Veronika Rafl-Huttova*, Vit Hlavac, Jakub Rafl and Martin Rozanek

Dependence of SpO₂ signal noise on the pulse oximeter averaging time

Abstract: A model of the pulse oximeter, which consists of a transfer function between arterial and peripheral blood oxygen saturation (SpO₂) and the noise typical for SpO₂ records, is an important part of a mathematical model of oxygenation in neonates that is designed to test and compare different algorithms of oxygen control. The noise level in the SpO₂ signal is affected by the averaging time setting of the pulse oximeter. This study aimed to characterize the noise level in the SpO₂ signal at the set pulse oximeter averaging times of 2–4, 8, and 16 seconds. We evaluated SpO₂ records of 17 healthy volunteers who underwent a laboratory experiment in which they evoked different types of artifacts. The noise level in the SpO₂ signal was characterized by two parameters, the deviation of SpO₂ from the true value and the SpO₂ time stability, defined as the interval during which the measured SpO₂ value remained unchanged. Statistical properties of the noise level for the three averaging times were represented by normalized histograms of both the parameters and varied according to the type of artifact. With motion artifacts, the SpO₂ readings deviated from the true value by more than $\pm 2\%$ SpO₂ in 10%, 7%, or 5% of the measurements when the set averaging time was 2–4 s, 8 s, or 16 s. The length of the interval over which the SpO₂ value remained unchanged was most frequently 2 seconds for all set averaging times. Implementation of the noise characteristics into the computer model of oxygenation in neonates will allow more faithful simulations of the output SpO₂ signal that better match clinical observations.

Keywords: Computer model, peripheral oxygen saturation, averaging time, noise model.

<https://doi.org/10.1515/cdbme-2021-2089>

1 Introduction

Previously, we presented a computer model of oxygenation in neonates that was designed to test and compare different algorithms of closed-loop automated systems for oxygen control [1]. The terminal section of the model is the pulse oximeter block, a module linking arterial (SaO₂) and peripheral blood oxygen saturation (SpO₂). In addition to the transfer function between SaO₂ and SpO₂, which captures the systematic bias of pulse oximetry, the pulse oximeter block should include the noise typical for the real SpO₂ records observed in clinical practice. The noise can be caused by many artifacts, e.g. motion artifact, low perfusion, anemia, or ambient light [2, 3]. Stability of the SpO₂ readings over time and associated noise level in the SpO₂ signal is affected by the setting of the pulse oximeter, specifically the sensitivity mode and averaging time defined as the length of time over which the system calculates the average of all data points [4].

The longer averaging time causes more stable SpO₂ readings and reduces the measured variations of SpO₂ resulting in fewer false alarms due to the artifacts [3, 4]. On the other hand, longer averaging delays the response of the pulse oximeter and it may smooth changes in oxyhemoglobin saturation, which can directly impact the diagnosis and treatment of patients [3]. McClure et al. [5] reported that about half of the low or high SpO₂ events detected with the 2-second averaging would be missed with the 16-second averaging. Petterson et al. [3] even claimed that the transient desaturations during sleep apnea detected with the 2-second averaging were almost completely lost with the 16-second averaging. Other studies [6, 7] also stated decreased ability of pulse oximeters to detect rapidly occurring hypoxemias with longer averaging times. Rheineck-Leyssius and Kalkman [8] found a reduction in alarms of almost 50% when comparing the averaging time of 10 seconds with 3 seconds. Vagedes et al. [9] described the desaturation rates using a formula for conversion between different averaging times. While the above studies focused on the success of detecting true desaturation episodes at different set averaging times, for complex evaluation of automated systems for oxygen control, we require the computer model to

***Corresponding author: Veronika Rafl-Huttova:** Department of Biomedical Technology, Faculty of Biomedical Engineering, Czech Technical University in Prague, nam. Sitna 3105, Kladno, Czech Republic, e-mail: veronika.huttova@fbmi.cvut.cz

Vit Hlavac, Jakub Rafl, Martin Rozanek: Department of Biomedical Technology, Faculty of Biomedical Engineering, Czech Technical University in Prague, Kladno, Czech Republic

Figure 1: SpO₂ waveforms for different averaging times in two series of measurements acquired from a single volunteer. The order of phases of simulated artifact and resting phases was identical for both series of measurements. Three averaging times were set in total; the averaging time of 8 seconds was set in both series. In one series, averaging times of 2–4 s and 8 s (1) were measured, and in the other series, averaging times of 8 s (2) and 16 s were measured.

simulate artifacts and the associated noise in the SpO₂ signal according to the specific set averaging time.

In this study we aimed to characterize how the noise level and artifacts in the SpO₂ signal depend on the set averaging times of the pulse oximeter.

2 Methods

We evaluated the dependence of SpO₂ signal noise on the pulse oximeter averaging time from continuous records of peripheral oxygen saturation obtained in laboratory experiments. A prospective interventional study on 17 healthy volunteers (21–28 years) was approved by the institutional review board of the Faculty of Biomedical Engineering, Czech Technical University in Prague. The clinical study was registered in the ClinicalTrials.gov database under the number NCT04933773.

During the laboratory experiments, SpO₂ was measured simultaneously with two identical pulse oximeters Root with the Radical-7 module (Masimo Corporation, Irvine, USA). The sensors were placed on the index finger and the middle finger of a volunteer's dominant hand in random order. The noise in the SpO₂ signal was recorded for three averaging time settings (2–4, 8, and 16 seconds) available on Masimo pulse oximeters. According to the manufacturer, the shortest set averaging time may range from 2 to 4 s, depending on the quality of the input signal [4]. For each volunteer, the measurements were organized in two series in which phases of simulated artifacts alternated with resting phases. Two series of measurements were necessary due to the requirement to compare the three most commonly used averaging times with the availability of only two identical pulse oximeters. In one

series, averaging times of 2–4 s and 8 s were set, and in the other series, averaging times of 8 s and 16 s were set. The order of the series for each volunteer was random. The period of stored pulse oximeter readings was 2 s and the sensitivity mode was set as normal.

Each series consisted of a simulation of four different artifacts: two motion artifacts, low perfusion artifact, and ambient light artifact. The motion artifacts—knocking the sensors into the soft pad and tremor of the wrist—were simulated by a volunteer. The low perfusion artifact was achieved by slightly squeezing the arm with an inflatable cuff and the ambient light artifact was simulated by opening the sensor. Each artifact was simulated for 60 seconds and individual artifacts were separated by a 60-second resting phase. An example of two series of measurements acquired from a single volunteer with measured SpO₂ values for all averaging times is shown in Figure 1.

The noise in the SpO₂ signal was characterized for each averaging time by two parameters: the deviation of SpO₂ from the true value and the SpO₂ time stability. The former parameter was calculated for all SpO₂ data points of the same averaging time record as the difference between the measured value and the true SpO₂ value that was determined for each volunteer separately as the median SpO₂ in the resting phases. For the signal analysis, the first 20 seconds were excluded from the SpO₂ signal of each phase to evaluate only the stable SpO₂ signal in resting phases and only the fully distorted SpO₂ signal in phases of simulated artifacts. The SpO₂ time stability was evaluated by calculating the length of intervals in which the measured SpO₂ value remained unchanged. Data for the averaging time of 8 seconds were pooled and evaluated together from both series. Data were processed in MATLAB R2021a (MathWorks, Natick, USA).

3 Results

Three normalized histograms in Figure 2 show the deviations of the SpO₂ signal with motion artifacts from the true value for set averaging times of 2–4, 8, and 16 seconds. The histograms were constructed by pooling the data from the motion artifact phases of all volunteers. As the averaging time increased, the interval containing 95% of all measured deviations narrowed. Table 1 summarizes the percentage of the measured samples that were within the interval $\pm 2\%$ from the true SpO₂ value, which is the accuracy of SpO₂ measurement specified by the pulse oximeter manufacturer [4].

Figure 2: Deviations of the SpO₂ signal with motion artifacts from the true value. The blue color represents 95% of all deviations, the red color represents the remaining 5% of deviations. As the averaging time increases, the deviations are smaller.

Table 1: Percentage of measured SpO₂ deviations from the true value within the accuracy interval $\pm 2\%$.

Type of artifact	Averaging time		
	2–4 s	8 s	16 s
No artifact (rest)	99%	100%	100%
Motion artifacts (knocking + tremor)	90%	93%	95%
Low perfusion	89%	89%	95%
Ambient light	18%	21%	32%

Normalized cumulative histograms of the SpO₂ time stability presented in Figure 3 show how often the displayed SpO₂ value changed in phases of simulated artifacts of all volunteers. Similar normalized cumulative histograms are

Figure 3: SpO₂ time stability for all simulated artifacts together.

Figure 4: SpO₂ time stability for resting phases.

presented in Figure 4 for resting phases. The displayed SpO₂ value changed due to the measurement noise, a change of true SpO₂ value was not expected. A 2-second time interval between the consecutive changes in SpO₂ was the most frequent time interval for all phases and averaging times. However, the figures show that longer time intervals between the consecutive changes in SpO₂ were relatively more common with the longer set averaging time and they were also relatively more common in resting phases compared to the phases of simulated artifacts. This is also documented by the values of the 95th percentile of time stability. During the phases of simulated artifacts, 95% of the time intervals were shorter than 14, 26, and 36 seconds for the set averaging times of 2–4, 8, and 16 seconds, respectively. For the resting phases, these values were higher (24, 36, and 46 seconds for the set averaging times of 2–4, 8, and 16 seconds, respectively).

4 Discussion

In this study, we quantified how the noise in the SpO₂ signal depends on the set averaging time of the pulse oximeter. We used two parameters, the deviation of SpO₂ from the true value and the SpO₂ time stability.

Normalized histograms of the noise in the SpO₂ signal for three set averaging times of the pulse oximeter (2–4, 8, and 16 seconds) showed that the longest set averaging time increased the percentage of values within the range of $\pm 2\%$ from the true SpO₂ value. The short averaging time setting increased the frequency of SpO₂ deviations from the true value that were greater than $\pm 2\%$, but also increased the frequency of zero SpO₂ deviations from the true value. The rapid response of the pulse oximeter to the simulated noise at the shortest averaging time setting deflected the SpO₂ output signal out of $\pm 2\%$ of the true value, but also quickly returned it to the true value. Conversely, the slow response of the pulse oximeter at the long averaging time setting dampened the error in the SpO₂ output signal but also delayed the return of the signal to the true value. The lowest accuracy of the measured values was registered during the simulation of the artifact of ambient light; however, during the measurement, the pulse oximeter often warned of low signal quality, therefore such sections of the SpO₂ signal would not be trusted in clinical practice.

Normalized cumulative histograms of the SpO₂ time stability showed that the output SpO₂ value most often changed in the interval of 2 seconds, which is also the period of stored pulse oximeter readings. The 2-second interval represented 54% of all intervals during the phases of simulated artifacts with the shortest averaging time setting and, on the contrary, in the resting phases it represented only 23% of all intervals with the longest averaging time setting. When the averaging time increased and/or in resting phases, the frequency of longer time intervals between consecutive changes of SpO₂ raised.

The biggest limitation of this study with respect to the subsequent implementation of the results into a computer model of oxygenation in neonates is that the noise characteristics were measured on healthy adult volunteers with no desaturations. Another limitation was that two series of measurements were necessary for each volunteer to determine the noise for three averaging times and the simulated noise properties in the two series might not have been identical.

5 Conclusion

This study quantified the noise in the SpO₂ signal as a function of the set pulse oximeter averaging time. The characteristics of the deviations of the SpO₂ signal from the true SpO₂ value and the SpO₂ time stability will be used to improve the computer model of oxygenation in neonates. The results will allow simulations of peripheral oxygen saturation more similar to the SpO₂ signal observed in clinical practice.

Author Statement

Research funding: The work was supported by grants SGS20/202/OHK4/3T/17 and SGS19/202/OHK4/3T/17 of CTU in Prague. **Conflict of interest:** Authors state no conflict of interest. **Informed consent:** Informed consent has been obtained from all individuals included in this study. **Ethical approval:** The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board.

References

- [1] Huttova V, Rafl J, Möller K, Bachman TE, Kudrna P, Rozanek M, et al. Model of SpO₂ signal of the neonate. *Curr Dir Biomed Eng* 2019;5(1):549–552.
- [2] Jubran A. Pulse oximetry. *Crit Care* 2015;19(1):272.
- [3] Petterson MT, Begnoche VL, Graybeal JM. The effect of motion on pulse oximetry and its clinical significance. *Anesth Analg* 2007;105(6):S78–S84.
- [4] Radical-7 Operator's Manual. Masimo Corporation 2012.
- [5] McClure C, Jang SY, Fairchild K. Alarms, oxygen saturations, and SpO₂ averaging time in the NICU. *J Neonatal Perinatal Med* 2016;9(4):357–362.
- [6] Barker SJ. "Motion-Resistant" Pulse Oximetry: A Comparison of New and Old Models. *Anesth Analg* 2002;95(4):967–972.
- [7] Ahmed SJ, Rich W, Finer NN. The Effect of Averaging Time on Oximetry Values in the Premature Infant. *Pediatrics* 2010;125(1):e115–e121.
- [8] Rheineck-Leyssius AT, Kalkman CJ. Influence of pulse oximeter lower alarm limit on the incidence of hypoxaemia in the recovery room. *Br J Anaesth* 1997;79(4):460–464.
- [9] Vagedes J, Bialkowski A, Wiechers C, Poets CF, Dietz K, Myers J. A Conversion Formula for Comparing Pulse Oximeter Desaturation Rates Obtained with Different Averaging Times. *PLoS One* 2014;9(1):e87280.