadvantages to unnecessarily high flows, such as: post operative neurological sequelae resulting from elevated intracranial pressures, fluid retention in interstitial edema, greater microemboli generation, possible increase in protein denaturation, and possible arterio-venous shunting. The technique described in this paper would help to prevent these disadvantages.

Some alter perfusion flowrates according to the mixed venous oxygen tension and saturations. Although this technique seems like a rational approach to assessing the patient's current oxygen requirements and does indeed reduce metabolic acidosis, it only assumes that the oxygen demand of all the tissues are being met. Even with this technique, which is employed at this institution, a mild metabolic acidosis requiring bicarbonate administration frequently occurs. A normal or high mixed venous saturation only demonstrates that the organ systems being perfused at the time are well oxygenated. For example, if tissue hypoxia occurs secondary to hypoperfusion, blood flow is diverted to the vital organs, such as the brain, heart, and kidney, because of compensatory vasoconstriction. Under these conditions the mixed venous oxygen content would be quite high even though ischemia is occurring in the mesentary, skeletal muscle mass, or skin. Since the latter systems consume approximately 25% of the total body's consumption, total oxygen consumption $\text{VO}_2$ would then decrease, anaerobic metabolism occur, and the hydrogen ion concentration increase. Mild shock would ensue despite a "normal" venous blood gas. Thus, a normal or high mixed venous tension or saturation is not necessarily a reliable index of good perfusion of all organ systems; especially if arterio-venous shunting is occurring or if the patient is vasoconstricted.

The mixed venous oxygen saturation can also be misleading because of the effects of temperature, carbon dioxide, and pH on the oxyhemoglobin dissociation curve. The high saturation, especially in hypothermia, may be due to the tenacity of oxygen for hemoglobin and a limitation to oxygen diffusion to the tissues resulting in an unsatisfied oxygen demand. Thus, even the arterial-venous oxygen content difference is not a
Figure 4. The $\dot{V}_O_2$ at B is enhanced to C while the oxygen supply remains unchanged at an optimum level A. The judicious use of vasodilators in constricted patients, vasoconstrictors in hypotensive patients, and increasing carbon dioxide tensions are possible methods used to increase $V_O_2$ to $\dot{V}_T O_2$ (point C) when oxygen consumption supply rate is already optimum. Moving from B to C demonstrates an improved oxygen distribution to previously hypoperfused tissue beds. D represents the ideal perfusion state, $V_n O_2$.

reliable indicator of the perfusion status. Therefore, to rule out the effects of temperature, carbon dioxide, and pH on oxyhemoglobin dissociation curve; the correction formula of Kelman was used.$^6$

Optimum perfusion can be expressed by the equation:

$$\frac{\dot{V}_T O_2}{V_n O_2} = 1$$  \hspace{1cm} \text{Eq. 4}$$

where $\dot{V}_T O_2$ is the patient's total actual oxygen consumption and $V_n O_2$ is the patient's total maximum oxygen needs of all the cells. If the ratio is less than one, a hypoxic metabolic acidosis should occur. The lower the ratio, the greater the acidosis. Since $V_n O_2$ cannot be measured, the perfusionist must assume that $V_n O_2$ is reached when $\dot{V}_T O_2$ is maximized by optimum oxygen supply and distribution. The perfusionist can empirically make Equation 4 near unity by enhancing oxygen consumption by 1) optimizing oxygen supply by pumping an adequate volume of oxygen in arterial blood, and, 2) maximally distributing oxygen from the arterial blood to all the cells in the body. Once the perfusionist pumps the optimum supply of oxygen in arterial blood (represented in Fig. 4 by A), a number of factors can be manipulated to enhance oxygen distribution, which will increase $\dot{V}_T O_2$ to approach $V_n O_2$ (represented by point D). Factors which enhance oxygen distribution or oxygen consumption are increased arterial pressure,$^{18}$ vasodila-
tors,\textsuperscript{19} vasoconstrictors,\textsuperscript{20,21} elevated venous pressure,\textsuperscript{22} carbon dioxide tension,\textsuperscript{16} and pH. Thus the perfusionist can greatly affect the patient’s oxygen consumption by manipulating many other factors other than flow.

A number of standard parameters are used to monitor the adequacy of perfusion. Arterial blood pressure and urinary output are maintained within normal limits or those set by the surgeon. However, these parameters describe the status of the vital organs only rather than all of the other organ systems. For instance, arterial pressure may be acceptable and urinary output adequate in a patient who is either hypertensive or normotensive but severely constricted; but hypoxia will occur in those ischemic tissue beds sacrificed to maintain the blood flow and pressure to the vital organs.

Instrumentation is not yet commercially available to ideally assess total perfusion. Ideal parameters to measure would be muscle or tissue pH\textsuperscript{19,23} and muscle or tissue oxygen tensions.\textsuperscript{18,24} A decrease in muscle pO\textsubscript{2} and the diffusion capacity of oxygen in the dog shock model has been shown to be associated with a decrease in total body consumption.\textsuperscript{25} In the absence of the appropriate instrumentation, then, continuously monitoring the patient’s total oxygen consumption would seem to be the best available method. Therefore, conducting perfusion so that oxygen consumption is always maximized would better insure that the patient’s oxygen demands are being met. Currently, there are two ways of measuring oxygen consumption on bypass, spirometrically\textsuperscript{22,26} and arterial and venous blood content measurements (Fick Equation). Since it is possible at the time of this writing to obtain accurate measurements of in-line oxygen tensions or saturations, and to calculate the data quickly and cheaply with programmable handheld calculators; the authors developed the technique herein described. A study is currently assessing the efficacy of this method on a group of patients.

REFERENCES


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