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Accuracy of pulse oximetry readings in an animal model of low perfusion caused by emerging pneumonia and sepsis

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Abstract *Objective:* To test the effects of low perfusion caused by emerging sepsis on the performance of two new pulse oximetry techniques: Masimo SET in comparison with Nellcor Oxismart XL. *Design:* Cohort study with random allocation of two pulse oximetry devices to two sensor sites. *Setting:* University animal research facility. *Subjects:* Twenty-five adult, anesthetized, ventilated rabbits. *Interventions:* Pneumonia/sepsis was induced by tracheal instillation of *E. coli*. *Measurements and results:* Oxygen saturation was measured by pulse oximetry (SpO₂) and recorded continuously until death. Arterial oxygen saturation (SaO₂) was measured hourly by CO oximetry and whenever a difference of >5% between the devices occurred. SpO₂ sensors were positioned at both forelegs and switched hourly. There was no difference in total signal dropout time [median 3.8 min (range 0.4–66.6 min) vs 3.3 min

(range 0–94.5 min), Masimo SET vs Oxismart XL]. There were fewer episodes with a false SpO₂ reading [1 (range 0–7) vs 2 (range 0–17)] using the Masimo SET vs the Oxismart XL as verified by CO oximetry; $p < 0.05$. Average bias (SpO₂–SaO₂) was significantly different between the two devices, and variability of bias values increased across time with both devices. *Conclusions:* Both devices were capable to measure SpO₂ during most of the experimental time in this model of low perfusion and therefore appear to be highly sensitive to pick up a signal; however, low perfusion caused by emerging sepsis may result in inaccurate measurements with both devices. These episodes were less common with the Masimo SET vs the Oxismart XL.

Keywords Physiologic monitoring · Blood gas monitoring · Transcutaneous · Sepsis · Bacterial infections

Introduction

Pulse oximetry is widely used in anesthesia as well as emergency, and critical care settings to monitor arterial oxygenation and to guide adjustments of FiO₂. Different filter techniques and software algorithms to separate noise from the true signal are used in pulse oximetry devices [1], which may result in a different performance when challenged by artifacts, such as motion or low perfusion [2, 3, 4]. The effect of low perfusion on pulse oximetry has been studied in healthy subjects using exposure to

hypothermia and tourniquet-occlusion techniques [4, 5, 6], or during hemorrhagic hypotension [7]; however, there are very few studies during low perfusion in subjects with sepsis, and these studies are limited by the fact that arterial oxygen saturation as measured by pulse oximetry (SpO₂) was compared with arterial oxygen saturation as measured by CO oximetry (SaO₂) at only very few different time points [8, 9]. As sepsis is a common event in ICU patients [10], it is important to know the performance characteristics of more recently available pulse oximetry techniques in this setting. We have

previously shown that low perfusion caused by experimental sepsis may result in significant signal dropout when using an older standard pulse oximeter (Nellcor N-200), and that SpO₂ measurements may be underestimated considerably [11].

The objective of this study was to test the hypothesis that a more recently available pulse oximetry technique (Masimo SET) would be less prone to signal loss, and therefore the total signal dropout time would be at least 50% shorter in comparison with a Nellcor Oxismart XL pulse oximeter in an animal model of emerging sepsis.

Materials and methods

All animals were cared for according to the current version of the German law on the protection of animals and to NIH guidelines for the care and use of laboratory animals. The protocol was approved by the appropriate government agencies. Twenty-five adult anesthetized, ventilated New Zealand White Rabbits received a tracheal instillation of *E. coli* to induce pneumonia/sepsis and were supported as described in detail previously [11].

Arterial hemoglobin saturation (SpO₂) was simultaneously measured with an IVY Model 405T (IVY Medical Systems, Branford, Conn.), equipped with a LNOP-Neo Sensor and Masimo SET (Masimo, Irvine, Calif.), and a Nellcor N-395 pulse oximeter equipped with a Sensor Type D-YS (Nellcor Puritan Bennett, Pleasanton, Calif.) and Nellcor Oxismart XL technique. To separate the arterial signal from noise signals, the Masimo SET uses an adaptive filter that identifies and removes frequency components in common with both signals and plots the remaining signal on a power curve where the arterial signal is identified. We expected that this very sophisticated technique would allow signal detection during conditions with a low-signal-to-high-noise ratio. In the Nellcor Oxismart XL a different adaptive filter technique is used, which takes into account the rate of SpO₂ change analyzed and assumes that rapid changes along with a high noise level may be caused by noise as well. After closely shaving both forelegs, the pulse oximeter sensors were randomly assigned to one foreleg each and switched hourly. Sensor sites were shielded against ambient light using an opaque cover throughout the study. SpO₂ readings and plethysmography curves of both pulse oximeters were recorded continuously.

Arterial blood gases and arterial hemoglobin O₂ saturation (SaO₂), i.e., functional saturation, as measured by CO oximetry (Omni 3, Roche Diagnostics, Graz, Austria), were drawn and analyzed within 2 min at hourly intervals, or whenever the absolute value of the difference between both SpO₂ readings was >5% for more than 60 s.

The primary outcome measure was the total signal dropout time. It was calculated as the sum of all episodes without a signal from

instillation of *E. coli* until death for each of the two devices. Secondary outcome measures were the number and duration of episodes with signal dropout, duration of final signal dropout, and the number and duration of episodes with a false SpO₂ reading, defined as a bias (difference between SpO₂ and SaO₂) of ≥5% or ≤-5%, and the maximal bias during these episodes. Bias was further calculated for both pulse oximeters at hourly intervals in each animal. Modified Bland-Altman plots of these hourly measured bias values were used to compare time-dependent changes of the accuracy of pulse oximetry measurements across experimental time [12]. Mean±2SD values of the differences (SpO₂-SaO₂) measured at each time point were calculated using an ANOVA model for repeated measurements. Moving averages derived from three consecutive measurements were used for smoothing of mean±2SD intervals. Paired *t* tests, Wilcoxon signed-rank tests, chi-square tests (including Yates correction), and repeated measures ANOVA on ranks, where appropriate, were used to compare differences between devices.

Results

Signal dropout

The animals survived until 10 h (range 4–31 h) after tracheal instillation of *E. coli*. Our hypothesis was not confirmed, as there was no significant difference in total signal dropout time comparing the two devices (Table 1). Although there were more episodes of signal dropout with the Masimo SET, the median duration of these episodes was shorter compared with the Nellcor Oxismart XL. There was no difference in the final dropout time, i.e., the time interval between final device failure and death.

Episodes of a false SpO₂ reading

We observed 108 episodes of a false SpO₂ reading in 21 of 25 animals (Masimo SET: 33 episodes; Nellcor Oxismart XL: 75 episodes). Fourteen animals had episodes with both devices, two had episodes with only the Masimo SET, 5 animals had episodes with only the Nellcor Oxismart XL, and 4 animals had no episode with either device. The Masimo SET pulse oximeter had fewer episodes of a false pulse oximetry reading than the Oxismart XL (*p*<0.05; Table 2), but there was no significant difference in the maximal bias or the median duration of these episodes (Table 2).

Table 1 Characteristics of episodes of signal dropout (no pulse oximetry signal)

	Masimo SET (IVY 405T)	Oxismart XL (Nellcor N-395)	<i>p</i> value
Total dropout time (min)	3.8 (0.4–66.6)	3.3 (0–94.5)	0.32
No. of episodes of signal dropout	3 (1–73)	1 (0–13)	<0.001
Duration of episodes of signal dropout (min)	0.6 (0.1–27.2)	2.5 (0.1–88.3)	<0.05
Duration of final signal dropout (min)	2.1 (0–20.4)	2.7 (0–88.3)	0.23

Values were obtained by calculating the median of the individual medians, the maximum of the individual maxima, and the minimum of the individual minima. The medians for each animal and device were compared. Values are median (range in parentheses). The *p* values refer to paired *t* tests or Wilcoxon signed-rank tests, where appropriate

Table 2 Characteristics of episodes of a false SpO₂ reading

	Masimo SET (IVY 405T)	Oxismart XL (Nellcor N-395)	<i>p</i> value
No. of episodes ^a	1 (0–7)	2 (0–17)	<0.05
Maximal bias (SpO ₂ –SaO ₂) during these episodes (%) ^b	6 (–87 – [+34])	–15 (–85 – [+24])	0.10
Duration of these episodes (min) ^b	20.9 (1.4–55.9)	18.7 (1.6–79.7)	0.69
Total duration of these episodes (min) ^a	13 (0–182)	40 (0–286)	0.06

Values given are median (range in parentheses)

^a Wilcoxon signed-rank test

^b Values were obtained by calculating the median of the individual medians and the maximum of the individual maxima and the minimum of the individual minima. The medians for each animal and device using Wilcoxon rank-sum tests were compared

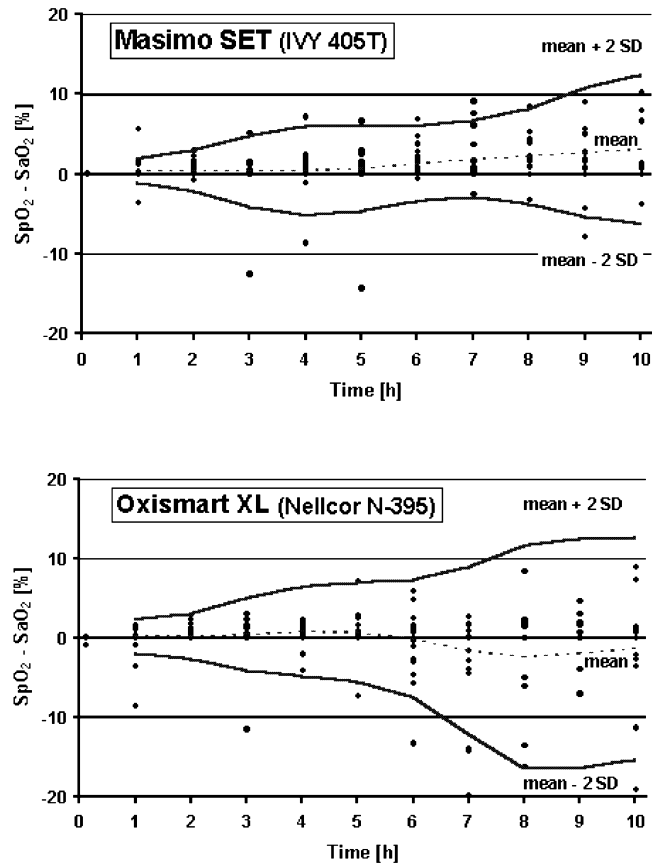


Fig. 1 Modified Bland-Altman plots of the measured bias values (SpO₂–SaO₂) across experimental time. *Each dot* refers to one measurement in each animal at each time point. Mean bias along with mean±2SD values of these individual bias values. *Upper panel* Masimo SET; *lower panel* Nellcor Oxismart XL. Bias across time was significantly different between the devices ($p<0.05$, RM-ANOVA on ranks): the Masimo SET overestimated SaO₂, whereas the Oxismart XL tended to underestimate SaO₂. Variability of individual bias values increased with both devices indicating decreasing precision across time. Note that three outliers in the upper panel and four outliers in the lower panel are not shown because they were beyond the y-axis scale

Bias and precision

Figure 1 shows the changes of mean bias and variability of bias values as a measure of precision across experimental time. Mean bias was very small initially with both devices (Fig. 1, time=0 h); however, whereas the Masimo SET overestimated oxygen saturation, the Oxismart XL tended to underestimate oxygen saturation, resulting in a significant difference in bias values comparing the two devices ($p<0.05$, RM ANOVA on ranks). Variability increased across time with both devices, as can be seen from the mean±2SD intervals. Individual bias values were beyond the ±2% error limit given by the manufacturers of most pulse oximetry devices designed for clinical use in 61 of 264 (23%; Masimo SET) vs 81 of 265 (31%; Nellcor Oxismart XL) of all hourly SpO₂/SaO₂ measurements.

Discussion

In this study we did not find a significant difference in total signal dropout time between devices. Episodes of signal dropout were significantly more common with the Masimo SET compared with the Nellcor Oxismart XL; however, they were shorter in duration as well. We speculate that this observation may be related to differences in data processing. Considering the fact that most of our animals had severely impaired hemodynamics toward the end of the study both systems seem to be very sensitive to pick up a signal. Both devices seem to work properly during normal hemodynamic conditions in this animal species, as suggested by the fact that during the first 30 min of the experiment only one of the animals had one single signal dropout of approximately 40 s with one device, and that there was no bias beyond ±2% at baseline in any animal with both devices.

We observed episodes of false SpO₂ readings as compared with CO oximetry with increasing bias toward the end of the experimental time. The fact that one device was overestimating, whereas the other one was underestimating, true arterial oxygen saturation during adverse hemodynamic conditions might be of potential clinical interest. Other investigators found an increased bias in

infants with poor peripheral perfusion caused by cardiopulmonary bypass and/or hypothermia [13], and in adults during circulatory failure [8], or with sepsis and low systemic vascular resistance [9]. Other investigators found increased bias of transcutaneously measured pulse oximetry values in comparison with SaO₂ in severely sick surgical adult patients with increased body temperature or low mean arterial blood pressure [14]. In the latter study the accuracy of a simultaneously used reflectance pulse oximetry device placed in the esophagus was improved in comparison with sensor placement at fingers [14].

The bias/precision data of our previous study [11] was limited by the fact that an FiO₂=1.0 was used throughout that study resulting in an SpO₂ close to 100% for most of the experimental time as the pulse oximeter was working mainly on the flat part of the oxygen-hemoglobin dissociation curve, which may have limited errors caused by potential over-reading of the true SaO₂. In this study the FiO₂ was adjusted to maintain a PaO₂ in a target range used in many non-neonatal critical care settings (100–150 mmHg). In contrast to our previous study [11], we were now able to demonstrate in this study that SpO₂ might be overestimated considerably, and the bias values calculated from hourly SpO₂ and SaO₂ measurements now show a nearly symmetrical distribution across time.

As pulse oximetry is widely used to adjust FiO₂ in many emergency and critical care settings, it is not reassuring that a pulse oximeter can display a normal looking plethysmography curve along with a heart rate matching the ECG heart rate, but a false SpO₂ reading. Whereas with one device (Nellcor) the user may be alerted by the decreasing size of the plethysmography curve, this is not the case with the IVY 405T monitor, as this device expands its plethysmography display automatically to fit the screen.

Currently, it is unknown how often episodes of false SpO₂ occur in a specific clinical setting, and how often these episodes would lead caretakers to inappropriate adjustments of FiO₂ or ventilator pressures, resulting in hyperoxic tissue injury such as chronic lung disease or

retinopathy of prematurity in preterm neonates, or in inappropriate decreases in FiO₂ promoting hypoxic tissue damage, such as hypoxic brain injury. The currently available pulse oximeters may perform better during low perfusion, i.e., they pick up a signal when previously available devices would have failed; however, our study results suggest that the price for this increase in sensitivity may be decreased accuracy during adverse hemodynamic conditions. We have not noticed a readily available physiological variable such as blood pressure or heart rate to be of any value to predict device failure; however, perfusion index (=pulsating signal indexed against non-pulsating signal) as a measure of local tissue perfusion is currently under investigation in another study to predict device failure.

Conclusion

In conclusion, we have shown that two more recently available pulse oximetry techniques were capable of measuring SpO₂ during most of the experimental time in this model of low perfusion caused by emerging sepsis; however, our data suggest that inaccurate measurements of SpO₂ may occur in this setting with both devices. Further studies are necessary to elucidate the exact mechanisms responsible for false SpO₂ readings. Meanwhile, pulse oximetry readings suggesting a changing FiO₂ requirement should alert the clinician taking care of a patient with impaired hemodynamics to validate this reading using arterial blood gas analyses and/or CO oximetry as there may be a potential for inappropriate interventions.

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