A Technique to Improve the Estimation of Hemoglobin Percent Oxygen Saturation During Cardiopulmonary Bypass

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Abstract

Algorithms that estimate hemoglobin percent O_2 saturation (%Hb·O_2) from pH, pO_2, and temperature assume a normal patient hemoglobin P_{50} equal to about 27 mmHg. Ischemic cardiac and peripheral vascular disease patients do not have P_{50}s near normal.

A new continuous pH and blood gas monitor allows the user to evaluate and employ the patient's pre-CPB P_{50} to estimate the subsequent %Hb·O_2. The P_{50} %Hb·O_2 algorithm estimate was calculated retrospectively for a normal patient blood gas data set and the % error between the estimate and a cooximeter measurement correlated well with the patient P_{50} (r = .976).

The patient P_{50} %Hb·O_2 algorithm estimate was compared to simultaneous in line %Hb·O_2 readings (r = .42), a cooximeter measurement (r = .673), and a blood gas analyzer %Hb·O_2 (assumes normal P_{50}) estimate (r = .589). To employ a pre-CPB patient P_{50} value to estimate %Hb·O_2 should improve the predicting power of a %Hb·O_2 estimating algorithm during CPB.

Background

In-line continuous monitoring of hemoglobin percent oxygen saturation (%Hb·O_2) has become a standard of care, especially for monitoring of extra-corporeal circuit (ECC) mixed venous %Hb·O_2 (SvO_2).[1–12] Many clinicians report important uses for continuous monitoring of SvO_2 and arterial blood hemoglobin SO_2. Monitoring SvO_2 allows the perfusionist to evaluate the adequacy of the ECC blood flow selection, to estimate the demand placed on the oxygenator to achieve an acceptable outlet pO_2 and SaO_2, and to predict the adequacy of the patient's cardiac output during CPB weaning.[6,7,10,12]

Direct cooximeter monitoring of %Hb·O_2 has been recommended during CPB due to the variability in the hemoglobin P_{50}.[5,11] Cardiac disease, ischemia, hypoxia, low cardiac output, and low left ventricular ejection fraction cause elevated hemoglobin P_{50}.[14–19] INVITRO standing blood gas/pH analyzers and on-line blood gas monitors employ various estimating equations to offer a calculated %Hb·O_2 for the user.[15]

The %Hb·O_2 may be estimated from pO_2, temperature, pH, and base excess.[15] The unknown major determinant of hemoglobin P_{50} is 2,3 diphosphoglycerate which increases significantly as the patient tissues experience hypoxia (*IL System 1301 pH/Blood Gas Analyzer Operator's Manual*, p. 10-8, Instrumentation Laboratory Inc., 113 Hartwell Avenue, Lexington, MA 02173).[14–19] We previously described a computer assisted technique to continuously monitor P_{50} that required a direct on-line continuous measurement of saturation and pO_2 and access to a microprocessor.[5]

The calculated value for oxygen saturation may not be equal to that directly measured for patients since saturation depends on the level of carbon monoxide and 2,3 diphosphoglycerate (2,3 DPG) in blood. Therefore, the value calculated by the analyzer should be used as an estimate of the actual O_2 saturation and should not be the control or standard for comparison (*User Handbook for the ABL4 Acid Base Laboratory*, p. 148–149, Radiometer, A/S, Endrupeuj 72, DK/2400 Copenhagen, NV, Denmark). The accuracy of an estimated %Hb·O_2 may be suspect in chronic cardiac hemodynamic disease patients with abnormal P_{50}s.[15]

The Blood Gas Monitoring System 300[a] provides the user the ability to perform an INVIVO calibration of the monitor to adjust the hemoglobin P_{50} employed to estimate the saturation on-line.

Figure 1 illustrates the overall agreement (r = .9796) of the System 300 saturation estimating algorithm with

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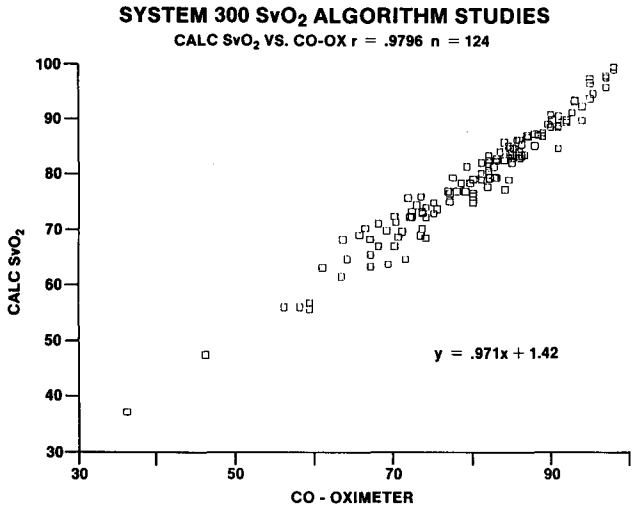

Figure 1: Patient test data to evaluate CDI System 300 saturation estimation algorithm.

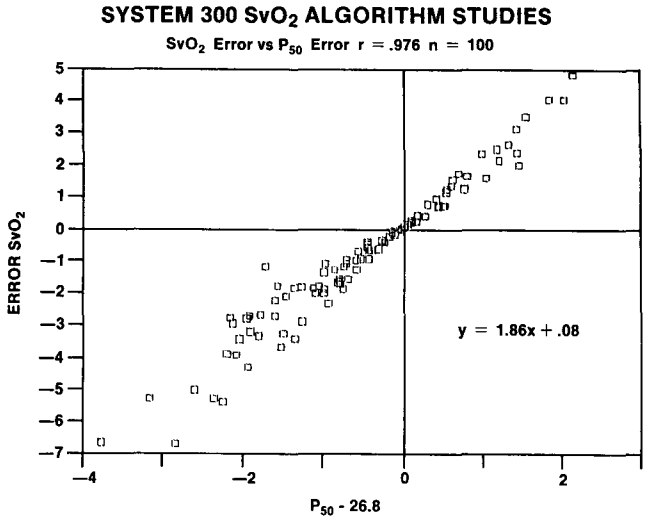

Figure 2: Accuracy of CDI System 300 saturation estimation algorithm ('SvO_2 Error' = IL 282 $\%SO_2$ - CDI 300 $\%SO_2$) versus patient hemoglobin P_{50}.

a direct cooximeter measurement, the IL282[b] (Personal communication with C. Vaughn Cassingham, Cardiovascular Devices, Inc., August 17, 1987). Figure 2 demonstrates that the error between the System 300 estimating equation and the control cooximeter measurement appears to correlate well with the hemoglobin P_{50} (r = .976).

We postulated that the estimation of the SvO_2 by the System 300 may be improved if the saturation estimate was based on the monitored patient's prebypass hemoglobin P_{50}. A technique was designed and the System 300 was programmed to allow the user to adjust the saturation estimate prebypass for a specific patient's hemoglobin P_{50}.

The method described herein is designed to discover the ability of the improved algorithm to monitor mixed venous saturation, as well as to tract other cooximeters and estimators, specifically, the in-line OxySAT 2 saturation monitor.[c]

Materials and Methods

Simultaneous CPB samples were collected for analysis of saturation by cooximeter (IL 282) or INVITRO blood gas analyzer saturation estimate (ABL3[d]). Digital readings for mixed venous saturation from the output displays of two in-line monitors, the CDI System 300 and the OxySAT 2 were recorded and grouped in a database[e] with the INVITRO saturation results for comparison by linear regression.[f]

Prior to initiation of bypass, a venous blood sample was collected from the patient and analyzed for pO_2, pH, pCO_2, and a direct measurement of saturation by the IL 282 Cooximeter. The pO_2, $\%Hb{\cdot}O_2$, pH, and pCO_2 values were introduced into the System 300 per the manufacturers instructions to perform an INVIVO calibration of the saturation estimator algorithm (*CDI Extracorporeal Blood Gas Monitoring System 300*, p. 4–13 to 4–15, Cardiovascular Devices, Inc., Irvine, CA, 92714-9961). All System 300 saturation estimates during CPB were based on the prebypass P_{50} INVIVO calibration.

Results

Table 1 presents the raw data from 38 simultaneous samples from six CPB patients with prebypass hemoglobin P_{50}s ranging from 26 to 30 mmHg. Tables 2 and 3 present the inter-device comparisons. Table 3 ranks the device agreements, illustrating the greatest agreement (r^2) appearing between the ABL 3 estimate and the IL 282 direct measurement. The INVITRO analyzers agreed well and the in-line devices generally agreed.

The System 300 saturation estimate from 'actual' blood (CDI @Temp) values (68.4 +/− 8.3%) generally tracts the OxySAT 2 measurement (70.2 +/− 9.5 %), however scatter is observed (r = .425, p < .0098) around the line of best fit (standard error of estimate = 8.6%) in Figure 3.

b Instrumentation Laboratories, Inc., Lexington, MA 02173
c Baxter, Bentley Laboratories, Inc., Irvine, CA 92714
d Radiometer, A/S, Endrupeuj 72, DK/2400 Copenhagen, NV, Denmark
e Lotus 123 Release 2.1, Lotus Development Corporation, Cambridge, MA 02142
f Microstat Release 4.1, Ecosoft, Corp., Indianapolis, IN 46260

Table 1

Cooximators/Saturation Estimation

Raw data for simultaneous comparisons of cooximeter saturation measurements and analyzer or monitor saturation estimations. Patient ID numbers and immediate prebypass P_{50}s are listed. All r^2 values are significant at $p < .0098$. Group means +/− 1 S.D. are as follows; CDI 300 @Temp = 69.5 +/− 9.1%, ABL3 = 74.4 +/− 14.6%, OxySAT 2 = 68.4 +/− 8.3%, IL282 = 76.3 +/− 8.3%, and CDI 300 @37OC = 74.4 +/− 8.5%

COOXIMATORS/SATURATION ESTIMATION

PATIENT INFORMATION	SAMP TIME	CDI 300 @ TEMP	ABL3 EST SAT	BAXTER OXYSAT 2	IL 282 SAT	CDI 300 @ 37 OC
188627801	1558	79	84.4	72.5	83.6	84
P50 = 28	1614	81	77.9	66.5	74.7	87
	1624	68	78.9	72.5	77.8	76
	1651	71		63.5	77.6	71
NA	1045	80	83.7	74.5	83.8	80
P50 = 29	1105	79	79.0	67.5	77.8	79
	1122	74	76.7	69.5	76.1	79
	1130	66	63.0	51.0	60.3	69
	1150	65	58.3	51.0	57.8	64
188475601	2122	78	82.4	76.0	81.8	78
P50 = 30	2140	70	86.4	80.0	85.5	70
	2200	80	84.7	80.0	84.3	69
	2216	68	83.5	77.5	82.5	79
	2230	71	87.0	80.5	85.0	82
	2300	71	85.9	79.0	85.0	84
	2320	74	79.3	71.5	78.4	81
	2342	66	69.4	64.5	67.6	69
	2400	69	68.0	64.0	68.6	69
177392107	934	52	71.8	66.0	70.2	64
P50 = 29	952	56	71.9	64.0	70.0	63
	1007	57	76.0	69.5	74.8	66
	1018	54	69.8	60.5	66.4	62
	1030	55	66.0	57.5	63.9	59
	1040	58	68.5	58.5	66.0	60
	1058	56	66.9	58.5		59
NA	1518	89		82.0		89
P50 = 26	1518	90			92.0	90
	1520	87	91.0	63.0	90.0	85
	1543	77	68.0	59.0	73.0	76
	1628	82	74.0	62.5	73.0	77
189102302	1240	79	87.1	79.0	8[illegible].0	86
P50=28	1251	71	80.1	73.0	81.5	79
	1307	61	73.1	70.5	75.0	72
	1318	68	77.3	72.5	78.6	77
	1329	71	81.5	74.5	81.4	80
	1345	73	75.7	69.0	76.1	80
	1355	70	68.0	60.0	67.4	73
	1420	66	68.9		68.3	69

Table 2

Improved Saturation Estimation Regression Matrix r—2 Values

Regression (r^2 values) matrix for comparison for all devices studied.

	DEVICE:			
DEVICE:	OxySAT II	IL 282	ABL3	CDI @37
CDI@TEMP	0.1762	0.4531	0.3467	0.7257
CDI @37	0.3632	0.5827	0.5327	---
ABL3	0.7649	0.9554	---	---
IL 282	0.7255	---	---	---

Discussion

The patient's hemoglobin P_{50} may be easily evaluated just prior to initiation of CPB by entering the results of a prebypass mixed venous blood gas analysis into the INVIVO saturation calibration technique offered in the System 300. The System 300 estimate of the patient's prebypass hemoglobin P_{50} alerts the perfusionist to a possible oxyhemoglobin dissociation curve abnormality. One author suggests ". . . hemoglobin P_{50} is a functional biopsy of the adequacy of tissue perfusion."[17] The perfusionist may assess the adequacy of the patient's prebypass Cardiac Index and tissue oxygenation, and may further predict the need for a greater blood pump Cardiac Index and/or altered ventilation requirement once on-bypass.

The comparision of the devices in Table 3 yields mixed results in that the INVITRO analyzers (ABL3 and IL282) agreed well and the on-line devices (OxySAT 2 and CDI300) generally agreed. These relationships suggest that the blood was contaminated with room air during the sampling and analyzing process, even though good laboratory practice was employed in this method. The System 300 estimate employing 37°C values correlated well with the IL282 direct measurement and ABL3. However, the OxySAT 2 was considered the control in this method because of our previous demonstration of the OxySAT accuracy by direct measurement of blood oxygen content.[10,13] Gabel insists that temperature corrected values of pO_2, pH and pCO_2 should be used to estimate saturation.[15] Therefore, the estimate of saturation by any monitor should be performed with blood gas and pH values corrected to blood temperature.

The System 300 employs four blood sensor values to estimate saturation. Variable blood sensor response time constants and constantly changing actual blood parameter values may be the cause of the 'noise' in

Table 3

Regression Coefficients and Y-Intercepts

Coefficients (slopes) and y-intercepts for inter-device linear regression comparisons.

COMPARISON	r^2	COEFF.	y-INT.
ABL 3 EST vs IL 282	0.9554	0.959	3.7
ABL 3 EST vs OxySAT 2	0.7649	0.853	18.1
CDI @37 vs CDI @Temp	0.7257	0.752	21.5
IL 282 vs OxySAT 2	0.7255	0.843	18.5
IL 282 vs CDI @37	0.5827	0.738	18.6
ABL 3 EST vs CDI @37	0.5327	0.763	15.8
ABL 3 EST vs CDI @37	0.5225	0.731	18.4
IL 282 vs CDI @Temp	0.4531	0.737	14.4
CDI @37 vs OxySAT 2	0.3632	0.607	33.0
ABL 3 EST vs CDI @Temp	0.3467	0.654	19.9
CDI @Temp vs OxySAT 2	0.1762	0.474	37.9

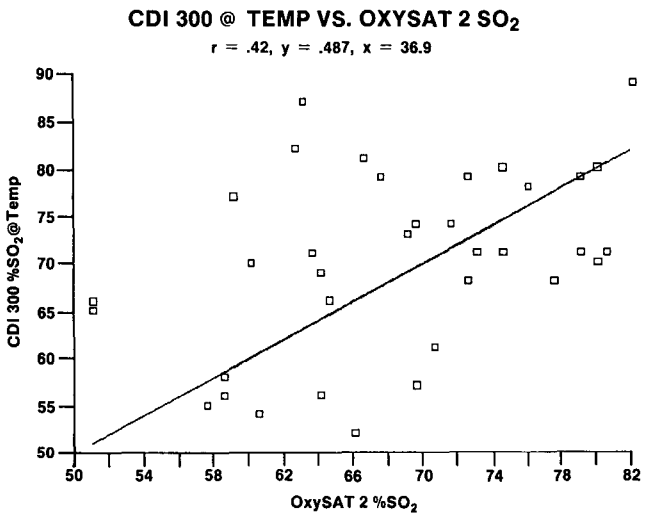

Figure 3: CDI System 300 saturation estimate (calculated from 'actual' blood values) versus OxySAT 2 directly measured saturation, n = 38, standard error of estimate = 8.6%.

the agreement between the System 300 estimate and the OxySAT 2 direct measurement.[3]

Results from six patients and 38 simultaneous samples are inadequate to judge the success of the method described in this communication. This technique was presented so that others may attempt to collect similar clinical experiences to evaluate the benefits to prebypass knowledge of the patient's P_{50} and to adjusting CPB saturation estimates for the patient's beginning P_{50}. We will continue to collect clinical data and provide a follow up report of the results to a larger database and a greater clinical deviation in hemoglobin P_{50}.

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Questions from the Audience

Question: Would you explain the better agreement between the in vitro bench top analyzer compared with the agreement on line?

Answer: That is a challenge to explain, like I said in the paper. The main issue is probably the changing blood values of saturation, pO_2, pH and the base excess or pCO_2, whichever you want to key off. The pH will change at a different rate in the blood from the pO_2 and we evaluate saturation off the key parameters which introduces noise into the estimate of a tracking monitor. When you take a discrete sample and put it into two discrete analyzers side by side on the bench, the blood has gone through a similar temperature change from the sampling process and is evaluated under the same in vitro conditions which tend to lead to more consistency. If we have steady state in all the systems and the blood values were not changing, then we would improve the accuracy and correlation trials.

Questions: Do you think the clinical benefits are worth the effort to calibrate the microprocessor?

Answer: I do. If you cannot afford both probes in the venous line, you have to make a decision and one of your decisions could be to go with the estimated saturation from the CDI 300 and avoid use of the Oxysat. If you use the Oxysat, avoid use of the in-line venous blood gas monitor. So, it's an economic decision that whenever you save dollars, you sacrifice accuracy.