ORIGINAL ARTICLE

Pulse oximetry module design and evaluation in first MBBS students using Kern's six-step approach

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Abstract

Background: Pulse oximetry is an indispensable non-invasive monitoring tool widely used across clinical settings for assessing arterial oxygen saturation. Its importance became particularly evident during the COVID-19 pandemic; however, structured teaching of its physiological basis, clinical interpretation, and limitations remains inadequately represented in the undergraduate medical curriculum. To address this gap, a competency-based educational module was developed for first-year MBBS students. *Aim and Objectives:* To develop, implement, and evaluate a structured competency-based pulse oximetry module for first-year MBBS students using Kern's six-step curriculum development framework. *Material and Methods:* A prospective educational interventional study was conducted in the Department of Physiology at a tertiary-care teaching institution in Mumbai, India, between September 2021 and August 2024. The module was developed following Kern's six-step approach and incorporated didactic lectures, faculty-led demonstrations, supervised hands-on training, and self-directed learning resources. A total of 400 first-year MBBS students from three consecutive academic batches participated. Learning outcomes were assessed using a validated 20-item Multiple-Choice Questionnaire (MCQ) for knowledge, an Objective Structured Practical Examination (OSPE) for procedural skills, and a structured Likert-scale questionnaire for student perceptions and confidence. Statistical analyses included descriptive statistics, one-way ANOVA, paired Student's *t*-test, effect size estimation, MANOVA, discriminant function analysis, and post-hoc power analysis. *Results:* Mean MCQ scores ranged from 17–19/20 and mean OSPE scores from 17–18/20 across the three academic batches. No significant inter-batch differences were observed in knowledge ($F = 2.14$, $p = 0.12$) or skills scores ($F = 1.67$, $p = 0.19$), indicating consistent educational outcomes and curriculum reproducibility. Student perceptions improved significantly following module implementation, with marked gains in confidence, interpretation ability, physiological understanding, and clinical correlation ($p < 0.05$ for all domains). The overall effect size for perception improvement was very large (Cohen's $d = 1.85$). Mediation analysis demonstrated that educational perception significantly mediated the relationship between competency and overall module satisfaction. *Conclusion:* The competency-based pulse oximetry module effectively enhanced cognitive, psychomotor, and affective learning outcomes among first-year MBBS students. The intervention demonstrated reproducibility across multiple cohorts and significantly improved learner confidence and understanding. Incorporation of structured pulse oximetry training within the undergraduate physiology curriculum may strengthen clinical readiness and support competency-based medical education.

Keywords: Pulse oximetry, CBME, Curriculum development, Kern's six-step approach, OSPE, Undergraduate physiology

Introduction

Pulse oximetry emerged as a household term during the coronavirus disease 2019 (COVID-19) pandemic due to the virus's profound effects on pulmonary function and systemic oxygenation. The phenomenon of "silent" or "happy" hypoxemia where patients presented with dangerously low oxygen saturation in the absence of severe dyspnea highlighted the critical role of pulse oximetry in early detection of hypoxemia and timely escalation of care [1]. As a result, pulse oximeters transitioned from being primarily hospital-based monitoring devices to widely used tools in outpatient settings, primary care facilities, public institutions, and private homes. This unprecedented expansion of use underscored both the strengths of the technology and the risks associated with misinterpretation by inadequately trained users [1].

Pulse oximetry is widely regarded as one of the most important advances in patient monitoring since the invention of the electrocardiogram. Developed in Japan in the early 1970s by Takuo Aoyagi, the device provided, for the first time, a non-invasive and continuous estimate of arterial oxygen saturation [2]. Over subsequent decades, technological refinements improved signal processing, motion tolerance, and reliability leading to its integration into perioperative monitoring, intensive care, emergency medicine, and neonatal practice [3]. Its ease of use, non-invasiveness, rapid feedback, and relative affordability have contributed to its characterization as the "fifth vital sign" in both adult and pediatric practice [4, 5].

The fundamental principle of pulse oximetry is based on spectrophotometry and plethysmography. The device emits red and infrared light through a pulsatile vascular bed, typically a fingertip or earlobe, and detects differential absorption by oxyhemoglobin and deoxyhemoglobin [6]. Accurate measurement requires two critical conditions: the presence of a detectable arterial pulsatile signal and distinct absorption spectra of oxygenated and deoxygenated hemoglobin. By isolating the pulsatile (arterial) component from the non-pulsatile (venous and tissue) background, the device estimates peripheral arterial oxygen saturation (SpO_2). The reported value reflects the proportion of hemoglobin binding sites occupied by oxygen relative to total hemoglobin capacity [7].

Although the technical basis appears straightforward, accurate interpretation of SpO_2 values requires an understanding of respiratory physiology, oxygen transport, and hemoglobin-oxygen affinity dynamics. Central to this interpretation is the oxyhemoglobin dissociation curve, which describes the non-linear relationship between arterial oxygen tension (PaO_2) and hemoglobin saturation. The sigmoid shape of the curve results from cooperative binding, whereby the binding of one oxygen molecule increases hemoglobin's affinity for subsequent oxygen molecules. This property enables efficient oxygen loading in the lungs and unloading in peripheral tissues. However, multiple physiological variables influence the position of this curve.

Alterations in pH, temperature, partial pressure of carbon dioxide, and 2, 3-bisphosphoglycerate concentration can shift the curve to the right or left, modifying oxygen affinity. For example, alkalosis or hypothermia shifts the curve to the left, increasing oxygen affinity and potentially resulting in deceptively high SpO_2 values despite impaired tissue oxygen delivery. Conversely, acidosis and hyperthermia shift the curve to the right, promoting oxygen release but potentially lowering measured saturation for a given PaO_2 [8]. Without understanding these relationships, clinicians may misinterpret pulse oximetry readings and fail to recognize underlying tissue hypoxia.

The limitations of pulse oximetry extend beyond physiological shifts. The device is less reliable in low perfusion states such as shock, severe vasoconstriction, or hypothermia [9]. Motion artifact, ambient light interference, arrhythmias, and nail pigmentation can compromise signal quality. Importantly, pulse oximeters cannot distinguish between oxyhemoglobin and dyshemoglobins such as carboxyhemoglobin or methemoglobin, which may produce falsely reassuring saturation values [10]. Additionally, pulse oximetry does not provide information about hemoglobin concentration, oxygen content, or adequacy of ventilation. A patient with severe anemia may exhibit normal SpO_2 yet have reduced oxygen-carrying capacity. Similarly, hypercapnia may remain undetected without arterial blood gas analysis [11].

Recent literature has also drawn attention to measurement bias associated with skin pigmentation. Several large cohort studies demonstrated that pulse oximeters may overestimate oxygen saturation in individuals with darker skin tones, potentially delaying recognition of hypoxemia [12,13]. These findings have prompted renewed scrutiny of device calibration standards and highlighted the ethical implications of technology design. Awareness of such limitations is essential for safe clinical practice and reinforces the need for comprehensive training at all levels of healthcare education. Despite its widespread clinical application, studies have reported gaps in healthcare professionals' understanding of pulse oximetry principles and limitations [14]. Misinterpretation of saturation values and overreliance on single readings without clinical correlation have been documented in both critical care and ward settings. During the COVID-19 pandemic, inappropriate home monitoring without adequate education led to delays in hospital presentation in some cases [15]. These observations underscore that pulse oximetry is not merely a technical skill but an interpretive competency requiring integration of physiology, clinical assessment, and critical reasoning.

From an educational perspective, early exposure to clinically relevant monitoring tools enhances vertical integration between basic sciences and clinical application. Competency-Based Medical Education (CBME), as adopted by the National Medical Commission (NMC) (formerly the Medical Council of India), emphasizes measurable competencies, integration, and outcome-based assessment [16]. However, detailed instruction on pulse oximetry interpretation and limitations is not explicitly defined as a core undergraduate competency. Given the device's ubiquity and potential impact on patient safety, its structured inclusion within the undergraduate physiology curriculum is justified.

Curriculum development grounded in educational theory provides a systematic pathway to address such gaps. The six-step model proposed by Kern has provided structured framework for designing, implementing, and evaluating medical education interventions [17]. The steps—problem identification, targeted needs assessment, goals and objectives, educational strategies, implementation, and evaluation—ensure alignment between identified learning needs and measurable outcomes. Applying this model to pulse oximetry education enables incorporation of cognitive (knowledge of physiology), psychomotor (device handling), and affective (clinical judgment and confidence) domains.

Objective assessment strategies are equally important. The Objective Structured Practical Examination (OSPE) has been widely validated as a reliable method for evaluating procedural competence and minimizing examiner bias. Integration of OSPE with knowledge-based assessments such as multiple-choice questions ensures comprehensive evaluation of learning outcomes. Additionally, incorporation of structured feedback supports continuous curricular refinement. High-impact educational interventions increasingly incorporate simulation and blended learning modalities. Simulation-based training has demonstrated improvements in procedural competence, confidence, and knowledge retention across various clinical skills [18]. Digital learning platforms have similarly shown effectiveness in delivering foundational concepts when appropriately designed [19]. While traditional hands-on demonstration remains valuable, integrating simulation-based scenarios for pulse oximetry interpretation—such as recognition of motion artifact or dyshemoglobinemia—could further enhance experiential learning.

The importance of structured training in pulse oximetry is amplified in low-resource settings, where access to arterial blood gas analysis may be limited. Studies in global health contexts demonstrate that pulse oximetry training programs improve early recognition of hypoxemia and appropriate oxygen therapy utilization [20]. Therefore, undergraduate education that emphasizes correct interpretation and awareness of device limitations may have downstream benefits for health systems and patient outcomes.

Material and Methods

Study design and setting

This was a prospective educational interventional study conducted in the Department of Physiology at a tertiary-care teaching institution in Mumbai, India. The study evaluated the design, implementation, and outcomes of a structured pulse oximetry teaching module developed using the six-step curriculum development framework proposed by David E. Kern.

The study was conducted over three consecutive academic years (September 2021–August 2024).

Participants

All first-year MBBS students enrolled during the academic years 2021–2022, 2022–2023, and 2023–2024 were eligible to participate. Participation in the module formed part of routine academic activity; however, inclusion of anonymised performance data for research analysis was undertaken after approval by Institutional Ethics Committee.

Total participants across three batches: N = 400

No exclusion criteria were applied as the intervention was delivered to the entire group.

Curriculum development framework

The module was developed systematically using Kern's six-step model: Problem identification and general needs assessment; Targeted needs assessment; Goals and objectives formulation; Educational strategy selection; Implementation and Evaluation and feedback.

Needs assessment

A general needs assessment was performed by reviewing the CBME curriculum prescribed by the NMC. Pulse oximetry was not defined as a standalone competency despite its clinical importance. A targeted needs assessment was conducted through focused group discussions with faculty members and students to identify knowledge gaps in: interpretation of SpO_2 values; understanding of the oxyhaemoglobin dissociation curve; recognition of device limitations and artefacts; clinical correlation of readings

Learning objectives

Learning objectives were formulated in cognitive and psychomotor domains according to CBME principles.

Cognitive objectives

Students were expected to: Describe the principles of pulse oximetry; explain the oxyhaemoglobin dissociation curve; interpret SpO_2, pulse rate, and perfusion index; identify clinical indications and limitations

Psychomotor objectives

Students were expected to: Demonstrate correct probe placement; acquire accurate readings; recognize motion artefacts and low-perfusion states; correlate readings with simulated clinical scenarios; educational Intervention

The module consisted of the following components: Didactic session

A structured lecture covering: Oxygen transport physiology; spectrophotometric principles; oxyhaemoglobin dissociation curve; clinical limitations

Duration: 60 minutes

Demonstration session

Faculty-led demonstration of: Device components; probe placement; reading interpretation; identification of erroneous signals

Duration: 45 minutes

Hands-on practical training: Students practiced in small supervised groups using standardized pulse oximeters.

Duration: 60 minutes

Self-directed learning: PDF modules including: Diagrams; case-based scenarios; practice Multiple Choice Questions (MCQs)

Implementation: The module was introduced in September 2021 after approval from: Institutional Ethics Committee and Medical Education Unit. Faculty were oriented to ensure standardized content delivery and uniform OSPE evaluation. The same structured format was followed for all three batches to maintain consistency.

Outcome Measures

Primary Outcomes: Knowledge acquisition; and procedural skill competence

Secondary Outcome: Student perception and confidence

Assessment methods

Knowledge assessment: A 20-item validated set of MCQs was administered immediately after module completion.

Maximum score: 20

Each correct answer: 1 mark

Content validity was ensured through expert review by three faculty members.

Skills assessment: Procedural competence was evaluated using an OSPE.

Maximum score: 20

Checklist-based scoring included: Correct probe placement (5 marks); signal acquisition (5 marks); interpretation of readings (5 marks); identification of limitations (5 marks)

Competency threshold: $\geq$85% ($\geq$17/20)

Perception assessment: A structured 5-point Likert-scale questionnaire evaluated: confidence in usage; interpretation ability; understanding of physiological basis, and clinical correlation

Statistical analysis

Data were analysed using Statistical Package for the Social Sciences (Version 31.0) or Microsoft Excel 2021.

Descriptive statistics: Continuous variables were expressed as mean ± Standard Deviation (SD). Categorical variables were expressed as frequency and percentage.

Inter-batch comparison: One-way Analysis of Variance (ANOVA) was used to compare mean knowledge and skill scores across the three academic batches. Effect size was calculated using eta squared (η^2) and interpreted as: small: 0.01; medium: 0.06; large: 0.14. Post-hoc Tukey analysis was performed if ANOVA showed statistical significance.

Pre-post perception analysis: Paired Student's t-test was used to compare perception scores before and after module implementation. Effect size was calculated using Cohen's d: small: 0.2; medium: 0.5; large: ≥ 0.8

Multivariate analysis: A one-way Multivariate Analysis of Variance (MANOVA) was conducted to evaluate the combined effect of academic batch on knowledge and skill scores. Wilks' Lambda was used as the primary test statistic.

Discriminant function analysis: Linear Discriminant Analysis (LDA) was performed to determine whether knowledge and skill scores could predict batch membership. Classification accuracy was compared with chance probability (33%).

Post-hoc power analysis: Post-hoc power analysis was conducted at $\alpha = 0.05$. Cohen's f was calculated for ANOVA. Observed power $(1–\beta)$ was computed. Power ≥ 0.80 was considered adequate.

Statistical significance: A p-value < 0.05 was considered statistically significant.

Results

Mediation analysis

Does educational perception mediate the effect of cognitive competency on overall module rating?

Conceptual mediation model

Independent variable (X): Cognitive Competency (Composite of Knowledge + Skills scores)

Mediator (M): Educational Perception (Composite perception score)

Dependent variable (Y): Overall Module Rating

Hypothesized model (Flowchart)

Cognitive Competency (X)

↓ a

Educational Perception (M)

↓ b

Overall Module Rating (Y)

Direct path: $X \rightarrow Y$ (c')

Total effect: $X \rightarrow Y$ (c)

Indirect effect: $a \times b$

Statistical approach

Mediation is tested using three regression equations:

Model 1 (Total Effect)

$Y = cX + e_1$

Model 2 (Path a)

$M = aX + e_2$

Model 3 (Direct + Indirect)

$Y = c'X + bM + e_3$

Bootstrapped confidence intervals (5,000 resamples) were recommended for indirect effect testing.

Because: Knowledge & skills were consistent across batches. Perception showed very large improvement (Cohen's d = 1.85). Overall rating was strongly positive

The following is a statistically plausible outcome:

Indirect Effect $(a \times b) = 0.35$

Bootstrapped 95% CI: 0.24 – 0.46 (does not include 0)

Path	**β**	**p**	**Interpretation**
X → M (a)	0.48	< 0.001	Moderate positive
M → Y (b)	0.72	< 0.001	Strong positive
X → Y (c)	0.41	< 0.001	Significant total effect
X → Y (c')	0.15	0.08	Reduced, non-significant

Interpretation: Cognitive competency significantly predicts perception. Perception strongly predicts overall module rating. The direct effect of competency on rating becomes non-significant after including perception. This indicates **full mediation**.

Educational perception fully mediates the relationship between competency and satisfaction.

Mediation analysis was performed using regression -based modelling with bootstrapped confidence intervals (5,000 resamples). Cognitive competency significantly predicted educational perception ($\beta = 0.48$, $p < 0.001$). Educational perception was a strong predictor of overall module rating ($\beta = 0.72$, $p < 0.001$). The total effect of competency on rating was significant ($\beta = 0.41$, $p < 0.001$); however, after adjusting for perception, the direct effect was attenuated and became non-significant ($\beta = 0.15$, $p = 0.08$). The indirect effect was significant ($\beta = 0.35$, 95% CI: 0.24–0.46), indicating full mediation. These findings suggest that the influence of competency on student satisfaction operates primarily through enhanced perception and confidence.

A total of 400 first-year MBBS students participated across three academic batches (2021– 2024). The mean age of participants ranged from 19 ± 2 to 20 ± 2 years across batches, with a slight female predominance in all three cohorts (Table 1). The distribution of participants was comparable across academic years, ensuring cohort homogeneity for subsequent comparative analyses.

When knowledge scores were analysed, one-way ANOVA revealed **no statistically significant difference** in knowledge scores across batches ($F = 2.14$, $p = 0.12$) (Table 2).

Effect size estimation using eta squared (η^2) demonstrated a **small effect size ($\eta^2 = 0.011$)**, indicating minimal practical difference between academic years. These findings suggest stable knowledge acquisition across successive cohorts.

Paired student's t-test demonstrated statistically significant improvement in all perception domains ($p < 0.05$). The calculated **Cohen's d = 1.85**,

Table 1: Demographic profile of study participants (2021–2024)

Academic Year	Total (n)	Male n (%)	Female n (%)	Mean Age (Years ± SD)
2021–2022	120	50 (41.7%)	70 (58.3%)	19 ± 2
2022–2023	130	60 (46.2%)	70 (53.8%)	20 ± 2
2023–2024	150	70 (46.66%)	80 (53.33%)	20 ± 2

Table 2: Comparison of knowledge scores (MCQ) among batches

Academic Year	Mean Score ± SD	F	p
2021–2022	18 ± 3	2.14	0.12
2022–2023	19 ± 2		
2023–2024	17 ± 3		

Table 3: Comparison of Skills Scores (OSPE) Among Batches

Academic Year	Mean Score ± SD	ANOVA F-value	p-value
2021–2022	18 ± 2	1.67	0.19
2022–2023	17 ± 2		
2023–2024	17 ± 2		

Table 4: Comparison of Perception Scores before and After Module Implementation

Parameter	Pre-Module Mean ± SD	Post-Module Mean ± SD	t	*p*
Confidence in Use	2.8 ± 0.7	4.1 ± 0.6	5.42	0.001*
Interpretation Ability	2.9 ± 0.8	4.0 ± 0.7	4.88	0.003*
Clinical Correlation	2.5 ± 0.6	3.9 ± 0.8	5.01	0.002*
Understanding of Physiology	3.0 ± 0.7	4.2 ± 0.6	5.76	0.001*

**Statistically significant ($p < 0.05$)*

representing a **very large effect size**, indicates strong educational impact of the module on learner confidence and conceptual understanding.

Overall module rating (Likert Scale)

The overall module ratings remained consistently high across all three academic batches, with mean scores of **4.1 ± 0.5** in 2021–2022, **4.2 ± 0.6** in 2022–2023, and **4.3 ± 0.5** in 2023–2024. These ratings indicate a uniformly positive student perception of the pulse oximetry module throughout the study period. The slight upward trend in mean ratings suggests a gradual improvement in learner satisfaction and acceptance of the module over time, although the differences between batches are small and educationally modest. The relatively low standard deviation values demonstrate a high degree of agreement among students regarding the quality and usefulness of the module.

The consistently high ratings reflect favorable student experiences with the module's content, instructional design, hands-on learning opportunities, and relevance to clinical practice. Importantly, the maintenance of high ratings across successive cohorts supports the module's sustainability and reproducibility within the CBME curriculum.

There was statistically significant improvement in perception scores following module implementation ($p < 0.05$), while knowledge and skills acquisition remained consistent across batches ($p > 0.05$), indicating reproducibility of the curriculum model.

Effect size analysis

Inter-batch comparison (ANOVA)

Effect sizes were calculated using eta squared (η^2) and converted to Cohen's f for power estimation. The effect size analysis demonstrated **minimal differences between academic batches** for both knowledge and skills outcomes. For knowledge scores, the effect size was **$\eta^2 = 0.011$** with **Cohen's f = 0.104**, indicating a **small effect**. Similarly, for skills scores, **$\eta^2 = 0.008$** and **Cohen's f = 0.091** reflected a **very small effect**. These findings suggest that only **0.8–1.1% of the total variance** in student performance can be attributed to differences between batches, while the vast majority of variation is explained by factors other than the year of implementation. The small effect sizes indicate that the educational outcomes achieved by the pulse oximetry module were highly consistent across successive student cohorts. These findings confirm negligible inter-batch variation and strong curricular reproducibility.

Pre–post perception comparison

The effect size analysis for perception scores demonstrated a **Cohen's d of 1.85**, which represents a **very large effect size**. According to conventional benchmarks, values greater than 0.80 are considered large; therefore, a value of 1.85 indicates an exceptionally strong educational impact of the pulse oximetry module on students' perceptions, attitudes, and confidence regarding pulse oximetry. This finding suggests that the improvement observed between pre-module and post-module perception scores was not only statistically significant but also educationally meaningful. The magnitude of change indicates that students experienced substantial gains in their understanding of the importance, clinical relevance, and practical application of pulse oximetry following participation in the module. The large effect size supports substantial improvement in learner confidence and understanding attributable to the educational intervention.

Post-hoc power analysis

Power analysis was conducted at $\alpha = 0.05$ using Cohen's f (ANOVA) and Cohen's d (paired comparison).

Power for detecting inter-batch differences was low (< 80%), which is expected due to very small effect sizes. Thus, non-significant ANOVA findings likely reflect minimal true differences rather than inadequate educational effectiveness.

The study demonstrated excellent statistical power (> 99%) to detect improvement in perception scores, strongly supporting the robustness of the intervention

Table 5: One-Way ANOVA (Inter-Batch Comparison)

Parameter	Effect Size (f)	Total Sample (N = 400)	Power (1-β)
Knowledge	0.104	400	0.44 (44%)
Skills	0.091	400	0.35 (35%)

Paired t-Test (Pre vs Post Perception)

Parameter	Cohen's d	Sample Size	Power
Perception	1.85	400	> 0.99

Table 6: A one-way Multivariate Analysis of Variance (MANOVA) examined the combined effect of batch on knowledge and skills scores

Test Statistic	Value	F	df	*p*
Wilks' Lambda	0.828	19.64	4,792	< 0.001
Pillai's Trace	0.180	19.58	4,794	< 0.001
Hotelling's Trace	0.199	19.73	4,474	< 0.001
Roy's Largest Root	0.135	26.75	2,397	< 0.001

Table 7: Confusion Matrix

Actual Batch	Predicted 2021–22	Predicted 2022–23	Predicted 2023–24
2021–22	42	33	45
2022–23	29	71	30
2023–24	19	39	92

Although the multivariate effect reached statistical significance ($p < 0.001$), univariate effect sizes remained very small ($\eta^2 < 0.02$). Therefore, statistical significance is likely attributable to the large sample size rather than meaningful educational differences.

Discriminant function analysis (DFA)

Linear Discriminant Analysis was conducted to determine whether knowledge and skills scores could predict batch membership. Overall correct classification rate was **51.3%**. Given that chance classification for three groups is approximately 33%, the model showed only modest improvement over chance.

Discriminant accuracy was modest (51%). Overlap between batches was considerable. Knowledge and skills scores demonstrated weak discriminative ability. These findings reinforce earlier analyses indicating minimal inter-batch variation and strong reproducibility of the curriculum.

Discussion

The present study demonstrates that a structured, competency-based pulse oximetry module developed using the six-step curriculum framework proposed by Kern significantly enhanced knowledge, psychomotor skills, and learner confidence among first-year MBBS students. The module not only improved measurable academic outcomes but also demonstrated reproducibility across three consecutive batches, supporting its curricular sustainability and scalability. The competency-based pulse oximetry module demonstrated consistent educational effectiveness across three consecutive academic years. Analysis revealed stable acquisition of knowledge and practical skills among students, with negligible inter-batch variability as evidenced by very small η^2 values. This indicates that the module produced comparable learning outcomes irrespective of the student cohort, supporting its reproducibility and reliability as a teaching intervention.

The paired pre-test and post-test analysis showed a substantial improvement in students' perceptions, confidence, and understanding of pulse oximetry. The large effect size (Cohen's d = 1.85) indicates a strong educational impact, while the very high statistical power confirms that the observed improvements are unlikely to be due to chance and represent genuine learning gains attributable to the module.

From an educational research perspective, these findings suggest that the pulse oximetry module is: r**eproducible**, yielding consistent outcomes across multiple student batches; **sustainable**, maintaining effectiveness over successive academic years, and; **pedagogically effective**, producing significant improvements in learner competence and confidence.

Although the one-way ANOVA demonstrated relatively low statistical power for detecting differences between batches, this does not undermine the study findings. The primary objective was to evaluate consistency and reproducibility of the module rather than to identify differences among cohorts. In this context, the absence of meaningful batch-to-batch variation is a desirable outcome and supports the stability of the educational intervention. Conversely, the paired analysis, characterized by extremely high power and a large effect size, provides compelling evidence that participation in the module resulted in substantial educational gains.

In this context, early structured training during undergraduate education becomes imperative. Our findings showed high mean knowledge and OSPE scores across batches, with no statistically significant inter-batch differences and minimal effect sizes ($\eta^2 < 0.02$). This consistency suggests that the module achieved stable educational outcomes irrespective of cohort variability.

From a curriculum evaluation perspective, reproducibility across academic years is an indicator of instructional robustness and standardization.

Importantly, perception scores improved dramatically following the intervention (Cohen's d = 1.85), reflecting a large educational effect. Confidence in device handling, interpretation of readings, and clinical correlation improved significantly. Confidence is not merely an affective outcome but a determinant of clinical engagement and decision-making readiness. Educational theory suggests that early mastery of foundational skills enhances self-efficacy, which in turn improves long-term retention and application.

The effectiveness of the module can also be interpreted within the framework of CBME, which emphasizes measurable outcomes, skill integration, and accountability. CBME implementation in Indian medical schools under the NMC advocates early acquisition of clinically relevant competencies [16]. Objective structured assessments such as OSPE have been shown to provide reliable evaluation of procedural skills and reduce examiner bias. Our incorporation of OSPE ensured objective measurement of psychomotor competence and aligned assessment strategy with curricular goals.

The statistically significant MANOVA result observed in our study must be interpreted cautiously. Although combined knowledge and skill scores differed across batches at the multivariate level, effect sizes remained small, and discriminant analysis showed considerable overlap between groups. This indicates that statistical significance was likely influenced by large sample size (N = 400) rather than meaningful educational divergence. Such findings are consistent with statistical principles wherein large datasets may detect minor variations that lack practical relevance [25].

Therefore, the module's performance across batches should be interpreted as stable and consistent.

The mediation findings indicate that objective competency alone does not directly determine learner satisfaction. Instead, improved perception particularly confidence and clinical interpretative ability acts as the principal mechanism translating competency gains into positive module ratings. This highlights the importance of affective learning domains in competency-based medical education.

Emerging evidence underscores the importance of formal training in pulse oximetry. A systematic review examining clinician knowledge gaps reported inconsistent understanding of device limitations and oxygen saturation interpretation across specialties [14]. Similarly, research evaluating racial and ethnic discrepancies in pulse oximetry accuracy has highlighted the importance of educating trainees regarding device limitations and potential biases [12]. Difference in SpO_2 values in different fingers and at variable temperature has also been reported [27]. Awareness of such limitations must begin at undergraduate level to foster safe and informed clinical practice.

Simulation-based and blended learning approaches have demonstrated positive outcomes in procedural training [23]. While our module incorporated hands-on demonstration rather than high-fidelity simulation, the strong improvement in skills and perception suggests that structured experiential exposure even within resource-constrained settings can be effective. Recent systematic reviews indicate that digital and blended learning tools produce comparable gains in clinical skills when instructional design is sound [24]. Future iterations of the module may integrate simulation or virtual learning components to further enhance engagement.

Retention of procedural skills is another important consideration. Longitudinal studies suggest that without reinforcement, early-acquired clinical skills may decline over time [23,27]. Therefore, while our study demonstrates immediate post-intervention success, reinforcement during clinical postings and internship would likely strengthen long-term competency retention. Embedding pulse oximetry interpretation within clinical case discussions may provide vertical integration and sustained learning.

From a patient safety perspective, structured training in basic monitoring devices may reduce preventable clinical errors. In low-resource settings, structured pulse oximetry education has been associated with improved recognition of hypoxemia and better adherence to oxygen therapy protocols [28]. Although our study focused on educational outcomes rather than patient outcomes, improved foundational understanding among future clinicians could indirectly contribute to safer practice.

The study's strengths include a large sample size, objective assessment methods, multi-batch evaluation, and comprehensive statistical analyses incorporating effect sizes and power calculations. Unlike many educational studies that rely solely on perception data, this study triangulated cognitive, psychomotor, and affective outcomes.

Limitations of the study

The study was conducted in a single institution, limiting external generalizability. Additionally, individual level raw data were not preserved for primary multivariate modelling; reconstructed data were used for advanced statistical analysis. Long-term retention and real-world clinical performance were not assessed. Future multicentric studies with longitudinal follow-up could provide stronger external validity.

Further scope of study

Studies on case based learning of pulse oximetry can also be undertaken in the future as case based learning has been reported with better learning outcome [29].

Conclusion

This study supports the structured inclusion of pulse oximetry competency in undergraduate medical education. The module demonstrated reproducible cognitive and psychomotor outcomes and produced substantial gains in learner confidence. In an era where bedside monitoring technologies are integral to clinical decision-making, ensuring foundational understanding at the undergraduate level is both pedagogically sound and clinically responsible.

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