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Model of SpO₂ signal of the neonate

Abstract: The advantages of automatic control of the fraction of inspired oxygen in neonates have been documented in recently published clinical trials. Many control algorithms are available, but their comparison is missing in the literature. A mathematical model of neonatal oxygen transport could be a useful tool to compare and enhance both automatic control algorithms and manual control of fraction of inspired oxygen. Besides other components, the model of neonatal oxygen transport must include a module linking arterial (SaO₂) and peripheral (SpO₂) oxygen saturation. The pulse oximeter module must reflect issues of SpO₂ measurement typical for clinical practice, such as overestimation of SpO₂ over SaO₂ documented by several studies, or inaccurate pulse oximeter readings due to high noise. The aim of this study was to describe both the bias between SaO₂ and SpO₂ and the noise, characteristic for continuous SpO₂ recording, for a computer model of oxygenation of a premature infant. The SpO₂–SaO₂ bias, derived from available clinical data, describes a typical deviation of the SpO₂ measurement as a function of the true SaO₂ value in three different SaO₂ intervals. The SpO₂ measurement noise was considered as a random process that affects biased SpO₂ values at each time point with statistical properties estimated from SpO₂ continuous recordings of 5 stable newborns. The results of the study will help to adjust a computer model of neonatal oxygenation to the real situations observed in the clinical practice.

Keywords: Measurement bias, neonatal model, noise model, oxygenation, pulse oximetry, SpO₂.

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1 Introduction

The advantages of automatic control of the fraction of inspired oxygen in neonates, especially in comparison with manual control, have been documented in recently published clinical trials [1, 2]. Many control algorithms are available, but the comparison of their efficiency is missing in the literature [2]. Due to safety and ethical risks of clinical tests on newborns, a mathematical model of neonatal oxygen transport could be a useful tool for testing of robustness and reliability of the automatic control algorithms, or for their preliminary comparison with manual control schemes of the fraction of inspired oxygen [3]. As both the automatic and manual control of oxygenation is primarily based on pulse oximetry measurement, a module linking arterial (SaO₂) and peripheral (SpO₂) oxygen saturation must be included in the model. Considering the inaccuracies in pulse oximetry measurements in children and neonates presented in the literature, the objective of this study is to establish the properties of the pulse oximeter module.

Many studies have shown that SpO₂ measurements systematically overestimate SaO₂ in children and neonates, especially at the lower values [4–6]. Ross et al. found the greatest SpO₂–SaO₂ bias in the SpO₂ range 81–85%, where the SpO₂ value was higher than SaO₂ value by an average of 6.6% [4]. In comparison, Bachman et al. published the SpO₂–SaO₂ bias amounting to 5% in the SpO₂ range 75–93%, based on an evaluation of 25,032 measurements from 1,007 critically ill neonates [6]. Both studies pointed out not only the SpO₂–SaO₂ bias, but also quite a large variability in the bias. Besides many other factors resulting in large variability in SpO₂ measurements, low perfusion or high noise arising from motion, bright lights, or electromagnetic interference can cause a low signal-to-noise ratio leading to inaccurate pulse oximeter readings [7, 8]. Even when SaO₂ remains practically unchanged, the SpO₂ values presented by the pulse oximeter changes in time and in case of abrupt motion of a neonate may even be falsely interpreted as rapid desaturations [8].

In this study we describe the bias between SaO₂ and SpO₂ typical for premature infants and the SpO₂ measurement noise, characteristic for continuous SpO₂ recording. The aim of the work was to prepare a credible model of the output of the pulse

oximeter for a computer simulation of oxygenation of a premature infant.

2 Methods

The mathematical model of the output signal of the pulse oximeter consists of two principal components: The SpO₂–SaO₂ bias that describes a typical deviation of the SpO₂ measurement as a function of the true SaO₂ value, and the SpO₂ measurement noise that affects biased SpO₂ values at each time point. All data were processed in Matlab (MathWorks, USA).

2.1 SpO₂–SaO₂ bias

The bias function was determined based on data from a clinical study by Ross et al. [4], a prospective multicentre observational study on 225 mechanically ventilated hypoxemic children aged between the 37th week of gestation and the 18 years, with SpO₂ ranging 65–97%. The subset of data for preterm and term infants less than 60 days after delivery were acquired from and processed with the authors' consent. For calculation of the SpO₂–SaO₂ bias, we used the selection that included SaO₂ measured by CO-oximetry—ABL800 (Radiometer Medical Aps, Denmark), Rapidlab 1265 (Siemens Healthcare, Germany) or Gem 3000 (Instrumentation Laboratory, USA)—from an arterial blood catheter. An SpO₂ value was recorded at the time when the blood sample was obtained. SpO₂ was measured by Masimo (Masimo Corporation, USA) and Nellcor (Covidien-Nellcor, USA) pulse oximeters depending on the Paediatric Intensive Care Unit.

The bias function was evaluated from 1,423 SpO₂–SaO₂ data pairs in three neighbouring SaO₂ intervals. For the SaO₂ range 70–96%, a median of measured SpO₂ values was calculated for each value of SaO₂ and a third-order polynomial was fitted through the medians. For SaO₂ below 70%, the SpO₂ bias was kept constant and equal to the SpO₂ bias at SaO₂ = 70% as determined by the third-order polynomial function, due to the lack of clinical data and non-guaranteed accuracy of pulse oximeters in this interval. For SaO₂ above 96%, the bias was set as zero, that is SpO₂ = SaO₂, due to the lack of clinical data for SpO₂ higher than 97%.

2.2 SpO₂ measurement noise

The model of the SpO₂ measurement noise was based on continuous neonatal SpO₂ records measured at the General

University Hospital in Prague. The data were collected based on a standard informed consent to hospitalization and to collection of anonymous observational data for research and educational purposes signed by a legal representative of a neonate. SpO₂ was measured by Masimo Rad-97 pulse oximeter (Masimo Corporation, USA). Data of 5 stable spontaneously breathing newborns without known pathologies acquired within the first day after delivery with a minimum recording time of 10 hours were processed. The sampling time of the SpO₂ records was 2 s with the averaging time set to 2 s.

In the available records, the most stable 50% of data points were isolated using a moving window algorithm: At each position of the window, the median of the measured SpO₂ values in the window was computed as well as the sum of absolute differences between the measured SpO₂ values and the median. The data points with the lowest 50% of sums of the absolute differences in the corresponding moving window were chosen for the noise evaluation. For each of the points, the difference between the median and the measured SpO₂ value at the point was considered as the noise level. An example of an SpO₂ signal record and the points selected for further calculations is shown in Figure 1. Statistical properties of the random noise were extracted from a histogram of the estimated noise that aggregates all chosen points from all patients. In addition, the statistical properties of the random noise in the two side intervals, SaO₂ ≤ 96% and SaO₂ ≥ 97%, were evaluated separately.

Figure 1: An SpO₂ record with a selection of the most stable 50% data points.

In order to determine the optimal length of the moving window, the algorithm described above was repeated for moving window lengths in the range of 2–60 minutes, with a 2-minute step. Normalized histograms of noise belonging to each length of the moving window were compared and the optimal window length, 20 minutes, was chosen, where the relative change was minimal in the zero noise level of SpO₂ between two consecutive histograms (Figure 2).

Figure 2: Relative change in the zero noise level between two consecutive histograms as a function of the moving window length.

3 Results

The SpO₂–SaO₂ bias function that is an estimate of a typical deviation of the SpO₂ measurement from the corresponding SaO₂ value is presented in Figure 3. The bias function consists of three distinctive parts:

For the SaO₂ range 0–70%:

$$SpO_2(\%) = SaO_2 + SpO_2^{SaO_2=70\%} = SaO_2 + 7.66 \quad (1)$$

For the SaO₂ range 70–96%:

$$SpO_2(\%) = -0.001 \cdot (SaO_2)^3 + 0.262 \cdot (SaO_2)^2 - 20.896 \cdot SaO_2 + 617.496 \quad (2)$$

For the SaO₂ range 96–100%:

$$SpO_2(\%) = SaO_2 \quad (3)$$

Table 1: Cumulative distribution function (CDF) of the SpO₂ measurement noise.

Deviation of SpO ₂ (%)	CDF (–) for all SaO ₂ values	CDF (–) for SaO ₂ ≤ 96%	CDF (–) for SaO ₂ ≥ 97%
-4	0.0019	0.0015	0.0022
-3	0.0076	0.0071	0.0079
-2	0.0338	0.0428	0.0293
-1	0.2257	0.2355	0.2212
0	0.8144	0.7773	0.8334
1	0.9864	0.9771	0.9912
2	0.9991	0.9978	0.9998
3	0.9999	0.9996	1
4	1	1	–

Figure 4 shows the normalized histograms of the SpO₂ measurement noise for all SaO₂ values and also for SaO₂ ≤ 96%

Figure 3: The SpO₂–SaO₂ bias function calculated from the data of Ross et al. [4].

and for SaO₂ ≥ 97%. The cumulative distribution function of the noise model is presented in Table 1.

Figure 4: Normalized histogram of the SpO₂ measurement noise.

4 Discussion

In this study, we quantified the bias between SaO₂ and SpO₂, typical for premature infants and neonates. In addition, the SpO₂ measurement noise characteristics of continuous SpO₂ recording were extracted from clinical data files.

Bias was determined based on the clinical data from the multicentre study provided by Ross et al. [4] in three different SaO₂ intervals separated by SaO₂ = 70% and 96% (Figure 3). In the main SaO₂ interval 70–96%, the SpO₂–SaO₂ bias was expressed as a third-order polynomial function. In this interval our results are in accordance with the results of Rosychuk et al. [5]. Bachman et al. [6] showed the SpO₂–SaO₂ bias with the similar trend as Ross [4], but with 1 to 2% higher bias values, probably due to different methods of measuring SaO₂ (CO-oximetry vs. blood gas analyser). In the side intervals SaO₂ < 70% or SaO₂ > 96%, the SpO₂–SaO₂ bias was kept constant due to the lack of clinical data in these intervals, because the study included only patients with SpO₂ 65–97%.

Moreover, for the model of neonatal oxygenation these side intervals are not critical as they are far beyond the SpO₂ target range used to minimize severe hypo- or hyperoxaemia in premature infants.

During the bedside monitoring, the SpO₂ value changes in time, even if SaO₂ is stable, due to low perfusion, motion artefacts, or another noise, such as bright light or electromagnetic interference [7–9]. We provided the characteristics of the noise by a histogram (Figure 4) and a cumulative distribution function (Table 1) from SpO₂ recordings, at least 10-hour long, of 5 stable newborns. The most stable 50% samples of signals were utilized, based on the findings of Fletcher et al. [10] that motion artefact can affect in overall up to 50% of SpO₂ recorded time. Distinct drops in the SpO₂ signal were excluded, as those could be caused either by strong motion artefact or by desaturation, which could have not been distinguished without motion capture. The motion artefacts leading to significant drops in the SpO₂ signal will be modelled separately in a future study with simultaneous recording of the SpO₂ signal and the motion capture.

This pulse oximeter model has some limitations. We estimated one general SpO₂–SaO₂ bias function based on the multicentre study on a relatively large number of SaO₂–SpO₂ pairs from various infants from different PICUs, but the biases among children may systematically vary depending on their diagnosis [4, 11], amount of fetal haemoglobin [4, 5, 11] or skin pigmentation [7, 8]. On the other hand, the SpO₂ measurement noise was only estimated from the stable newborn recordings without known pathologies. The main target group of the model—premature infants or newborns requiring ventilation support—may have less stable SpO₂ recordings that need to be investigated in a future study.

5 Conclusion

This study proposed methods for quantifying the bias between arterial and peripheral oxygen saturation that is typical for premature infants and the noise in peripheral oxygen saturation signal presented in SpO₂ recordings during bedside monitoring of a premature infant. These results may help to improve the model simulations of neonatal oxygenation compared to the real situations observed in clinical practice, and thereby enhance development of automatized controllers for neonatal ventilation.

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