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Original Research Article

Role of Artificial Intelligence-Assisted Hemodynamic Monitoring in Predicting Intraoperative Hypotension during General Anesthesia

Vidushi Purohit[1], Prajapati Parthkumar Vasudevbhai[2], Kanabar Sonal Vijaybhai[3]

[1]**MD Anaesthesia, Department of Anaesthesia, Narendra Modi Medical College, Ahmedabad, Gujarat, India**

[2,3]**Thirs Year Resident Doctor, Department of Anaesthesia, Narendra Modi Medical College, Ahmedabad, Gujarat, India**

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Corresponding author: Dr. Kanabar Sonal Vijaybhai

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Abstract

Background: Intraoperative hypotension during general anesthesia is a modifiable risk factor that is linked to organ hypoperfusion and poor postoperative outcomes, but traditional monitoring methods may fail to detect hypotension until it has reached a critical level. This prospective randomized study aimed to assess the ability of artificial intelligence (AI) based hemodynamic monitoring to predict and mitigate intraoperative hypotension (IOH) in adults undergoing elective noncardiac surgery under general anesthesia.

Method: A total of 160 patients who needed radial arterial pressure monitoring were randomly assigned to the AI-assisted waveform monitoring group with an alert-driven treatment protocol (n=80) or the standard arterial pressure monitoring group (n=80). Intraoperative hypotension was defined as mean arterial pressure (MAP) <65 mmHg for at least 1 minute. Alerts were triggered by AI if the hypotension risk index was >=85. Predictive accuracy, incidence of hypotension, duration of hypotension, use of vasopressors, fluid therapy, lactate, urine output and early postoperative complications were documented.

Results: The incidence of intra-operative hypotension was 22 patients (27.5%) in the AI group and 39 patients (48.8%) in the standard group (p=0.006). Median hypotension duration was lower with AI monitoring (4.0 [IQR 0-8] vs 11.0 [IQR 3-22] min; p<0.001), and time-weighted average MAP <65 mmHg decreased from 0.24±0.31 to 0.08±0.16 mmHg (p=0.002). The sensitivity, specificity, PPV, NPV, and AUC of the AI alerts for predicting hypotension were 86.2%, 80.4%, 71.4%, 91.2%, and 0.89, respectively.

Conclusion: The mean warning time prior to hypotension was 6.7±2.8 minutes. AI-based hemodynamic monitoring had excellent predictive accuracy and minimized hypotensive exposure during general anesthesia.

Keywords: Artificial intelligence; hemodynamic monitoring; intraoperative hypotension; general anesthesia; machine learning; mean arterial pressure; Hypotension Prediction Index.

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Introduction

Intraoperative hypotension (IOH) is a common hemodynamic event during general anesthesia and is a critical issue in perioperative safety. There is systematic evidence that both the depth and duration of hypotension are linked to postoperative organ injury and mortality [1]. Observational studies have shown that lower intraoperative mean arterial pressure (MAP) is associated with adverse outcomes after noncardiac surgery [2]. In particular, the association of MAP below commonly used thresholds with acute kidney injury following elective noncardiac surgery has been reported [3].

Absolute MAP values around 65 mmHg and relative changes from baseline are both clinically significant, depending on the definition of IOH. Salmasi and colleagues found correlations between absolute and relative hypotension thresholds and myocardial and kidney injury [4]. Baseline patient risk, comorbidity and preoperative renal reserve also affect the risk of hypotension [5]. The Perioperative Quality Initiative has therefore focused on personalizing blood pressure management and minimizing exposure to low MAP during elective surgery [6].

Traditional blood pressure management during surgery is reactive, meaning that the surgeon intervenes when the MAP is below a threshold. AI and machine learning provide a chance to move from reactive to predictive care. Hatib et al. created a machine learning algorithm based on high fidelity arterial pressure waveform features to predict hypotension prior to its occurrence [7]. Further validation studies demonstrated that arterial waveform derived hypotension prediction indices can predict subsequent hypotensive events in surgical patients [8].

Clinical research has been conducted to assess the impact of prediction alerts on care. A machine-learning based early warning system with a treatment protocol was shown to decrease the severity and duration of hypotension in elective noncardiac surgery in the HYPE randomized clinical trial [9].

The Hypotension Prediction Index was also shown to be feasible in moderate- to high-risk noncardiac surgery [10]. Routine physiologic signals such as arterial pressure, electrocardiography and electroencephalography have also been used to predict hypotension in deep learning models, which demonstrated that multiple intraoperative biosignals can be used for advanced hypotension prediction [11,12].

Although these developments are promising, there are still uncertainties about the clinical utility of AI-driven hemodynamic monitoring in everyday general anesthesia. European multicentre registry data and randomized studies indicate lower exposure to hypotension, but concerns remain for alert fatigue, interpretation, selection bias, and whether prediction is associated with meaningful outcomes [13-16]. The value of smart alerts, goal-directed protocols and thresholds for action are still being refined in recent studies [17,18]. The aim of the present study was to assess the predictive accuracy and clinical utility of AI-aided hemodynamic monitoring in adult patients undergoing elective noncardiac surgery under general anesthesia.

Materials and Methods

This was a prospective randomized controlled study carried out in a tertiary care hospital operating room complex for nine months. Invasive radial arterial pressure monitoring was planned in adult patients (18-75 years) undergoing elective noncardiac surgery under general anesthesia, who were evaluated in the pre-anesthetic clinic. All participants gave informed consent.

The sample size was determined based on the anticipated rate of IOH as the main clinical endpoint. IOH was expected in about 48% of the cases for standard monitoring, based on previous institutional audit data. A sample size of 72 patients per group was needed for an absolute difference of 20% with 80% power and alpha 0.05. The number of patients enrolled per group was 80, with 160 patients in total, allowing for data loss due to waveform artefact or surgical cancellation. Patients were included in the study if they had ASA physical status I-III, surgery anticipated to be longer than 90 minutes, general anesthesia and endotracheal intubation, and need for invasive arterial pressure monitoring for surgical or patient reasons. Exclusion criteria were emergency surgery, atrial fibrillation or frequent arrhythmia that would interfere with the ability to analyze the arterial waveform, severe aortic stenosis, left ventricular ejection fraction <35%, mechanical circulatory support, pregnancy, sepsis, dialysis-dependent renal failure, and failure to obtain adequate arterial waveform quality.

Sealed opaque envelopes were used to randomly allocate patients to either AI-assisted hemodynamic monitoring or standard arterial pressure monitoring 1:1. Standard monitoring was performed on all patients, including electrocardiography, non-invasive blood pressure, pulse oximetry, capnography, temperature, neuromuscular monitoring, and invasive arterial pressure. The AI group had an AI-assisted hypotension risk algorithm continuously analyzing the arterial waveform data and showing a hypotension risk index ranging from 0-100. If >=85, a structured protocol was followed: assessment of preload responsiveness, anesthetic depth, heart rate, bleeding, vasodilation, and contractility; balanced crystalloid bolus, vasopressor, or decrease in anesthetic depth based on clinical assessment. The standard group had the AI turned off and clinicians treated hypotension as per their normal practice.

Standardization of general anesthesia was performed using fentanyl, propofol, vecuronium or rocuronium, and sevoflurane or desflurane to maintain BIS 40-60. IOH was defined as MAP <65 mmHg for at least one minute.

Incidence of IOH was the main clinical outcome. Secondary outcomes were total hypotension time, time-weighted average MAP <65 mmHg, number of hypotensive episodes, lowest MAP, vasopressor dose, fluid balance, urine output, lactate at the end of surgery, postoperative acute kidney injury within 48 hours, myocardial injury screening when clinically indicated, PACU stay, and hospital stay. In the AI group, the predictive performance of AI alerts was assessed by sensitivity, specificity, positive predictive value, negative predictive value, accuracy, and area under the receiver operating characteristic curve.

Data were analyzed using SPSS (version 26) and MedCalc. Continuous variables were expressed in terms of mean ± SD and compared using independent t-test. Median (IQR) was used for non-normal variables and compared using Mann-Whitney U test. Categorical variables were expressed as frequency and percentage and compared using chi-square or Fisher exact test. AI alert prediction for IOH within 10 minutes was used for ROC analysis. A p value of < 0.05 was deemed statistically significant.

Results

Of 179 screened patients, 160 were randomized and analyzed, with 80 in each group. Baseline demographic variables, ASA status, comorbidities, baseline MAP, type of surgery, duration of anesthesia, and estimated blood loss were comparable between groups. Mean age was 53.8±12.4 years in the AI group and 55.1±11.9 years in the standard group. Major abdominal procedures accounted for 45.0% and 47.5% of cases, respectively.

Table 1: Baseline and intraoperative characteristics

Variable	AI-assisted group (n=80)	Standard group (n=80)	p-value
Age (years)	53.8 ± 12.4	55.1 ± 11.9	0.50
Male sex, n (%)	43 (53.8)	45 (56.3)	0.75
BMI (kg/m²)	26.1 ± 4.2	25.8 ± 4.5	0.66
ASA I/II/III, n	10/46/24	8/48/24	0.83
Hypertension, n (%)	31 (38.8)	34 (42.5)	0.63
Baseline MAP (mmHg)	91.6 ± 10.8	92.4 ± 11.1	0.64
Duration of anesthesia (min)	168.5 ± 52.4	172.9 ± 55.1	0.60
Estimated blood loss (mL)	312 ± 186	329 ± 201	0.58

AI-assisted monitoring showed good predictive performance for IOH. Using an alert threshold of >=85, AI monitoring predicted hypotension within 10 minutes with sensitivity 86.2%, specificity 80.4%, positive predictive value 71.4%, negative predictive value 91.2%, and overall accuracy 82.5%.

The area under the ROC curve was 0.89 (95% CI 0.83-0.95). Mean warning time before MAP crossed <65 mmHg was 6.7±2.8 minutes.

Table 2: Predictive performance of AI alert threshold >=85 for IOH within 10 minutes

Metric	Value	95% CI/remarks
Sensitivity	86.2%	74.6-93.9
Specificity	80.4%	70.8-87.9
Positive predictive value	71.4%	60.0-81.0
Negative predictive value	91.2%	83.2-96.1
Overall accuracy	82.5%	75.7-88.0
Area under ROC curve	0.89	0.83-0.95
Mean warning time	6.7 ± 2.8 min	Before MAP <65 mmHg

The clinical burden of hypotension was significantly lower in the AI group. IOH occurred in 22 patients (27.5%) compared with 39 patients (48.8%) in the standard group (p=0.006). Median total hypotension duration was 4.0 minutes (IQR 0-8) versus 11.0 minutes (IQR 3-22; p<0.001). Time-weighted average MAP <65 mmHg was 0.08±0.16 mmHg in the AI group and 0.24±0.31 mmHg in the standard group (p=0.002).

The number of hypotensive episodes per patient was also lower (0.6±0.9 vs 1.4±1.6; p<0.001).

Table 3: Intraoperative hypotension and recovery-related outcomes

Outcome	AI-assisted group (n=80)	Standard group (n=80)	p-value
Patients with IOH, n (%)	22 (27.5)	39 (48.8)	0.006
Total IOH duration (min), median (IQR)	4.0 (0-8)	11.0 (3-22)	<0.001
TWA MAP <65 mmHg (mmHg)	0.08 ± 0.16	0.24 ± 0.31	0.002
Hypotensive episodes/patient	0.6 ± 0.9	1.4 ± 1.6	<0.001
Lowest MAP (mmHg)	60.8 ± 5.1	56.4 ± 6.7	<0.001
Crystalloid volume (mL)	1420 ± 460	1485 ± 510	0.40
End-of-surgery lactate (mmol/L)	1.5 ± 0.5	1.8 ± 0.7	0.006
Urine output (mL/kg/h)	0.74 ± 0.31	0.61 ± 0.29	0.018
Postoperative AKI, n (%)	2 (2.5)	6 (7.5)	0.15

The AI group received more anticipatory interventions before hypotension but did not require greater total fluid administration. Phenylephrine boluses were administered earlier and at lower cumulative doses, while norepinephrine infusion was used in similar proportions. End-of-surgery lactate was lower in the AI group (1.5±0.5 vs 1.8±0.7 mmol/L;

p=0.006), and urine output was higher (0.74±0.31 vs 0.61±0.29 mL/kg/h; p=0.018). Postoperative AKI occurred in 2 patients (2.5%) in the AI group and 6 patients (7.5%) in the standard group, but this difference was not statistically significant (p=0.15).

Discussion

In the present study, AI-assisted hemodynamic monitoring was shown to be highly sensitive, had a high negative predictive value, and provided clinically useful lead time prior to the onset of IOH (MAP < 65 mmHg). More importantly, when the AI alert was made visible to the clinicians and a structured treatment protocol was followed, the number, duration and severity of hypotensive exposure during general anesthesia was significantly reduced.

Our results confirm previous studies showing that arterial waveform-based machine learning can detect early changes in vascular tone, preload and contractility before the conventional MAP thresholds are exceeded [7,8]. The predictive performance reported in this study is similar to that of the large clinical trials and validation studies, but direct comparisons are not possible due to differences in prediction window, alert thresholds, population risk, and IOH definition. The decrease in the duration of hypotension is similar to what was reported in the HYPE trial, where an early warning system with treatment guidance decreased hypotension when compared to standard care [9,10].

Recent deep learning research has revealed that routine biosignals can be used to enhance hypotension prediction and that the morphology of the waveforms may hold clinically relevant information beyond just MAP [11,12]. But the utility of AI is not just about accuracy of the model, it's also about the path of the response. In our study, alerts were not associated with automatic vasopressor administration, but rather a hemodynamic assessment protocol. This is significant because hypotension can be caused by vasodilation, relative hypovolemia, impaired contractility, overdose of anesthetic, or bleeding, and each of these causes will require a different approach.

Registry and observational studies have shown decreased hypotensive exposure with HPI-guided management in noncardiac surgery [13,14]. However, more recent comparative studies have raised doubts about the clinical benefit of HPI compared with well-controlled MAP thresholds in all settings [15]. The results of the current study indicate that AI can best be used as an early warning and decision support system, not as a substitute for the judgment of the anesthesiologist. The high negative predictive value may assist clinicians to remain vigilant and not treat unnecessarily during low-risk periods.

The study also noted that the AI group had lower lactate levels and higher urine output, indicating better intraoperative perfusion. Postoperative AKI and length of stay were not significantly different, however. This study was not designed to have sufficient power to detect organ injury endpoints, and hypotension is just one of the factors contributing to renal and myocardial complications. Systematic evidence recently has emerged that AI and HPI methods have some predictive power, but that benefits for outcomes will need to be demonstrated in larger trials with standardized intervention protocols and with careful consideration of alert fatigue, over-treatment, and generalizability [16-18].

The limitations are single-center design, lack of blinding of the anesthesiologists, dependence on the quality of the arterial waveform, and exclusion of patients with arrhythmias or severe cardiac dysfunction. Many AI algorithms are proprietary, which can make them difficult to interpret. Moreover, the intervention consisted of both AI alerts and a treatment protocol, which prevented the effect of the algorithm from being separated from the effect of the treatment protocol. Further research is needed to assess the multicenter implementation, integration with electronic anesthesia records, cost-effectiveness, and effect on clinically relevant outcomes including AKI, myocardial injury, delirium, and mortality.

Conclusion

Arterial waveform analysis with AI predicted intraoperative hypotension several minutes before the MAP fell below the treatment threshold and significantly reduced the exposure to hypotension during general anesthesia. The technology seems to be most useful when combined with a clinician-led hemodynamic response protocol. More multi-center studies are required to validate organ injury and postoperative results.

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