Anaesth Crit Care Pain Med 45 (2026) 1–9

Contents lists available at ScienceDirect

Anaesthesia Critical Care & Pain Medicine

journal homepage: www.elsevier.com

Original Article

Impact of hypotension prediction index-guided management on intraoperative hypotension and postoperative outcomes in abdominal surgery: A meta-analysis of randomized controlled trials

Javier Ripollés-Melchor [a,b,c,*], Andrés Zorrilla-Vaca [c,d], Ángel V. Espinosa [c,e], César Aldecoa [c,f], Begoña Quintana-Villamandos [b,g], Alfredo Abad-Gurumeta [a,b], Juan V. Lorente [c,h], Manuel I. Monge-García [c,i]

[a] Universidad Complutense de Madrid, Spain
[b] Infanta Leonor University Hospital, Madrid, Spain
[c] Fluid Therapy and Hemodynamic Monitoring Group of the Spanish Society of Anesthesiology and Critical Care, Madrid, Spain
[d] Department of Anesthesia, Brigham and Women's Hospital, Boston, United States
[e] Froedtert Hospital Medical College of Wisconsin, Milwaukee, WI, United States
[f] Department of Anesthesia, Río Ortega University Hospital, Valladolid, Spain
[g] Department of Anesthesia, Gregorio Marañón University Hospital, Madrid, Spain
[h] Department of Anesthesia, Juan Ramón Jiménez University Hospital, Huelva, Spain
[i] Department of Critical Care, Puerto del Real Hospital, Cádiz, Spain

ARTICLE INFO

Article history:
Available online 30 October 2025

Keywords:
Fluid therapy/methods*
Hemodynamics/physiology
Postoperative complications/epidemiology
Fluid therapy/statistics & numerical data

ABSTRACT

Background: The Hypotension Prediction Index (HPI) is a machine-learning algorithm designed to predict hypotension. by maintaining mean arterial pressure (MAP) above 65 mmHg. This meta-analysis evaluated whether HPI-guided management improves postoperative outcomes and included post hoc analyses of intraoperative hypotension (IOH) metrics in adults undergoing major abdominal surgery.
Methods: A comprehensive search of PubMed, EMBASE, and Cochrane databases identified randomized controlled trials comparing HPI-guided management with standard care. Primary outcomes were postoperative complications, acute kidney injury (AKI), perioperative mortality, and hospital length of stay (LOS). Post hoc analyses assessed IOH metrics, including time-weighted average (TWA) of MAP $<$ 65 mmHg, area under the threshold (AUT), total time with MAP $<$ 65 mmHg, and intraoperative fluid use. Meta-analyses were conducted using random-effects models to calculate pooled standardized mean differences (SMDs), odds ratios (ORs), and mean differences (MDs).
Results: Eight trials involving 1534 patients were included. No significant differences were observed for AKI (OR: 0.85; 95% CI: 0.64–1.13), postoperative complications (OR: 1.10; 95% CI: 0.83–1.46), mortality (OR: 0.96; 95% CI: 0.32–2.83), LOS (SMD: −0.15; 95% CI: −0.73 to 0.42), or fluid use (SMD: −0.06; 95% CI: −0.35 to 0.24). HPI reduced TWA MAP $<$ 65 mmHg (SMD: −0.25; MD: −20.5 min), AUT (SMD: −0.83), and total time with MAP $<$ 65 mmHg (SMD: −0.74).
Conclusions: HPI-guided management did not significantly improve patient-centered outcomes. Post hoc analyses indicated a reduction in IOH metrics, but the clinical relevance of these findings remains uncertain given the lack of blinding and high risk of bias.
Registration: PROSPERO: CRD42023490654.

* Corresponding author.
E-mail address: javiripo@ucm.es (J. Ripollés-Melchor).

https://doi.org/10.1016/j.accpm.2025.101656

1. Introduction

Intraoperative hypotension (IOH) is a well-recognized risk factor for postoperative complications, including acute kidney injury (AKI), myocardial infarction, and increased mortality [1,2]. Maintaining an adequate mean arterial pressure (MAP) during surgery is critical for ensuring tissue perfusion and preventing organ dysfunction [3]. Despite advances in hemodynamic monitoring, IOH episodes remain frequent [2], and are often attributed to delayed recognition or the challenge of responding promptly to sudden physiological changes. Although observational studies consistently associate IOH with adverse outcomes, interventional trials targeting specific MAP thresholds have not consistently demonstrated improvements in patient-centered outcomes such as AKI or mortality. This discrepancy highlights the complexity of translating hemodynamic targets into clinical benefit and underscores the need for a mechanistically informed, data-driven approach to hypotension prevention.

The Hypotension Prediction Index (HPI) is a machine learning algorithm developed to predict IOH by real-time analysis of arterial pressure waveforms [4]. HPI-guided management aims to enable proactive interventions, such as fluid administration or vasopressor use, by identifying high-risk periods (HPI $>$ 85) up to 15 min before hypotensive events [5]. While early studies have shown that HPI reduces the duration and severity of IOH [6], its impact on clinically meaningful outcomes, such as AKI or mortality, remains unclear [7].

Existing evidence highlights that perioperative complications are multifactorial and influenced not only by MAP but also by factors such as fluid balance, vasopressors, and patient-specific comorbidities [1,8,9]. As such, achieving a MAP $>$ 65 mmHg may not fully mitigate the risks associated with IOH. Moreover, the added benefit of HPI compared to standard hemodynamic protocols, including goal-directed hemodynamic therapy (GDHT), is not established.

This meta-analysis was conducted to evaluate the effect of HPI-guided intraoperative management on patient-centered outcomes in adult patients undergoing major abdominal surgery. The primary outcomes of interest were 30-day mortality, postoperative complications, and hospital length of stay (LOS). In addition, we performed post hoc analyses to explore the impact of HPI on key intraoperative metrics of hypotension—specifically time-weighted average (TWA) MAP $<$ 65 mmHg, area under the threshold (AUT), and total duration of hypotension—as well as on intraoperative fluid administration. These additional outcomes were included to provide mechanistic insights into how HPI-guided strategies might influence postoperative recovery and to address concerns raised in recent trials and expert commentaries regarding the clinical relevance of intermediate perfusion targets.

2. Methods

This meta-analysis adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [10] and was registered in the PROSPERO database before initiation (CRD42023490654). Ethical approval was not required as all data were derived from previously published studies, as the study used previously published data and did not involve human or animal subjects.

2.1. Study selection

The research question was formulated using the PICO (Population, Intervention, Comparison, Outcome) framework as follows: In adult patients undergoing major abdominal surgery, does intraoperative hemodynamic management guided by the HPI, compared to standard intraoperative hemodynamic management, with or without GDHT influence IOH exposure and postoperative outcomes (AKI, postoperative complications, mortality, intraoperative fluid administration, and LOS). Trials were considered for inclusion if they compared intraoperative hemodynamic management guided by HPI to standard care, which may or may not include intraoperative GDHT.

2.2. Criteria for eligibility

Studies were included if they met the following criteria: randomized controlled trials (RCTs) published in peer-reviewed journals involving adult patients undergoing major abdominal surgery, compared HPI-guided management with standard care, and reported outcomes relevant to IOH or postoperative complications.

The exclusion criteria included non-randomized studies, observational designs, conference abstracts, studies not focusing specifically on abdominal surgery or with mixed patient populations without sufficient subgroup analysis, and studies lacking sufficient data to calculate effect sizes.

2.3. Search strategy

A comprehensive systematic search was conducted using PubMed and EMBASE databases. The search strategy combined synonyms and medical subject headings (MeSH) related to the Hypotension Prediction Index and intraoperative hypotension. The search was limited to RCTs published between 2018 and 2025, as the HPI algorithm was not available prior to 2018. No additional filters, such as language or study type, were applied to maximize the retrieval of pertinent data. Furthermore, the bibliographies of the included articles were manually reviewed to identify additional relevant studies that may have been missed during the initial search. The exact search terms were [hypotension prediction index (all fields) OR HPI (all fields) OR machine learning (all fields) OR artificial intelligence (all fields) OR management (all fields) OR prevention (all fields)] and intraoperative hypotension (all fields).

2.4. Article screening, data extraction, and risk of bias assessment

Two independent reviewers (JRM and AE) screened titles and abstracts for eligibility. Full-text articles were reviewed for studies that met the inclusion criteria, and disagreements were resolved by consensus or consulting a third reviewer (MIMG).

Two independent reviewers (JRM and AE) extracted the data using a standardized data collection form designed to capture study characteristics, patient demographics, intervention details, and outcomes of interest. Any discrepancies during data extraction were resolved through discussion or, when necessary, by consulting a third reviewer (AZV). Extracted variables included year of publication, study design, sample size, patient characteristics, intervention protocols, and control group management strategies.

The risk of bias in the individual studies was assessed using the Cochrane Risk of Bias 2 (RoB 2) tool (JRM and AE) [11]. This evaluation considered the following domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, completeness of outcome data, selective reporting, and other potential sources of bias. Each domain was rated as low risk, some concerns, or high risk. Risk of bias for intraoperative hypotension metrics (TWA MAP $<$ 65 mmHg, AUT, and time with MAP $<$ 65 mmHg) was assessed separately using the RoB 2.0 tool. (JRM and AE) This separate assessment was performed given the distinct suscepti-

bility of these outcomes to performance and detection bias compared to patient-centered outcomes. Disagreements in bias assessments were resolved by consensus to ensure consistency in the evaluation process. In addition to standard risk of bias assessment, we conducted a structured, descriptive evaluation of potential conflicts of interest (COI), inspired by the domains proposed in the TACIT tool (currently under development). (JRM and AE).

2.5. Outcomes

This meta-analysis focused primarily on patient-centered outcomes, as pre-specified in the registered protocol. The primary outcomes were perioperative mortality, the incidence of postoperative complications, and LOS, defined as the number of days from surgery to discharge. The incidence of AKI, defined according to KDIGO criteria [13], was considered a secondary outcome within this same framework. These outcomes were selected *a priori,* given their relevance to patient safety, recovery, and overall surgical risk.

In addition to these pre-specified endpoints, we conducted post hoc analyses to explore the effect of HPI-guided management on intraoperative physiological parameters and fluid therapy. Specifically, we examined three metrics of IOH: TWA MAP $<$ 65 mmHg, which accounts for both the duration and severity of hypotension during surgery. Hypotension was defined as a MAP of $<$65 mmHg sustained for at least 1 min. A hypotensive event was considered concluded when the MAP was $\geq$65 mm Hg for at least 1 min. TWA was calculated by dividing the AUT by the total duration of surgery: TWA = (depth of hypotension in millimeters of mercury below a MAP of 65 mmHg $\times$ time in minutes spent below a MAP of 65 mmHg) $\div$ total duration of operation in minutes [12]. Other metrics of IOH included the AUT for MAP $<$ 65 mmHg and the total time spent in hypotension, defined as the cumulative time with MAP $<$ 65 mmHg. As part of the same exploratory approach, we also assessed total intraoperative fluid administration.

2.6. Statistical analysis

A random-effects meta-analysis was conducted to account for variability across the included studies. Continuous outcomes were summarized as standardized mean differences (SMD) or mean differences (MD) with 95% confidence intervals (CI), calculated using the inverse variance method. For studies reporting medians and interquartile ranges, these values were converted to means and standard deviations (SD) using Shi *et al.*'s updated method [14]. This approach has been shown to provide improved accuracy for skewed data distributions and is recommended for meta-analyses requiring harmonization of summary statistics. All transformations applied are transparently reported in Supplementary Table S1.

Dichotomous outcomes were summarized as odds ratios (ORs) with 95% CIs, using the Mantel-Haenszel method. In cases of rare events, Peto's method was employed for greater accuracy.

The total intraoperative fluid volume was computed by summing the volumes of crystalloids and colloids administered intraoperatively. When reported separately, the combined SD was calculated using the following formula: $SD_{total} = \sqrt{\left(SD_{crystalloid}{}^2 + SD_{colloid}{}^2\right)}$

If either crystalloid or colloid data were missing, the study's definition of total volume was used.

Heterogeneity was assessed using Cochran's Q test and the I^2 statistic, with thresholds for interpretation as follows: low ($<$25%), moderate (25%–75%), and high ($>$75%). A random-effects model was used when substantial heterogeneity ($I^2 >$ 50%) was detected. Statistical significance was set at $p < 0.05$. For dichotomous outcomes, a prediction interval (PI) was calculated to estimate the range within which the true effect of a new study, conducted under similar conditions, is expected to lie. This approach provides additional insight into the variability of effects across studies and the potential reproducibility of the findings. The prediction interval was calculated using the random-effects model with the Hartung-Knapp-Sidik-Jonkman adjustment for variance. Prediction intervals were not calculated for continuous outcomes, as they were outside the scope of this analysis.

Sensitivity analyses were conducted to evaluate the robustness of the results. These analyses included excluding studies with a high risk of bias, based on the RoB 2 tool [11], to ensure that pooled estimates were not disproportionately influenced by lower-quality studies. Results were also compared using fixed-effect and random-effects models to evaluate the consistency of the pooled effect estimates under different assumptions about between-study variability. Leave-one-out analyses were performed by systematically excluding each study from the meta-analysis to assess the influence of individual studies and identify potential outliers. Finally, analyses were conducted by including only studies with clearly defined outcomes, such as AKI defined using KDIGO criteria [13], to ensure consistency in outcome definitions. Sensitivity analyses were specifically conducted for AKI, given its relevance as a patient-centered outcome and the potential heterogeneity in its definition and reporting across studies. AKI represents a clinically significant marker of perioperative organ damage, directly associated with postoperative complications and mortality [15]. Due to its clinical importance and variability in reporting, sensitivity analyses for AKI ensured that findings were robust and not disproportionately influenced by differences in study methodology.

Number needed to treat (NNT) was calculated for key clinical outcomes by taking the inverse of the absolute risk reduction (ARR) between control and HPI-guided groups (NNT = 1/ARR). This was performed as a post hoc analysis because no statistically significant differences were observed in the pooled effect estimates.

To assess potential publication bias, funnel plot asymmetry was analyzed for studies reporting the patient-centered primary outcomes. All statistical analyses were performed using Python for data handling and computation [16]. Meta-analyses were performed using Meta-Mar (version v4.02), an online meta-analysis platform [17], and R Statistical Software (v4.1.2; R Core Team 2021) utilizing the 'meta' package for conducting meta-analyses and 'forestplot' for visualizing the results [18].

3. Results

3.1. Characteristics of included studies

Eight RCTs [7,12,19–24] were included in the meta-analysis, comprising 1534 patients undergoing major abdominal surgery (Fig. 1). The characteristics of the included studies are summarized in Table 1. Risk of bias for patient-centered outcomes was generally low across trials (Fig. 2), whereas intraoperative outcomes such as IOH metrics consistently exhibited a high risk of bias due to the unblinded nature of interventions and susceptibility of outcome measurement to bias (Supplementary Fig. S1). A structured evaluation of potential conflicts of interest is presented in Supplementary Table 2.

3.2. Patient-centered outcomes

Four trials, including 1310 patients, analyzed the incidence of postoperative AKI [7,20,23,25]. HPI-based hemodynamic management was not associated with a decrease in postoperative AKI (RR

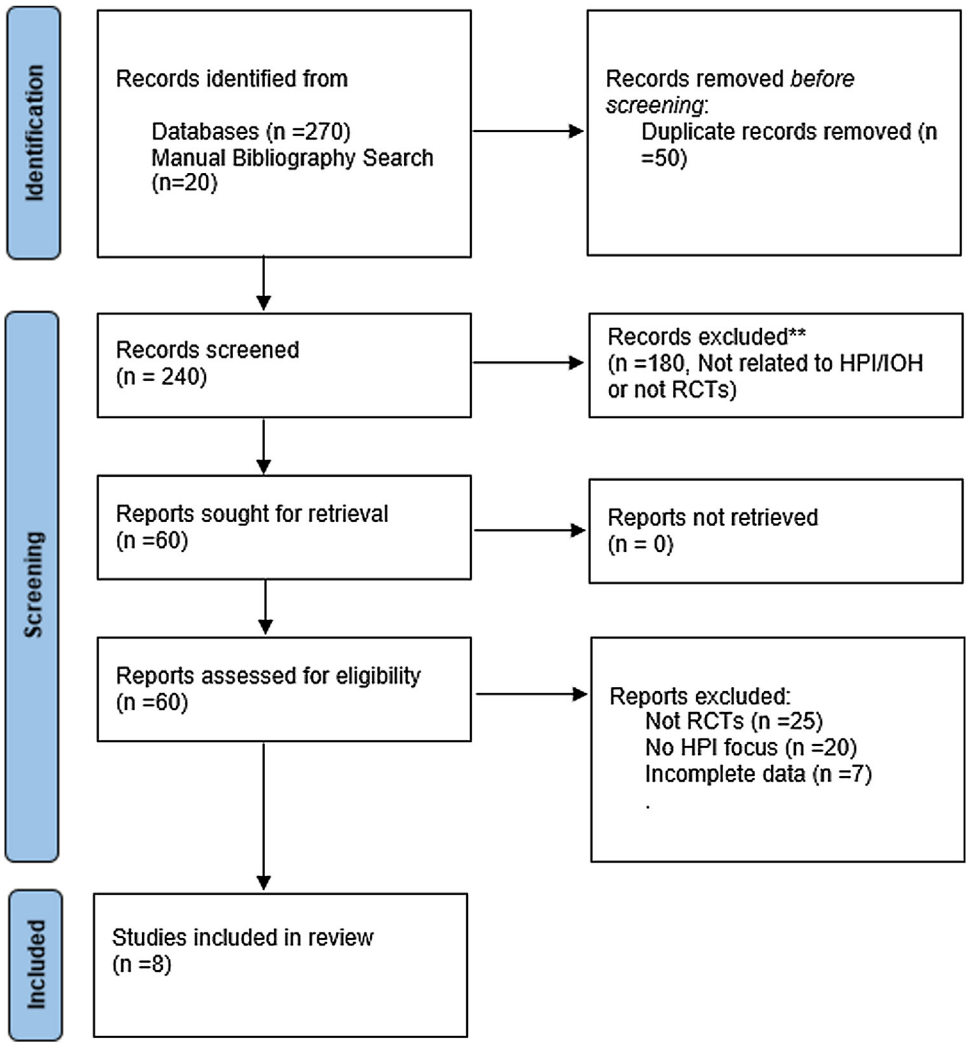

Fig. 1. PRISMA 2020 flow diagram of the study selection.

0.85; 95% CI, 0.64–1.13). The prediction interval (PI) for AKI was 0.31–2.52 (Fig. 3). Similarly, HPI-guided management did not significantly reduce the incidence of postoperative complications (Four RCTs [7,20,23,25], 1310 patients: OR 1.10; 95% CI, 0.83–1.46). PI 0.01–94.68 (Fig. 4), mortality (Four RCTs [7,20,23,25], 1310 patients: OR 0.96; 95% CI, 0.32–2.83) PI 0.00–1408 (Supplementary Fig. S2), or LOS (Four RCTs [7,20,23,25], 1310 patients: SMD: −0.15 [−0.73; 0.42]) (Supplementary Fig. S3), compared to standard care.

3.3. Post hoc analyses: intraoperative hypotension metrics outcomes

Seven trials (617 patients) assessed the TWA of hypotension [12,20–25]. The SMD in TWA MAP < 65 mmHg was −0.25 (95% CI, −0.41 to −0.09), indicating that HPI-guided intraoperative management was associated with a reduction in TWA of IOH (Fig. 5). Six trials (577 patients) assessed the AUT of hypotension [12,20,22,21–25]. The SMD in AUT was −0.83 [−1.37, −0.28] (Supplementary Fig. S4), and seven trials (617 patients) assessed the median time with hypotension during surgery [12,20–25]. The SMD was 0.74 [−1.10, −0.37] (Supplementary Fig. S5). To improve clinical interpretability, we also re-analyzed this outcome using MD, based on absolute time in minutes. The pooled analysis showed that HPI-guided management reduced total time with MAP < 65 mmHg by−20.54 min (95% CI: −33.41 to −7.68), consistent with the direction and significance of the SMD result (Supplementary Fig. S6).

3.4. Post hoc analyses: intraoperative fluid administration

There were no differences in the total intraoperative fluid administration (colloid and crystalloid), (SMD: −0.06 [−0.35; 0.24]) (Supplementary Fig. S7).

3.5. Sensitivity analyses

While all studies were rated as having an overall moderate risk of bias, none were classified as having a high risk in critical domains such as randomization, blinding of participants and personnel, or incomplete outcome data. Consequently, no studies were excluded from the primary analysis based on risk of bias.

A sensitivity analysis comparing fixed-effect and random-effects models showed consistent results. The fixed-effect model yielded an OR of 0.85 (95% CI: 0.64–1.13; $p = 0.253$), while the random-effects model produced an OR of 0.89 (95% CI: 0.62–1.28; $p = 0.522$) (Supplementary Fig. S8). Despite slight differences, the

Table 1
PICO characteristics of included studies.

Study	Population	Intervention	Comparator (Control Group)	Outcomes	Study design
Maheshwari *et al.*, 2020 [19]	Moderate- to high-risk non-cardiac surgical patients (ASA III-IV). N = 214	HPI-based GDHT, with interventions triggered at HPI > 85 (vasopressors, fluids, inotropes) targeting MAP > 65 mmHg	Standard care without HPI; MAP maintained by routine clinician management	Primary: TWA of hypotension; Secondary: AUC MAP < 65 mmHg, AKI, ICU length of stay, hospital length of stay, 30-day mortality	Multicenter RCT
Wijnberge *et al.*, 2020 [12]	Elective non-cardiac surgical patients with invasive BP monitoring. N = 60	HPI-guided GDHT with alerts at HPI > 85, protocolized responses (fluids, vasopressors)	Conventional intraoperative management targeting MAP ≥ 65	Primary: Depth and duration of IOH; Secondary: incidence of IOH, complications, hospital length of stay, total fluid balance	Single-center RCT
Tsoumpa *et al.*, 2021 [20]	Moderate- to high-risk abdominal surgical patients under general anesthesia. N = 99	HPI-directed protocol initiating treatment at HPI ≥ 85 with MAP monitoring and volume management	Standard GDHT approach with SV and MAP optimization, using FloTrac monitoring	Primary: Incidence and duration of IOH; Secondary: fluid volume, ICU admissions, complications, 30-day mortality	Single-center RCT
Murabito *et al.*, 2022 [21]	Major elective non-cardiac surgery patients requiring continuous BP monitoring. N = 40	HPI-based GDHT with early warning system to prevent IOH, integrating fluids and vasopressors when HPI > 85	Standard MAP-based GDHT, maintaining MAP > 65 mmHg according to clinical judgment	Primary: Biomarker changes (AKI, troponin); Secondary: oxidative stress markers, hypotension duration, norepinephrine requirements	Single-center RCT
Frassanito *et al.*, 2023 [22]	Patients undergoing major non-cardiac surgery with risk of hemodynamic instability. N = 60	HPI-based protocol with specific alerts for HPI > 85, allowing early fluid and vasopressor interventions	Standard hemodynamic management with MAP-focused interventions	Primary: Duration of MAP < 65 mmHg; Secondary: incidence of IOH, postoperative complications, AKI, ICU admission, hospital stay, 30-day mortality	Multicenter RCT
Lorente *et al.*, 2023 [23]	High-risk abdominal surgery patients with hemodynamic monitoring needs. N = 80	HPI-based predictive monitoring with treatment initiated at HPI > 85; includes fluid and vasopressor protocol	MAP-based management protocol targeting MAP > 65 mmHg	Primary: Duration and incidence of IOH; Secondary: AKI, postoperative complications, ICU stay, 30-day mortality	Multicenter RCT
Yoshikawa *et al.*, 2024 [24]	Moderate-risk major non-cardiac surgery patients. N = 64	HPI-guided GDHT with treatment interventions at HPI > 85, excluding advanced dP/dt, Eadyn parameters	Standard GDHT, based on FloTrac hemodynamic parameters for MAP and SV optimization	Primary: TWA MAP < 65 mmHg and cumulative hypotension duration; Secondary: fluid volume, incidence of MAP < 50 mmHg events, norepinephrine use	Single-center RCT
Ripollés-Melchor *et al.*, 2025 [7]	Adults undergoing elective major abdominal surgery at high risk. N = 917	HPI-directed GDHT with treatments activated at HPI > 80; targeting MAP > 65 mmHg with standardized fluid and vasopressor interventions	Conventional with or without GDHT	Primary: AKI, major postoperative complications, ICU length of stay, hospital length of stay	Multicenter RCT

Abbreviations: ASA: American Society of Anesthesiologists; AKI: Acute Kidney Injury; AUC: Area Under the Curve; BP: Blood Pressure; dP/dt: Rate of Pressure Change in the Artery Over Time; Eadyn: Dynamic Arterial Elastance; GDHT: Goal-Directed Hemodynamic Therapy; HPI: Hypotension Prediction Index; ICU: Intensive Care Unit; IOH: Intraoperative Hypotension; MAP: Mean Arterial Pressure; NSE: Neuron-Specific Enolase; NGAL: Neutrophil Gelatinase-Associated Lipocalin; RCT: Randomized Controlled Trial; SV: Stroke Volume; TWA: Time-Weighted Average.

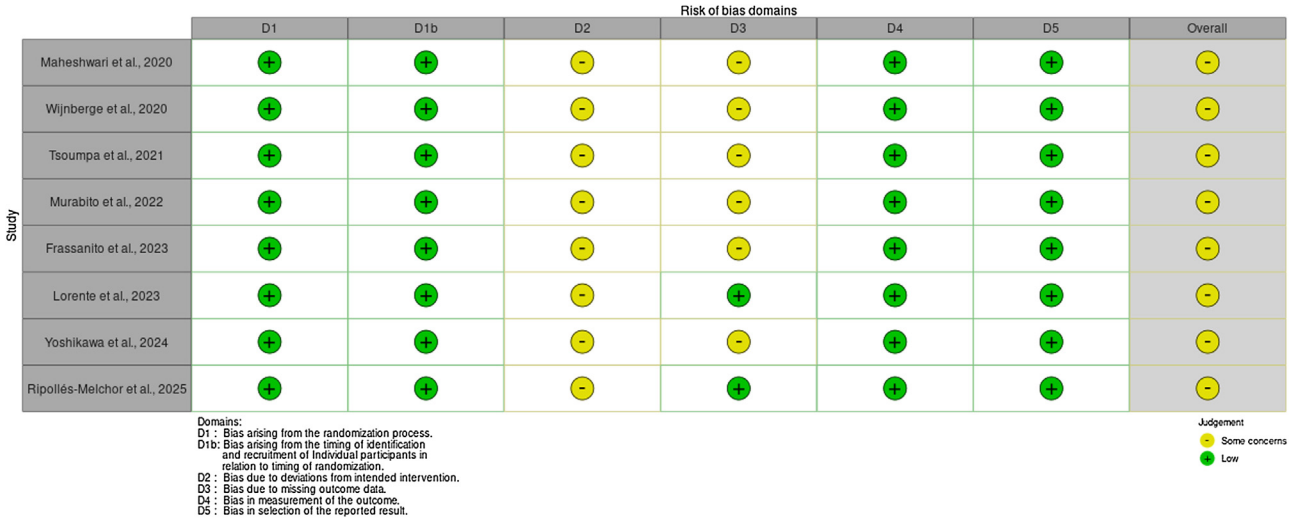

Fig. 2. Quality assessment of included trials for patient-centered outcomes.

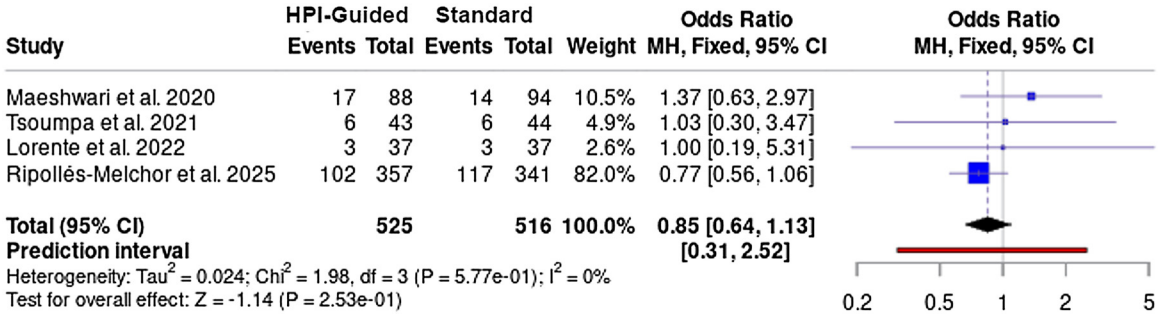

Fig. 3. Forest plot of incidence of postoperative acute kidney injury (AKI) of included eligible studies. CI, confidence interval.

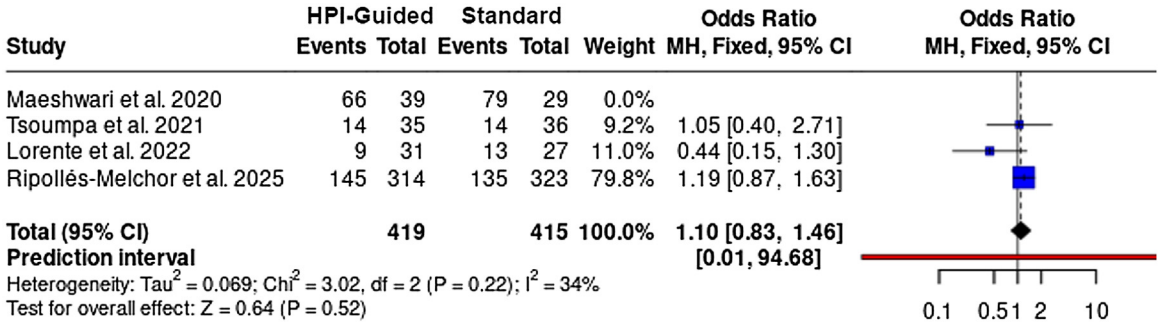

Fig. 4. Forest plot of incidence of postoperative complications of included eligible studies. CI, confidence interval.

pooled estimates remained consistent between models, indicating that the findings are robust to assumptions regarding between-study variability.

A leave-one-out sensitivity analysis was performed to evaluate the influence of individual studies on the pooled effect estimate. Across most exclusions, the pooled OR remained consistent, ranging from 0.78 to 0.84, with overlapping confidence intervals. Notably, the exclusion of Ripollés-Melchor *et al.* [7], resulted in a larger pooled OR of 1.22 (95% CI: 0.66–2.24), accompanied by a wider confidence interval. However, none of the exclusions led to statistically significant results ($p > 0.05$), indicating that the overall findings were robust and not disproportionately influenced by any single study (Supplementary Table 3).

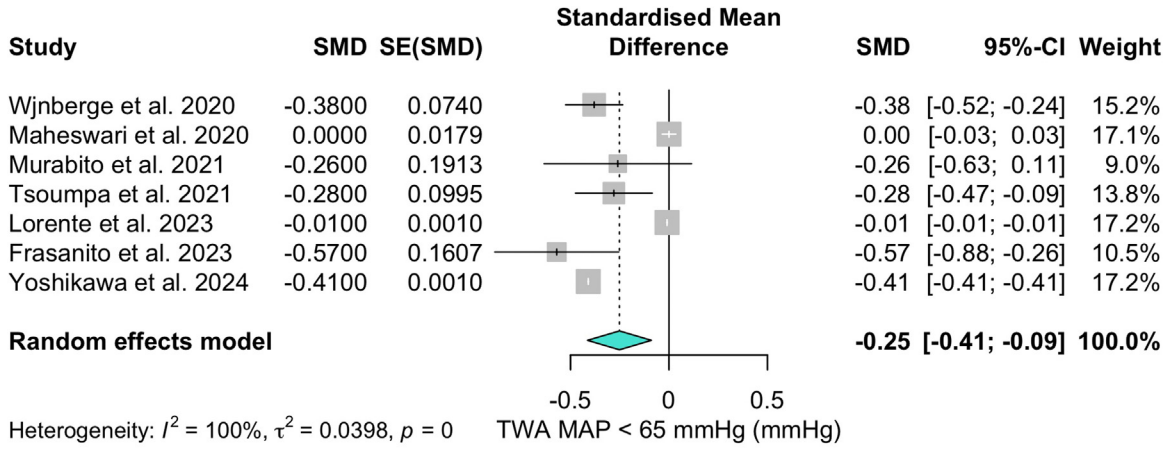

Fig. 5. Effect of HPI on time-weighted average of hypotension.

Finally, a sensitivity analysis including only studies that defined AKI using the KDIGO criteria was conducted. Two studies, Maheshwari *et al.* [25], and Tsoumpa *et al.* [20], were excluded due to unclear or inconsistent AKI definitions. The pooled OR for the remaining studies was 0.77 (95% CI: 0.56–1.05; p = 0.1090).

3.6. Number needed to treat

Exploratory NNT estimates were calculated post hoc for descriptive purposes. The estimated NNT for AKI was 30, although this was not statistically significant. For complications, the NNT was negative (−48), reflecting a non-significant trend toward increased complications in the HPI group. For mortality, the NNT was approximately 2000, highlighting the absence of any clinically meaningful absolute risk reduction. These values are exploratory and should not be interpreted as definitive (Supplementary Table S4).

3.7. Publication bias

Visual inspection of funnel plots did not indicate substantial asymmetry for the primary outcomes (Supplementary Fig. S9). However, due to the limited number of included studies, formal tests for publication bias were not conducted.

4. Discussion

This meta-analysis confirms that HPI-guided intraoperative management did not significantly reduce 30-day mortality, postoperative complications, AKI, or LOS. These findings are consistent across the included trials and reflect the current uncertainty regarding the clinical benefit of HPI-based hemodynamic strategies. Post hoc analyses suggested a reduction in surrogate IOH metrics such as TWA-MAP, AUT, and total hypotension time, but the high risk of bias for these outcomes precludes definitive interpretation.

A fixed MAP target may overlook patient-specific variables, including physiological variability, comorbidities, and surgical complexity [26,27]. The HPI algorithm, developed through machine learning, has demonstrated the potential for reducing the TWA of hypotension [6,28]. However, its clinical utility remains a subject of debate [29]. Recent studies suggest that HPI does not consistently outperform simpler MAP-based alert systems [30]. Both HPI and MAP-based thresholds are limited by low positive predictive values, which raises concerns regarding overtreatment and highlights the need for further validation before widespread clinical adoption [31].

Although observational reports have suggested potential operational feasibility of HPI-guided protocols, the interpretation of such findings is limited by consistent high risk of bias due to lack of blinding and outcome subjectivity [32]. Moreover, the reduction in TWA MAP < 65 mmHg observed reflects a modest change with uncertain clinical relevance. Unlike total time with MAP < 65 mmHg, there is no clear evidence that small variations in TWA MAP < 65 mmHg translate into improved outcomes, and this should be interpreted with caution [32]. Furthermore, the HPI algorithm is intrinsically linked to MAP, with previous analyses showing correlation coefficients (r^2) exceeding 0.95. For instance, an HPI value of 85 typically corresponds to a MAP of approximately 72 mmHg [33], raising the question of whether the observed reductions in IOH metrics result from the algorithm's predictive capabilities or from conventional MAP monitoring and management. Whether clinical effects attributed to HPI reflect true predictive benefit or merely earlier MAP detection remains uncertain. Future research should aim to disentangle these effects by comparing HPI-triggered protocols to MAP-based alert systems with matched thresholds, or by designing new algorithms that reduce dependency on MAP and incorporate additional physiologic signals [34].

Postoperative organ dysfunction is multifactorial and may be influenced by several factors such as fluid balance, vasopressor use, and pre-existing conditions [35,36]. While the clinical significance of reducing IOH remains uncertain, we aimed to improve interpretability by reporting both SMD and MD for the outcome "total time with MAP < 65 mmHg". The SMD (–0.74 [–1.10 to –0.37]) provides a scale-independent estimate of effect, but it is unitless and may be misinterpreted. Therefore, we also calculated the pooled MD, which showed a reduction of –20.54 min (95% CI: –33.41 to –7.68) of hypotension in the HPI group. Observational studies have reported associations between cumulative hypotension exposure and increased risk of postoperative complications, including AKI and mortality [5]. However, the causal relationship remains unproven, and our meta-analysis did not demonstrate improvements in patient-centered outcomes. These findings support the physiological rationale for avoiding hypotension, but they do not establish that reducing its duration translates into improved clinical outcomes.

While HPI-based GDHT incorporates tools to detect and address IOH, it initiates intervention when the index exceeds 80–85, which anticipates IOH and may therefore be considered a proactive approach compared to conventional responses triggered by established hypotension. Traditional GDHT aims to optimize stroke volume or cardiac output, with any rise in MAP being a secondary consequence rather than a primary target [37].

However, recent high-quality RCTs evaluating cardiac output-guided therapy—such as the iPEGASUS trial, which tested maintenance of post-induction cardiac index [38], and OPTIMISE II, which assessed fluid and inotrope-guided protocols [39]—have not demonstrated improvements in clinical outcomes, and in some cases reported increased risk of complications. These findings suggest that the utility of conventional flow-based protocols remains uncertain and support the need for cautious interpretation of HPI-based algorithms until direct comparisons with alternative approaches are available. The INPRESS trial demonstrated that individualized systolic blood pressure (SBP) targets tailored to baseline physiology reduced postoperative organ dysfunction compared to standard MAP-based care [38]. However, its control group had a low SBP target (<80 mmHg), likely corresponding to a MAP < 65 mmHg [40]. Furthermore, the intervention group received continuous norepinephrine, whereas the control group used intermittent vasopressor boluses. These factors may have contributed to outcome differences, and the findings should therefore be interpreted with caution. A recent meta-analysis emphasized the need for flexible IOH management. Permissive hypotension (MAP ≤ 60 mmHg) was not associated with increased mortality and correlated with lower atrial fibrillation incidence and shorter hospital stay [26].

Our study has several limitations. First, the number of included studies was limited, which reduced the power to detect differences in patient-centered outcomes, such as AKI and mortality. Second, there was considerable heterogeneity across the studies in terms of population characteristics, surgical procedures, and intervention protocols, which may have influenced the pooled estimates. Third, the definitions of outcomes, particularly postoperative complications, varied across the included studies, potentially introducing a bias. Fourth, while the primary outcomes were well documented in most studies, data on fluid administration and other secondary outcomes were often incomplete, limiting the ability to draw firm conclusions regarding these variables. Finally, the lack of long-term follow-up in the included studies precludes the assessment of the sustained impact of HPI-guided management on outcomes beyond the immediate postoperative period.

While the pooled OR suggested no significant reduction in AKI with HPI-guided management, the prediction interval (PI: 0.31–2.52) highlights substantial variability in potential outcomes. This indicates that future studies conducted under similar conditions might report effects ranging from harm to benefit. The wide PI underscores the need for further high-quality RCTs to confirm these findings and explore the factors contributing to variability, such as population characteristics and intervention protocols. Despite the low heterogeneity (I^2 = 0%), the prediction interval reveals residual uncertainty, reinforcing the need for cautious interpretation of the pooled estimate and further validation. This study extends beyond algorithm refinement to include its integration within a broader perioperative hemodynamic framework. Several included studies presented potential commercial bias, especially when sponsors contributed to the design, analysis, or writing. In unblended settings, such involvement may influence intraoperative decision-making and reporting of surrogate outcomes, such as hypotension metrics. This aligns with the RoB 2.0 findings of high performance and detection bias in intraoperative endpoints due to the lack of blinding and the subjective nature of clinical thresholds. The combined findings suggest that reported improvements in TWA MAP < 65 mmHg, AUT, or total duration of MAP < 65 mmHg may reflect, at least in part, the influence of study design, COIs, and clinician behavior rather than the intrinsic benefit of the intervention. Notably, these surrogate improvements did not translate into better patient-centered outcomes across the included trials. This reinforces concerns regarding the interpretative value of intermediate endpoints and highlights the need for independent, rigorously conducted studies before widespread clinical adoption of predictive hemodynamic algorithms such as HPI. Future studies should assess HPI-based GDHT protocols that personalize both flow and pressure targets, allowing for a more balanced approach to hemodynamic stability and perfusion tailored to each patient's physiology and surgical context. Expanding research across diverse patient populations will help clarify the role of HPI and its potential to improve clinical outcomes.

5. Conclusion

HPI-guided management did not significantly improve patient-centered outcomes. Post hoc analyses indicated a reduction in IOH metrics; however, these findings stem from studies at consistently high risk of bias due to the absence of blinding and susceptibility of outcome measurement, and their clinical relevance remains uncertain.

CRediT authorship contribution statement

JRM: Conceptualization, Study Design, Statistical Analysis, Data Interpretation, Manuscript Writing, Critical Revision, Final Approval.

AZV: Data Acquisition, Data Analysis, Drafting Manuscript Sections, Critical Revision, Final Approval.

AVE: Systematic Search Coordination, Data Extraction, Data Interpretation, Critical Revision, Final Approval.

CA: Study Design, Data Synthesis, Manuscript Drafting, Critical Revision, Final Approval.

BQV: Methodology Supervision, Data Interpretation, Critical Revision, Final Approval.

AAG: Data Acquisition, Manuscript Drafting, Critical Content Revision, Final Approval.

JVL: Quality Assessment of Included Studies, Data Extraction, Manuscript Revision, Final Approval.

MIMG: Data Synthesis, Results Interpretation, Manuscript Writing and Editing, Critical Revision, Final Approval.

Informed consent and patient details

The authors declare that this report does not contain any personal information that could lead to the identification of the patient(s).

Funding statement

Support was provided solely from institutional and/or departmental sources.

Declaration of competing interest

JRM reports personal fees from Edwards Lifesciences, Baxter and Fresenius Kabi outside the submitted work; JVL reports personal fees from Edwards Lifesciences, Baxter, Fresenius Kabi and bioMérieux outside the submitted work. AAG personal fees from Edwards Lifesciences, MSD and 3M outside the submitted work. MIMG is a consultant for Edwards Lifesciences and Dynocardia. The other authors declare no competing interests.

Acknowledgements

No.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.accpm.2025.101656.

References

[1] Chiu C, Fong N, Lazzareschi D, Mavrothalassitis O, Kothari R, Chen LL, et al. Fluids, vasopressors, and acute kidney injury after major abdominal surgery between 2015 and 2019: a multicenter retrospective analysis. Br J Anaesth 2022;129:317–26.

[2] Gregory A, Stapelfeldt WH, Khanna AK, Smischney NJ, Boero IJ, Chen Q, et al. Intraoperative hypotension is associated with adverse clinical outcomes after noncardiac surgery. Anesth Analg 2021;132:1654–65.

[3] Ackland GL, Brudney CS, Cecconi M, Ince C, Irwin MG, Lacey J, et al. Perioperative Quality Initiative consensus statement on the physiology of arterial blood pressure control in perioperative medicine. Br J Anaesth 2019;122:542–51.

[4] Hatib F, Jian Z, Buddi S, Lee C, Settels J, Sibert K, et al. Machine-learning algorithm to predict hypotension based on high-fidelity arterial pressure waveform analysis. Anesthesiology 2018;129:663–74.

[5] Ripollés-Melchor J, Ruiz-Escobar A, Fernández-Valdes-Bango P, Lorente JV, Jiménez-López I, Abad-Gurumeta A, et al. Hypotension prediction index: from reactive to predictive hemodynamic management, the key to maintaining hemodynamic stability. Available from: Front Anesthesiol 2023;21138175, https://www.frontiersin.org/articles/10.3389/fanes.2023.1138175.

[6] Pilakouta Depaskouale MA, Archonta SA, Katsaros DM, Paidakakos NA, Dimakopoulou AN, Matsota PK. Beyond the debut: unpacking six years of Hypotension Prediction Index software in intraoperative hypotension prevention - a systematic review and meta-analysis. J Clin Monit Comput 2024;38:1367–77.

[7] Ripollés-Melchor J, Tomé-Roca JL, Zorrilla-Vaca A, Aldecoa C, Colomina MJ, Bassas-Parga E, et al. Hemodynamic management guided by the hypotension prediction index in abdominal surgery: a multicenter randomized clinical trial. Anesthesiology 2025;142:639–54.

[8] Zarbock A, Weiss R, Albert F, Rutledge K, Kellum JA, Bellomo R, et al. Epidemiology of surgery associated acute kidney injury (EPIS-AKI): a prospective international observational multi-center clinical study. Intensive Care Med 2023;49:1441–55.

[9] Zhuo XY, Lei SH, Sun L, Bai YW, Wu J, Zheng YJ, et al. Preoperative risk prediction models for acute kidney injury after noncardiac surgery: an independent external validation cohort study. Br J Anaesth England 2024;133:508–18.

[10] Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009;6e1000097.

[11] Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ 2019;366.

[12] Wijnberge M, Geerts BF, Hol L, Lemmers N, Mulder MP, Berge P, et al. Effect of a machine learning–derived early warning system for intraoperative hypotension vs standard care on depth and duration of intraoperative hypotension during elective noncardiac surgery. JAMA 2020;323:1052–60.

[13] Kellum JA, Lameire N, Aspelin P, MacLeode AM, Barsoum RS, Mehta RL, et al. Kidney disease: improving global outcomes (KDIGO) acute kidney injury work group. KDIGO clinical practice guideline for acute kidney injury. Kidney Int Suppl 2012;2.

[14] Shi J, Luo D, Weng H, Zeng XT, Lin L, Chu H, et al. Optimally estimating the sample standard deviation from the five-number summary. Res Synth Methods England 2020;11:641–54.

[15] Molinari L, Sakhuja A, Kellum JA. Perioperative renoprotection: general mechanisms and treatment approaches. Anesth Analg 2020;131:1679–92.

[16] Steven Bird, Klein Ewan LE. Natural language processing with python. Sebastopol: O'Reilly Media; 2023.

[17] Meta-mar.com M-M v4. 0. 2025.

[18] Statistical RCT (2021). RA language and environment for, computing. R Foundation for Statistical Computing, Vienna A, Https://www.R-project.org.

[19] Maheshwari K, Shimada T, Yang D, Khanna S, Cywinski JB, Irefin SA, et al. Hypotension prediction index for prevention of hypotension during moderate- to high-risk noncardiac surgery: a pilot randomized trial. Anesthesiology 2020;1214–22.

[20] Tsoumpa M, Kyttari A, Matiatou S, Tzoufi M, Griva P, Pikoulis E, et al. The use of the hypotension prediction index integrated in an algorithm of goal directed hemodynamic treatment during moderate and high-risk surgery. J Clin Med 2021;10:5884.

[21] Murabito P, Astuto M, Sanfilippo F, La Via L, Vasile F, Basile F, et al. Proactive management of intraoperative hypotension reduces biomarkers of organ injury and oxidative stress during elective non-cardiac surgery: a pilot randomized controlled trial. J Clin Med 2022;11:392.

[22] Frassanito L, Giuri PP, Vassalli F, Piersanti A, Garcia MIM, Sonnino C, et al. Hypotension prediction index guided goal directed therapy and the amount of hypotension during major gynaecologic oncologic surgery: a randomized controlled clinical trial. J Clin Monit Comput 2023;37:1081–93.

[23] Lorente JV, Ripollés-Melchor J, Jiménez I, Becerra AI, Mojarro I, Fernández-Valdes-Bango P, et al. Intraoperative hemodynamic optimization using the hypotension Prediction index vs. goal-directed hemodynamic therapy during elective major abdominal surgery: the Predict-H multicenter randomized controlled trial. Front Anesthesiol 2023;21193886.

[24] Yoshikawa Y, Maeda M, Kunigo T, Sato T, Takahashi K, Ohno S, et al. Effect of using hypotension prediction index versus conventional goal-directed haemodynamic management to reduce intraoperative hypotension in non-cardiac surgery: a randomised controlled trial. J Clin Anesth 2024;93111348.

[25] Maheshwari K, Shimada T, Yang D, Khanna S, Cywinski JB, Irefin SA, et al. Hypotension prediction index for prevention of hypotension during moderate- to high-risk noncardiac surgery. Anesthesiology 2020;133:1214–22.

[26] D'Amico F, Fominskiy EV, Turi S, Pruna A, Fresilli S, Triulzi M, et al. Intraoperative hypotension and postoperative outcomes: a meta-analysis of randomised trials. Br J Anaesth 2023;131:823–31.

[27] Michard F, Joosten A, Futier E. Intraoperative blood pressure: could less be more? Br J Anaesth 2023;131:810–2.

[28] Li W, Hu Z, Yuan Y, Liu J, Li K. Effect of hypotension prediction index in the prevention of intraoperative hypotension during noncardiac surgery: a systematic review. J Clin Anesth 2022;83110981.

[29] Michard F, Futier E. Predicting intraoperative hypotension: from hope to hype and back to reality. Br J Anaesth 2023;131:199–201.

[30] Mulder MP, Harmannij-Markusse M, Fresiello L, Donker DW, Potters J-W. Hypotension prediction index is equally effective in predicting intraoperative hypotension during noncardiac surgery compared to a mean arterial pressure threshold: a prospective observational study. Anesthesiology 2024;141:453–62.

[31] Davies SJ, Sessler DI, Jian Z, Fleming NW, Mythen M, Maheshwari K, et al. Comparison of differences in cohort (forward) and case control (backward) methodological approaches for validation of the hypotension prediction index. Anesthesiology 2024;141:443–52.

[32] Kouz K, Monge García MI, Cerutti E, Lisanti I, Draisci G, Frassanito L, et al. Intraoperative hypotension when using hypotension prediction index software during major noncardiac surgery: a European multicentre prospective observational registry (EU HYPROTECT). BJA Open 2023;6100140.

[33] Rellum SR, Noteboom SH, van der Ster BJP, Schuurmans J, Kho E, Vlaar APJ, Schenk J, et al. The hypotension prediction index versus mean arterial pressure in predicting intraoperative hypotension: a clinical perspective. Eur J Anaesthesiol 2025;42:527–35.

[34] Vistisen ST, London MJ, Mathis MR, van Klei WA, Huzurbazar S, Jacquet-Lagrèze M. Shedding needed light on a black box approach to prediction of hypotension. Anesthesiology 2024;141:421–4.

[35] Pinsky MR, Cecconi M, Chew MS, De Backer D, Douglas I, Edwards M, et al. Effective hemodynamic monitoring. Crit Care 2022;26:294.

[36] Saugel B, Sander M, Katzer C, Hahn C, Koch C, Leicht D, et al. Association of intraoperative hypotension and cumulative norepinephrine dose with postoperative acute kidney injury in patients having noncardiac surgery: a retrospective cohort analysis. Br J Anaesth 2025;134:54–62.

[37] Calvo-Vecino JM, Ripollés-Melchor J, Mythen MG, Casans-Francés R, Balik A, Artacho JP, et al. Effect of goal-directed haemodynamic therapy on postoperative complications in low–moderate risk surgical patients: a multicentre randomised controlled trial (FEDORA trial). Br J Anaesth 2018;120:734–44.

[38] Funcke S, Schmidt G, Bergholz A, Argente Navarro P, Azparren Cabezón G, Barbero-Espinosa S, et al. Cardiac index-guided therapy to maintain optimised postinduction cardiac index in high-risk patients having major open abdominal surgery: the multicentre randomised iPEGASUS trial. Br J Anaesth 2024;133:277–87.

[39] OPTIMISE II Trial Group. Cardiac output-guided haemodynamic therapy for patients undergoing major gastrointestinal surgery: OPTIMISE II randomised clinical trial. BMJ 2024;387e080439.

[40] Futier E, Lefrant JY, Guinot PG, Godet T, Lorne E, Cuvillon P, et al. Effect of individualized vs standard blood pressure management strategies on postoperative organ dysfunction among high-risk patients undergoing major surgery: a randomized clinical trial. JAMA 2017;318:1346–57.