An Extra-Corporeal Flow Formula for All Patients

Emanuel Bagby, C.C.P.

Charlotte Memorial Hospital and Medical Center
Charlotte, North Carolina 28232

To address the question of adequate perfusion, one must first determine what the oxygen needs are which we seek to satisfy by perfusion. Total oxygen demand may vary widely between individuals due to differences in age, weight, height, and to a lesser degree, sex and metabolic rate and perhaps many other unknown factors. In the open heart theater, add the rapidly changing variables of temperature and anesthesia levels and exact determination of oxygen need at any given time is impossible. However, through careful study of those determinants which can be assigned a numerical value (even if the values are only estimates), one can derive a figure close enough to the patients actual need, that a formula can be written to predict adequate perfusion rates for open heart surgery. When the perfusion rate is calculated to satisfy the oxygen need of a patient at rest, and that rate is used to perfuse a patient who is not only at rest but also asleep with a non-beating heart and general muscular paralysis, one can expect to provide a more than adequate supply of available oxygen for the body tissues.

To provide an adequate oxygen supply to all patients at all times with minimal over-perfusion, even at low temperatures, is the aim of the perfusion technique which follows. This aim is accomplished by utilizing an EXTRA-CORPOREAL FLOW FORMULA (Figure I), which incorporates age, weight, height, temperature, and hemoglobin, the key factors in oxygen supply and demand. A constant PO_2 factor equal to 200 mm Hg. is also included in the formula.

The total oxygen need for any patient at rest (Basal Metabolic Rate) can be estimated by multiplying the age factor times the body surface area (in meters square) and dividing this product by the temperature factor.

The age factor is derived from oxygen consumption studies done in the mid 1930's by physiologists Boothby, Berkson, and Dunn[1] of the Mayo Foundation in Rochester, Minnesota. From those studies, an exponential curve was drawn showing extremely high oxygen consumption in children, (200 cc/M^2 per min. at age 1), decreasing sharply until early adulthood, (148 cc/M^2 at age 20), then decreasing more slowly with age in mature adults, (119 cc/M^2 at age 60). A formula was then written to fit this curve. This formula, $2000/(\sqrt{\text{age}} + 9)$, gives the age factor used in the overall flow formula (Figure I). For example, the age factor of a 16 year old is calculated: $2000/\sqrt{16} + 9 = 2000/(4 + 9) = 2000/13 = 153.8$. Thus, the at rest O_2 need of a 16 year old is 153.8 $cc/M^2/min$.

The body surface area is calculated using the familiar formula by Dubois and Dubois ($\text{B.S.A. } M^2 = (\text{Wt./Kg.})^{.425} \times (\text{Ht./Cm.})^{.725} \times .007184$).

Ostigaard, et al[2] show oxygen need in *adults* to be four (4) cc per Kg. per minute

Address inquiries To: Emanuel Bagby, c/o Cardiac Lab, Charlotte Memorial Hospital & Medical Center, P.O. Box 32861, Charlotte, NC 28232.

EXTRA-CORPOREAL FLOW FORMULA

$$O_2\ \text{need} = \frac{\dfrac{2000}{\sqrt{\text{age}} + 9} \times ((\text{Wt. Kg.})^{.425} \times (\text{Ht. Cm.})^{.725}) \times .007184}{\dfrac{37^2}{(\text{Patient's temp.})^2}}$$

$$\text{FLOW} = \rule{10cm}{0.4pt}$$

$$O_2\ \text{Factor} = \frac{\dfrac{1.39 \times \text{Hgb.}}{4} + 0.6}{100}$$

Figure I

at 37 degrees C, decreasing to 2 cc/Kg./min. at 29 degrees C, and decreasing similarly with further reduction in temperature. The temperature factor used in the above extra-corporeal flow formula, $37^2/(\text{patient's temp.})^2$, differs in that it works in conjunction with the patient's age, weight, and height (not just weight) which makes it applicable to all patients. It also offers slightly more oxygen at lower temperatures since the colder patient's capacity to extract oxygen may be somewhat reduced.

Since oxygen supply to the patient depends upon the oxygen carrying capacity of the perfusate, careful consideration must be given to hemoglobin and arterial PO_2 levels when planning flow rates. Changes in hemoglobin are automatically compensated for in the above flow formula (Figure I) and an arterial PO_2 level of 200 mm Hg. is assumed since our statistics show the average arterial PO_2 at that level during bypass. However, arterial PO_2 variations within acceptable limits may be used without fear of overperfusion or underperfusion.

To evaluate this formula, 110 test cases were studied with regard to predicted oxygen need at rest and actual oxygen consumption during cardiopulmonary bypass. The average oxygen consumption for all cases was 65% of the predicted at rest need, with variations from a low of 48% to a high of 98%. The average consumption of 65% of predicted oxygen need does not mean however that one could safely reduce calculated oxygen need during bypass by 35%. To do so may severely underperfuse some patients whose consumption may vary to the high side of normal.

EVALUATION PROCEDURE

Using a Sarns Model 5000 roller pump and a Bentley BOS-10 or Q-200A oxygenator, the extra-corporeal circuit was primed with 2 to 2.5 liters of Lactated Ringers in adult cases. Whole blood or packed cells was added as needed to maintain hemoglobin

Averages from 110 Cases

pH — 7.415
PCO_2 — 36.2
PO_2 — 272.7
HCO_3 — 23

Base Excess −1
Arterial Sat. 95.2%
Venous Sat. 82.6%
A-V Sat. Difference 12.6%

Figure II

at such levels as to satisfy the calculated oxygen need without exceeding a flow rate of 6L/min. Q-110 oxygenators, primed with 500 cc of blood and 500 cc of Lactated Ringers, were used in pediatric cases.

The average beginning bypass temperature was 35 degrees C. If normal thermia was to be maintained, beginning flow was calculated for a temperature of 37 degrees C. Ten to fifteen minutes of bypass time was allowed for cooling, after which the hemoglobin was determined and flow adjustments made. An additional fifteen minutes equilibration time at the desired temperature, (usually 29 degrees C) and a constant flow rate, was allowed before samples were taken for analysis. Simultaneous arterial and mixed venous samples were taken for analysis of arterial pH, PCO_2, PO_2, O_2 saturation, and venous O_2 saturation and hemoglobin. All samples were taken after placement of the aortic cross clamp and during periods of minimal blood loss to increase the accuracy of the measurement of blood reaching body tissues. If blood continued to flow through the left ventricular vent line, it was estimated and subtracted from the total bypass flow.

Very few analyses were done at normal temperature because the aortic cross clamp was usually released and the heart restarted before equilibration time could be allowed. Flows were recalculated and adjusted at various intervals during cooling and rewarming.

EVALUATION RESULTS

Blood gas analysis was within normal limits (Figure II).

Flow rates were generally lower than those used during the previous year using other calculating methods. In some cases flows were as much as 1600 cc/min. less than those calculated using 2.4 L/M^2 as the only criteria for determining flow. In other cases, especially patients with low hemoglobins and at normal temperatures, flows were higher by more than 1600 cc/min. Figure III shows the range of patient data and flow rate in the test cases.

Age range (yrs)	.66 to 77	average = 51
Weight (lbs)	11.7 to 270	average = 158
Height (ins)	28.7 to 75	average = 66
BSA (M^2)	.328 to 2.42	average = 1.81
Temp. (C)	17 to 37.9	average = 29.3
Flow (cc/min)	500 to 5700	average = 3667

Figure III

No. Patients	Ht. in inches	% of predicted O_2 used
29	66 or less	56.4
18	66.5 to 68	63.0
27	68.5 to 70	67.2
15	70.5 to 72	73.5
6	72.5 or more	78.1

(Fifteen (15) children not included)
Figure IV

Tall patients required notably more oxygen than short patients of equal body surface area and age (Figure IV).

A slight increase in the percent of predicted O_2 actually used was also noted with increased body surface area. However, evidence indicates that this increase is again a reflection of increased height. Therefore, a separate height factor (now being studied) could be used to increase the accuracy of flow predictions.

CALCULATIONS

Using a Model TI-59 Programmable Calculator (by Texas Instruments, Inc.), the flow formula was entered through the keyboard and was recorded on a magnetic card*. Once the calculator is programmed, either by entering the formula through the keyboard or by simply inserting the pre-recorded card, initial flow calculation can be made in less than one (1) minute and recalculation to compensate for changes in temperature and hemoglobin takes less than ten (10) seconds.

The following is one of several ways which this formula may be entered into a calculator program.

Step	Key	Comments	Step	Key	Comments	Step	Key	Comments
1	*LBL		16	)		31	*PRT	
2	*E	Age (Yrs.)	17	=	$O_2/M^2/MIN$	32	INV,SBR	
3	STO		18	STO		33	*LBL	
4	00		19	01		34	B	Ht. (in.)
5	2		20	*PRT		35	STO	
6	0		21	INV,SBR		36	04	
7	0		22	*LBL		37	*PGM	
8	0		23	A	WT. (lbs.)	38	24	
9	÷		24	STO		39	A	Ht. (cm)
10	(		25	02		40	STO	
11	RCL		26	*PGM		41	05	
12	00		27	25		42	RCL	
13	$\sqrt{x}$		28	E	WT. (Kg.)	43	03	
14	+		29	STO		44	Y^x	
15	9		30	03		45		

* See instruction manual for Model TI-59 calculator by Texas Instruments, Inc.

Step	Key	Comments	Step	Key	Comments	Step	Key	Comments
46	4		72	*LBL		98	÷	
47	2		73	C	Temp. (C)	99	4	
48	5		74	X^2		100	+	
49	x		75	÷		101	.	
50	(		76	3		102	6	
51	RCL		77	7		103	=	
52	05		78	X^2		104	÷	
53	Y^x		79	=		105	1	
54	.		80	x		106	0	
55	7		81	RCL		107	0	
56	2		82	01		108	=	O_2 factor
57	5		83	x		109	STO	
58	)		84	RCL		110	08	
59	x		85	06		111	*PRT	
60	.		86	=	O_2 need	112	INV,SBR	
61	0		87	STO		113	*LBL	
62	0		88	07		114	E	
63	7		89	*PRT		115	RCL	
64	1		90	INV,SBR		116	07	
65	8		91	*LBL		117	÷	
66	4		92	D	Hgb	118	RCL	
67	=	BSA(M^2)	93	x		119	08	
68	STO		94	1		120	=	flow
69	06		95	.		121	STO	
70	*PRT		96	3		122	09	
71	INV,SBR		97	9		123	*PRT	
						124	INV,SBR	

USER INSTRUCTIONS

Step	Enter	Press	Display
1	Age (yrs)	E′	O_2/M^2/min
2	Wt (lbs)	A	Wt (Kg)
3	Ht (in)	B	BSA (M^2)
4	Temp (°C)	C	O_2 need
5	Hgb	D	O_2 factor
6		E	flow

The above program is written with instructions which allow its use either with or without a printer (Model PC100-A by Texas Instruments, Inc.).

CONCLUSION

This formula has proven to be most valuable in preplanning perfusion techniques for children and extremely large patients, and patients with low hemoglobins. It has made it possible to start a procedure absolutely confident that the right combination of oxygenator size, pump tubing, perfusion catheter, etc., has been chosen to satisfy the patient's need, regardless of size. The comforting reassurance of repeated blood gas analysis during long procedures is no longer necessary, nor is Sodium Bicarbonate given during the rewarming phase to compensate for possible underperfusion.

The decision to add blood or non-blood perfusate when replacing lost volume can be made quickly and wisely by calculating its affect on hemoglobin and flow.

Flows slightly higher than calculated may be used at times, (especially in deep hypothermia), to increase arterial pressure. Flows lower than calculated may be used at normal or near normal temperatures when overperfusion is obvious. However, the evidence indicates that strict adherence to precalculated flow rates never failed to completely satisfy the patient's oxygen demand.

REFERENCES

1. Berkson, J. and W. M. Boothby. Studies of the energy of metabolism of normal individuals. A comparison of the estimation of basal metabolism from (1) a linear formula and (2) "surface area". *Am. J. Physiol.* 116: 485, 1936.
2. Ostigaard, P., et al., Adjusting oxygen availability to tissues. *J. Extracorporeal Tech.* 8: 136, 1976.