Pulse oximetry during low perfusion caused by emerging pneumonia and sepsis in rabbits

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Objective: **This study tested the effects of low perfusion caused by emerging sepsis on the reliability of a new pulse oximetry technology (Masimo SET; IVY 405T) compared with a standard pulse oximeter (Nellcor N-200).**

Design: **Randomized trial.**

Setting: **University animal research facility.**

Subjects: **Twenty-six anesthetized, ventilated (Fio_2, 1.0), adult rabbits.**

Interventions: **Pneumonia/sepsis was induced by tracheal instillation of *Escherichia coli*. Oxygen saturation was measured by pulse oximetry (Spo_2) and recorded continuously until death. Arterial oxygen saturation (Sao_2) was measured hourly by oximetry and whenever Spo_2 dropped to ≤95%, or whenever a difference of ≥5% between devices occurred. Spo_2 sensors were positioned at both forelegs and switched hourly.**

Measurements and Main Results: **The total time of signal loss was longer with the N-200 vs. the IVY: 65 (4–299) mins vs. 7 (0–97) mins [median (range)], $p < 0.001$. Signal loss was more prevalent during the first 80% of the experimental time with the N-200 compared with the IVY. Nineteen of 26 animals had a total of 62 episodes of a falsely low Spo_2 value with either one of the two devices associated with hemodynamic deterioration. Median bias ($Spo_2 - Sao_2$) was small, but variability of bias values increased toward the end of the experimental time with both devices.**

Conclusions: **The pulse oximeter equipped with Masimo SET was less prone to signal loss than the standard pulse oximeter in this sepsis model. Episodes of falsely low Spo_2 readings may occur, and deviation of Spo_2 from Sao_2 may be increased with deteriorating hemodynamics with both devices. (Crit Care Med 2002; 30:2501–2508)**

KEY WORDS: monitoring, physiologic; hyperoxia; septicemia; bacterial infection

Pulse oximetry is used widely in the intensive care unit (ICU) as well as in emergency care settings (1). It is an important noninvasive tool to assess arterial oxygenation in critically ill patients and has been termed the "fifth vital sign" (2–4). The use of pulse oximetry is routine in small, premature neonates from birth until they are considered stable and frequently is used to guide Fio_2 adjustments (5–7). Manufacturers of these devices use different filters and algorithms to separate noise from the true signal (1, 8), which may result in different performances of these devices when challenged by artifacts such as movement or ambient light (9, 10). It is important to know the limitations of pulse oximetry in circumstances such as low perfusion (9, 11).

In previous studies investigating the effect of low perfusion on pulse oximetry, different techniques were used. Tourniquet occlusion techniques (9, 11, 15), intra-arterial infusion of vasoconstrictive agents (11), hemorrhagic hypotension (16), general exposure to hypothermia (17–19), or local cooling of a test arm (13) were used, or oxygen saturation measured by pulse oximetry (Spo_2) and arterial oxygen saturation (Sao_2) were compared in patients with low perfusion caused by sepsis at just one single or a few different time points (20, 21).

Sepsis, a common event in pediatric (22–24) and adult ICU patients (25, 26), may impair hemodynamics and perfusion. To our knowledge, the effects of impaired perfusion on the performance of pulse oximetry have not been evaluated over time in subjects with sepsis. The objective of this study was to evaluate the effects of low perfusion on the reliability of a new pulse oximetry technique called Masimo Signal Extraction Technology (SET), which has been shown to be very sensitive and less affected by motion artifact than other available techniques (27–31), compared with a standard pulse oximeter in an animal model of sepsis. We hypothesized that Masimo SET would be less prone to signal loss and therefore the total dropout time would be shorter compared with a standard pulse oximeter.

MATERIALS AND METHODS

Animal Preparation. All animals were cared for according to the current version of the German law on the protection of animals and according to National Institutes of Health guidelines for the care and use of laboratory animals, and all experiments were approved by the Animal Care Committee of the government agencies of Baden-Württemberg. Twenty-six adult New Zealand White rabbits (mean ± SD weight, 3449 ± 201 g) were given 0.5 mg of atropine and were anesthetized with 5–13 mg/kg ketamine and 0.5–1.3 mg/kg xylazine intravenously. After supine positioning, the animals were intubated with a 3.5-mm internal diameter cuffed endotracheal tube. A rectal temperature probe (Siemens Sirecust 302,

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Erlangen, Germany) was placed, and a core temperature of 38.5–39.5°C was maintained by using a heating mattress and an overhead warmer (Babytherm 8000; Dräger, Lübeck, Germany). Anesthesia was maintained by a continuous infusion of ketamine and xylazine, and the dose was adjusted individually to maintain anesthesia deep enough to prevent spontaneous movements other than respiration. The animals were placed on volume-controlled, synchronized intermittent positive pressure ventilation by using a Stephanie Ventilator (Stephan Medizintechnik GmbH, Gackenbach, Germany) with the following settings: Fio_2, 0.4; tidal volume, 6 mL/kg; positive end-expiratory pressure, 0.4 kPa (4 cm H_2O); inspiratory time, 0.4 secs; respiratory rate, 30 breaths/min. The rate was adjusted to maintain a $Paco_2$ within the target range of 35–45 mm Hg (4.7–6.0 kPa). Dextrose 5% with 70 mmol/L Na, 18 mmol/L K, and 1 unit of heparin/mL was administered at 8 mL/kg/hr into a peripheral vein. A 3.5-Fr arterial femoral catheter was inserted for continuous blood pressure monitoring and sampling for blood gas analyses. The line was flushed continuously with heparinized (1 unit/mL) normal saline at a rate of 3 mL/hr. A 4-Fr thermodilution catheter was introduced via the right jugular vein. Its tip was successfully placed into the pulmonary artery in 25 of the 26 animals to measure cardiac output by thermodilution with a Sat-2 Cardiac Output Monitor (Baxter, Santa Ana, CA). The pulmonary arterial and central venous catheters were flushed continuously with heparinized normal saline (1 unit/mL) at a rate of 2 mL/hr.

Pulse Oximetry. Arterial hemoglobin saturation (Spo_2) was measured simultaneously with a Nellcor N-2000 pulse oximeter equipped with a Sensor Type D-YS (Nellcor Puritan Bennett, Pleasonton, CA) and an IVY 405T (IVY Medical Systems, Branford, CT), equipped with a LNOP-Neo Sensor and Masimo SET (Masimo Corp., Irvine, CA). This technique assumes that the arterial signal can be detected among noise signals (i.e., venous and motion signals). The raw signal is fed into an adaptive filter that identifies and removes frequency components in common with both signals (27). The remaining signals are plotted on a power curve where a Discrete Saturation Transform identifies the correct arterial signal. The reusable Nellcor sensor was used for all animals. The disposable Masimo sensor was replaced after three or four animals or when it was soiled, whichever occurred first. Averaging times were set to "normal" or mode 1 (5–7 secs) in the N-2000 and to 4 secs in the IVY 405T. The Nellcor N-2000 was used as the standard pulse oximeter because this device currently is used widely in our neonatal/pediatric ICU and in other ICUs and critical care settings throughout the world (27).

After both forelegs were shaved closely, the pulse oximeter sensors were assigned randomly, to one foreleg each, and were switched hourly. Sensor sites were shielded against ambient light by using an opaque cover throughout the study. Spo_2 and plethysmography curves of both pulse oximeters were recorded along with arterial blood and central venous pressure and electrocardiogram continuously from the time of bacteria instillation until death, with a sample rate of 1000 Hz, and were stored on a computer for later analysis.

Protocol. After instrumentation, pneumonia was induced by tracheal instillation of (4.5–7.2)·10^{10} colony-forming units of *Escherichia coli*, which was suspended in normal saline and given in several aliquots over a 3-hr period. Animals were supported until they died, and death was defined as systolic blood pressure <12.5 mm Hg (1.7 kPa) or systolic

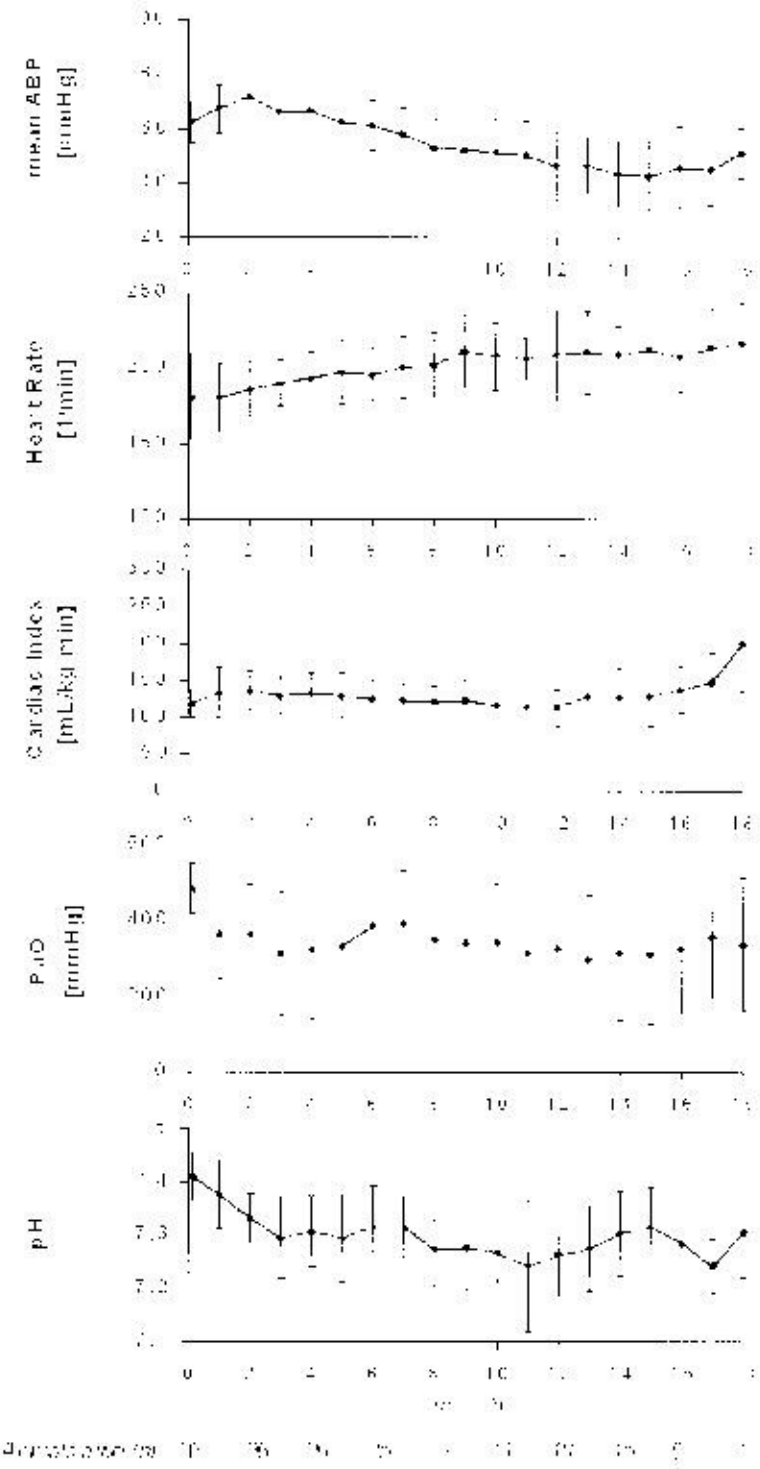

Figure 1. Mean arterial blood pressure (*ABP*), heart rate, cardiac index, Pao_2, and pH across experimental time. The numbers in italics refer to the actual number of animals alive at each time point given. Values are mean ± SD.

blood pressure ≤ 25 mm Hg (3.4 kPa) and HR ≤120 beats/min, whichever occurred first. Hemodynamics were supported by intravenous volume challenges of 15 ml/kg normal saline given within 15 mins, whenever the diastolic blood pressure dropped to ≤50 mm Hg (6.7 kPa), and whenever two volume challenges were unsuccessful, by continuous dopamine infusion in increments of 5 μg/kg/min up to 50 μg/kg/min.

Arterial blood gases and arterial hemoglobin oxygen saturation (Sa_{O_2}), that is, functional saturation (7), as measured by carbon monoxide (CO) oximetry (Omni 3, AVL-List GmbH, Graz, Austria), were analyzed within 2 mins whenever one Sp_{O_2} reading dropped to ≤95% and/or when the difference between both Sp_{O_2} readings was ≥5% for 60 secs. In this event, the sensors were not repositioned until they were due to be switched to the other leg to observe the "natural course" of these episodes.

Data Analysis. The primary outcome measure was the total dropout time. It was calculated as the sum of all episodes without a signal for ≥5 secs duration beginning from the first instillation of *E. coli* until death. Episodes of 5 secs duration were not counted because they were considered to be of no clinical significance. The following variables were defined as secondary outcome measures: number and duration of episodes with signal dropout, duration of final signal dropout (time interval between final loss of signal and death), number and duration of episodes with a falsely low Sp_{O_2} reading, defined as a bias (difference between Sp_{O_2} and Sa_{O_2}) of ≥5%; and the maximal bias during these episodes. Systolic, diastolic, and mean blood pressure and blood pressure amplitude were measured during the episodes with a falsely low Sp_{O_2} signal and compared with the corresponding values 5 mins before the beginning of this episode to assess whether acute changes in blood pressure were related to these episodes.

Bias was calculated further for both pulse oximeters at hourly intervals in each animal. Finally, Pa_{O_2}, pH, arterial blood pressure, heart rate, and cardiac output were obtained hourly to characterize the condition of the animals. Cardiac output was calculated as the average of three serial thermodilution measurements and corrected for weight.

Statistics. The initial site for each pulse oximeter sensor was assigned randomly to one foreleg by using opaque sealed envelopes. Differences of paired, continuous variables (i.e., blood pressure changes) were analyzed by using two-tailed paired *t*-tests or Wilcoxon's signed rank tests when these differences were not distributed normally. Differences of proportions were analyzed by using Fisher's exact or chi-square tests (including Yates correction). We considered $p < .05$ to be statistically significant. Values presented are mean ± SD or median (range). We expected the Masimo SET system to be less prone to signal loss. However, we were unable to perform a sample size calculation for the pulse oximetry study, because the variance of the primary outcome measure was unknown. Therefore, we decided to use 26 animals, which was a predefined sample to study the microbiological manifestations of this animal model, for this pulse oximetry study and to perform an adaptive interim analysis (32) thereafter. It was decided *a priori* to stop the pulse oximetry study if either $p > .50$ for the primary outcome measure, assuming there is no difference in signal dropout time, or if $p < .0233$, proving a significant difference. If $p > .0233$, a sample size calculation would have been performed to continue the pulse oximetry study. The *p* values for secondary outcome measures were not corrected for multiple comparisons.

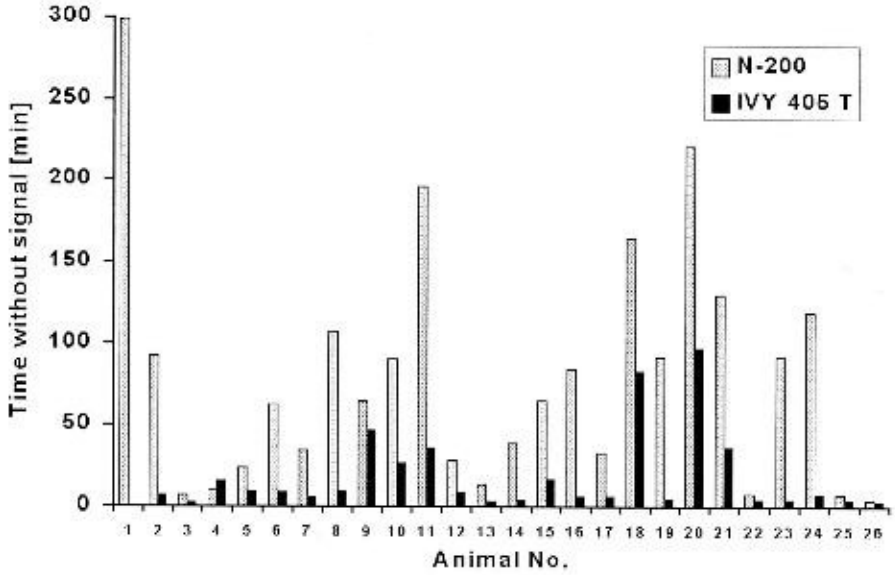

Figure 2. Time without signal displayed for each animal and both pulse oximetry devices.

RESULTS

The survival time was 15.1 hrs (5.2–27.6 hrs) after tracheal instillation of *E. coli*. The hemodynamic and gas exchange characteristics of this model are shown in Figure 1.

Signal Dropout. The total dropout time was significantly longer when using the Nellcor N-200 vs. the IVY 405T pulse oximeter for all but one animal (Fig. 2 and Table 1).

The mean difference comparing the two systems was 63 mins (95% confidence interval, 36–89 mins), which corresponds to 7.4% (95% confidence interval, 4.4–10.3%) of the total experimental time. There was no difference in the number of episodes of signal dropout between the two devices (Table 1). However, the duration of these episodes and the

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

	Nellcor N-200	IVY 405T (Masimo SET)	*p* Value
Total dropout time, mins	64.6 (3.7–298.6)	6.8 (0–97.0)	< .001
No. of episodes of signal dropout	5.5 (1–79)	6.5 (0–79)	.88
Duration of episodes of signal dropout, mins*	1.3 (0.1–146.3)	0.3 (0.1–18.0)	< .001
Duration of final signal dropout, mins	8.9 (1.1–141.4)	2.6 (0–42.9)	< .001

*Final signal dropout not included; values were obtained by calculating the median of the individual medians, the maximum of the individual maxima, and the minimum of the individual minima. Compared were the medians for each animal and device. Values are median (range). *p* values refer to paired *t*-tests or Wilcoxon's signed-rank tests, where appropriate.

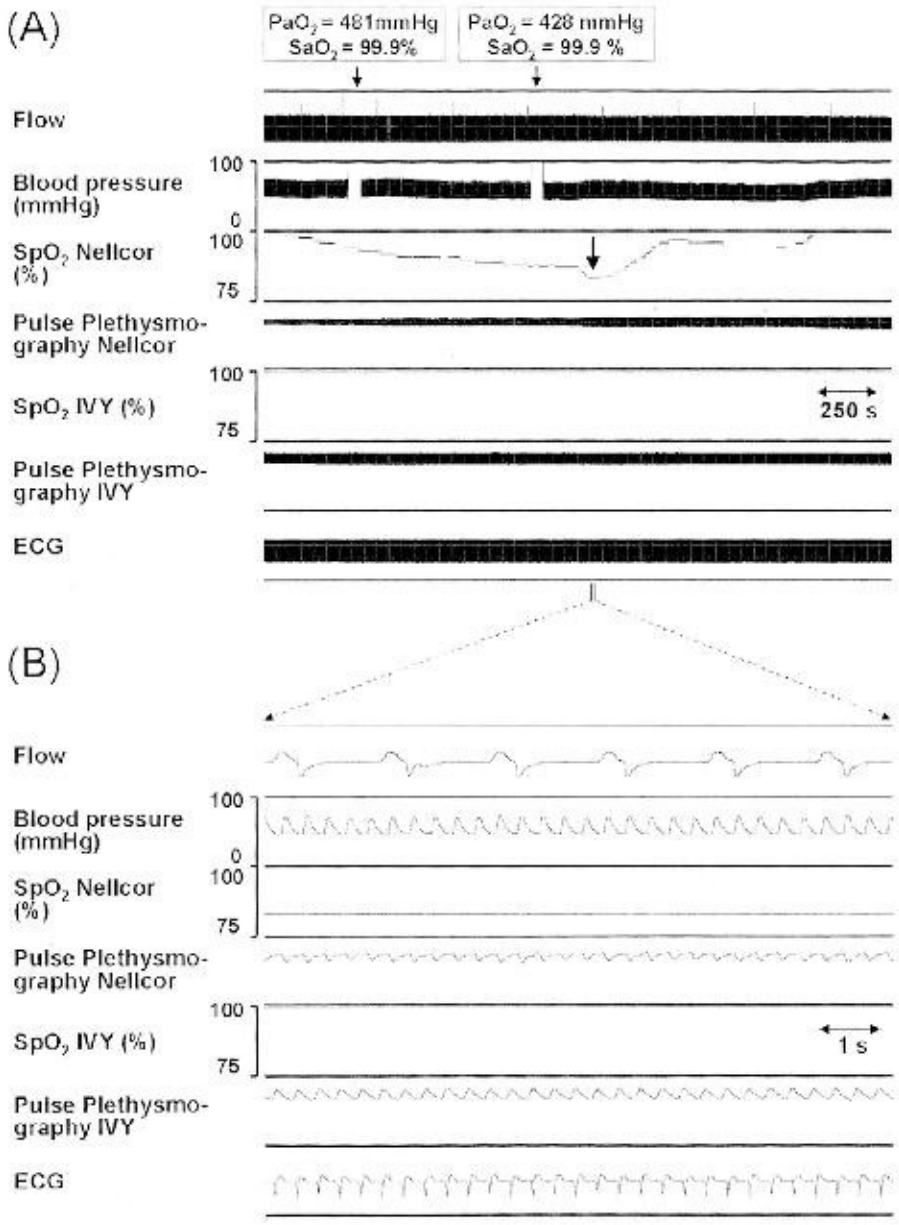

Figure 3. Episode of a falsely low reading of oxygen saturation measured by pulse oximetry (Spo_2). *A*, the Nellcor N-200 displays a falsely low Spo_2 for a total of 35 mins. The reading drops to values as low as 83% (*downward-pointing arrow*) and was proven to be incorrect by two arterial blood gas samples (Pao_2/arterial oxygen saturation [Sao_2], 481 mmHg/99.9% and 428 mmHg/99.9%). *B*, same episode displayed at a different scale: Despite a normal plethysmography curve matching the heart rate and suggesting a correct reading, the Nellcor N-200 displays a falsely low reading of 83%.

final dropout time (i.e., the time interval between final device failure and death) was longer with the Nellcor N-200 compared with the IVY 405T (Table 1). Episodes of signal dropout occurred more often during the first 80% of the experimental time (corrected for individual study duration) with the Nellcor N-200 compared with the IVY 405T (67.9% vs. 7.8%; $p < .001$).

Episodes of a Falsely Low Spo_2 Reading. We observed 62 episodes of falsely low Spo_2 values (Nellcor N-200, n = 38; IVY 405T, n = 24). Seven animals had no episode, six animals had episodes with only the Nellcor N-200, four had episodes solely with the IVY 405T, and nine had episodes with both devices. Figure 3 shows an example of such an episode.

When we compared the two devices, there was no significant difference in the number or duration of the episodes, in the maximal bias, or in the Pao_2 during these episodes (Table 2).

The episodes were terminated a) by loss of signal in nine vs. one events (Nellcor N-200 vs. IVY 405T); b) because switching of the sensor to the other foreleg was scheduled (nine vs. seven events); and c) because of the animals' death in two vs. three events. In addition, episodes ended spontaneously in 18 vs. 13 events. Systolic, diastolic, and mean arterial blood pressure and blood pressure amplitude were lower during the episodes of falsely low Spo_2 reading compared with values obtained 5 mins before the onset of these episodes (Table 3).

Figure 4 shows an example of a falsely low reading of a pulse oximeter that resolved with improving blood pressure.

Episodes with a falsely low Spo_2 reading occurred more often during the first 80% of the experimental time (corrected for individual study duration) when using the Nellcor N-200 compared with the IVY 405T (65.8% vs. 20.8%; $p < .001$).

Bias. Figure 5 shows the changes of median, minimum, and maximum bias for both devices across experimental time.

Median bias was very small during the complete experimental time, but variability increased somewhat early with the Nellcor N-200, and later with both devices, as can be seen from the minimal and maximal bias values. Bias was beyond the ±2% error limit given by the manufacturers in 17 of 297 (5.7%; Nellcor N-200) vs. 13 of 309 (4.2%; IVY 405T; nonsignificant) of all hourly Sao_2/Spo_2 measurements during the first 80% of experimental time, and in 15 of 51 (29.4%) vs. 22 of 66 (33.3%) of all measurements during the last 20% of the experimental time (nonsignificant).

DISCUSSION

This is the first study evaluating the performance of pulse oximetry systematically during a complete course of emerging sepsis compared with CO oximetry of arterial blood samples as the "gold standard." The principal finding of our study is that the Nellcor N-200 is more prone to signal dropout than the IVY 405T in this animal model of emerging pneumonia and sepsis. The median duration of dropout episodes and the duration of the final signal dropout before death were longer with the Nellcor N-200. It is important to emphasize that the majority of these episodes with the Nellcor N-200 occurred during the first 80% of the experimental time, that is, when gas exchange and he-

Table 2. Characteristics of episodes of a falsely low pulse oximetry (Spo_2) reading

	Nellcor N-200	IVY 405T (Masimo SET)	*p* Value
No. of episodes[a]	1 (0–7)	0.5 (0–1)	.38
Maximal bias (Spo_2 − Sao_2) during these episodes, %[b]	−9.7 (−50.3–[−5.7])	−18.3 (−96.0–[−5.6])	.10
Pao_2 during these episodes, mm Hg[b]	257 (54–543)	230 (82–540)	.55
Duration of these episodes, mins[b]	14.1 (1.6–56.6)	10.6 (1.4–57.0)	.23

[a]Wilcoxon's signed-rank test; [b]values were obtained by calculating the median of the individual medians, the maximum of the individual maxima, and the minimum of the individual minima. Compared were the medians for each animal and device using Wilcoxon's rank-sum tests. Values given are median (range). There were no significant differences between devices.

Table 3. Arterial blood pressure during the episodes of a falsely low pulse oximetry (Spo_2) reading in comparison with the values obtained immediately before those episodes

	During Episodes of Falsely Low Spo_2 Reading	5 Mins Before Beginning of Episodes of Falsely Low Spo_2 Reading	*p* Value
Systolic blood pressure, mm Hg	62.3 ± 21.4	67.6 ± 19.8	<.001[a]
Diastolic blood pressure, mm Hg	37.0 ± 15.8	40.1 ± 14.7	<.001[a]
Mean blood pressure, mm Hg	46.5 ± 17.1	50.6 ± 15.9	<.001[a]
Blood pressure amplitude, mm Hg	25.3 ± 9.2	27.4 ± 8.5	<.01[b]

p values refer to paired *t*-tests[a] and Wilcoxon's signed-rank tests.[b] Values are mean ± SD; $n = 58$ (four episodes were excluded from this analysis: two because they were clearly related to a catecholamine flush, one because it was related to an intravenous ketamine/xylazine bolus injection, and another one, which was during the first minute of the recording). Values were obtained by calculating the mean values of all episodes in each animal to calculate the mean values across animals.

modynamics were considered to be relatively stable. Low perfusion, the likely cause of signal loss in our animal model, previously has been identified as a clinically relevant problem: In a large clinical trial, pulse oximetry was not working at all in the operating room in 7.2% of the patients with severe systemic disorders, and 50% of failures were thought to be related to low perfusion (33). A system failure time as high as 299 mins (32% of experimental time), as found in our study, is quite disturbing, because the sicker the patient, the more commonly hypoxemia may occur, and the more advantageous a functioning pulse oximetry device would be.

Experimental vasoconstriction caused by intra-arterial norepinephrine infusion has been shown to increase the blood pressure threshold at which failure of pulse oximetry occurs in healthy human adults (11). Our finding that signal dropout was more common toward the end of the experimental time (at least with the IVY 405T) may be related in part to vasoconstriction caused by increasing dopamine dose.

A very important finding is the unexpected observation of episodes of a falsely low Spo_2 reading occurring with both devices in at least 50% of all animals. Most of these episodes were detected because of different readings when comparing the two devices. The fact that a pulse oximeter can display a normal-looking plethysmography curve along with a heart rate matching the electrocardiogram heart rate, but a falsely low Spo_2, is quite disturbing for intensive care in general, because pulse oximetry is widely used to adjust the Fio_2, especially in neonatal intensive care (5–7). A falsely low Spo_2 reading may lead to inappropriate increases in Fio_2 or ventilator pressures, which may expose the subject to unnecessary hyperoxic injury or barotrauma. Our observations are in agreement with data obtained in healthy volunteers suggesting that experimental hypotension combined with vasoconstriction may result in underreading of the measured Spo_2 (11).

Recently, we observed a preterm infant with a sudden increase in Fio_2 requirement (guided by pulse oximetry), which finally was proven to be related to a falsely low Spo_2 reading (Spo_2, 91% with a Pao_2 of 285 mm Hg). Another term neonatal ICU patient with poor peripheral perfusion caused by congestive heart failure intermittently showed an arterial Po_2 of 310 mm Hg and 234 mm Hg along with Spo_2 measurements of 90% and 86%, respectively (unpublished observations). These observations, along with a case report of a false desaturation in an adult with hemorrhagic shock reported in the literature (1, 11), suggest that this finding indeed may occur in humans as well. Proposed mechanisms may be vasoconstriction and shock with essentially no blood flow but detectable pulsatility in arterioles resulting in gradual desaturation of the arterial blood within the skin (1, 11), or arteriolar dilation and opening of arteriovenous shunts resulting in pulsations being transmitted to the capillary level and/or resulting in pulsatile venous flow (21). Although blood pressure fluctuations within the range observed during episodes of falsely low Spo_2 readings often do not change Spo_2 readings in clinical practice, the timely relationship with episodes of falsely low Spo_2 readings suggests that changes in systemic vascular resistance during sepsis may play an important role in the pathogenesis of these episodes. The clinical significance of this finding is presently unclear, because it is unknown how often these episodes in a clinical setting would lead caretakers to inappropriately increase Fio_2 or ventilator pressures. Furthermore, it is unknown if these episodes occur in humans sufficiently often and long enough to cause interventions that result in excessive hyperoxemia and hyperoxic tissue injury, such as retinopathy of prematurity in neonates.

Sensor malpositioning causing an optical light shunt, also called "penumbra

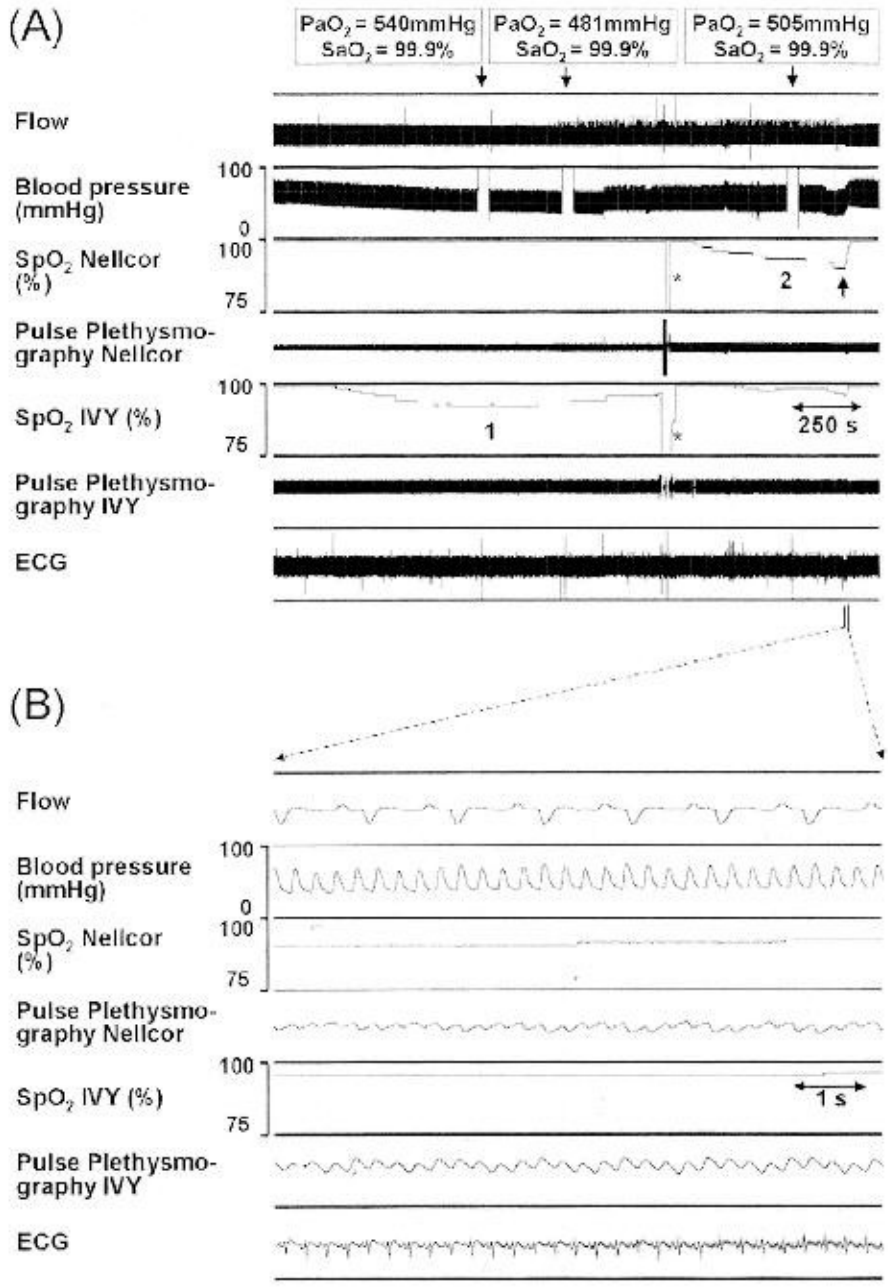

Figure 4. Two episodes of a falsely low reading of oxygen saturation measured by pulse oximetry (Spo_2) and their relationship to blood pressure changes. *A*, along with declining blood pressure, the reading of the IVY 405T drops to values as low as 93% for more than 18 mins (episode 1). There is some increase in the Spo_2 reading as blood pressure improves just before the scheduled change of sensor sites to the alternate foreleg (*). About one minute after the change of sensor sites, the Nellcor N-200 shows a decrease of the Spo_2 reading to values as low as 91% (episode 2) along with some minor decrease of the IVY 405T to 96%. Both devices return back to a 100% reading in close timely relationship with improvement of blood pressure (*upward-pointing arrow*). The pulse oximetry readings were proven to be incorrect by three carbon monoxide oximetry analyses of arterial blood. *B*, different scale: Despite a normal plethysmography curve matching the heart rate and suggesting a correct reading, both devices show readings below the measured arterial oxygen saturation (99.9%).

Given the potential for inappropriate interventions during episodes of falsely low Spo_2 values, we suggest that pulse oximeters recognize and warn for conditions of low perfusion.

effect" (34–36), and motion artifacts (1) have been shown to result in readings close to 85%. We can rule out these artifacts as a cause of the observed episodes of a falsely low Spo_2 reading, because the legs were not restrained, because meticulous care was taken to closely shave the sensor sites, because we used correct placement and shielding of the sensor probes, and because the anesthetized animals did not show any leg or body movements during the study. Venous congestion in neonates (37) and systolic venous pulsations secondary to congestive heart failure or to tricuspid valve regurgitation have been shown to cause Spo_2 desaturation (38–40). However, the continuously recorded central venous pressure waveforms did not show any increased venous pulsations during episodes of falsely low Spo_2 (data not presented). Methemoglobinemia as a cause of falsely low Spo_2 readings (41, 42) can be excluded, because CO oximetry revealed methemoglobin levels <2.3% in all blood samples.

We did not find significant differences regarding the characteristics of the episodes of falsely low Spo_2 values between devices. However, given the variability of some of these secondary outcome measures and the relatively small number of subjects, the power to detect small or moderately sized differences was limited.

We found increasing bias toward the end of the experimental time, which is in agreement with findings from other investigators who found an increased bias in adults during circulatory failure (20) or in infants with poor peripheral perfusion caused by cardiopulmonary bypass and/or hypothermia (17, 43). A study in adults with sepsis showed that Spo_2 was lower than Sao_2 in patients with a low systemic vascular resistance (21). The authors of the latter study (21) speculated that arteriolar dilation and opening of arteriovenous shunts may have resulted in pulsations being transmitted to the capillary level and/or in pulsatile venous flow. Our bias/error data are limited by the fact that an $Fio_2 = 1.0$ was used throughout the study resulting in an Spo_2 close to 100% for most of the experimental time. Therefore, the pulse oxime-

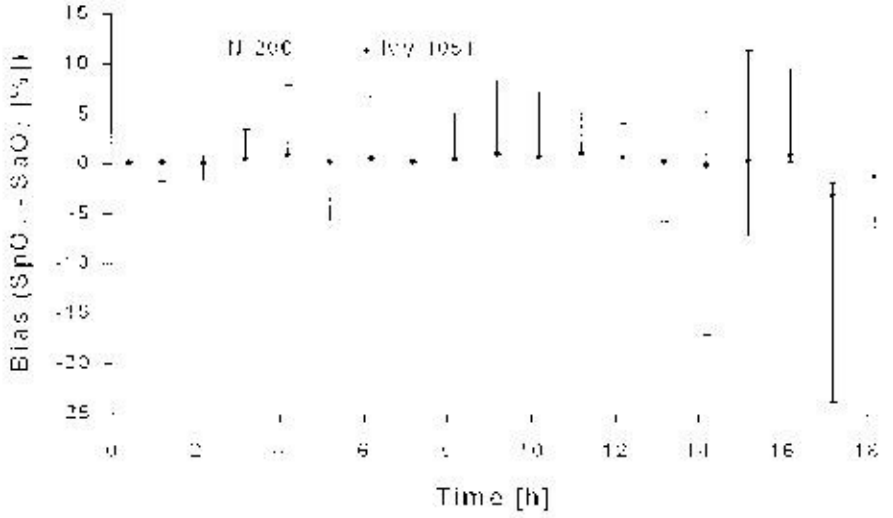

Figure 5. Bias (oxygen saturation measured by pulse oximetry [Spo_2] − arterial oxygen saturation [Sao_2]) across the experimental time is shown as median (range). Whereas median bias was very small across the experimental time, variability increased earlier with the Nellcor N-200 and later with both devices.

ter was working mainly on the flat part of the oxygen-hemoglobin dissociation curve, resulting in little changes of Spo_2 and Sao_2 with changing Pao_2, limiting errors caused by potential overreading the true Sao_2. Therefore, one could speculate that variability of bias values may be even larger if the devices were tested at a lower Spo_2 range.

Severe anemia (hematocrit < 10%) has been shown to cause increased bias and decreased precision (44). The hematocrit of our animals decreased over time but remained above 30% in most and above 18% in all animals at all times. Hematocrits in that range do not affect bias to a clinically significant degree (44). Other investigators have studied the effects of hemorrhagic hypotension on the performance of an earlier available pulse oximeter in rabbits and showed that, as long as the pulse oximeter picked up a signal, Spo_2 values correlated well with Sao_2 values as measured by CO oximetry (16). Currently available pulse oximeters may perform better during low perfusion; that is, they pick up a signal when earlier available devices would have failed already. However, as our study results have shown, the price for this increase in sensitivity may be decreased accuracy.

A limitation of our study could be the fact that the data are derived from animals. However, *in vitro* measurements of absorption characteristics of hemoglobin measured at the wavelengths of interest showed no differences between rabbit and human hemoglobin (45). Therefore, current pulse oximetry technique should not result in systematic errors when used in rabbits, and, in fact, standard pulse oximeters are used widely in veterinary medicine and animal research (46, 47).

Another limitation of our study may be the use of a reusable sensor for the Nellcor N-200. We cannot rule out that application pressure was suboptimal for any one of the sensor types. However, both sensors were applied by using a commercially available, opaque bandage, as it would have been used in clinical practice.

CONCLUSIONS

We have shown that a new pulse oximetry technique is less likely to fail because of signal dropout compared with a standard pulse oximeter in this animal model of emerging pneumonia and sepsis. Furthermore, our data suggest that episodes of falsely low Spo_2 reading may occur with both devices tested, which may result in a significant underestimation of the true arterial oxygen saturation and may lead to inappropriate increases in Fio_2 or ventilator pressures in a clinical setting. Arterial blood gas analyses may be warranted if there is any doubt regarding a given pulse oximetry reading, especially if it implies an increased Fio_2 requirement, or if it coincides with hemodynamic deterioration. Bias may be increased with deteriorating hemodynamics with both devices. Given the potential for inappropriate interventions during episodes of falsely low Spo_2 values, we suggest that pulse oximeters recognize and warn for conditions of low perfusion.

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