In Line Oxygen Saturation Monitor

Jeffrey B. Riley, Melinda R. Young, Jeffrey N. Kauffman, Richard L. Rigatti, Donna L. Facer, William L. Daly, Charles T. Walker, and Marsha K. Williams
Emory University Clinic and Hospitals
Atlanta, Georgia

Abstract
The first year, 800 cardiopulmonary bypass (CPB) (infant to adult) case experience with the Bentley Laboratories Oxy-Sat Meter (O-SM) demonstrated numerous patient management advantages to monitoring the percent saturation of hemoglobin (O₂ SAT). The O-SM exhibited accuracy equal to present O₂ SAT monitoring. Patient management advantages fall into two categories: (1) Respiratory, from measuring the adequacy of arterial O₂ SAT to documenting oxygen transfer, and (2) Metabolic, judging the adequacy of extracorporeal circuit (ECC) blood flow.

The O-SM was found to have acceptable agreement with Instrumentation Laboratories 282, American Optical Unistat and Oximetrix catheter oximeters or the Severinghaus formula and Corning blood gas machine analog O₂ SAT estimators. Forty-three intermittent O-SM readings were compared to Lexington Instrument Corporation Lex-02-Con hemoglobin content and capacity measurements. The agreement standard deviation is equal to 1.4% O₂ SAT for pH from 7.27 to 7.47, Base Excess from -8. to 4. mEq/L, temperature from 26 to 36 °C and hematocrit from 18 to 33%. Monitoring O₂ SAT during CPB is useful and reliable with the Oxy-Sat Meter.

Purpose
The purpose of this presentation is three-fold: first, to quantitate the agreement of the Bentley Laboratories Oxy-Sat Meter (O-SM) with other techniques for monitoring or predicting the percent saturation of hemoglobin with oxygen (O₂ SAT); second, to confirm the manufacturer’s calibration procedure in a clinical setting employing the Lexington Instrument Corporation Lex-O₂-Con TL oxygen content analyzer; and third, to present the results of the first year’s learning experience with in-line continuous monitoring of arterial and venous O₂ SAT during cardiopulmonary bypass (CPB).

Method
Forty-three simultaneous blood samples and readings from five O-SM venous Optical Transmission Cells (OTC) during eight CPB procedures were collected and processed in the following manner:

I. The blood sample was introduced into all or some of the following calibrated oximeters for measuring O₂ SAT: i. IL 282 Oximeter (n = 27), ii. Unistat Oximeter (n = 17), iii. OSMZ Hemoximeter (n = 16).

II. In two CPB procedures, the OS/1270 A calibrated fiber optic catheter-tipped oximeter was...
introduced into the ECC venous line (n = 18) for comparative sampling.

III. Eighteen predicted $O_2$ SAT readings were collected for comparison from the Corning 175$^*$ blood gas analyzer. $O_2$ SAT predictor and blood gas analyzer values were substituted in Thomas’s $O_2$ SAT predictor algorithm$^7$ for comparison (n = 43).

IV. Lastly, each blood sample was processed with the Lex-$O_2$-Con in the following manner:

$O_2$ SAT was calculated from the ratio of the Lex-$O_2$-Con TL oxygen content ($O_2$ Vol% ) measurements of blood sample $O_2$ content and room air blood oxygen content adjusted for $O_2$ volumes % dissolved in solution. The accuracy of the Lex-$O_2$-Con TL is well established$^{3,4}$ and may be used as a standard to compare to the OS-M $O_2$ SAT readings.

$O_2$ content bound to hemoglobin (HB $O_2$ Vol %) was found by employing Equation 1:

$$\text{HB } O_2 \text{ Vol } \% = \frac{\text{Lex } O_2 \text{ Content} - \text{O}_2 \text{ Content Dissolved}}{\text{[1]}}$$

where

$$\text{Lex } O_2 \text{ Content} = \text{the total } O_2 \text{ Vol } \% \text{ measurement from the venous blood sample by the Lex-}O_2\text{-Con TL}$$

$$\text{O}_2 \text{ Content Dissolved} = O_2 \text{ solubility at } 37^\circ\text{C}$$

multiplied by the blood gas analyzer venous $pO_2$ at $37^\circ\text{C}$ divided by the atmospheric pressure minus water vapor

The blood sample was shed, transported and analyzed employing anaerobic techniques. Therefore the total $O_2$ content did not change.$^2$ The oxygen content dissolved did not change with sample warming for hemoglobin saturations in the normal venous blood range. Therefore the $O_2$ content dissolved at $37^\circ\text{C}$ was the same as that at the temperature the blood was shed.$^2$

Hemoglobin oxygen content at room air $pO_2$ was assumed to be hemoglobin (HB) $O_2$ capacity and was calculated employing Equation 2:

$$\text{HB } O_2 \text{ Capacity} = \frac{\text{Lex } O_2 \text{ Content} - \text{O}_2 \text{ Content Dissolved}}{\text{[2]}}$$

where

$$\text{Lex } O_2 \text{ Content} = \text{the Lex-}O_2\text{-Con TL total } O_2 \text{ Vol } \% \text{ measurement for the venous blood sample tonometered with room air}$$

$$\text{O}_2 \text{ Content Dissolved} = \text{the atmospheric } pO_2 \times (\text{atmospheric pressure } - \text{water vapor pressure})$$

multiplied by the solubility of $O_2$ at room temperature$^1$

% $O_2$ SAT from the Lex-$O_2$-Con TL was calculated by Equation 3:

$$\% \text{ HB}-O_2 = \left(\frac{\text{HB } O_2 \text{ Content}}{\text{HB } O_2 \text{ Capacity}}\right) \times 100 \text{[3]}$$

where

$$\% \text{ HB}-O_2$$

is the $O_2$ SAT calculated from Lex-$O_2$-Con TL measurements.

The hemoglobin p50 according to Severinghaus was then calculated from the % HB-O2 and the temperature-corrected Corning 175 blood gas analyzer results$^5$.

A linear regression model was employed to quantitate the correlation between the OS-M $O_2$ SAT and comparison device readings or calculated $O_2$ SATs. The correlation is reported as significant at $p = .01$ for a two-tailed t-distribution.

### Results

Table 1 presents the results of several random, simultaneous $O_2$ SAT samplings by other devices or techniques during adult CPR procedures compared to the OS-M venous OTC $O_2$ SAT readings.

<table>
<thead>
<tr>
<th>Device and Manufacturer</th>
<th>Sample Average Difference</th>
<th>Correlation Coefficient</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL 282</td>
<td>-4.0</td>
<td>.948</td>
<td>$p &lt; .01$</td>
</tr>
<tr>
<td>Instrumentation Laboratories Inc., Lexington, MA 02173</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unisatal</td>
<td>-1.8</td>
<td>.977</td>
<td>$p &lt; .01$</td>
</tr>
<tr>
<td>American Optical Inc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS/1270 A</td>
<td>-1.5</td>
<td>.984</td>
<td>$p &lt; .01$</td>
</tr>
<tr>
<td>Diametrix Processor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diametrix Inc., Mountain View, CA 94043</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS/636</td>
<td>-1.8</td>
<td>.975</td>
<td>$p &lt; .01$</td>
</tr>
<tr>
<td>Hemoximeter, The London Co., Cleveland, OH 44145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corning 175</td>
<td>-7.8</td>
<td>.983</td>
<td>$p &lt; .01$</td>
</tr>
<tr>
<td>Corning Medical and Scientific, Medfield, MA 02052</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thomas: LJ</td>
<td>-2.2</td>
<td>.932</td>
<td>$p &lt; .01$</td>
</tr>
</tbody>
</table>

Table 1. Oxy-Sat Meter agreement with other devices or techniques for monitoring or predicting $O_2$ SAT

---

$^1$ Corning Medical and Scientific, Medfield, MA 02052
The O-SM agreement with these comparison devices and techniques is acceptable for clinical patient management decisions \((p < .01)\) with the greatest average disagreement being with the Corning 175 analog \(O_2\) SAT predictor.

Figure 1 presents the correlation between forty-three O-SM readings and calculated \(O_2\) SAT from the Lex-\(O_2\)-Con TL measurements. The O-SM readings yielded an accuracy confidence limit equal to 1.4% \(O_2\) SAT for \(7.27 < \text{pH} < 7.47\), -8. < Base Excess < 4. mEq/L, \(26^\circ\text{C} < \text{blood temperature} < 36^\circ\text{C}\) and 18 < hematocrit < 33%.

To better predict the accuracy of the O-SM with temperature and acid base change, the agreement of the O-SM and Lex-\(O_2\)-Con TL calculated \(O_2\) SAT is expressed as a function of the hemoglobin \(p50\). Figure 2 depicts the agreement of the O-SM demonstrated an accuracy of 1% \(O_2\) SAT for hemoglobin \(p50\) from 24 to 35 mmHg in this method and acceptably tracked change in \(p50\) through the range normally experienced during CPB.

**Discussion**

Continuous, monitoring of \(O_2\) SAT during CPB with the O-SM is equally accurate to current clinically employed direct measurement devices and techniques for predicting \(O_2\) SAT. An attempt to quantitate the accuracy of the O-SM between 94 and 99.5% \(O_2\) SAT was not made in this protocol. The standard deviation (+/− 1.7% \(O_2\) SAT) experienced in this study of the venous \(O_2\) SAT range would lead to data scattering that would yield unacceptable, low correlation coefficients in the arterial range. However, for discussion, it may be assumed that the accuracy measured in the venous range may be extrapolated to the arterial range. This is a weak assumption due to the extreme slope change at 87. to 93.5% \(O_2\) SAT in the oxyhemoglobin saturation curve and the great affect a small hemoglobin affinity change has on the actual \(O_2\) SAT.

The benefits of continuous, in line monitoring of \(O_2\) SAT fall into two categories; Respiratory (artificial oxygenator) and Metabolic (patient).

A sustained clinical experience with the O-SM will allow the user to realize facilitated artificial blood oxygenator management by monitoring the arterial \(O_2\) SAT. Monitoring the venous \(O_2\) SAT allows the accurate prediction of the demand for \(O_2\) SAT transfer by the oxygenating device.6 Ar-
Artificial lung function is quantitated by measuring arterial-venous $\% O_2$ SAT difference.

The artificial oxygenator may be minimally ventilated to attain an arterial $\% O_2$ SAT above 97% or to control the arterial $pO_2$ within a given range if the hemoglobin $p50$ is known prior to CPB. Monitoring arterial $O_2$ SAT during CPB prevents large, possibly deleterious changes in the arterial oxygen content.

The metabolic benefits to monitoring $O_2$ SAT are appreciated in the manipulation of Equation 4.

$$\dot{V}O_2 = A-V O_2 \text{ Vol} \% / 100 \times \dot{Q} \ [4]$$

where

- $\dot{V}O_2 =$ oxygen transfer in ml $O_2$/minute
- $A-V O_2 \text{ Vol} \% =$ the total arterial-venous $O_2$ content difference in ml $O_2$/100 ml blood
- $\dot{Q} =$ ECC blood flow in ml blood/minute

Equation 4 states the relationship between arterial and venous blood $O_2$ content, ECC blood flow and ECC oxygen transfer.

If the oxygen carried dissolved in solution is not considered in the blood $O_2$ content, then the arterial-venous hemoglobin $O_2$ volumes $\%$ may be substituted for $A-V O_2 \text{ Vol} \%$ in Equation 4 to obtain;

$$\dot{V}O_2 = \frac{A-V O_2 \text{ SAT}}{100} \times HB \times 1.34 \times \dot{Q} \ [5]$$

where

- $HB =$ hemoglobin concentration in grams/100 ml blood
- $1.34 =$ $O_2$ capacity of hemoglobin in ml $O_2$/gm HB

The oxygenator will likely transfer as much oxygen to hemoglobin as the patient removes if the arterial $O_2$ SAT is monitored and maintained at maximum. Equation 6 results when constants are dropped and the arterial $O_2$ SAT = 100 $\%$.

$$\dot{V}O_2 \alpha (100 - \text{venous } O_2 \text{ SAT}) \times HB \times \dot{Q} \ [6]$$

Rearranging

$$100 - \text{venous } O_2 \text{ SAT} \ [7]$$

To isolate venous $O_2$ SAT

$$\text{Venous } O_2 \text{ SAT} \alpha 100 - \frac{\dot{V}O_2}{HB \times \dot{Q}} \ [8]$$

Equation 8 demonstrates the potential utility of monitoring the venous $O_2$ SAT to diagnose the adequacy of the CPB blood flow ($\dot{Q}$), the oxygen carrying capability (HB) and the patient oxygen consumption during CPB.

The venous $O_2$ SAT represents the majority of the venous blood oxygen content, except during extreme hemodilution and hypothermia. Therefore Equation 8 predicts the change in venous blood oxygen content (venous $O_2$ SAT) with change in any or all of the operands.

For example, in theory, if patient oxygen consumption remains constant and hemodilution is completed, the continuous monitoring of the venous blood oxygen content (venous $O_2$ SAT) will potentially assist the perfusionist in assessing the adequacy of the combination of the ECC blood flow and CPB patient left heart cardiac output in supporting the patient’s oxygen transfer requirement during the gradual initiation and termination of bypass.

CPB blood flow may be altered to maintain the venous $O_2$ SAT at a given value to assure an adequate mixed venous $pO_2$ if the hemoglobin $p50$ is known. For example, normal hemoglobin and acid base conditions at 28° C in an actual $pO_2$ equal to 40 mmHg will be about 93% saturated with oxygen.

Monitoring the relationship between venous blood oxygen content (venous $O_2$ SAT) and $pO_2$ is useful in the management of the institution and reversal of deep hypothermia in infant and pediatric perfusion for accurate selection of a minimal, yet adequate, blood flow to support the attendant extreme change in patient oxygen consumption.

Continuous, in line measurement of $O_2$ SAT to monitor blood oxygen content to quantitate tissue respiration and artificial oxygenator function offers many potential patient management benefits.

Acknowledgment

The authors wish to thank Norma R. McGraw, Richard D. Gentsch, John E. Lewis, Jeffrey T. Lewis, Alfred S. Yin, Lynne M. Dorsey and Larry
D. Snipes for their technical assistance in preparing this manuscript and executing the protocol.

References