Optimising Cardiopulmonary Bypass Utilizing Continuous Oxygen Saturation Monitoring

Paul A. Page, Irv B. Birenbaum, Larry Thomas, Robert C. Baldwin, and Arnold Benak

The Johns Hopkins Hospital Section of Perfusion Technology
Baltimore, MD

Abstract

Proper management of cardiopulmonary bypass requires the analysis of both arterial and venous blood gases at regular intervals, and is most critical during the rewarming phase.[3,4] In some hospitals blood gas results are received as long as 15 to 30 minutes after the sample is drawn. More frequent blood gas analysis or ideally continuous measurement of oxygen saturation allows the perfusionist to make continuous adjustments as the patient's oxygen requirements change. Two hundred patients were selected for study. One hundred were perfused using regular periodic blood analyses. A second group of one hundred patients were perfused utilizing an in-line saturation meter.

The blood flow rate was 6% lower during hypothermia and 5% lower while warm in the group utilizing the saturation meter. The total gas flow rate was reduced by 20% while cold and 16% while warm in the metered group. The CPB arterial and venous pO_2 ranges were reduced with the use of the oxygen saturation meter. The same make of hybrid oxygenator was utilized on all patients in both study groups.

Based on the close correlation of the oxygen saturations afforded by the saturation meter and those measured by the blood gas laboratory, we found the Bentley Oxygen Saturation Meter reliable and accurate. It may help protect the patient from extremes in oxygenation and allows the perfusionist to regulate the oxygenator in the most precise and efficient operation.

Direct communications to: Paul A. Page, B.S., CCP, PA., Blalock Room 614, 600 North Wolfe Street, Baltimore, MD 21205

Introduction

Proper management of cardiopulmonary bypass requires the analysis of both arterial and venous blood gases at regular intervals.[3,4] The venous is by far the most important of these gases since it reflects the physiological response of the patient on extracorporeal bypass. Changes in the venous oxygen saturation reflect changes in the amount of oxygen being utilized by the patient. Using both the arterial and the venous blood gases, patient oxygen consumption can be calculated and adjustments to blood flow and/or oxygenating gases can be made. During the hypothermic period when gas solubility is increased and oxygen demand is lower, these adjustments may help reduce the risk of overoxygenation which can lead to gaseous emboli formation and respiratory alkalosis.

Close monitoring of blood gases is also critical during the rewarming phase of bypass because of the increased need for oxygen by the patient during this period.[1] Unfortunately, at many hospitals the time lapse between drawing the blood sample and receiving the results may be as long as 15 to 30 minutes. Depending on the patient, significant metabolic changes can take place during this interval which increase the patient's demand for oxygen. Most current oxygenators are designed to operate with the venous inlet blood having a saturation of greater than approximately 65%. If the pH is within normal limits, this will guarantee that the oxygenator will be able to produce an arterial saturation of 98-99%.[9] The availability of continuous measurement of arterial and venous oxygen saturations, rather than periodic gas analyses, will enable the perfusionist to better control the cardiopulmonary bypass procedure in response to changes in the patient's physiological status.

Methods & Materials

Two hundred consecutive patients were selected for study. Group I consisted of one hundred patients whose perfusions were performed utilizing standard periodic blood gas analyses. Group II consisted of one hundred patients utilizing the new Bentley OxySAT, in-line saturation meter.[a] The cases were done utilizing the same pump equipment, blood gas analysis technique, perfusion technique, and anesthetic protocol in both groups. In the adults the prime consisted of 1600-2000 cc Lactated Ringers solution adjusted in volume to give an approximate ''on-bypass'' hematocrit of 25%. Dextrose 50% was added to make the prime approximately a 2.5% dextrose solution. Mannitol (12.5 grams) was added as a diuretic.

The SARNS 5000 roller pump console was utilized.[b] The Harvey H-1500 oxygenator and the H-700-F filtered cardiotomy reservoir were employed in all cases in this study.[c] The blood gases were all done under controlled conditions by members of the perfusion staff. Radiometer — Copenhagen digital model PHM72 Mk 2 acid — base analyzer and a BMS3 Mk 2 blood gas analyzer were used for pO_2, pCO_2, and pH analysis.[d] A Hewlett Packard model 67 programmable calculator was used to calculate corrected blood gas values using the Henderson — Hasselbach equation formula.[e] All saturation values were calculated using an Instrumentation Lab blood gas calculator model 39999.[f] ''Uncorrected'' saturations obtained from the Radiometer and ''corrected'' saturations from the IL calculator were recorded.

Use of the in-line saturation meter was a simple procedure. The proper size probes were inserted into the arterial and venous lines. A special calibration probe with a known saturation value is supplied with each probe sensor. Prior to bypass this calibration probe can be placed in the sensor and the calibration value will be displayed on the meter if everything is in order. The meter is battery powered using nicad rechargeable batteries. Battery life is around 38 hours of operation with a 16 hour charge. The Bentley OxySAT meter is a compact solid state dual wavelength oximeter. The light reflectance is proportional to the blood oxygen saturation. The unit can accurately compensate for hematocrit changes, between 20 to 50% hematocrit due to utilization of the dual wavelengths.[6,8,9]

Results

The parameters of the two patient groups were closely matched even though they were done as 200 consecutive patients. Mean weights for both groups were 74 kilograms. The mean patient age was 54 years for the unmetered group (Group I) and 56 years for the OxySAT metered group (Group II). Total bypass time was a mean of 114 minutes for the group without the saturation meter and 107 minutes mean for the group with the meter. The mean hematocrit during bypass was the same for both groups (26%). The mean oxygenator blood level was within 100 cc between the two groups. A summary of all recorded data items is shown in Figure 1.

The following items were significantly different between the two groups: in group II we were able to maintain more physiologic venous pO_2 levels and perfuse at a lower blood flow rate, six percent lower while cold, and five percent lower while warm (Figure 2). Total gas flow rate was reduced by 20% while cold and 16% while warm (see Figures 3, 5 &6). This resulted in an 11% average lower gas-to-blood flow ratio (Figure 7). With continuous monitoring of the arterial and venous saturation, pO_2's were maintained in a narrow range. On the arterial side the range was reduced by

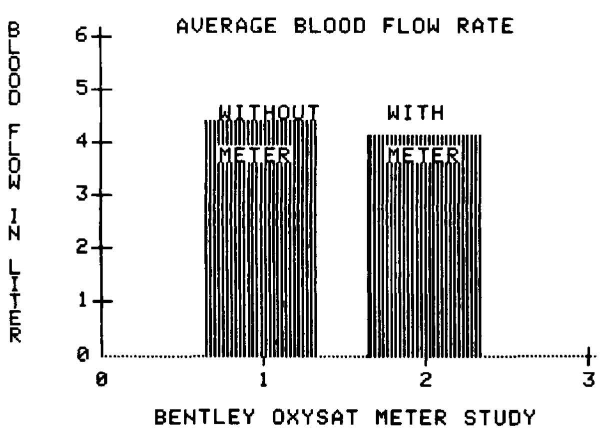

FIGURE 2. Graph showing the difference in average blood flow rates between Group I (control) and Group II the OxySAT metered group.

[a]American Bentley, Irvine, CA 92714
[b]Sarns Inc., Ann Arbor, MI 48103
[c]C.R. Bard, Santa Ana, CA 92705
[d]The London Company, Cleveland, OH 44145
[e]Hewlett Packard Corporation, San Diego, CA 92127
[f]Instrumentation Laboratory Inc., Lexington, MS 02173

The JOHNS HOPKINS HOSPITAL
SECTION OF PERFUSION TECHNOLOGY

COMPARISON STUDY OF 200 CASES DONE WITH AND WITHOUT THE BENTLEY INLINE SATURATION METER

ITEM	100 PATIENTS W/O SAT METER				100 PATIENTS WITH SAT METER			
	Mean	High	Low	S.D	Mean	High	Low	S.D
Patient Weights (kg)	74.0	146.0	40.7	17.0	74.1	120.0	7.0	16.8
Patients Ages (years)	54.2	80.0	15.0	13.2	56.0	76.0	0.6	12.5
Total Bypass Time (min)	114.6	300.0	28.0	44.2	107.7	230.0	35.0	36.7
Hematocrits During Bypass (%)	26.6	39.0	19.0	3.6	26.3	35.0	17.0	3.2
Oxygenator Blood Level (cc)	1560	2900	500.0	470.0	1423	4000	400.0	587.0
Blood Flow While Cold (deg)	4351	5800	2800	632.0	4079	5400	900.0	676.0
Blood flow warm (cc)	4482	5600	2000	649.0	4256	5600	800.0	686.0
Esop Temp at Rewarm (deg)	25.3	32.3	19.7	2.2	25.7	34.4	19.7	1.9
Rect Temp at Rewarm (deg)	26.9	34.5	21.4	2.6	27.8	34.9	20.5	1.8
Number Degrees Esop Warm	12.4	17.9	5.3	2.2	10.7	18.3	2.6	2.8
Number Degrees Rect Warm	6.3	11.6	0.5	2.5	4.6	12.8	0.1	2.9
Rewarm Time (rect=33) (min)	36.6	70.0	10.0	14.4	33.3	107.0	8.0	33.3
Esop Rewarm to 37 Deg	23.3	45.0	8.0	7.5	24.1	50.0	8.0	7.2
95/5% Gas Flow Cold (l/min)	3.7	8.0	1.0	1.3	3.2	6.0	0.5	1.3
95/5% Gas Flow Warm (l/min)	2.9	6.0	1.0	1.1	0.7	4.0	0.0	0.9
Oxygen Flow Cold (l/min)	2.4	4.0	1.0	0.9	0.2	4.0	0.0	0.5
Oxygen Flow Warm (l/min)	2.6	7.0	0.0	1.5	4.1	6.5	0.5	1.4
Total Gas Flow Cold (l/min)	4.1	10.0	1.0	1.8	3.3	6.0	0.5	1.3
Total Gas Flow Warm (l/min)	5.1	9.5	1.5	1.6	4.3	7.5	1.3	1.2
Gas to Blood Flow Ratio Cold	0.9	2.1	0.3	0.4	0.8	1.9	0.3	0.3
Gas to Blood Flow Ratio Warm	1.1	2.0	0.3	0.4	1.0	2.4	0.3	0.3
PAO2 Values While Cold	266.0	522.0	90.0	93.2	235.0	487.0	112.0	64.1
PAO2 Values Warming & Warm	260.0	444.0	81.0	80.5	268.0	410.0	131.0	65.9
PVO2 Values While Cold	56.3	254.0	21.0	40.5	41.7	167.0	21.0	17.9
PVO2 Values Warming & Warm	47.4	89.0	27.0	9.5	43.0	86.0	26.0	7.9
PACO2 Values While Cold	31.2	43.0	20.0	4.1	32.2	54.0	18.0	4.2
PACO2 Values Warming & Warm	36.0	49.0	22.0	4.9	33.7	47.0	22.0	4.3
PVCO2 Values While Cold	32.3	71.0	22.0	5.2	32.5	53.0	21.0	5.0
PVCO2 Values Warming & Warm	42.6	64.0	27.0	6.2	37.9	54.0	27.0	5.1
Art Sat Corrected Cold	99.9	100.0	94.0	0.5	97.9	100.0	92.0	2.0
Art Sat Uncorrected Cold	-----	-----	-----	-----	99.9	100.0	96.4	0.3
Art Saturation Meter Cool	-----	-----	-----	-----	98.9	106.0	92.0	3.2
Art Saturation Warm	99.9	100.0	95.0	0.6	99.9	100.0	99.8	0.2
Art Saturation Meter Warm	-----	-----	-----	-----	97.7	106.0	78.0	3.2
Ven Sat Corrected Cold	73.6	100.0	40.0	17.4	91.1	100.0	69.9	6.2
Ven Sat Uncorrected Cold	-----	-----	-----	-----	90.5	99.0	75.0	5.1
Ven Saturation Meter Cool	-----	-----	-----	-----	91.3	103.0	69.0	6.2
Ven Saturation Warm	74.9	95.0	44.0	9.7	78.2	98.0	46.0	8.0
Ven Saturation Meter Warm	-----	-----	-----	-----	75.9	100.0	51.0	8.8

FIGURE 3. Table showing the recorded values of Group I patients done without in-line saturation monitoring and those in Group II with the in-line saturation monitor.

OxySAT-Saturation Meter Evaluation

Parameter Measured	Control Group I	OxySAT Group II	% Diff	P < (T test)
Blood Flow Rate Cold cc/min	4351 ± 39	4097 ± 47	06%	<.001
Blood Flow Rate Warm cc/min	4481 ± 51	4256 ± 57	05%	<.01
Total Gas Flow Cold l/min	4.1 ± .11	3.3 ± .09	20%	<.001
Total Gas Flow Warm l/min	5.1 ± .12	4.3 ± .09	16%	<.001
Gas to Blood Flow Ratio Cold	0.9 ± .02	0.8 ± .02	12%	<.001
Gas to Blood Flow Ratio Warm	1.1 ± .03	1.0 ± .02	10%	<.04
pAO_2 mm Hg Mean	263 ± 5.1	253 ± 3.9	05%	<.04
pVO_2 mm Hg Mean	52 ± 1.8	42 ± .80	19%	<.001

FIGURE 3. Table showing the percent difference and the significance of the difference ($P <$ T-test values) between unmonitored Group I and those in Group II with the in-line saturation monitor. All values plus/minus standard error of the mean.

OxySAT-Saturation Meter Evaluation
Range of Values — Control Group vs OxySAT Meter Group

Parameter	Highest	Lowest	Range	Difference
pAO_2 mm Hg Control Group	483	86	397	18.0%
pAO_2 mm Hg OxySAT Mtr Group	449	122	327	
pVO_2 mm Hg Control Group	172	24	148	31.1%
pVO_2 mm Hg OxySAT Mtr Group	126	24	102	
TOT Gas Flow l/min-Control	9.5	1.3	8.2	28.1%
TOT Gas Flow l/min-OxySAT	6.8	0.9	5.9	

FIGURE 4. Table showing range of values and the percent difference between Control Group I and those in Group II with the in-line saturation monitor.

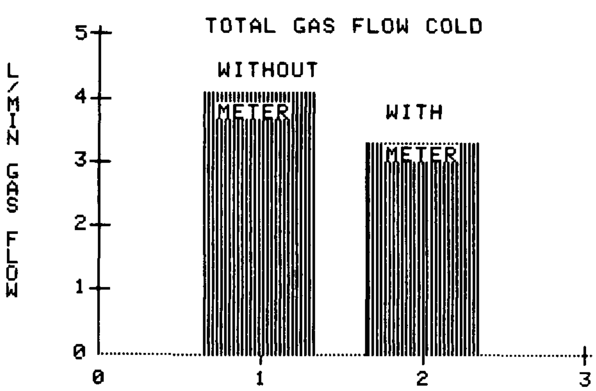

FIGURE 5. Graph showing the difference in the total gas flow rate cold between Group I (control) and Group II the OxySAT metered group.

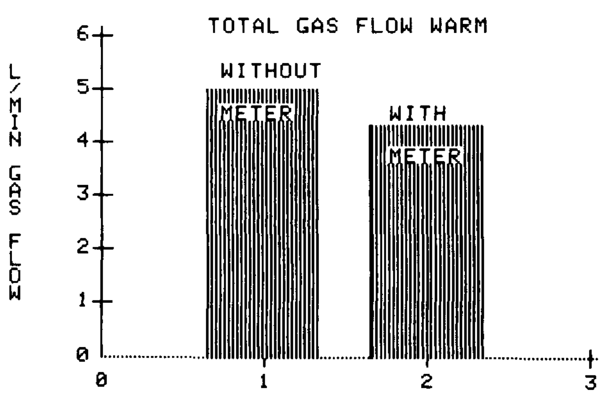

FIGURE 6. Graph showing the difference in the total gas flow rate warm between Group I (control) and Group II the OxySAT metered group.

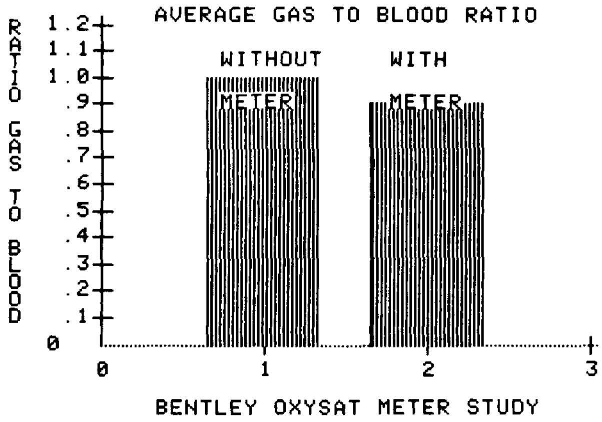

FIGURE 7. Graph showing the difference in the average gas to blood flow rate between Group I (control) and Group II the OxySAT metered group.

18% and on the venous side by 31% (Figure 4). The lowest arterial pO_2 without the saturation meter was 86 mmHg. Using the saturation meter to regulate the pO_2 the lowest arterial value was 122 mmHg. The better regulation of the pO_2 allowed us to reduce the total gas flow range by 28% (Figure 4).

After several weeks of use, we not only felt comfortable using the Bentley OxySAT unit but, as the results show, we were able to regulate the perfusion precisely. When cold, the arterial saturation was within 1.0% of the laboratory determined saturation. The cold venous saturation was within 0.2% of the lab value. Warm, the arterial oxygen saturation was 2.2% from the lab determined value while the venous oxygen saturation was within 2.3%. (Figure 8)

Comparison of Laboratory Values With OxySAT Readings

Parameter Measured	Value	SEM	% Diff
Mean Laboratory Arterial Saturation Corrected Cold	97.9%	±.13	1.0%
Mean OxySAT Meter Arterial Saturation Corrected Cold	98.9%	±.20	
Mean Laboratory Arterial Saturation Corrected Warm	99.9%	±.06	2.2%
Mean OxySAT Meter Arterial Saturation Corrected Warm	97.7%	±.26	
Mean Laboratory Venous Saturation Corrected Cold	91.1%	±.41	0.2%
Mean OxySAT Meter Venous Saturation Corrected Cold	91.3%	±.40	
Mean Laboratory Venous Saturation Corrected Warm	78.2%	±.57	2.3%
Mean OxySAT Meter Venous Saturation Corrected Warm	75.9%	±.72	

FIGURE 8. Table showing comparison of laboratory values to results obtained with the OxySAT in-line saturation meter.

Discussion

Sometimes, due to various conditions such as inadequate blood flow or changes in body temperature, the patient consumes more oxygen from the blood than is expected and the venous inlet saturation can drop to below normal limits. If the blood gases are not done frequently the perfusionist might not be aware of a lowered inlet venous saturation. If the inlet venous oxygen saturation is below the rated operating range of the oxygenator being used, low arterial pO_2 and saturation may result. Many times the perfusionist, not realizing until too late that the venous saturation is getting low, will attempt to raise the arterial oxygen saturation values by increasing the oxygen gas flow. If the design limitations of the oxygenator are exceeded, increasing the gas flow will not totally correct the low arterial pO_2 problem. This is because the demand for oxygen by the patient has exceeded the design capabilities of the oxygenator. Unfortunately most times the oxygenator is blamed as being defective because of its inability to oxygenate, when it may be the perfusionist's failure to respond or to be aware of the low venous inlet saturations and make the necessary adjustments.

In-line monitoring can also prevent excessive ventilation of the oxygenator with resulting high pO_2's. High arterial pO_2 may lead to higher embolic activity due to the effect of turbulence on the increased concentration of oxygen dissolved in the blood plasma.[2] Although plasma hemoglobin was not measured, historically lower gas-to-blood flow ratios and lower blood flows result in lower blood trauma and a reduction of gaseous microemboli production.[10]

More frequent blood gas analysis or in-line measurement of pO_2 or saturation can help prevent a low pO_2 situation by allowing the perfusionist to make continuous adjustments as the patient requirements change. The oxygen saturation value is advantageous because it takes into account the effects of pH, base excess, pCO_2, temperature, 2,3 DPG and ATP concentrations as well as aberrations in an individual's hemoglobin molecule. Monitoring oxygen saturation directly during bypass is probably therefore more effective than periodically measuring pO_2 and attempting to predict saturation and total blood oxygen content.[3]

The Bentley saturation meter is the only product readily available on the market for continuous extracorporeal in-line measurement of saturation at this time.[4,5] We found the Bentley unit to be accurate and dependable. All units used both in the arterial and venous lines worked without any problem.

In the past we had utilized an in-line pO_2 sensor on our cases. When we first decided to try the in-line saturation approach, we were somewhat skeptical that the accuracy would be precise enough to allow accurate regulation of perfusion. We have found that the Bentley OxySAT Oxygen Saturation Meter is a reliable, accurate addition to the perfusion circuit. It will help protect the patient from extremes in oxygenation and allow the perfusionist to operate the oxygenator in the most efficient operating range.

References

1. Riley, J.B., Snyder, J.E.: A Technique for Extrapolation of Analyzed Values of Blood pH, pCO_2, and pO_2 to Hypothermic States. *JECT* 9(2):86-91, 1977.
2. Galletti, P.M. and Brecher, G.A.: *Heart Lung Bypass: Principles and Techniques of Extra-Corporeal Circulation*. New York: Grune and Stratton, 1962, pp. 229-231.
3. Berger, E.C.: *The Physiology of Adequate Perfusion*. St. Louis: The C.V. Mosby Company, 1979, pp. 47-52, 143-144.
4. Reed, C.C., Clark, D.C.: *Cardiopulmonary Perfusion*. Houston: Texas Medical Press, 1975, pp. 168-169.
5. Martin, W.E., et al: Oxygen Saturation Versus Oxygen Tension. *J. Thorac Cardovac. Surg*. 65(3): 1973.
6. Iatridis, A., Heinemann, S., DeRocher, R., Osborne, J.: Continuous Monitoring of Blood Oxygen Saturation During Extracorporeal Circulation. *JECT* 13(4):233-236, 1981.
7. Sistino, J.J.: Continuous Measurement of Oxygen Saturation During Cardiopulmonary Bypass. "Megatropolis News": Winter 1982.
8. Mook, Garritt A., et al: Fibre Optic Reflection Photometry on Blood. *Cardiovascular Res*. 2: 199-209, 1968.
9. The Association for the Advancement of Medical Instrumentation (AAMI): Standard for Blood Gas Exchange Devices. Page 10, February 1982 Revision.