Ventilation Technique for CPB Patients Less Than 10 Kilograms Employing a 1.6 m^2 Hollow Fiber Membrane

G.A. Justison, G.P. Wagner, and J.B. Riley
Extracorporeal Technologies, Inc.
Indianapolis, IN

Abstract

The purpose of this study was to document the performance of a 1.6 m^2 hollow fiber membrane blood oxygenator (HFMO) in a specific ventilation technique for a patient population averaging 6 kilograms and .34 m^2 BSA.

Continuous monitoring was utilized to maintain actual PaO_2 about 200 mmHg and PvO_2 above 35 mmHg. HFMO expired gas pCO_2 was monitored to select the optimal O_2/room air sweep rate to maintain actual p_aCO_2 between 35 and 40 mmHg.

Cardiopulmonary bypass (CPB) blood flow was initiated at 160 ml/min/kg and decreased to 100 ml/min/kg at 20°C. During warming, blood flow was increased to 175 ml/min/kg at 38°C. The hematocrit averaged 18% during cooling, low blood flow and/or exsanguination. Transfusion raised the average hematocrit to 29% at 38°C. HFMO average control parameters were:

	$\dot{V}O_2$	FiO_2	$\dot{V}CO_2$	Sweep Ratio	Temperature
Cooling	97.	62	44.	.35	34°C
	19.	33	4.	.10	20°C
Warming	65.	48	300.	1.2	20°C
	170.	75	105.	.63	38°C
	ml/min/M^2	%	ml/min/M^2	Gas: Blood Flow	

The Terumo HFMO integral heat exchanger cooled these patients at an average rate of .16°C/min/kg, warming with a safe gradient yielded an average rate of .09°C/min/kg.

The 1.6 m^2 HFMO provides more than adequate heat, oxygen and carbon dioxide transfer for this patient population.

Direct communications to: George A. Justison, 3380 Founders Road, Indianapolis, IN 46268.

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Introduction

The purpose of this study is to document a specific ventilation technique employing a 1.6 square meter Hollow Fiber Membrane Oxygenator (HFMO). Eleven infant patients weighing less than 10 kilograms, averaging 5.9 ± 2.5 kg (1 SD), were randomly selected and subjected to hypothermic (20°C esophageal) low flow perfusion (36%) and/or circulatory arrest (64%). Arterial and venous pO_2, percent oxygen saturation of hemoglobin, HFMO expired gas pCO_2, and blood temperature were continuously monitored. Oxygen and carbon dioxide transfer, as well as FiO_2 and gas sweep ratios were plotted with respect to temperature for CPB cooling and warming phases. These results will aid the perfusionist in selecting the HFMO ventilation parameter settings and increase the chance of obtaining desired blood gas results early in a specific institution's HFMO experience.

Methods

The extracorporeal circuit (ECC) consisted of a Terumo[a] 1.6 m^2 HFMO and 400 cc venous reservoir bag. A ⅜-inch venous drainage line and ¼-inch arterial line with a 37 micron arterial filter were used. The Orange Medical Instruments[b] pO_2 and temperature probes were placed in the arterial and venous lines with the American Bentley[c] Oxy-SAT probes following manufacturer's instructions.

[a]Terumo Corporation, Piscataway, NJ 08854
[b]Orange Medical Instruments, Costa Mesa, CA 92626
[c]American Bentley, Inc., Irvine, CA 92714

The ECC was primed with 300 cc of a balanced electrolyte solution, 200 ml fresh frozen plasma, 200 mg $CaCl_2$, and 1500 units of heparin. Sodium bicarbonate was added to adjust the pH to 7.4 and packed red blood cells to yield a post dilution hematocrit between 20 and 25 percent. The total ECC priming volume averaged 750 milliliters.

The actual p_aO_2 was maintained about 200 mmHg by varying the ventilating gas FiO_2 using a Sechrist[d] oxygen blender. The percent oxygen of the gas mixture was continuously verified using the Ohio Medical Products Model 201 O_2 analyzer.[e] Expired gas pCO_2 was monitored using a Biochem International Inc.[f] capnometer to select the oxygen/room air gas sweep rate to maintain actual p_aCO_2 between 35 and 40 mmHg.

A single right atrial and aortic cannulae were placed and CPB was initiated at 141.8 (± 37.6) ml/min/kg. Rapid cooling was induced to an esophageal temperature of 20°C and hypothermic blood flows were reduced to 85.7 (± 52.2) ml/min/kg. Either low flow perfusion or total circulatory arrest was maintained during surgical repair. Upon completion, rapid rewarming was induced and blood flow was returned to 165.9 (± 27.8) ml/min/kg. Transfusion with packed red blood cells during rewarming was utilized to raise the average hematocrit to 29%.

The FiO_2 and gas sweep ratios needed to maintain the desired blood gas parameters along with oxygen and carbon dioxide transfer were plotted versus temperature for the cooling and warming phases. The respiratory quotient (RQ) was calculated at the initiation and termination of each phase as $\dot{V}CO_2/\dot{V}O_2$. Heat exchanger performance was quantitated as the average rate of temperature change per minute per kilogram (°C/min/kg) during each phase observing safe water-blood gradients. Statistical analysis included linear regression correlation coefficients and standard deviation of the means.

Results

Figure One represents the $\dot{V}O_2$ (ml/min/kg) versus temperature for the cooling and warming phases respectively for this patient population. A similar scattergram is found for the inspired gas FiO_2 (Figure Two) as well as the venous saturation (SvO_2) (Figure Three).

Carbon dioxide transfer is illustrated with respect to temperature for the cooling phase and

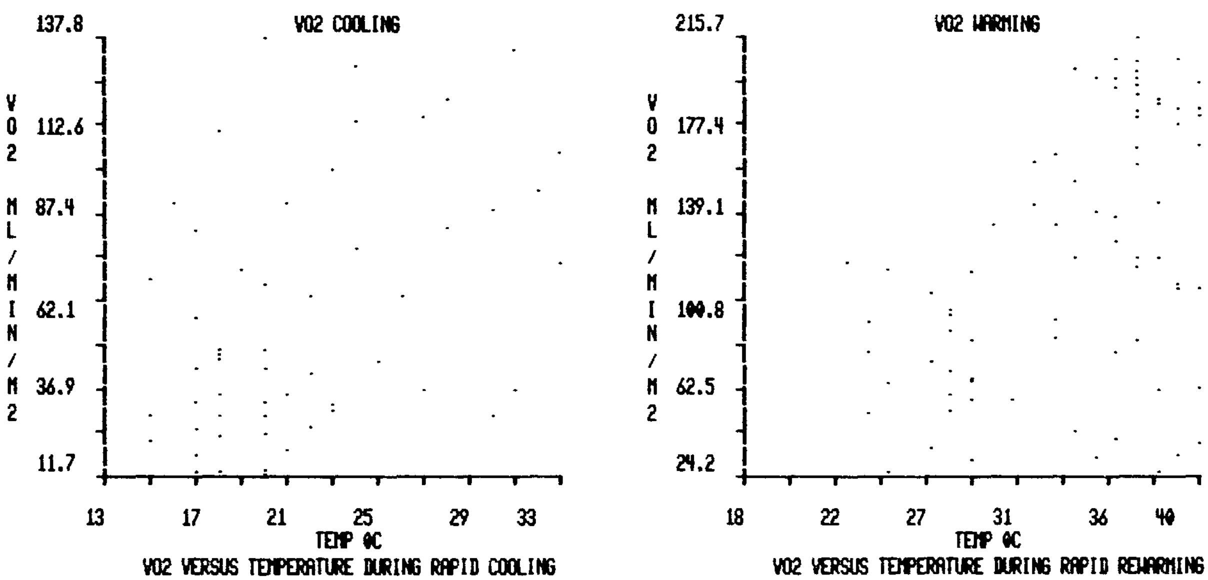

FIGURE 1. Oxygen transfer versus temperature during rapid cooling and warming phases.

[d]Sechrist Industries, Inc., Anaheim, CA 92806
[e]Arco, Inc., Madison, WI 53701
[f]Biochem International, Inc., Milwaukee, WI 53213

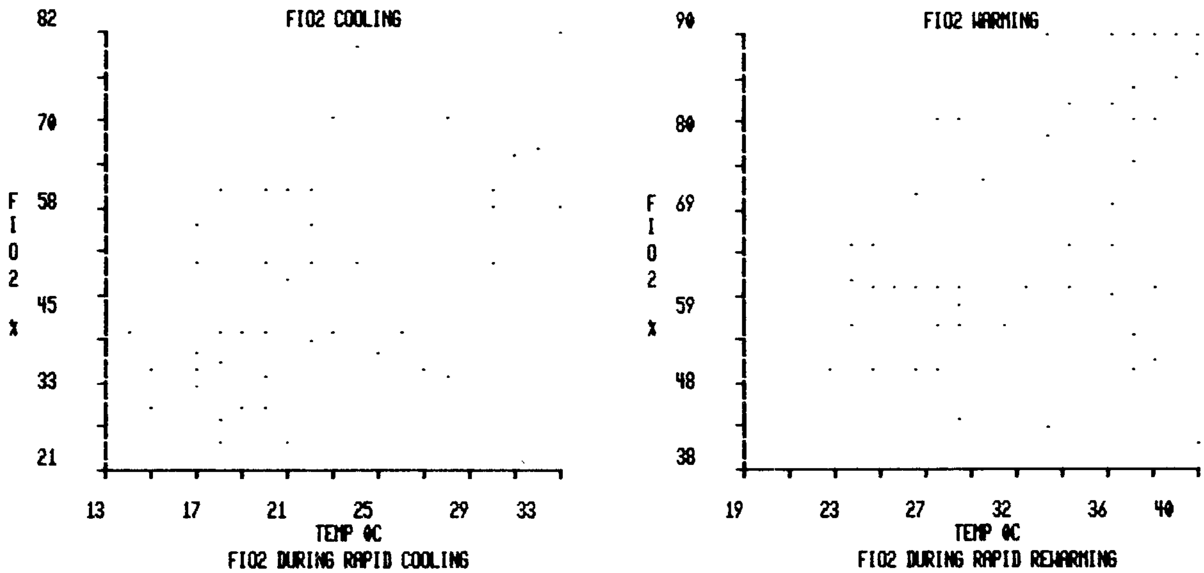

FIGURE 2. HFMO ventilating gas FiO_2 at respective temperatures during rapid cooling and warming.

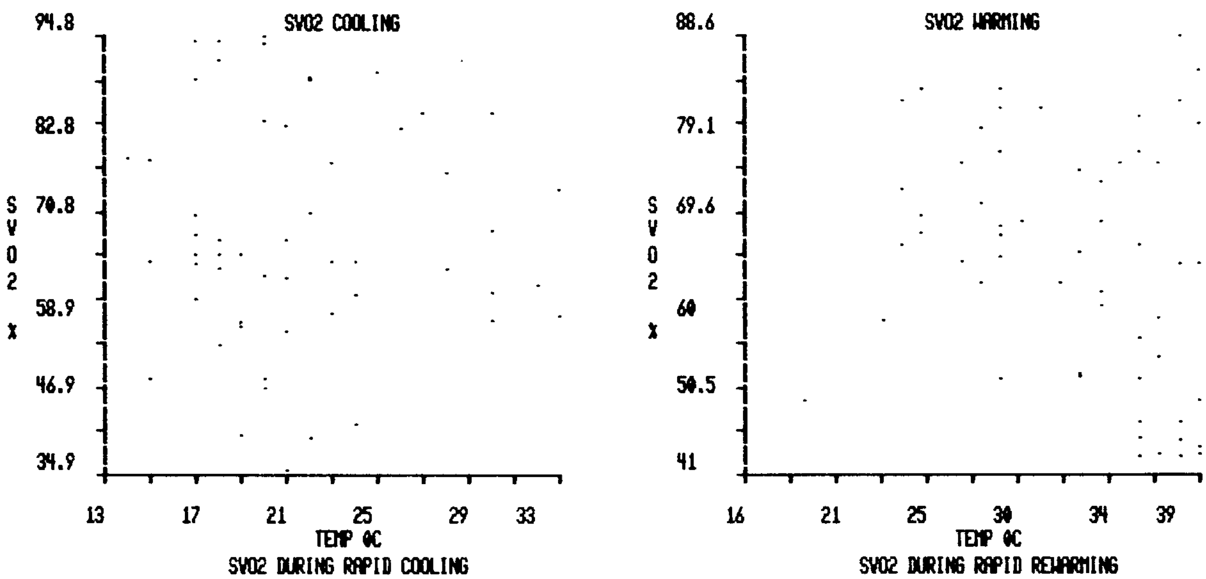

FIGURE 3. Venous hemoglobin oxygen saturation during cooling and warming versus respective temperatures.

rewarming phase in Figure Four. Similar graphs are presented for each phase showing the gas sweep ratios (Figure Five). Related nomograms of cardiac index (ml/min/kg) are shown in Figure Six.

Patient morphology and primary surgical procedures are listed in Table One. The mean values for the CO_2 transfer parameters and pCO_2 are listed in Table Two with the respective temperatures at the beginning and end of each phase. The mean respiratory quotient (RQ) was listed for each point. Table Three lists related factors for oxygen transfer (FiO_2, SvO_2, $\dot{V}O_2$, Hct, and CI) at the same points for each phase.

Statistical results of the infant CPB patient management parameters are listed in Table Four. $\dot{V}O_2$, $\dot{V}CO_2$, FiO_2 and gas sweep ratios (QG:QB) for each cooling and warming phase are shown with the number of pairs, linear regression correlation coefficients, and significance for each group. All parameters were significant with a 99% confidence interval except $\dot{V}CO_2$ cooling.

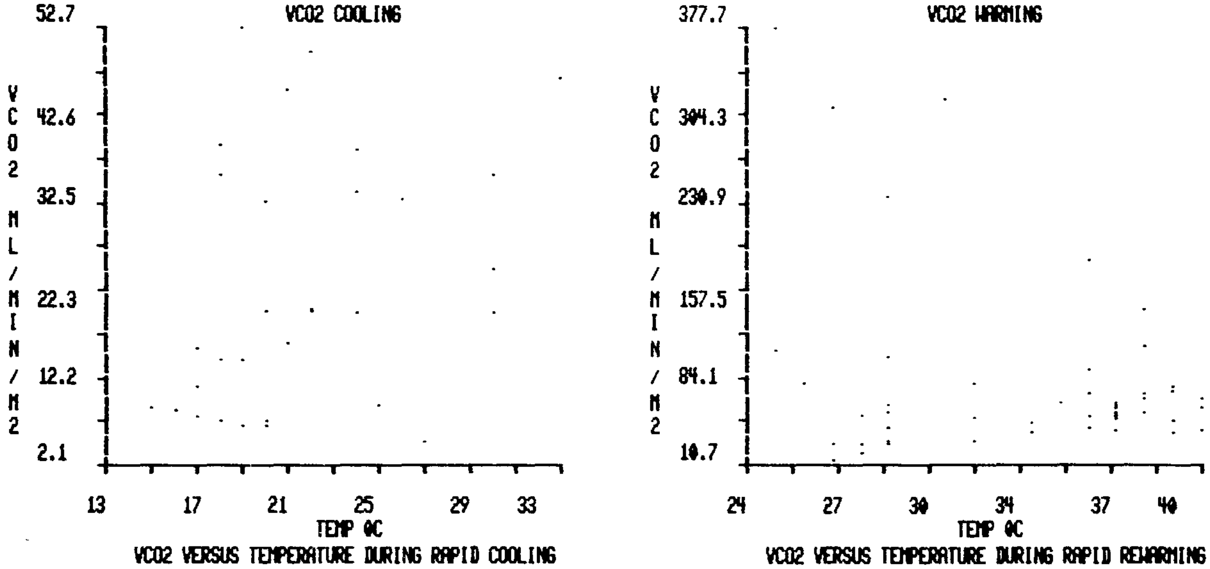

FIGURE 4. Carbon dioxide transfer versus temperature during rapid cooling and warming.

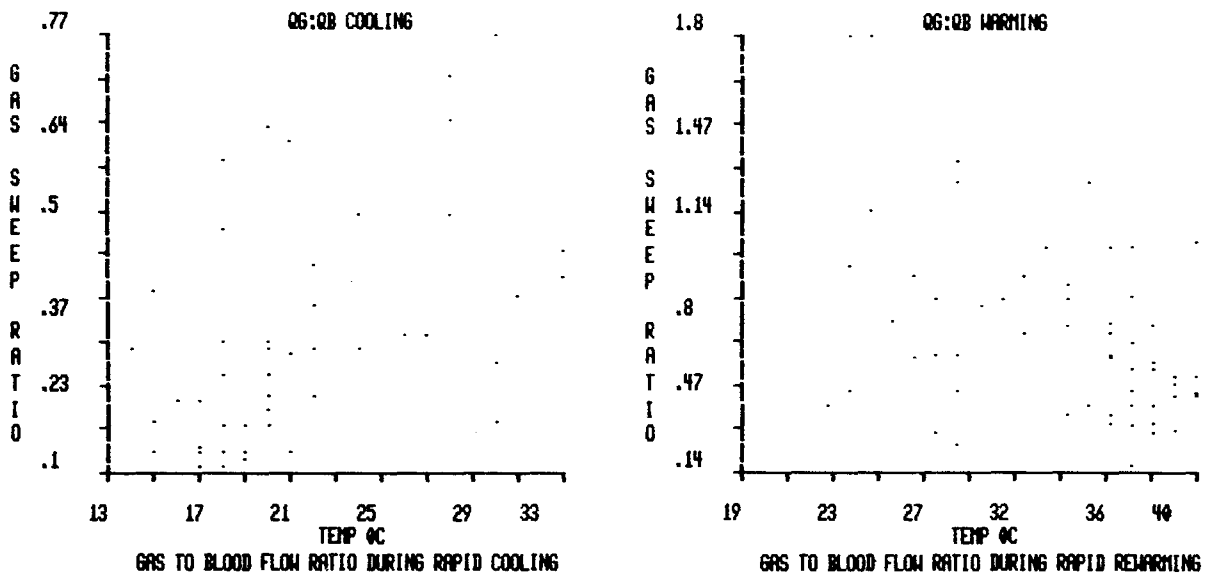

FIGURE 5. Gas sweep ratio scattergram with respect to patient temperature during cooling and rewarming.

Discussion

Eleven infant case reports are averaged and presented in which 64% of the population was categorically diagnosed with congenital cyanotic heart disease. This patient population of less than 10 kilograms presents a challenge to the perfusionist since large pre-CPB oxygen debts must be paid back during rapid cooling and post exsanguination or low flow reperfusion. Oxygenator performance is often stressed due to low venous O_2 contents.

The Terumo 1.6 m^2 HFMO was challenged with a mean SvO_2 of 58.6% at the initiation of CPB and transferred an average of 102.5 ml/min/kg of oxygen to maintain the average actual p_aO_2 about 200 ± 51 mmHg. The HFMO was able to repay this large O_2 debt due with a mean inspired ventilating gas FiO_2 of 74% at 34°C esophageal which was reduced to an average of 36% at 20°C. Figure One represents $\dot{V}O_2$ with respect to temperature during the cooling phase. High $\dot{V}O_2$s during hypothermia are indicative of the pre-CPB oxygen debt, re-

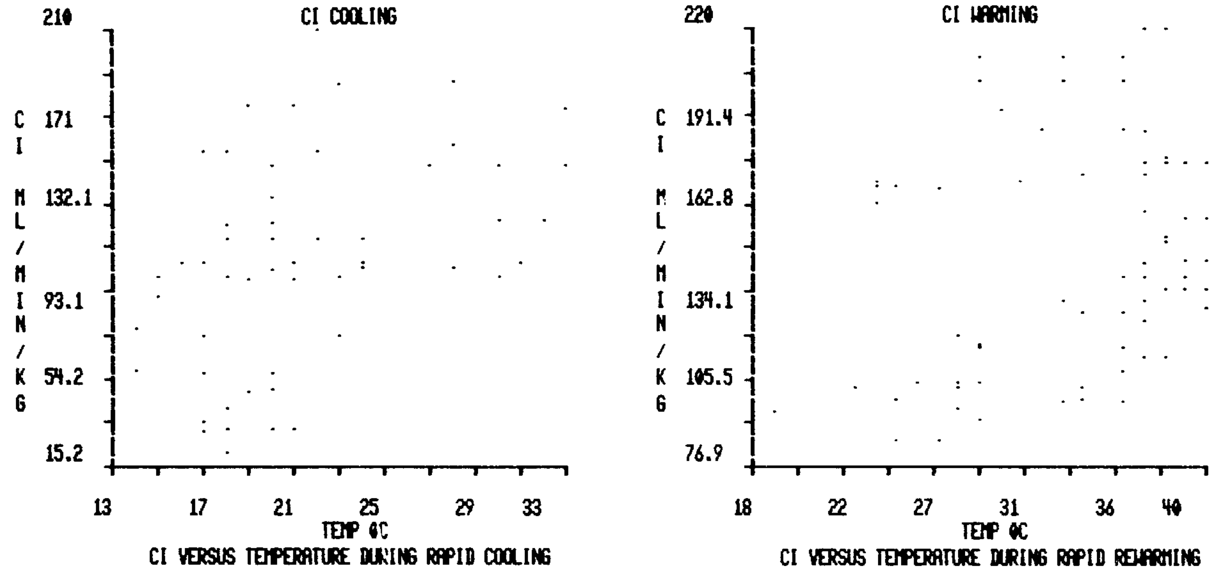

FIGURE 6. Cardiac Index versus temperature during rapid CPB cooling and warming phases.

TABLE 1
1.6 m^2 HFMO infant patient morphology and primary etiology data.

1.6M^2 HFMO/INFANT

	LIMITS	MEAN	S.D.
Patient Age (mos.)	.25-17	6.5	4.9
Patient Weight (Kg.)	2.6-10.1	5.9	2.5
Patient BSA (M^2)	.24-.48	.35	.08
Total CPB Time (min.)	28-180	95.9	49.5

Patient Etiology	
TGA	54.5%
Septal Defect	18.2%
APVR	9.1%
Hypoplastic LV	9.1%
RA Tumor (n=11)	9.1%

TABLE 2
Mean carbon dioxide transfer, gas sweep ratios, p_aCO_2, and respiratory quotients (RQ) at respective temperatures for beginning and end points of the cooling and warming phases.

1.6M^2 HFMO/INFANT CO_2 TRANSFER

	Temp.	Sweep Ratio	$PaCO_2$	VCO_2	RQ
Cooling	34	.39	31	40.7	.40
	20	.20	33	28.3	.97
Warming	20	1.1	36.5	172.2	2.39
	38	.55	37.7	57.6	.34
	°C	Gas: Blood flow	mmHg	ml/min /M^2	CO_2:O_2

TABLE 3
Average oxygen transfer, HFMO ventilating gas FiO_2, SvO_2, hematocrit, and cardiac index for the beginning and end of each cooling or warming phase.

1.6M^2 HFMO/INFANT O_2 TRANSFER

	Temp.	FiO_2	S_vO_2	$\dot{V}O_2$	$\overline{HCT}$	$\overline{CI}$
Cooling	34	74	58.6	102.5	23	141.8
	20	36	69.7	29.2		85.7
Warming	20	50	66.1	72	31	125.4
	38	75	60.4	170.6		165.9
	°C	%	%	ml/min /M^2	%	ml/min /Kg

TABLE 4

1.6 m^2 HFMO infant patient management parameters statistical summary including n = number of data pair, r = linear regression correlation coefficients, and significance for each cooling and warming phase.

INFANT CPB PATIENT MANAGEMENT PARAMETERS

Parameter	No. Pairs (n)	Correlation Coefficient (r)	Significance (p)
$\dot{V}O_2$ cooling	61	.33	< .01
$\dot{V}O_2$ warming	78	.37	< .01
$\dot{V}CO_2$ cooling	33	.17	N. S.
$\dot{V}CO_2$ warming	55	-.43	< .01
FiO_2 cooling	51	.48	< .01
FiO_2 warming	63	.55	< .01
QG:QB cooling	53	.44	< .01
QG:BQ warming	64	-.37	< .01

sulting from congenital cyanotic heart disease, traumatic intubations, and p_aO_2s which deviate above the desired limit.

Large oxygen debts are encountered once again at the initiation of the warming phase incurred from the decreased $\dot{V}O_2$ during low flow perfusion or circulatory arrest.

At the initiation of warming, the HFMO transferred 72 ml/min/m^2 of oxygen using a mean ventilating gas FiO_2 of 50% at 20°C. Increased oxygen consumption during warming required an average of 170.6 ml/min/m^2 of oxygen to be transferred. This was accomplished using a mean HFMO ventilating gas mixture of 75% oxygen at 38°C. Figure One illustrates $\dot{V}O_2$ during rapid rewarming in relation to patient temperature. The FiO_2 required during this same phase is depicted in Figure Two. Linear regression correlation coefficients for the mean FiO_2 during rewarming ($r = .51$) are significant at a confidence interval equal to 99%. This suggests that during rewarming, an inspired gas FiO_2 of less than 80% was sufficient for this extreme patient population. Higher ventilating gas FiO_2s result in increased arterial pO_2 above the desired limits. Even in the face of significantly low SvO_2 as illustrated in Figure Three, the Terumo 1.6 m^2 transferred an adequate amount of oxygen to maintain the arterial pO_2 in an acceptable range.

Carbon dioxide transfer at the initiation of CPB with a mean gas to blood flow ratio of .39 averaged 40.7 ml/min/m^2 yielding a mean p_aCO_2 of 31 mmHg at 34°C. A common disorder associated with cyanosis is hypercapnia. However, the low p_aCO_2 experienced at the initiation of the cooling phase is the result of high $\dot{V}CO_2$ resulting from HFMO hyperventilation. The result of obtaining p_aCO_2s in the desired limits at the end of cooling is the result of purposeful CO_2 retention obtained by decreasing the gas sweep ratio and minimizing the HFMO RQ. At 20°C only an average of 28.3 ml/min/m^2 of CO_2 were transferred at a gas sweep ratio of .20.

During reperfusion after hypothermic low flow perfusion and circulatory arrest CO_2 production and retention are often experienced. At initiation of CPB and rewarming, significantly high mean $\dot{V}CO_2$ of 172.2 ml/min/m^2 are required to maintain the p_aCO_2 at 36.5 ± 6.1 mmHg. This requires an HFMO gas to blood flow ratio of approximately 1.1:1. The 1.6 m^2 HFMO transferred significantly more CO_2 ($r = .46$. $p = .01$) during early rewarming and required only a .55 gas sweep ratio at 38°C to transfer an average of 57.6 ml/min/m^2 of CO_2 yielding mean p_aCO_2s of 37.7 ± 6.2 mmHg.

The ability to accomplish extreme $\dot{V}CO_2$ in early rewarming and return to expected $\dot{V}CO_2$ at 37°C illustrates the 1.6 m^2 HFMO's efficiency and controllability in dealing with extreme CO_2 transfer situations found in this patient group.

The 1.6 m^2 HFMO's integral heat exchanger cooled this patient population at an average rate of .21°C/min/kg. Rewarming with a safe temperature gradient of 8°C or less between venous blood and water inlet temperature yielded a rate of .09°C/min/kg.

Observation of the results from this challenging patient group yields these recommendations:

1. Average gas sweep ratios of .39 and ventilating gas FiO_2 of 74% at the initiation of rapid cooling provides adequate O_2 and CO_2 transfer under these conditions to maintain 37°C normal blood gas results.
2. Upon initiation of rapid cooling, ventilation parameters should be decreased with respect to decreasing temperature to avoid deviation outside of desired limits. HFMO control parameter values at 20°C are an average gas sweep ratio of .20 and inspired gas FiO_2 of 36%.
3. Initiation of rapid warming requires an average sweep ratio of 1.1:1 and an FiO_2 of 50% to provide adequate gas transfer due to CO_2 retention and O_2 deficit incurred during circulatory arrest. Prolonged arrest periods may require ventilation parameters above these means.
4. During rewarming and at normothermia, the average gas sweep ratio may need to be reduced to .55, while the average FiO_2 will increase to 75% to handle increased patient oxygen consumption.

Presented with large O_2 deficits and high CO_2 transfer situations, the Terumo 1.6 m^2 HFMO is capable of transferring adequate amounts of oxygen, carbon dioxide, and heat without stressing the oxygenator's capabilities. Use of the temperature graphs presented will aid the perfusionist in selecting and understanding the HFMO ventilation parameters required for optimal blood gas results.

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