



BIOPHYSICAL PRINCIPLES OF PULSE OXIMETRY IN NURSING PRACTICE AND FACTORS AFFECTING MEASUREMENT ACCURACY

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Abstract

This article analyses the optical and physiological principles of pulse oximetry, factors affecting measurement reliability, and their relevance to nursing practice. A literature-informed educational model combines biophysical explanation, practical training, and clinical interpretation. The proposed experimental and control groups comprise 60 and 56 learners, respectively. In a hypothetical example used solely to demonstrate calculations, the proportions meeting a practical criterion are 85.0% and 60.7%, a between-group difference of 24.3 percentage points. These figures are not actual research findings and do not establish effectiveness. The proposed approach requires evaluation using real data, with measurement skills assessed separately from device diagnostic accuracy.

Keywords: pulse oximetry, biophysics, nursing, SpO₂, photoplethysmography, measurement error, simulation-based education.

Introduction

Pulse oximetry is a monitoring method that enables the non-invasive assessment of haemoglobin oxygen saturation in arterial blood. The device displays



SpO₂ and pulse rate; nurses use these data for initial patient assessment, recording changes over time, and recognising deterioration promptly. However, the presence of a numerical reading does not mean that it is reliable under all conditions. The World Health Organization training manual links the use of the device to an understanding of its operating principles and an appropriate response to the clinical situation [1].

The United States Food and Drug Administration states that pulse oximeter readings may be affected by factors such as peripheral circulation, skin pigmentation, temperature, and nail coatings. Therefore, SpO₂ is interpreted alongside the patient's symptoms and observed signs rather than as an isolated number [2]. In nursing practice, the task extends beyond switching on the device to include assessing measurement conditions, checking signal reliability, and responding appropriately to a questionable result.

In a study by Hasanien and Albusoul involving 210 emergency and intensive care nurses, the mean pulse oximetry knowledge score was 12.33 out of 21 points, or 58.7% [3]. A study by Milutinović and colleagues involving 198 nurses identified gaps in understanding certain technical limitations and external factors [4]. These findings relate to the respective samples studied abroad and cannot be regarded as a direct indicator of the level of nursing preparation in Uzbekistan.

The aim of this article is to link the biophysical mechanisms of pulse oximetry to nursing activities, systematise the factors affecting measurement reliability, and propose an educational model for developing practical skills. A design involving groups of 60 and 56 learners and a hypothetical statistical example are presented for evaluating the model. The main research question is whether combining practice with an explanation of the underlying biophysical causes improves performance in following the practical procedure.



Biophysical Principles of Pulse Oximetry

A conventional dual-wavelength pulse oximeter contains red and near-infrared light sources and a photodetector. Commonly used wavelengths are approximately 660 and 940 nm. Because oxyhaemoglobin and deoxyhaemoglobin have different light absorption spectra, the optical signals recorded in the two channels provide information for estimating oxygen saturation. In a transmission sensor, light passes through the tissue to the detector; in sensors that detect reflected light, the source and detector are positioned on the same side [5, 11].

For a homogeneous medium containing a single absorbing substance, the ideal Bouguer–Lambert–Beer law expresses optical density as follows:

$$A_{\lambda} = \log_{10}\left(\frac{I_{0,\lambda}}{I_{\lambda}}\right) = \varepsilon_{\lambda} c L$$

Here, A_{λ} is optical density; $I_{0,\lambda}$ and I_{λ} are the incident and transmitted light intensities, respectively; ε_{λ} is the molar absorption coefficient at the specified wavelength; c is concentration; and L is the optical path length. Because biological tissue is highly scattering and contains several absorbing components, this ideal equation does not fully represent the clinical calculation algorithm of a pulse oximeter. Accounting for the light path through tissue and spectral differences requires empirical calibration in commercial devices [5].

The constant component of the photoplethysmographic signal, DC, represents the contribution of tissue and blood volume that changes little with the pulse, whereas the variable component, AC, represents pulsatile changes associated with the cardiac cycle. Calculating the AC/DC ratio compares pulsatile information with the constant optical background. For the two channels, the ratio of ratios, R , is obtained:

$$R = \frac{AC_{660} \cdot DC_{940}}{DC_{660} \cdot AC_{940}}; \quad SpO_2 = f_{cal}(R)$$



The calibration function represents the calibration relationship for the device–sensor system. Therefore, it is not appropriate to assume the same linear formula for all pulse oximeters. In teaching, the practical meaning of the equation is explained as follows: if the pulsatile signal weakens or is distorted by movement, the algorithm may be unable to reliably distinguish information associated with the arterial pulse. Viewing the signal on the screen, checking that it corresponds to the pulse, and waiting for it to stabilise follow from this characteristic of optical measurement [5, 8].

SpO₂ denotes saturation estimated from a peripheral optical signal, whereas SaO₂ denotes arterial saturation determined in an arterial blood sample using an appropriate laboratory method. Because functional and fractional saturation are not defined identically, comparisons between methods require clarification of the quantity reported by the laboratory. Conventional pulse oximetry does not directly measure carbon dioxide, haemoglobin concentration, or the total amount of oxygen delivered to tissues. The dual-wavelength method also has limitations in the presence of dyshemoglobins [1, 7, 11].

Factors Affecting Measurement Accuracy

It is useful to classify sources of measurement discrepancies into factors related to the device, the patient's physiological condition, and the operator's actions. This classification provides a systematic approach to identifying the cause of an error, although several factors may occur simultaneously in practice. For example, a cold hand, poor peripheral perfusion, and motion artefact may jointly reduce signal quality. Gehring and colleagues showed that the effects of motion and low perfusion differ across devices [8]. The recommendations in the table should be aligned with the manufacturer's instructions and local clinical procedures.

Table 1. Factors Associated with Measurement Reliability and Nursing Observation



Factor	Biophysical or Technical Mechanism	Focus of Nursing Checks
Movement and tremor	Optical changes unrelated to the pulse are superimposed on the useful signal.	Keep the hand in a comfortable position and assess pulse signal stability.
Low perfusion and cold skin	The pulsatile component decreases, reducing the signal-to-noise ratio.	Assess peripheral conditions; select an appropriate measurement site according to the instructions.
Incorrect sensor placement	Alignment of the source and detector or optical contact with the tissue is disrupted.	Check the sensor type, size, position, and secure attachment.
Strong ambient light	Additional background light may reach the detector.	Shield the sensor from light using the recommended method.
Nail coatings	Optical transmission may change; the effect depends on the colour and device.	If the signal is questionable, assess the coating and an alternative site according to the instructions.
Skin pigmentation	Systematic bias associated with optical properties and calibration may occur.	Recognise clinical discrepancies; do not apply a universal numerical correction.
Device and sensor condition	Battery charge, optical surfaces, compatibility, and cleaning or processing status affect the signal.	Check device readiness and sensor integrity before use.



The table summarises information from the literature and official recommendations [1, 2, 6–8, 11]. The issue associated with skin pigmentation differs from a simple operator error: correct sensor placement does not eliminate all systematic bias. Bickler and colleagues identified pigmentation-related bias in some devices at low saturation levels [6]. In a prospective investigation by Gudelunas and colleagues, the combination of low perfusion and darker pigmentation was associated with errors involving overestimation [7].

In retrospective clinical data, Sjoding and colleagues reported a higher frequency of hypoxaemia not detected by pulse oximetry in certain groups [9]. This observation cannot be converted into a fixed numerical correction for every patient: skin colour, the device, perfusion, and measurement conditions are interrelated. The FDA's 2025 document also focuses on evaluating device performance across different levels of pigmentation; this source is draft guidance, not a mandatory standard [10].

Materials and Methods

This article was developed on the basis of a targeted literature review and an educational research model. Sources were selected from studies on the physical principles of pulse oximetry, its clinical limitations, and nurses' knowledge; this process is not presented as a full systematic review or meta-analysis. The proposed design and hypothetical data illustrating the calculations are presented below. Because no actual participant list, measurement protocol, or individual assessment forms are available, no claim is made that an experiment was conducted.

The research model is a quasi-experimental design with two non-equivalent groups and baseline and final assessments. It envisages 60 learners in the experimental group and 56 in the control group, comprising a total of 116 nursing learners. These numbers were specified for the model and do not represent a sample



size derived from a statistical power calculation. Participants are assessed as learners acquiring pulse oximetry skills, not as patients.

In an actual study, inclusion criteria may comprise enrolment in a nursing programme, completion of the relevant biophysics topic, and voluntary consent. Previous clinical experience, stage of study, and baseline skill level should be recorded. If existing classes are used to form the groups, baseline differences and within-group similarities should be taken into account in the analysis. Non-attendance or the absence of a final assessment should be reported separately; a missing value must not be replaced by a successful outcome.

Three 80-minute sessions, with the same total duration for both groups, are proposed for the experimental model. In the experimental group, explanations of the optical mechanism, guided practical exercises, and scenario discussions are integrated. In the control group, the same topic is taught through conventional explanation, demonstration, and routine practice. Keeping the amount of content, instructional time, device type, and assessment tasks equivalent in both groups helps distinguish the effect of the teaching method from that of additional practice time.

The primary outcome is the proportion of learners meeting a predefined criterion in the final practical assessment. Assessment using an observation checklist comprising 10 actions is proposed. Each action is scored as follows: 0 points — not performed or performed incorrectly; 1 point — partially performed or requiring assistance; and 2 points — performed independently and correctly. The maximum score is 20 points. The passing criterion is a total of at least 16 points, with 2 points awarded for every critical action.

Table 2. Proposed Practical Assessment Checklist



Action Assessed	Score	Critical Action
Identify the patient and explain the procedure	0–2	No
Perform hand hygiene and appropriate sensor cleaning or processing	0–2	No
Check the readiness of the device and a compatible sensor	0–2	No
Assess perfusion, movement, and optical interference	0–2	No
Position the sensor according to the instructions	0–2	Yes
Check pulse signal reliability and stability	0–2	Yes
Interpret SpO ₂ together with clinical signs	0–2	Yes
Reassess the patient and measurement conditions if the result is questionable	0–2	No
Follow the procedure for calling for assistance when danger signs are present	0–2	Yes
Document the result, time, and measurement conditions	0–2	No

This checklist is an assessment instrument proposed by the authors; its validity and reliability are not considered established. Before use in an actual study, its content should be reviewed by biophysics and nursing specialists, a small pilot test should be conducted, and assessors should agree on the scoring criteria. Wherever possible, the final assessor should be unaware of the learner's group allocation. If there are two independent assessors, agreement should be examined using an appropriate statistical measure.



Baseline assessment may be scheduled before the training, final assessment within one week after the last session, and assessment of skill retention 4–6 weeks later. Additional outcomes may include a theoretical knowledge test, artefact recognition, and completeness of documentation. However, the hypothetical example below provides figures only for the primary practical criterion; no conclusions are drawn about unavailable additional outcomes or long-term effects.

Practical Content of the Educational Model

The first session addresses the relationship between oxygen saturation, light absorption, and the photoplethysmographic signal. The teacher explains the AC and DC components using a prepared optical diagram or demonstration signal. Rather than merely answering the question “What does a pulse oximeter measure?”, the learner explains why finger movement affects the signal. Instead of memorising a formula, learners are required to connect the physical concept to an action performed with the device.

In the second session, a standard workstation is set up, and learners practise sensor selection, device checks, and recording readings. Learners take turns acting as the operator, observer, and the person explaining the situation. After each performance, the observer provides specific feedback based on the items in the assessment checklist. Low perfusion and severe desaturation are demonstrated using prepared signal recordings or a simulator; inducing hypoxaemia in a participant for educational purposes is not envisaged.

The third session focuses on clinical interpretation. The scenarios include three types of task: recognising signal artefacts, identifying discrepancies between the reading and the patient’s condition, and clearly communicating the observation to another healthcare professional. For example, in a scenario depicting breathing difficulty despite a relatively high saturation reading on the screen, the learner must



not dismiss the risk solely on the basis of the number. The sequence for seeking assistance is adapted to the local clinical protocol.

Results and Their Hypothetical Statistical Analysis

The results below constitute a hypothetical example constructed to demonstrate statistical calculation methods. They are not observational data collected from 116 actual participants. In the model, the numbers meeting the criterion at baseline and final assessment are set at 22 and 51 in the experimental group and 20 and 34 in the control group, respectively. The remaining participants are modelled as not meeting the practical criterion at the corresponding assessment. There are no missing observations in the hypothetical calculation.

Table 3. Hypothetical Results for Meeting the Practical Criterion

Outcome	Experimental Group n = 60	Control Group n = 56
Met the criterion at baseline assessment	22 (36.7%)	20 (35.7%)
Did not meet the criterion at baseline assessment	38 (63.3%)	36 (64.3%)
Met the criterion at final assessment	51 (85.0%)	34 (60.7%)
Did not meet the criterion at final assessment	9 (15.0%)	22 (39.3%)
Change in proportion from baseline to final assessment	+48.3 percentage points	+25.0 percentage points

Note: all outcome figures in the table are hypothetical. Percentages are calculated relative to the full size of the respective group. A “percentage point”



denotes the arithmetic difference between two percentages; it is not the same as a relative percentage increase.

The proportions meeting the criterion at final assessment are $51/60 = 0.850$ in the experimental group and $34/56 = 0.607$ in the control group. Their absolute difference is 0.243, or 24.3 percentage points. Based on a simple independent binomial model and a normal approximation, the 95% confidence interval for the difference is calculated as 8.6 to 39.9 percentage points. This interval shows what the calculation would yield if the hypothetical figures represented actual independent observations; it must not be interpreted as a confidence interval for a real effect.

For the final 2×2 table, Pearson's chi-square test without Yates' correction yields $\chi^2 = 8.724$, with 1 degree of freedom and $p = 0.0031$. The expected cell frequencies are greater than 5. Verification using the two-sided Fisher's exact test yields $p = 0.0036$. These p-values are likewise only mathematical properties of the hypothetical table; they do not demonstrate that the educational model was effective in practice. Therefore, the article does not draw the empirical conclusion that "effectiveness was confirmed experimentally".

The arithmetic between-group difference in the changes in proportions from baseline to final assessment is $48.3 - 25.0 = 23.3$ percentage points. However, because paired results for individual participants at the two assessments are not provided, the standard error, confidence interval, or p-value for a paired comparison of the change cannot be calculated. Regression adjusted for baseline performance also requires individual-level data. Consequently, claiming that within-group improvement is statistically significant on the basis of aggregate proportions would be methodologically unjustified.



Discussion

The main value of the proposed model lies in linking biophysics content to observable actions performed by nurses. Teaching appropriate measurement procedures, signal quality assessment, and clinical interpretation together generates an educational hypothesis worth testing against teaching limited to isolated theoretical definitions. The hypothetical table explains which outcome measures can be used to evaluate this hypothesis, but it cannot serve as evidence confirming it.

Knowledge gaps reported in nursing studies conducted abroad support the need to improve educational content [3, 4]. However, performance on a knowledge test, performance at a practical assessment station, and safe decision-making for an actual patient are not fully interchangeable. A learner may answer a test question correctly yet omit a signal check in practice. It is therefore recommended that theoretical and practical assessments be planned together and subsequently supplemented by workplace observation.

A nurse's technical literacy may help identify operator-related errors, but it does not automatically eliminate a device's systematic limitations associated with pigmentation or low perfusion [6, 7, 9]. An apparently stable signal likewise does not guarantee complete agreement with a laboratory result. The educational model therefore distinguishes between an "apparently reliable signal" and a "clinically justified conclusion". Nurses need to know how to reassess a questionable situation and seek assistance within their scope of practice.

Improved practical skills must not be equated with improved diagnostic accuracy of the pulse oximeter. Evaluating diagnostic accuracy requires appropriately time-matched SpO₂ and arterial co-oximetry measurements, compatible definitions of saturation, and information about the device model and clinical setting. Such an evaluation uses approaches addressing systematic bias and



limits of agreement; simple correlation is insufficient. The present model measures the learner's performance skills, not the error in the patient's SpO₂ reading.

The model has clear limitations: the results are simulated, statistical power has not been justified, the assessment checklist has not been validated, and the groups have not been randomly allocated. Transfer of skills to clinical situations, long-term retention, and educational costs have not been evaluated. Differences between educational institutions and participants may also limit generalisability. These issues should be specified in advance in the protocol for a subsequent actual study.

Recommendations for Nursing Practice

When documenting pulse oximetry results, it is useful to record not only the SpO₂ value but also the measurement time, sensor site, signal quality, the patient's observed condition, and whether the patient is receiving oxygen. Changes in conditions should be considered when comparing repeated readings. Recording both the reason for an action and the action taken on the observation chart helps ensure clear communication during handover. This documentation format should be aligned with the institution's existing procedures.

When a reading is inconsistent with the clinical condition, patient assessment, signal and sensor checks, and notification of the responsible healthcare professional should be coordinated. In the presence of danger signs, repeatedly adjusting the device must not delay necessary clinical care. Oxygen therapy targets, authority to adjust therapy, and criteria for calling for assistance depend on the patient's condition and local protocol. During teaching, these rules are conveyed through approved procedures rather than personal assumptions [1, 2].

Conclusion

The reliability of pulse oximetry in nursing practice depends on the combined influence of optical signal formation, peripheral physiological conditions, device



characteristics, and the operator's actions. A three-session model and a 20-point assessment checklist integrating biophysical explanation, practical exercises, and clinical interpretation were proposed. In a hypothetical example involving an experimental group of 60 and a control group of 56 learners, the proportions meeting the criterion at final assessment were 85.0% and 60.7%, respectively. This is a hypothetical calculation. Scientific validation of the model requires real individual-level data, a validated assessment instrument, and an analysis that accounts for baseline differences.

Ethics and Data Transparency

No patient data were used for the hypothetical analysis, and no experiment involving human participants was reported as having been conducted. Before an actual study begins, appropriate ethical review, voluntary participant consent, and procedures for protecting personal data must be established. The final scientific publication should state the date and location of the work conducted, the approved protocol, and the actual results.

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