In Vivo Comparison of Two Mixed Venous Saturation Catheters

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The accuracy and stability of mixed venous saturation pulmonary arterial catheters under adverse physiologic conditions has not been assessed. Either a Shaw Opticath® catheter (three-wavelength) or a Swan-Ganz® oximetry TD catheter (two-wavelength) was calibrated in vitro and positioned in the pulmonary artery in each of ten mongrel dogs. The in vivo saturations were compared to measured saturations from anaerobically collected mixed venous blood analyzed with a reference cooximeter at each step in the protocol. Oxygen delivery was varied to obtain a broad range of mixed venous saturations ($\text{S}O_2$) by altering inspired oxygen concentration, isovolemic hemodilution, reducing cardiac output, and increasing afterload. Calculated oxygen consumption varied from 128 to 311 ml/min. Pre-insertion calibration for both catheter types compared favorably with the cooximeter prior to physiologic manipulations, although the three-wavelength catheter more closely approximated the cooximeter. The three-wavelength catheter tracked measured $\text{S}O_2$ accurately under adverse conditions for up to 10 h (R = .994; SEE = 2.2%). The two-wavelength catheter tended to drift under the same conditions (R = .808; SEE = 10.6%). At the conclusion of the experiment, the two-wavelength system was uniformly higher then the cooximeter by 5-31% with a mean of 21% (P < .003 as compared with the initial difference by paired Student's t-test). Pending further analysis of the tendency of the two wavelength system to drift it would seem prudent to limit its clinical application. (Key words: Blood, hemoglobin; saturation. Equipment, monitors: mixed venous saturation catheter. Measurement technique: reflectance spectrophotometry. Monitoring: $\text{S}O_2$, mixed venous saturation.)

SPECTROPHOTOMETRIC DETERMINATION of hemoglobin saturation replaced analytical chemical determinations in the 1940s, due to the pioneering efforts of Brinkman and Zijlstra.§ Many subsequent attempts to apply spectrophotometric techniques to in vivo monitoring via reflectance oximetry have met with limited success.¹⁻⁴ Specific obstacles have included fragility of glass optical fibers, vessel wall artifact, loss of light intensity, and the confounding effect of varying hematocrit. Some of the problems were overcome by the use of fiber optics, light emitting diodes, and multiple reference light wavelengths. These features have been incorporated into the Shaw Opticath® pulmonary arterial catheter (Oximetrics Inc., Mountain View, CA) and the Swan-Ganz® flow-directed oximetry TD catheter (American Edwards Laboratories, Santa Ana, CA). Both catheters continuously monitor $\text{S}O_2$ via fiberoptic reflectance spectrophotometry. The Edwards oximetry system permits the user to update hemoglobin or hematocrit values, but uses two-reference wavelengths. The Oximetrics system has no provision for incorporating changes in hemoglobin or hematocrit, but employs three-reference wavelengths. This study compares the ability of these two in vivo $\text{S}O_2$ oximetry systems to track true $\text{S}O_2$, as measured by a benchtop in vitro cooximeter, under widely varied physiologic conditions.

Methods

Ten fasted mongrel dogs were anesthetized with pentobarbital (30 mg/kg), ventilated with a volume ventilator to achieve normocarbia, and paralysed with pancuronium (0.1 mg/kg). A 6-Fr catheter was placed percutaneously into a femoral artery using the Seldinger technique, and was used to withdraw blood and monitor arterial pressure. An 8.5-Fr introducer sheath was similarly placed in a femoral vein. In five each of the ten dogs, either a two-wavelength (Edwards) or a three-wavelength (Oximetrics) $\text{S}O_2$ catheter was inserted following calibration in vitro according to the manufacturer's specifications. Each catheter was positioned in the pulmonary artery by observing the characteristic pressure waveforms displayed via a Hewlett-Packard monitoring system (Model 1280C transducers, Model 8805D amplifiers, and a Model 7754B recorder) (Waltham, MA).

All arterial and mixed venous blood samples were collected anaerobically into heparinized syringes and analyzed immediately with both an Instrumentation Laboratory Model 285 Cooximeter and Model 1306 pH/Blood Gas Analyzer (Lexington, MA). The cooximeter was adjusted for dog hemoglobin. It was calibrated and standardized daily to known reagents. The blood gas analyzer was calibrated prior to use and between each sample to reference gases and pH solutions. Two reference gases having the following compositions were used: gas 1—5% CO₂, 20% O₂, 75% N₂ and gas 2—10% CO₂ and 90% N₂. The fraction of inspired O₂ was adjusted according to a Vetronics Oxygen Monitor with Model 5584 EC Oxygen Sensor.

The following measurements were collected as a baseline and subsequent to each experimental manipulation after equilibration: mean arterial pressure; central venous pressure; thermal dilution cardiac output; arterial and mixed venous blood gases, hemoglobin saturation, and hemoglobin; and in vivo $\text{S}O_2$. Oxygen consumption was
calculated as the difference between arterial and mixed-venous $O_2$ content times the cardiac output. Oxygen contents were derived from measured saturations, $O_2$ tensions, and hemoglobin. For the five experiments with the two-wavelength catheters, the current hemoglobin was updated prior to each measurement. The influence of hemoglobin variation upon the two-wavelength system was examined by also obtaining the $SV_O_2$ with an erroneously updated hemoglobin 3 g higher and 3 g lower than the measured value for each $SV_O_2$.

The experimental protocol consisted of sequentially manipulating those variables that contribute to $SV_O_2$. $F_iO_2$ was varied from 1.0–0.12 initially and after each of the other manipulations. Isovolemic hemodilution to a hemoglobin level of less than 10 g/dl was then achieved by removing aliquots of blood (25 cc/kg) and replacing it with Ringers Lactate (75 cc/kg). Next, incremental doses of propranolol were administered until either cardiac output was reduced to 50% of baseline, or until a total propranolol dose of 1 mg/kg had been reached. Finally, phenylephrine was used to double the systemic vascular resistance. Temperature was maintained between 37–38° C during all experiments by warming the iv fluids and by using a warming blanket. All data was obtained during periods of relative hemodynamic stability (defined as a minimum of 10 min and an unchanging $SV_O_2$ occurring after physiologic manipulation).

At the conclusion of the protocol, each catheter was recalibrated in vivo according to the manufacturer's instructions. Validity of the recalibration was confirmed by checking a subsequent sample for saturation, which was required to be within 1% of the displayed catheter value. At the conclusion of the series of experiments, both $SV_O_2$ monitors were returned to their respective manufacturers who confirmed their proper functioning.

Paired data points (in vivo and in vitro saturations) were analyzed by the method of least squares, which yielded a regression line and correlation coefficient for each catheter. Fisher's Z test was used to compare the differences in correlation between catheters overall and in selected ranges. Fisher's Z test was also used to test the effect of varying hemoglobin in the two-wavelength catheters. The difference between the initial in vivo $SV_O_2$ and the measured $SV_O_2$ and the same difference at the conclusion of each experiment was analyzed with paired Student's $t$ test to assess each catheter's tendency to drift.

**Results**

Each experiment lasted from 6–10 h due to the variability in reaching the physiological endpoints defined by the protocol. The two groups were similar in this regard. Catheter performance was examined over a wide range of $SV_O_2$ from 9.4–89.6%. The derived $O_2$ consumption varied from 128–311 ml/min.

The in vivo calibration of both $SV_O_2$ catheters initially approximated the coximeter $SV_O_2$ with the five three-wavelength catheters differing by 1.54 ± 1.63% (SD) and the five two-wavelength catheters differing by 0.64 ± 5.48%. At the conclusion of the experiment, the three-wavelength catheters differed from the coximeter by 0.26 ± 2.43% and the two-wavelength catheters had drifted by a mean of 21.02 ± 9.99% ($P < 0.003$ by paired $t$ test for the two-wavelength catheters) (fig. 1). All of the two-wavelength catheters displayed a higher $SV_O_2$ than the measured $SV_O_2$ at the end of the protocol.

The individual regression lines, correlation coefficients, standard errors of the estimate, and 95 percentile confidence intervals are shown for three-wavelength and two-wavelength catheters versus the coximeter in figures 2 and 3, respectively. The correlation coefficients between catheter $SV_O_2$ and measured $SV_O_2$ are presented in three ranges in table 1. Fisher's Z test was used to compare differences in correlation between catheters. The effect of varying the hemoglobin either 3 g higher or 3 g lower than the measured value did not change the correlation coefficients for the two-wavelength catheters significantly (Fisher's Z test).

**Discussion**

The value of a continuous determination of mixed venous saturation depends on how accurately the in vivo $SV_O_2$ approximates measured saturations under adverse physiologic conditions. Clinical comparisons have been limited to measurements predominantly made at greater than 60% range of $SV_O_2$. In the present study, the experimental model allowed for the manipulation of physiologic variables that reduced cardiopulmonary reserve sufficiently to produce the broad range of observed $SV_O_2$. Four variables contributing to $O_2$ delivery (concentration of inspired $O_2$, hemoglobin level, cardiac output, and afterload) were manipulated. Calculated $O_2$ con-
Table 1. Correlation Between In Vivo and In Vitro Saturations

<table>
<thead>
<tr>
<th>$S_{O_2}$ Range</th>
<th>Three-wavelength, R (N)</th>
<th>Two-wavelength, R (N)</th>
<th>Significance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0.994 (88)</td>
<td>0.808 (77)</td>
<td>$P &lt; 0.001$</td>
</tr>
<tr>
<td>IL ≤ 46%</td>
<td>0.949 (50)</td>
<td>0.603 (58)</td>
<td>$P &lt; 0.001$</td>
</tr>
<tr>
<td>IL ≥ 46–60%</td>
<td>0.909 (20)</td>
<td>0.268 (21)</td>
<td>$P &lt; 0.001$</td>
</tr>
<tr>
<td>IL &gt; 60%</td>
<td>0.987 (58)</td>
<td>0.789 (18)</td>
<td>$P &lt; 0.001$</td>
</tr>
</tbody>
</table>

* Fisher's Z test used to compare differences in correlations between catheters.

N = number of observations per group; IL = reference cooximeter.

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References


\[ Y = 1.67X - 2.1 \quad R = 0.994 \quad \text{SEE} = 2.2 \quad N = 88 \]

Fig. 2. Regression line for in vivo determination of $S_{O_2}$ by the three-wavelength system versus the in vitro reference cooximeter. Dashed lines represent the 95 percentile confidence interval. Inset: Regression slope and intercept, correlation coefficient (R), standard error of the estimate (SEE), and number of data points represented (N).

Drifted during the course of the experiments, resulting in deviations from the measured $S_{O_2}$ from 5–31% at the conclusion of the experiments. Importantly, all five of the two-wavelength catheters showed a higher $S_{O_2}$ than the actual measurement. The protocol does not allow one to conclude whether the drift observed in the two-wavelength system occurred due to the adverse physiologic conditions, or time, or both.

The magnitude of the error measured in the two-wavelength system is sufficiently large to be clinically important. Until further explanation of this discrepancy is available, it would seem prudent to reserve its clinical applications to rigorously controlled experimental observations. The three-wavelength system accurately reflects measured $S_{O_2}$ during a wide variety of simulated clinical conditions.

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