2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Influence of Measurement Location on Reflectance Pulse Oximetry in Sleep Apnea Patients: Wrist vs. Upper Arm

Fabian Braun*[1], Guillaume Bonnier[1], Patrick Theurillat[1], Martin Proença[1], Yara-Maria Proust[1], Florent Baty[2], Maximilian Boesch[2], Simon Annaheim[3], Martin Brutsche[2], Damien Ferrario[1], Mathieu Lemay[1]

***Abstract*— Peripheral oxygen saturation (SpO_2) plays a key role in diagnosing sleep apnea. It is mainly measured via transmission pulse oximetry at the fingertip, an approach less suited for long-term monitoring over several nights.**

In this study we tested a more patient-friendly solution via a reflectance pulse oximetry device. Having previously observed issues with pulse oximetry at the wrist, we investigated in this study the influence of the location of our device (upper arm vs. wrist) to measure SpO_2. Accuracy was compared against state-of-the-art fingertip SpO_2 measurements during a full overnight polysomnography in nine patients with suspected sleep apnea.

The upper arm location clearly showed a lower root mean square error A_{RMS} = 1.8% than the wrist A_{RMS} = 2.5% and a lower rate of automatic data rejection (19% vs 25%). Irrespective of the measurement location the accuracies obtained comply with the ISO standard and the FDA guidance for pulse oximeters. In contrast to the wrist, the upper arm location seemed to be more resilient to deteriorating influences such as venous blood.

Reflectance pulse oximetry at the wrist remains challenging but the upper arm could provide remedy for more robust SpO_2 estimates to reliably screen for sleep apnea and other diseases.

***Clinical Relevance*— The performance of reflectance pulse oximetry measured at the upper arm during sleep is superior to measurements at the wrist which are perturbed by undesired large fluctuations suspected to be caused by venous blood. If confirmed, this could also apply to the optical measurement of other vital signs such as blood pressure.**

I. Introduction

Sleep-disordered breathing (SDB) has a high prevalence in the general population [1]. SDB is associated with arterial hypertension and contributes to the development of cerebral and cardiovascular comorbidities. The measurement of peripheral oxygen saturation (SpO_2) via pulse oximetry is crucial and internationally recommended for the detection and diagnosis of SDB [2]. Repetitive cessation of airflow due to SDB reduces oxygen supply and can lead to a reduced blood oxygen saturation. Fully noninvasive and relatively unobtrusive, the state-of-the-art SpO_2 sensors at the fingertip are well suited for many monitoring applications. However, for the long-term monitoring over several nights or in combination with an established nocturnal ventilation, fingertip SpO_2 sensors are too obtrusive. Since the severity of sleep apnea can vary between different nights [3] the long-term monitoring of SDB is crucial to provide correct diagnosis [4].

In view of less obtrusive SDB monitoring, we have developed a reflectance pulse oximeter (Figure 1) to be placed at various body locations such as the wrist, upper arm, or leg. It is embedded in a watch-like device which makes it less obtrusive than fingertip sensors and more suitable for long-term monitoring. Yet, reflectance pulse oximetry – as applied by our device – is more challenging than transmission pulse oximetry (used with fingertip sensors) for various reasons detailed in [5], [6]. In a recent study we investigated the performance of our device (Figure 1) at the wrist of 57 subjects undergoing a full overnight polysomnography (PSG) recording [7]. Even though the resulting performances complied with the ISO standard for pulse oximeters [11], we observed undesired large fluctuations in certain subjects which were hypothesized to stem from changes in venous blood contribution or insufficient sensor contact pressure which may adversely affect SpO_2 estimates.

The aim of this work was to investigate the influence of the measurement location on SpO_2 performance via reflectance pulse oximetry. To this end, we compared our device to simultaneous full overnight PSG recordings in nine patients with suspected sleep apnea.

Figure 1. *PulseWatch* device attached to the wrist. The device includes three PPG channels (green, red and infrared) as well as an accelerometer sensor.

II. Methods

A. PulseWatch: Proprietary Reflectance Pulse Oximeter

Figure 1 shows our in-house *PulseWatch* reflectance pulse oximetry device used in this study. It includes an accelerometer, and three photoplethysmography (PPG) channels with green (525 nm), red (660 nm), and infrared (850 nm) light. The recorded data were locally stored on the device and retrieved at a later stage for offline analysis.

*Corresponding author (e-mail: fbn@csem.ch).
[1]Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland.
[2]Cantonal Hospital St. Gallen, Lung Center, St. Gallen, Switzerland.
[3]Empa, Laboratory for Biomimetic Membranes and Textiles, St. Gallen, Switzerland.

B. Study Protocol and Population

This study was performed at the sleep lab of the Cantonal Hospital St. Gallen in St. Gallen, Switzerland. The study was approved by the local ethics committee (Ethikkommission Ostschweiz, EKOS 19/038, BASEC Nr. 2019-00450). Ten patients with suspected sleep apnea were enrolled in this pilot study and underwent a full overnight PSG according to AASM, including SpO_2 reference measurements via a fingertip sensor (Xpod 1430000, Nonin Inc., Plymouth, USA) and two-channel electrocardiogram (ECG). In parallel, each patient wore two *PulseWatch* devices, one at the wrist and the other at the upper arm. The three SpO_2 devices (*PulseWatch* at wrist and upper arm, reference at fingertip) were placed on the same arm.

C. Data Pre-Processing

In a first step, the PPG signals of both *PulseWatch* devices were individually aligned in time with the PSG signals by synchronizing the PPG-derived inter-beat intervals (IBI) with the ECG-derived IBIs using the algorithm described in [8]. This procedure allows to correct for temporal offset and drift with a precision of a few hundred milliseconds. For both measurement locations the resulting PPG signals were processed with MATLAB using the algorithm described in [9]. In summary, this algorithm estimates, every 5 seconds, the time-modulating (AC) and non-modulating (DC) components of light intensities for every PPG channel by averaging over a sliding window of 20 seconds. The heartbeats used for these estimations were detected from the green PPG channel, known to have the highest signal quality. The AC and DC components of the red and infrared PPG channels were then used to compute the ratio-of-ratios (ROS) as required for SpO_2 estimation [9], [10]. If the number of heartbeats detected was insufficient, the estimated SpO_2 was set as invalid.

D. SpO_2 Estimation and Signal Quality Estimation

The *PulseWatch*-based SpO_2 estimates (SpO_{2Est}) were computed from the ROS via a linear calibration function:

$$SpO_{2Est} = a \cdot ROS + b. \quad (1)$$

The coefficients a and b were obtained from a previous study on a single healthy subject who underwent a controlled 20-minute experiment of normoxemia and mild hypoxemia ($SpO_2 \geq 87\%$).

In addition, our algorithm provides a quality index (QI) which indicates the reliability of the SpO_2 estimates. Ranging from 0 (worst) to 1 (best), it assesses the physiological origin of the PPG pulses to evaluate the quality of the SpO_2 estimation (see [9] for details). Signals with a QI below the empirically-derived threshold of 0.75 were rejected. This threshold, estimated in a previous investigation [7], aims at the best compromise between low data rejection and high SpO_2 estimation accuracy.

E. SpO_2 Performance Evaluation

The SpO_2 estimations via reflectance pulse oximetry were evaluated using the amplitude of the root-mean-square error (A_{RMS}), the accuracy metric recommended by the ISO 80601-2-61:2017 standard [11]. It is defined as the root-mean-square difference between the estimated SpO_2 values (SpO_{2Est}) and the reference SpO_2 values (SpO_{2Ref}). The A_{RMS} requires to be below 4% according to the ISO standard for monitoring applications [11] and below 3.5% for reflectance type sensors according to the FDA guidance [12].

To study the reliability and robustness of our signal quality indicator (QI), two methods of data rejection were evaluated: a) Only data with invalid SpO_{2Ref} or insufficient heartbeats for SpO_{2Est} were rejected, b) Data with QI < 0.75 were rejected. The performance was evaluated for both methods of data rejection and for both measurement locations (upper arm and wrist) in terms of A_{RMS} and Bland-Altman analysis (SpO_{2Est} vs. SpO_{2Ref}). For each patient, the analysis was restricted to the time ranging from first time asleep until the last time asleep (including potential wake episodes in between).

III. RESULTS

Out of the ten patients enrolled in this pilot study, one had to be excluded from analysis due to missing *PulseWatch* data. The remaining nine patients (5 males/4 females) had the following characteristics, given as median (1^{st} – 3^{rd} quartile): age: 49 (33 – 50) years; BMI: 30 (30 – 32.5) kg/m^2; AHI (apnea-hypopnea index): 33.4 (20.8 – 42.0) events/h.

Table I provides a summary of the SpO_2 estimation performance for both measurement locations (upper arm and wrist) and the two data rejection methods. Figure 2 provides a Bland-Altman analysis of the corresponding agreement between estimate (SpO_{2Est}) and reference (SpO_{2Ref}). Figure 3 shows time plot examples of estimated and reference SpO_2 for two patients comparing SpO_2 estimation of reflectance pulse oximetry at the wrist or upper arm vs. reference measurements via transmission pulse oximetry at the fingertip.

TABLE I. PERFORMANCE OF SpO_2 ESTIMATION

Performance Metric	Data Rejection Method			
	a) Minimal†		*b) QI < 0.75*	
	Wrist	*Upper Arm*	*Wrist*	*Upper Arm*
SpO_2 A_{RMS} Error	5.2%	**2.3% ***	**2.5% ***	**1.8% ***
Error Bias	-0.5%	1.0%	0.5%	1.3%
Acceptance Rate	98%	100%	75%	81%
Data Duration	49.9 h	50.6 h	38.1 h	41.1h

*. Compliant with ISO standard [11] and FDA guidance for reflectance type sensors [12].

†. Rejected data with invalid SpO_{2Ref} or insufficient heartbeats for SpO_{2Est} (see Sections II.C / II.D).

IV. DISCUSSION

In this study we investigated the influence of the measurement location (upper arm vs. wrist) on reflectance pulse oximetry in ten patients with suspected sleep apnea during a full overnight PSG.

A. SpO_2 Performance of Reflectance Pulse Oximetry

For the nine patients included in the final analysis a total of 50 hours of data was analyzed. The overall SpO_2 estimation performance, without considering the data quality, showed an A_{RMS} of 5.2% at the wrist and 2.3% at the upper arm. The automatic rejection of low-quality data (QI < 0.75) excluded 25% and 19% of data for the wrist and the upper arm, respectively. This improved the performance for both locations with an A_{RMS} of 2.5% at the wrist and of 1.8% at the upper arm.

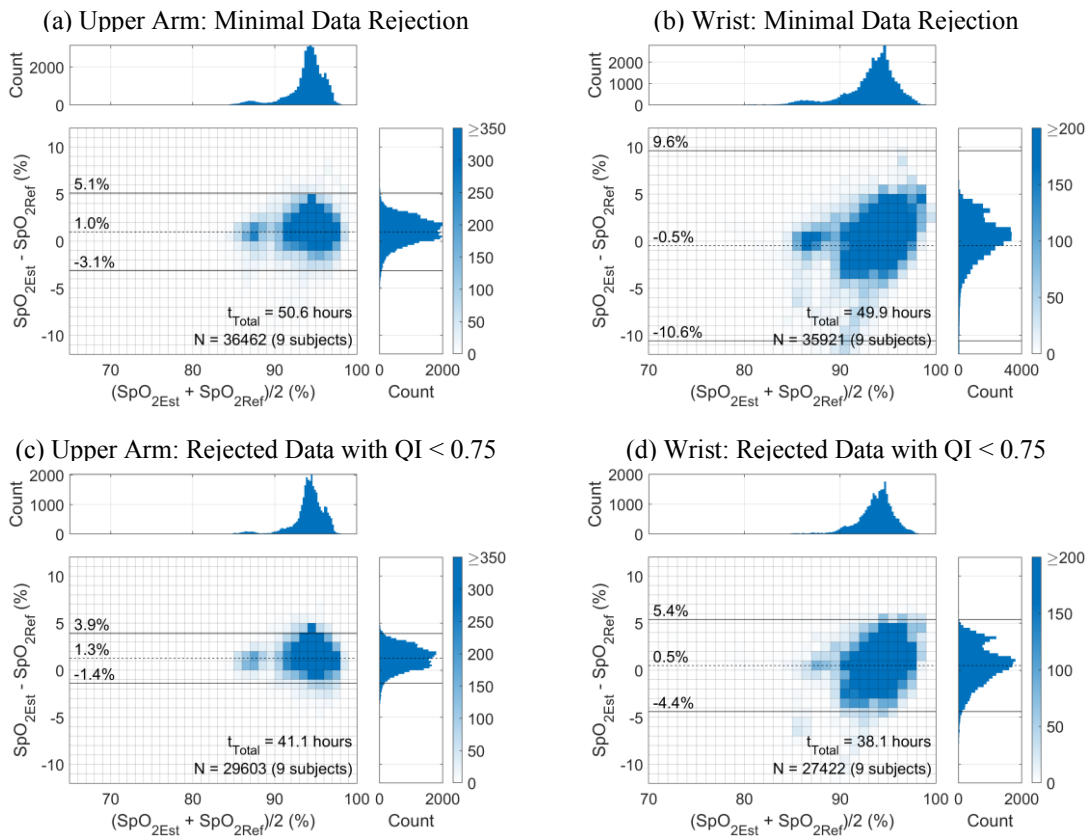

Figure 2. Bland-Altman analysis and corresponding histograms of the estimation error ($SpO_{2Est} - SpO_{2Ref}$) and average (($SpO_{2Est} + SpO_{2Ref}$)/2) for two measurement locations ((a) and (c): upper arm; (b) and (d): wrist) and two data rejection scenarios ((a) and (b): minimal data rejection, see Table I; (c) and (d): rejected data with QI < 0.75). The dashed and solid black lines show the bias and the 95% limits of agreement, respectively. N is the number of data points of SpO_2 estimates. To better highlight the density of data points, the Bland-Altman plots show color-coded rectangles with gray border and intensity proportional to the number of data points (white: low density vs dark blue: high density, see colorbar). To allow distinguishing less populated rectangles, the colorscale is saturated at a superior threshold which corresponds to 10% of the maximal possible counts in all rectangles.

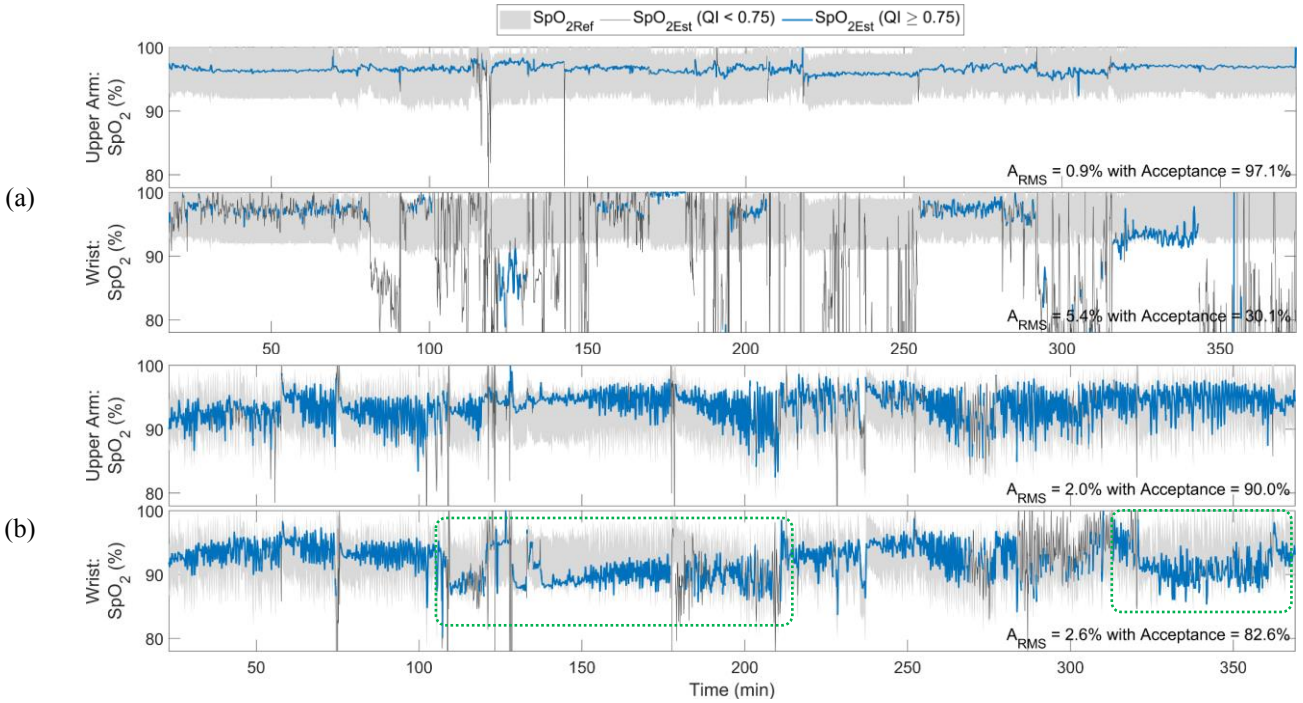

Figure 3. Examples of SpO_2 estimates for two measurement locations (wrist and upper arm). The light gray shaded areas illustrate reference SpO_{2Ref} values ± 4% of fingertip transmission pulse oximetry. The SpO_{2Est} values estimated via reflectance pulse oximetry are shown in black if the signals are considered of insufficient quality (QI < 0.75), and in blue if the signals are of sufficient quality (QI ≥ 0.75). The subplots correspond to two patients with (a) no SDB: AHI of 0.2 events/h, and (b) severe SDB: AHI of 94 events/h. The green dotted rectangles highlight areas with undesired large fluctuations of wrist-based SpO_{2Est} (see text in Discussion section).

While these results highlight the importance of the QI to provide robust SpO_2 estimates (particularly for the wrist-based signals), they also show that the signals acquired at the upper arm are of better quality and lead to more accurate estimations. In terms of compliance with the ISO standard [11] and FDA guidance [12], it is worth noting that at the upper arm SpO_2 estimations meet the necessary requirement ($A_{RMS} \leq 3.5\%$) even without rejection of low-quality data. The SpO_2 estimations from the wrist-based signals on the other hand, meet this requirement after the rejection of 25% of the data ($A_{RMS} = 2.5\%$) and still remain less accurate than the upper arm-based estimations without rejection of low-quality data ($A_{RMS} = 2.3\%$). This difference between both locations is confirmed by the Bland-Altman analysis in Figures 2c and 2d which reveal about two-fold larger 95% limits of agreement for the wrist than for the upper arm. On the other hand, the upper arm estimates show a relatively high error bias of 1.3% (against 0.5% at the wrist) which could be explained by a slightly inaccurate ROS-to-SpO_2 calibration function (based a single healthy subject). Even though this suboptimal calibration might induce other errors, the overall performance shows that, in the SpO_2 range covered by our study, these errors remain low.

B. Metrological Issues at the Wrist vs. Upper Arm

The green dotted rectangles in Figure 3 highlight undesired large fluctuations in wrist-based SpO_2 estimates, which appear to be of unphysiological origin. These rapid and large variations of SpO_{2Est} coincide with changes in the position of the pulse oximetry device, which corroborate similar observations made in our previous study [7] already revealing such issues at the wrist. In contrast, abrupt changes in SpO_{2Est} of this magnitude could not be observed in the upper arm-based estimates (see Figure 3 for two examples). As previously reported [7], we suspect the measurement at the wrist to be very susceptible to influences of venous blood pulsations which vary with the pressure applied by the device on the skin [6], [13]. This can also be influenced by a (partial) occlusion of the blood vessels in the arm which could result in a gradual increase in venous blood. Based on the present findings and the above explanations we conclude that reflectance pulse oximetry measured at the wrist is more prone to such deteriorating influences that when measured at the upper arm. This might also be the case for other PPG-derived vital signs (such as blood pressure) and requires further investigations.

Although the wrist might be a more appealing location for reflectance pulse oximetry measurements (e.g., smartwatch) it seems to be less suitable to obtain robust medical-grade estimates for SpO_2. This might also explain why there is currently hardly any wrist-based device on the market providing medical-grade SpO_2 (except for the Oxitone 1000M which uses a special setup measuring at the ulnar bone).

C. Limitations and Future Work

The relatively small sample size limits the generalizability of our study and warrants follow-up investigations. Further work should include larger cohort of SDB patients as well as investigating other respiratory disease entities. An improved calibration function (ROS-to-SpO_2) and an optimization of the sliding window size would reduce errors – such as the relatively high bias observed at the upper arm (Figure 2c) – and allow for a better tracking of fast SpO_2 changes, respectively. A larger study with other reflectance pulse oximetry devices should be considered to generalize our findings without dependency on a single device.

V. Conclusion

We studied the performance of a reflectance pulse oximeter device for two measurement locations (upper arm and wrist) in nine patients with suspected sleep apnea. When compared with the gold-standard fingertip, our SpO_2 estimations are compliant with the ISO standard [11] and the FDA guidance [12]: $A_{RMS} = 2.5\%$ at wrist vs. $A_{RMS} = 1.8\%$ at upper arm. In contrast to the wrist, the upper arm SpO_2 seems to be less sensitive to deteriorating influences such as venous blood. In conclusion, when properly processed and combined with other vital signs, reliable upper arm-based SpO_2 could allow for an unobtrusive solution for long-term monitoring of sleep apnea, as well as other diseases involving respiratory symptoms.

References

[1] R. Heinzer *et al.*, "Prevalence of sleep-disordered breathing in the general population: the HypnoLaus study," *The Lancet Respiratory Medicine*, vol. 3, no. 4, pp. 310–318, Apr. 2015, doi: 10.1016/S2213-2600(15)00043-0.

[2] V. K. Kapur *et al.*, "Clinical Practice Guideline for Diagnostic Testing for Adult Obstructive Sleep Apnea: An American Academy of Sleep Medicine Clinical Practice Guideline," *JCSM*, vol. 13, no. 03, pp. 479–504, Mar. 2017, doi: 10.5664/jcsm.6506.

[3] I. Fietze, M. Glos, S. Zimmermann, and T. Penzel, "Long-term variability of the apnea-hypopnea index in a patient with mild to moderate obstructive sleep apnea," *Journal of Clinical Sleep Medicine*, vol. 16, no. 2, pp. 319–323, Feb. 2020, doi: 10.5664/jcsm.8192.

[4] L. R. A. Bittencourt *et al.*, "The variability of the apnoea-hypopnoea index," *J Sleep Res*, vol. 10, no. 3, pp. 245–251, Sep. 2001, doi: 10.1046/j.1365-2869.2001.00255.x.

[5] M. Lemay *et al.*, "Applications of Optical Cardiovascular Monitoring," in *Wearable Sensors*, 2nd ed., E. Sazonov, Ed. Elsevier, 2020, pp. 487–517.

[6] A. Reisner, P. A. Shaltis, D. McCombie, and H. H. Asada, "Utility of the Photoplethysmogram in Circulatory Monitoring," *Anesthesiology*, vol. 108, no. 5, pp. 950–958, May 2008, doi: 10.1097/ALN.0b013e31816c89e1.

[7] F. Braun *et al.*, "Pulse Oximetry at the Wrist During Sleep: Performance, Challenges and Perspectives," in *EMBC 2020*, Montréal, Canada, Jul. 2020, pp. 5115–5118, doi: 10.1109/EMBC44109.2020.9176081.

[8] M. Lemay *et al.*, "Wrist:Located Optical Device for Atrial Fibrillation Screening: a Clinical Study on Twenty Patients," presented at the 2016 Computing in Cardiology Conference, Sep. 2016, doi: 10.22489/CinC.2016.200-350.

[9] M. Proença *et al.*, "Performance Assessment of a Dedicated Reflectance Pulse Oximeter in a Neonatal Intensive Care Unit," in *EMBC 2018*, Jul. 2018, pp. 1502–1505, doi: 10.1109/EMBC.2018.8512504.

[10] J. Moyle, *Pulse Oximetry*. Oxford: Blackwell Pub., 2002.

[11] ISO 80601-2-61:2017, *Medical Electrical Equipment - Part 2-61: Particular Requirements for Basic Safety and Essential Performance of Pulse Oximeter Equipment*. Geneva, Switzerland: International Organization for Standardization (ISO), 2017.

[12] *Pulse Oximeters - Premarket Notification Submissions [510(k)s]: Guidance for Industry and Food and Drug Administration Staff*. Silver Spring, USA: U.S. Department of Health and Human Services, Food and Drug Administration, 2013.

[13] K. H. Shelley, D. Tamai, D. Jablonka, M. Gesquiere, R. G. Stout, and D. G. Silverman, "The Effect of Venous Pulsation on the Forehead Pulse Oximeter Wave Form as a Possible Source of Error in Spo2 Calculation:," *Anesthesia & Analgesia*, vol. 100, no. 3, pp. 743–747, Mar. 2005, doi: 10.1213/01.ANE.0000145063.01043.4B.