

Helmut D. Hummler
Anja Engelmann
Frank Pohlandt
Josef Högel
Axel R. Franz

Decreased accuracy of pulse oximetry measurements during low perfusion caused by sepsis: is the perfusion index of any value?

Received: 15 August 2005
Accepted: 24 May 2006
Published online: 30 June 2006
© Springer-Verlag 2006

This article is discussed in the editorial available at: <http://dx.doi.org/10.1007/s00134-006-0255-x>

This research was funded by a grant from the German Research Foundation, Bonn, Germany (DFG: FR 1455/1). The AVL Omni 3 blood gas analyzer was provided by AVL Medizintechnik GmbH, Graz, Austria, and the Radical pulse oximeter by Masimo Corp., Irvine, Calif., USA

H. D. Hummler (✉) · A. Engelmann ·
F. Pohlandt · A. R. Franz
University of Ulm, Division of Neonatology
and Pediatric Critical Care, Department of
Pediatrics, Children's Hospital,
89070 Ulm, Germany
e-mail: helmut.hummler@uni-ulm.de
Tel.: +49-731-50027740
Fax: +49-731-50026739

J. Högel
University of Ulm, Department of Biometry
and Medical Documentation,
89070 Ulm, Germany

Introduction

Pulse oximetry is used in many emergency and critical care settings to monitor arterial oxygenation and to guide adjustments of FIO_2 . Pulse oximetry devices use different techniques to process the signal [1, 2, 3] which may result in a different performance when challenged by artifacts or low perfusion [4, 5, 6, 7]. Although the effect of low perfusion on pulse oximetry readings has been studied using ex-

Abstract Objective: To evaluate the effects of deteriorating perfusion caused by sepsis on the accuracy of pulse oximetry measurements using two more recently available techniques (Nellcor N-395 and Masimo Radical) and to evaluate the perfusion index as a marker of impaired peripheral perfusion to indicate that accuracy of pulse oximetry readings may be affected. **Design and setting:** Interventional cohort study in a university animal research facility. **Subjects:** Thirty-seven adult anesthetized, ventilated rabbits. **Interventions:** Pneumonia/sepsis was induced by tracheal instillation of *Escherichia coli*. **Measurements and results:** Oxygen saturation and perfusion index as a marker of peripheral perfusion were measured by pulse oximetry (SpO_2) and recorded continuously for 8 h. Arterial oxygen saturation (SaO_2) was measured every 30 min by CO oximetry, and bias ($SpO_2 - SaO_2$) was calculated at each time point for each device to assess time-dependent changes

in bias. Bias increased significantly across time for both devices tested comparing the first with the second half of the experimental period. Bias measurements during the second half of the experimental time were beyond the $\pm 3\%$ error limit in 21.4% of cases with Nellcor and in 22.6% with Masimo. A lower perfusion index was associated with increased bias, but sensitivity, specificity, and positive and negative predictive values of this marker for increased bias was very limited. **Conclusions:** We conclude that accuracy of pulse oximetry measurements was considerably affected with both devices with progressively deteriorating hemodynamics in this animal model of severe sepsis. Perfusion index as a marker for increased risk of bias was not a useful tool.

Keywords Monitoring · Physiological · Blood gas monitoring · Transcutaneous · Pulse oximetry · Sepsis

posure to hypothermia, vasoconstriction, and hemorrhagic hypotension [5, 8, 9, 10, 11, 12], only limited and conflicting data are available on the effect of sepsis on the accuracy of pulse oximetry readings [13, 14]. An unexpected and thus secondary finding of our previous studies in septic animals with low perfusion was that SpO_2 measurements may under- or overestimate SaO_2 considerably [15, 16].

The objective of this study was to test the hypothesis that progressively deteriorating perfusion would affect

accuracy of pulse oximetry measurements using the latest available techniques in an animal model of emerging sepsis. Further, we wanted to evaluate whether the perfusion index can serve as a useful marker of impaired peripheral perfusion to alert the clinician that accuracy of pulse oximetry readings may be affected.

Materials and methods

All animals were cared for according to current German laws on the protection of animals and to NIH guidelines for the care and use of laboratory animals and all experiments were approved by the appropriate government agencies. Thirty-seven anesthetized and ventilated adult New Zealand white rabbits received *Escherichia coli* by tracheal instillation to induce pneumonia/sepsis and were supported for 8 h as described previously in detail [15]. Arterial hemoglobin oxygen saturation (SpO_2) was simultaneously measured with a Radical Masimo SET, software version 4.1.0.1 (Masimo, Irvine, Calif., USA) equipped with an LNOP-Neo Sensor, and a Nellcor N-395 Oxismart XL, software version 1.6.2.0 pulse oximeter equipped with a Sensor type D-YS (Tyco Healthcare/Mallinckrodt, St. Louis, Mo., USA). 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.

Using pulse oximetry a variable amount of light is absorbed by pulsating arterial flow (AC), and a constant amount of light is absorbed by nonpulsating blood and tissue (DC). The pulsating signal indexed against nonpulsating signal and expressed as ratio is commonly referred to as the “perfusion index” = $\text{AC} \times 100 / \text{DC}$. It has been suggested as a marker of poor peripheral perfusion in critically ill patients [17, 18].

Arterial hemoglobin O_2 saturation (SaO_2) as measured by CO oximetry (Omni 3, Roche Diagnostics, Graz, Austria) was drawn every 30 min to calculate individual bias (defined as $\text{SpO}_2 - \text{SaO}_2$) for each device in each animal at each time point. From all absolute bias values of any given animal during the first 4 h an individual median bias was calculated and compared to the corresponding median bias value derived from data obtained from the second 4 h of the experimental period in each animal. Differences in paired, continuous variables were analyzed by using the two-tailed paired *t* test or Wilcoxon signed rank test where appropriate. Differences in proportions were analyzed by using the χ^2 test (including Yates' correction). Repeated measurements across time were analyzed with repeated-measures analysis of variance on ranks. Differences with a *p* value less than 0.05 were considered statistically significant. Values presented are mean \pm SD or median (range). Primary outcome measure in this study was the absolute bias value ($|\text{SpO}_2 - \text{SaO}_2|$). In a previous study the average absolute bias value comparing the first 4 h with the

following 4 h increased [15], and the standard deviation of this change was 1.64. A power calculation based on this data set revealed that 37 animals would provide a power of 0.9 to obtain a significant test result, if an increase in the absolute value of bias by 1.0 is present, corresponding to an approximate tripling of the average bias comparing the two study periods.

Results

Comparing the first with the second half of the experimental period, the individual absolute value of bias calculated from individual measurements increased with progressively deteriorating hemodynamics with both devices: from a median of 0.10% (range 0.10–0.65%) to one of 1.1% (0.10–14.6%) with Nellcor ($p < 0.001$) and from 0.10% (0.10–0.65%) to 1.3% (0.1–5.7%) with Masimo ($p < 0.001$). Bias values increased over time for both devices, indicating that accuracy is affected upon

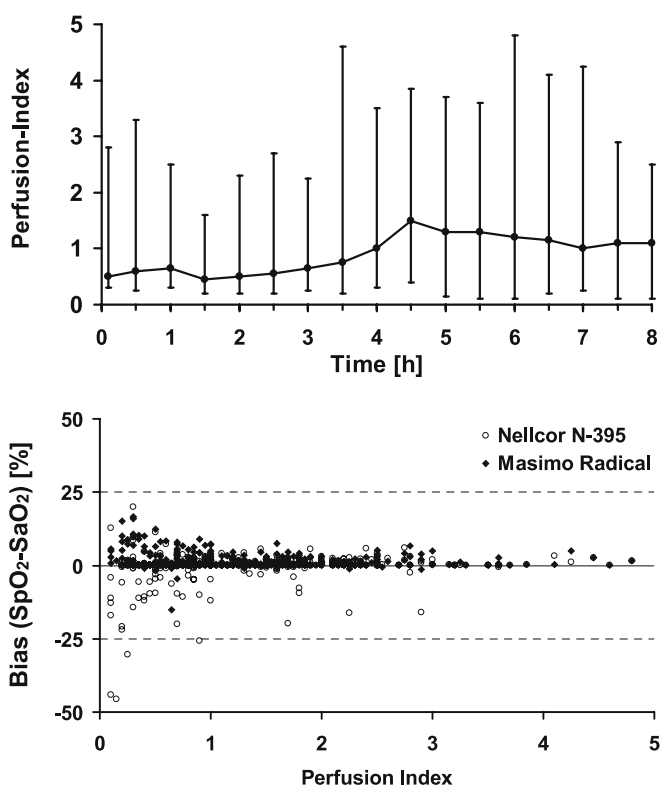


Fig. 1 Perfusion index (for definition see text) across time (*upper panel*) and relationship of bias to perfusion index (*lower panel*). *Upper panel* Data are median (range) derived from all animals. Perfusion index increased across time ($p < 0.001$, repeated-measures analysis of variance on ranks). *Lower panel* Relationship of bias (defined as $\text{SpO}_2 - \text{SaO}_2$) to perfusion index. Each dot refers to one measured bias value with its corresponding perfusion index value in one given animal at one given time point. Note: Large bias values seem to coincide with low perfusion index values

Table 1 Sensitivity, specificity, positive (PPV) and negative predictive values (NPV) of the perfusion index to detect bias exceeding the $\pm 3\%$ error limit using two different cutoffs: percentages

	Sensitivity	Specificity	PPV	NPV
Perfusion index < 0.5%				
Nellcor N-395 (Oxysmart XL)	33.3	80.1	17.1	90.7
Radical (Masimo SET)	31.3	80.3	16.7	90.3
Perfusion index < 1.0%				
Nellcor N-395 (Oxysmart XL)	66.7	46.7	13.3	91.9
Radical (Masimo SET)	64.2	46.5	13.1	91.2

time with progressing sepsis (detailed data available upon request). Individual bias values exceeded the $\pm 3\%$ error limit given for conditions of low perfusion by the manufacturers of pulse oximetry devices designed for clinical use in human subjects in 10.9% of SpO₂/SaO₂ measurements with the Nellcor Oxismart XL (66/603) vs. 11.2% of those with the Masimo SET (67/600) and in 21.4% of measurements during the second half of the experimental period (4–8 h) with the Nellcor Oxismart XL (66/309) vs. 22.6% of those with the Masimo SET (66/305).

The perfusion index, obtained from the Masimo SET pulse oximeter showed a wide variation and increased across time (Fig. 1, upper panel), indicating increasing pulsatility in the peripheral vascular bed toward the end of the experimental period, i.e., at a time when absolute bias values increased as well. However, when individual bias values are plotted along with the corresponding perfusion index values (Fig. 1, lower panel), large bias values seem to coincide more with low perfusion index values. Whereas bias values with the Nellcor N-395 were observed in both directions, the Radical overestimated oxygen saturation during episodes with low perfusion as indicated by a lower perfusion index (Fig. 1, lower panel). Bias exceeding the $\pm 3\%$ error limit was more common with a perfusion index less than 0.5 than with a perfusion index of 0.5 or greater (Nellcor: 22/129, 17.1%, vs. 44/474, 9.3%, $p < 0.05$; Masimo: 21/126, 16.7%, vs. 46/474, 9.7%, $p < 0.05$), suggesting that the perfusion index may be used as a marker for situations of low perfusion at risk for increased bias. Sensitivity, specificity, and positive and negative predictive values for two different perfusion index cutoffs to detect bias exceeding the $\pm 3\%$ error limit are shown in Table 1. These data show that sensitivity and positive predictive values with a cutoff of 0.5 are quite low. Using a cutoff of 1.0 increases sensitivity but causes a considerable loss of specificity.

Discussion

The findings of this study confirm that individual bias values may be affected considerably with emerging sepsis even when using more recently available pulse oximeters, as observed in our previous study using older

techniques [15]. A false SpO₂ reading may lead to inappropriate interventions such as increases or decreases in FIO₂ or ventilator pressures, which may expose the subject on mechanical ventilation to unnecessary hypoxemic or hyperoxic injury or barotrauma. The fact that more than 20% of SpO₂ measurements during the second half of the experimental period were beyond the $\pm 3\%$ error limit in conditions of low perfusion given by the manufacturers of pulse oximetry devices for clinical use may not be reassuring for the clinician.

We evaluated the perfusion index as a measure of peripheral pulsatility to detect the subject at risk for increased bias of pulse oximetry readings. The median perfusion index increased across time, suggesting increasing pulsatility in the peripheral vascular bed and decreasing peripheral vascular resistance, which would be in agreement with findings from other investigators, who found an increased bias in adults with sepsis and low systemic vascular resistance [13]. However, in this present study large bias values seemed to coincide with low perfusion index values. We found a higher percentage of bias beyond the $\pm 3\%$ error limit when perfusion index was below 0.5, suggesting that the perfusion index indeed may be used as a tool in situations of low peripheral perfusion at risk for increased bias of pulse oximetry readings. Using a perfusion index less than 0.5 as a cutoff, specificity was approx. 80% in both devices tested, whereas sensitivity was only 33% and 31% and the positive predictive value was approx. only 17% for both devices. If an arterial blood gas and/or CO oximetry were obtained in that particular situation, 83% of measurements would not show increased bias. Using a perfusion index less than 1.0 as a cutoff would increase sensitivity as expected, but causes a considerable decrease in specificity and positive predictive values. Other investigators have evaluated the relationship of the perfusion index to clinical signs of poor perfusion and found that a value of below 1.4 was a useful indicator of low perfusion in critically ill adult patients [17] and 1.24 or less in severely ill neonates [18]. Unfortunately, neither study provides data regarding bias of pulse oximetry readings to be compared with ours. Based on our data the preliminary conclusion may be drawn that the clinician faced with a perfusion index less than 0.5 may decide to obtain an arterial blood gas and/or CO oximetry to confirm or disprove the pulse oximetry reading, especially if the patient is septic and/or other clinical findings suggest poor peripheral perfusion.

Another approach may be to use a reflectance pulse oximetry device placed in the esophagus, as bias seems to be reduced in comparison to peripheral measurements during adverse hemodynamic conditions in severely ill adult patients [19]. Whereas bias values had a more symmetrical distribution using the Nellcor, the Masimo Radical overestimated SaO₂ during episodes of low perfusion. This finding may be important for the clinician, and we speculate that the different performance of the devices may be related to signal processing.

In summary, our findings show that the bias of pulse oximetry readings is considerably affected during experimental sepsis with both devices tested. Increased bias was more common with a low perfusion index. However, because of limited sensitivity, specificity, and positive predictive value the perfusion index is not a useful tool as a marker for increased risk of bias. Therefore intermittent blood gas measurements or CO oximetry may be warranted in septic patients with severely affected hemodynamics and respiratory failure.

References

- Severinghaus JW, Kelleher JF (1992) Recent developments in pulse oximetry. *Anesthesiology* 76:1018–1038
- Rusch TL, Sankar R, Scharf JE (1996) Signal processing methods for pulse oximetry. *Comput Biol Med* 26:143–159
- Goldman JM, Petterson MT, Kopotic RJ, Barker SJ (2000) Masimo signal extraction pulse oximetry. *J Clin Monit Comput* 16:475–483
- Bohnhorst B, Peter CS, Poets CF (2000) Pulse oximeters' reliability in detecting hypoxemia and bradycardia: comparison between a conventional and two new generation oximeters. *Crit Care Med* 28:1565–1568
- Severinghaus JW, Spellman MJ (1990) Pulse oximeter failure thresholds in hypotension and vasoconstriction. *Anesthesiology* 73:532–537
- Hay WW Jr, Rodden DJ, Collins SM, Melara DL, Hale KA, Fashaw LM (2002) Reliability of conventional and new pulse oximetry in neonatal patients. *J Perinatol* 22:360–366
- Barker SJ (2002) "Motion-resistant" pulse oximetry: a comparison of new and old models. *Anesth Analg* 95:967–972
- Iyer P, McDougall P, Loughnan P, Mee RBB, Al-Tawil K, Carlin J (1996) Accuracy of pulse oximetry in hypothermic neonates and infants undergoing cardiac surgery. *Crit Care Med* 24:507–511
- Trivedi NS, Ghouri AF, Shah NK, Lai E, Barker SJ (1997) Effects of motion, ambient light, and hypoperfusion on pulse oximeter function. *J Clin Anesth* 9:179–183
- Falconer RJ, Robinson BJ (1990) Comparison of pulse oximeters: accuracy at low arterial pressure in volunteers. *Br J Anaesth* 65:552–557
- Gehring H, Hornberger C, Matz H, Konecny E, Schmucker P (2002) The effects of motion artifact and low perfusion on the performance of a new generation of pulse oximeters in volunteers undergoing hypoxemia. *Respir Care* 47:48–60
- Barrington KJ, Ryan CA, Finer NN (1986) Pulse oximetry during hemorrhagic hypotension and cardiopulmonary resuscitation in the rabbit. *J Crit Care* 1:241–246
- Secker C, Spiers P (1997) Accuracy of pulse oximetry in patients with low systemic vascular resistance. *Anaesthesia* 52:127–130
- Ibanez J, Velasco J, Raurich JM (1991) The accuracy of the Biox 3700 pulse oximeter in patients receiving vasoactive therapy. *Intensive Care Med* 17:484–486
- Hummler HD, Pohlandt F, Franz AR (2002) Pulse oximetry during low perfusion caused by emerging pneumonia and sepsis in rabbits. *Crit Care Med* 30:2501–2508
- Hummler HD, Engelmann A, Pohlandt F, Högel J, Franz AR (2004) Accuracy of pulse oximetry readings in an animal model of low perfusion caused by emerging pneumonia and sepsis. *Intensive Care Med* 30:709–713
- Lima AP, Beelen P, Bakker J (2002) Use of a peripheral perfusion index derived from the pulse oximetry signal as a noninvasive indicator of perfusion. *Crit Care Med* 30:1210–1213
- De Felice C, Latini G, Vacca P, Kopotic RJ (2002) The pulse oximeter perfusion index as a predictor for high illness severity in neonates. *Eur J Pediatr* 161:561–562
- Vicenzi MN, Gombotz H, Krenn H, Dorn C, Rehak P (2000) Trans-esophageal versus surface pulse oximetry in intensive care unit patients. *Crit Care Med* 28:2268–2270