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# Technique to Give Relevance to Calculated Oxygen Transfer During Cardiopulmonary Bypass\*

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## Abstract

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A technique to give relevance to results of oxygen transfer calculation during total cardiopulmonary bypass is presented.

An accurate calculation scheme to quantitate total blood oxygen transfer is outlined. Clinical relevance is given to the oxygen transfer calculation result by reporting the value as a percent of an expected oxygen transfer rate. An expected oxygen transfer value is predicted from large population metabolic rate study results employing patient sex, age, body surface area, and temperature.

Calculating the percent of expected oxygen consumption value will benefit the perfusionist by increasing the validity of CPB management decisions. The calculation of actual oxygen consumption will aid the perfusionist in selecting an appropriate artificial oxygenator ventilation rate and patient blood flow.

## Technique: Calculating Oxygen Transfer during Cardiopulmonary Bypass (CPB)

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Table 1 lists measurements that must be made to calculate oxygen transfer ( $\dot{V}_{O_2}$ ) to five percent accuracy during CPB.<sup>1</sup>

To accurately calculate  $\dot{V}_{O_2}$  during CPB, accurate values for  $\dot{Q}$  must be employed. Roller pump blood flow is dependent on physical factors such as blood temperature preload, afterload, and occlusion setting. Therefore a pump calibration curve to predict  $\dot{Q}$  measurement or an electromagnetic flow meter is ideal.<sup>2</sup>

Hematocrit may be employed to predict hemoglobin concentration if direct measurement of Hb is not possible;<sup>3</sup>

$$\text{Hb gm\%} = .35 \times \% \text{ Hematocrit}$$

Direct oximeter measurements of %Hb·O<sub>2</sub> are preferable to blood gas analyzer or nomogram prediction of %Hb·O<sub>2</sub>.<sup>4</sup> Formula and nomogram %Hb·O<sub>2</sub> predictors assume a beginning hemoglobin P<sub>50</sub> = 28. mmHg.<sup>5,6</sup> Disease states and red cell chemical imbalances probably alter the P<sub>50</sub> and decrease the accuracy of the %Hb·O<sub>2</sub> prediction.<sup>7</sup>

The arterial admixture to venous blood after leaving the patient and prior to oxygen content analysis should be avoided. Possible sources for arterial admixture are shunting of arterial line filter bleed port to venous line and endogenous oxygenation by room air in the venous return line.

To increase the accuracy of the  $\dot{V}_{O_2}$  calculation, one must employ the absolute value of the pO<sub>2</sub> ("temperature corrected") to predict the oxygen content dissolved in plasma and red cell water. Accurate, direct measurement of %Hb·O<sub>2</sub> and temperature at the pO<sub>2</sub> sample site are required to temperature correct the blood gas analyzer result and obtain an accurate pO<sub>2</sub>.<sup>8</sup> Direct and contin-

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MEASUREMENT	ABBREVIATION	UNIT OF MEASURE	ACCURACY
Blood Flow	$\dot{Q}$	ml $\times$ min <sup>-1</sup>	+/- 50.
Hemoglobin Concentration	Hb	Gm $\times$ dL <sup>-1</sup>	+/- .2
Percent Oxygen Saturation of Hemoglobin	% Hb-O <sub>2</sub>	%	+/- 2.0
Hematocrit	Hct	%	+/- 2.0
Partial Pressure of Oxygen	pO <sub>2</sub>	mmHg	+/- 3.0

TABLE 1. The measurements, abbreviations, units of measure and accuracy required for calculation of oxygen transfer

uous measurement of pO<sub>2</sub> is preferred and minimizes sampling and temperature correction error.

The Fick Formula to calculate cardiac output is rearranged and employed to calculate oxygen transfer ( $\dot{V}_{O_2}$ ):<sup>9</sup>

$$C.O. = \frac{\dot{V}_{O_2}}{A-V O_2 \text{ Content}}$$

where

- C.O. = cardiac output in ml blood/minute
- $\dot{V}_{O_2}$  = ml O<sub>2</sub>/minute
- A-V O<sub>2</sub> = arterial-venous ml O<sub>2</sub>/ml blood Content

$\dot{Q}$  is substituted for C.O. and A-V C<sub>O<sub>2</sub></sub> for oxygen is calculated from measured parameters. The following equation results:

$$\dot{V}_{O_2} = \frac{A-V O_2 \text{ Content}}{100} \times \dot{Q}$$

where

$$A-V O_2 \text{ Content} = \text{ml O}_2/100 \text{ ml blood}$$

$$\dot{Q} = \text{ml blood/minute}$$

Total blood oxygen content is calculated employing the respective blood value for dissolved oxygen content (C<sub>d</sub>) and hemoglobin oxygen content (C<sub>h</sub>).

$$\text{Blood O}_2 \text{ Content} = C_d + C_h$$

The difference in arterial and venous blood content is employed in the third equation.

Henry' Law is used to calculate oxygen content dissolved in blood and red cell water.

$$\text{Oxygen Content} = pO_2 \times O_2 \text{ Solubility}$$

where

$$\text{Oxygen Content} = \text{ml O}_2/100 \text{ ml blood}$$

$$O_2 \text{ Solubility} = \text{ml O}_2/\text{ml blood}/760 \text{ mmHg pO}_2$$

O<sub>2</sub> Solubility may be read from a table format employing blood temperature (T) and hemoglobin concentration.<sup>10</sup> A computer may predict oxygen blood solubility (S), with the following statement:<sup>11</sup>

$$S = -(4 \times 10^{-6} \times Hb + 3.46 \times 10^{-4}) \times T + (1.3 \times 10^{-4} \times Hb + 3.5 \times 10^{-2})$$

Dissolved oxygen content (C<sub>d</sub>) in blood is predicted:

$$C_d = ((pO_2/760) \times S) \times 100$$

where

$$C_d = \text{ml O}_2/100 \text{ ml blood}$$

Arterial and venous blood dissolved oxygen content is calculated employing the respective Hb, T, and pO<sub>2</sub>. If arterial blood Hb and T are identical, the arterial-venous dissolved oxygen content difference is calculated:

$$A-V C_d = (PaO_2 - PvO_2)/760 \times S \times 100$$

where

$$PaO_2 = \text{Arterial pO}_2$$

$$PvO_2 = \text{Venous pO}_2$$

Hemoglobin oxygen content (C<sub>h</sub>) is calculated:

$$C_h = \left( \frac{\%Hb \cdot O_2}{100} \right) \times Hb \times 1.34$$

where

$$C_h = \text{ml O}_2/100 \text{ ml blood}$$

$$Hb = \text{gram Hb}/100 \text{ ml blood,}$$

$$1.34 = \text{ml O}_2/\text{gram Hb,}$$

C<sub>h</sub> assumes that one gram of normal hemoglobin is capable of binding and carrying 1.34 ml O<sub>2</sub> when Hb is fully saturated.<sup>12</sup>

The respective values for arterial and venous %Hb·O<sub>2</sub> are employed to calculate arterial-venous C<sub>h</sub> difference.

$$A-V C_h = ((SaO_2 - SvO_2)100) \times Hb \times 1.34$$

where

$$SaO_2 = \text{Arterial \%Hb}\cdot O_2$$

$$SvO_2 = \text{Venous \%Hb}\cdot O_2$$

The difference between arterial and venous total blood oxygen (A-V  $C_{O_2}$ ) is computed and substituted in Equation 3 with the appropriate  $\dot{Q}$  to yield  $\dot{V}_{O_2}$ .

The instantaneous value for  $\dot{V}_{O_2}$  is calculated with nine computer statements, seven directly measured parameters ( $SaO_2$ ,  $SvO_2$ ,  $PaO_2$ ,  $PvO_2$ , Hct,  $\dot{Q}$ , and T), and two predicted values (S and Hb).

The attainment and stabilization of an adequate arterial blood  $O_2$  content assures the perfusionist that the oxygenator oxygen transfer is equal to the oxygen consumption by the patient at that instant during CPB.

The oxygen added to the venous blood with an artificial lung is equal to the CPB patient oxygen consumption if arterial blood oxygen content is unchanging. Continuous, arterial and venous extracorporeal line measurement of  $pO_2$ ,  $\%Hb\cdot O_2$ , temperature, and hemoglobin or hematocrit afford the opportunity to continuously and accurately calculate  $\dot{V}_{O_2}$  during CPB with a simple computer. Analog signals from in-line monitors may supply a small computer to facilitate the speed and accuracy of operations.

Once the accurate prediction of an instantaneous  $\dot{V}_{O_2}$  value is derived, how is the perfusionist to interpret the quantity? The following logical technique is offered to give relevance to the  $\dot{V}_{O_2}$  value to aid in the management of CPB patient.

### Technique: Predicting Expected Oxygen Transfer During CPB

Reporting  $\dot{V}_{O_2}$  as a percentage of patient expected  $\dot{V}_{O_2}$  will offer the perfusionist a variable to quantitate the adequacy of perfusion during CPB techniques that continuously alter patient oxygen consumption. Monitoring % expected  $\dot{V}_{O_2}$  will normalize  $\dot{V}_{O_2}$  to specific patient data and increase the perfusionist's ability to standardize CPB patient management.

Large population studies of human basal metabolic rate allow the prediction of an adult's  $\dot{V}_{O_2}$  given age, body surface area (BSA), and sex.<sup>16</sup>

Previously, an extracorporeal flow formula predicted a  $\dot{Q}$  that will result in a normal venous blood oxygen content given a patient's age, BSA, temperature, and hemoglobin concentration.<sup>13</sup> The numerator of that flow formula (modified Fick Equation) predicts an expected  $\dot{V}_{O_2}$  for a specific patient:

$$\dot{V}_{O_2, \text{exp}} = \frac{2000 \times BSA}{\frac{\sqrt{A} + 9}{T^2}}$$

where  $\dot{V}_{O_2, \text{exp}}$  = expected ml  $O_2$ /minute

A = age in years

BSA = meter<sup>2</sup>

T = temperature in °C

The above equation does not allow for a  $\dot{V}_{O_2}$  difference between sexes and is a mathematical simplification of others' work. The equation also assumes adults have the same  $\dot{Q}_{10}$  as dogs.<sup>13,14</sup>

A more accurate prediction of an expected  $\dot{V}_{O_2}$  is obtained using the following equations:

for males

$$\dot{V}_{O_2}/M^2 \text{ BSA} = e^{(-.003907 \times A + 5.034)}$$

for females

$$\dot{V}_{O_2}/M^2 \text{ BSA} = e^{(-.002806 \times A + 4.8934)}$$

These equations were derived from the work of Boothby and agree with a more recent study by LaFarge for ages from 17 to 70 years.<sup>15,16</sup> Figure 1 plots the affect of age on  $\dot{V}_{O_2}/M^2$  for males and females.<sup>15</sup>

The effect of temperature on expected  $\dot{V}_{O_2}/M^2$  is related in the following equation:

$$\dot{V}_{O_2}/M^2 = \dot{V}_{O_2}/M^2 \times \frac{(e^{(.083291 \times T + 1.5234)})}{100}$$

The previous equation assumes a  $Q_{10}$  of 2.3.<sup>17</sup>

The derived  $\dot{V}_{O_2}/M^2$  for sex and age is inserted in the above equation to arrive at an expected  $\dot{V}_{O_2}$ . The  $\dot{V}_{O_2}/M^2$  result is multiplied by the BSA to arrive at a value for expected  $\dot{V}_{O_2}$  ( $\dot{V}_{O_2, \text{exp}}$ );

$$\dot{V}_{O_2, \text{exp}} = \dot{V}_{O_2}/M^2 \times BSA$$

The instantaneous actual  $\dot{V}_{O_2}$  calculation may be referenced to the expected  $\dot{V}_{O_2}$  by reporting actual as a percentage of expected:

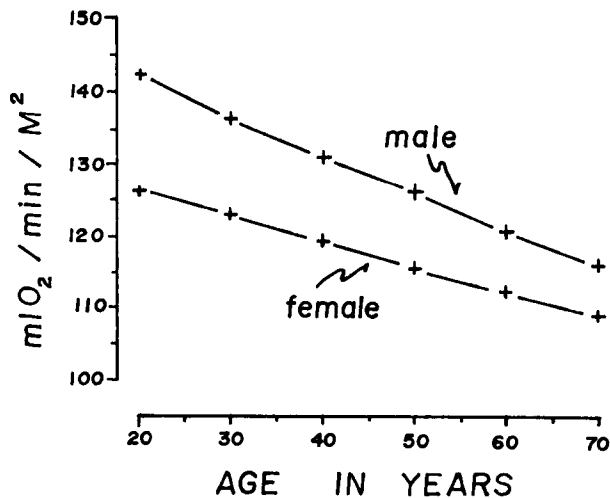


FIGURE 1. The change in oxygen consumption with age according to Berkson<sup>15</sup> as predicted by Equations Eleven and Twelve for normothermic, unanesthetized subjects.

$$\% \dot{V}_{O_2, \text{exp}} = (\text{actual } \dot{V}_{O_2} / \dot{V}_{O_2, \text{exp}}) \times 100$$

hence, giving relevance to the calculated  $\dot{V}_{O_2}$  and normalizing it for a specific CPB patient instance.

The derivation of  $\dot{V}_{O_2, \text{exp}}$  assumes a patient has an average metabolic rate for their particular age, sex, and BSA. Furthermore,  $\dot{V}_{O_2, \text{exp}}$  assumes the patient mass is at one temperature.

### Interpretation: Percent Expected Oxygen Transfer

The interpretation of the oxygen transfer reported as a percentage of expected  $\dot{V}_{O_2}$  for body surface area, temperature, and patient age is probably best appreciated in the following example.

#### Anesthesia and muscle blockade effect

Sixteen male coronary artery bypass graft patients were studied for the affect of anesthesia and 80% muscle blockade on the change in expected  $\dot{V}_{O_2}$ .

Premedication included morphine (n = 8), .1mg/kg, or fentanyl (n = 8), 150–200 ug/m, plus oral diazepam, 5–10 mg, and IM scopolamine, .2–.3mg. Anesthesia was induced with an infusion rate of 2.7 ug/kg/min of fentanyl (n = 8) for 20 minutes followed by a maintenance rate of .3 ug/kg/min, or with an infusion rate of 60 ug/kg/min of morphine (n = 8) for 20 minutes followed by a maintenance rate of 6 ug/kg/min. Neuromuscular blockade was

evaluated by applying supramaximal stimulus at the wrist and recording the thumb adductor response through a force transducer. Eighty percent twitch height reduction was maintained by a curare infusion.

Table 2 lists the physical characteristics of the patients,  $\dot{V}_{O_2}/M^2$  and  $\% \dot{V}_{O_2, \text{exp}}$  for awake - sedated and anesthetized - 80% muscle blockade. Blood flow rate and mixed venous samples were collected with a pulmonary artery catheter equipped to perform thermodilution cardiac output measurements. Arterial blood gases were collected from the radial artery. Nasopharyngeal temperature was used in all calculations.  $\dot{V}_{O_2}$  and  $\% \dot{V}_{O_2, \text{exp}}$  were calculated using the technique described in this work.

Patient No.	Age Years	B.S.A. M2	Awake/Sedate $\dot{V}O_2/M^2$	Anesth./Musc. Blk. $\dot{V}O_2/M^2$	Temperature °C
<b>Fentanyl</b>					
1	52	2.03	89.3	78.8	35.5
2	61	2.01	118.0	88.7	35.6
3	65	1.90	106.6	67.7	34.9
4	43	2.36	124.6	86.9	35.1
5	62	1.90	144.2	92.3	35.4
6	38	1.97	138.6	91.0	35.3
7	63	1.75	103.2	93.2	35.5
8	56	2.12	121.6	63.9	35.4
Mean	55	2.01	118.3	82.8	35.3
1 S.D.	9	.17	17.1	10.7	.2
<b>Morphine</b>					
9	38	2.03	94.5	86.5	35.0
10	52	1.74	122.5	90.6	35.6
11	67	2.12	108.7	80.2	34.7
12	36	1.82	93.7	74.0	34.2
13	65	1.84	99.9	85.9	35.3
14	60	1.80	123.3	120.4	34.4
15	64	2.06	139.0	65.8	35.5
16	52	2.08	116.9	88.2	35.6
Mean	54	1.94	112.3	86.5	35.0
1 S.D.	11	.14	15.0	15.0	.6

Patient No.	Awake/Sedate % $\dot{V}O_2, \text{exp}$	Anesth./Musc. Blk. % $\dot{V}O_2, \text{exp}$
1	71.9	73.0
2	98.4	84.4
3	90.3	69.8
4	96.9	80.7
5	120.8	89.3
6	105.7	81.4
7	86.8	90.2
8	99.5	60.7
9	71.9	79.5
10	98.6	83.2
11	92.8	85.0
12	70.9	72.8
13	84.6	85.4
14	102.4	127.7
15	115.9	63.2
16	94.1	81.0
Mean	93.8	81.7
1 S.D.	14.0	14.5

Paired t-Test:  $p = .022$  ( $p < .05$ ),  $n = 16$  pairs

TABLE 2. The effect of anesthesia (Anesth.) and muscle blockade (Musc. Blk.) on percent expected oxygen consumption ( $\% \dot{V}_{O_2, \text{exp}}$ ). The mean and standard deviation (S.D.) are reported for two anesthesia technique, patient groups. Collectively, anesthesia and muscle blockade decreases  $\% \dot{V}_{O_2, \text{exp}}$  from 93.8% to 81.7% (p is probability)

Table 2 depicts a substantial drop in  $\dot{V}_{O_2}/M^2$ . Are the  $\dot{V}_{O_2}/M^2$  values reasonable? The awake - sedated  $\dot{V}_{O_2}$  calculation is  $93.8 \pm 14\%$  (mean  $\pm$  1 S.D.) of expected oxygen consumption. Ninety-four percent of basal  $\dot{V}_{O_2}$  may be a reasonable expectation for a sedated male prior to anesthesia for CPB. A simple paired sample t-test yields no difference in  $\dot{V}_{O_2}/M^2$  or  $\% \dot{V}_{O_2,exp}$  between anesthesia regimens. Induction of anesthesia and muscle blockade significantly reduced  $\% \dot{V}_{O_2,exp}$ , from  $93.8 \pm 14\%$  to  $81.7 \pm 14.5\%$  ( $p < .05$ ).

It appears that common anesthesia technique for CPB with 80% muscle blockade decreases the percent expected  $\dot{V}_{O_2}$  by a mean of 12%. However, the percent expected  $\dot{V}_{O_2}$  is a calculation subject to possible error. Therefore, each individual must ultimately serve as their own reference during treatment.

The perfusionist should expect values of 80 to 85% of ideal  $\dot{V}_{O_2}$  during CPB if the patient has a normal metabolic rate for their age and BSA, and the majority of their tissue mass is at one temperature and is being perfused. The percent expected oxygen consumption will quantitate any deviation from these assumptions.

## Discussion

Use of continuous, in line blood oxygen content monitors and the  $\dot{V}_{O_2}$  calculation technique described herein will aid the perfusionist in the selection of blood flow and ventilation rates to assure that constantly changing, specific patients  $\dot{V}_{O_2}$  expectations are fulfilled during CPB.

The prediction of an expected  $\dot{V}_{O_2}$  and reporting calculated  $\dot{V}_{O_2}$  as a percentage of that expected value gives relevance to oxygen transfer calculation during CPB.

The technique presented here makes the following assumptions:

- a. no extracorporeal arterial-venous shunts exist,
- b. the large population study results cited in this work are representative of the future CPB patient population, 17 to 70 years of age, and
- c. all patient tissue are at one temperature.

Employing the calculation of  $\% \text{ expected } \dot{V}_{O_2}$  in future studies will aid investigators in quantitating:

- a. the beneficial reduction of  $\dot{V}_{O_2}$  during CPB hypothermia,

- b. the deleterious effects of vasoconstriction and maldistribution of organ perfusion, and
- c. the selection of an adequate blood flow rate during CPB to avoid organ hypoperfusion secondary to hypotension or possible arteriovenous precapillary shunting.

Future studies will employ vascular resistance measurement with the  $\% \text{ expected } \dot{V}_{O_2}$  calculation and assessment of lactic acidosis to demonstrate the efficacy of commonly employed perfusion and CPB anesthesia techniques.

It appears from the data presented herein that one should expect CPB values of 80 to 85% for  $\% \text{ expected } \dot{V}_{O_2}$  with adequate organ perfusion, and uniform patient cooling and warming. Deviation from expected  $\dot{V}_{O_2}$  values during CPB will probably be explained by vascular resistance abnormalities, uneven distribution of organ blood flow or the repaying of an oxygen debt recently accrued during inadequate ventilation for continuously changing patient  $\dot{V}_{O_2}$ .

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### Appendix: \_\_\_\_\_

Basic computer language algorithms to calculate % exp,  $\dot{V}_{O_2}$ :

Arterial blood  $O_2$  content ( $C_a$ ) employing arterial blood temperature ( $T_a$ ):

- 100  $S = (4 * 10^{-6} * Hb + 3.46 * 10^{-4}) * T_a + 1.3 * 10^{-4} * Hb + 3.5 * 10^{-2}$
- 110  $C_d = (P_aO_2/7.6) * S$
- 120  $C_h = (SaO_2/100 * Hb * 1.34$
- 130  $C_a = C_d + C_h$

Venous blood  $O_2$  content ( $C_v$ ) employing venous blood temperature ( $T_v$ ):

- 140  $S = (4 * 10^{-6} * Hb + 3.46 * 10^{-4}) * T_v + (1.3 * 10^{-4} * Hb + 3.5 * 10^{-2})$
- 150  $C_d = (P_vO_2/7.6) * S$
- 160  $C_h = (SvO_2/100) * Hb * 1.34$
- 170  $C_v = C_d + C_h$

Oxygen transfer ( $V_O$ ) is derived:

- 180  $V_O = ((C_a - C_v)/100) * \dot{Q}$
- $\dot{V}_{O_2}/M^2$  (VI at 37°C);
- 190 Input "Is the Patient Male (M) or Female (F)?" ; S\$
- 200 If S\$ = "M" then Go to 220
- 210 VI = Exp (-.002806 \* A + 4.8934);  
Go to 230
- 220 VI = Exp (-.003907 \* A + 5.034)
- Adjusting  $\dot{V}_{O_2}/M^2$  for temperature and deriving expected  $\dot{V}_{O_2}$ ; (VI);
- 230 VI = VI \* (Exp(.0832908 \* T + 1.52341/100)
- 240 VI = VI \* BSA
- Calculating % Exp  $\dot{V}_{O_2}$  (VI); using actual  $\dot{V}_{O_2}$  (VO);
- 250 VI = (VO/VI) \* 100