



REVIEW ARTICLE

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Intraoperative blood pressure management strategies and postoperative outcomes in patients undergoing noncardiac surgery: a systematic review and meta-analysis

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Abstract

Background Current recommendations for intraoperative blood pressure management suggest maintaining mean arterial pressure (MAP) at ≥ 60 –65 mmHg to avoid hypotension. However, controversy remains regarding whether higher or individualized MAP targets improve clinically important outcomes in surgical patients. We aimed to determine whether intensive intraoperative blood pressure management, defined as higher fixed or individualized MAP targets, reduces major postoperative morbidity compared with standard management (MAP ≥ 60 –65 mmHg).

Methods We systematically searched PubMed, Embase, the Cochrane Library, and Web of Science for randomized controlled trials (RCTs) comparing intensive and standard intraoperative blood pressure management in adults undergoing noncardiac surgery. The primary outcomes were postoperative myocardial injury, postoperative delirium (POD), and acute kidney injury (AKI). Secondary outcomes included postoperative mortality, stroke, heart failure, acute respiratory distress syndrome (ARDS), pneumonia, intensive care unit (ICU) admission, surgical site infection (SSI), and hospital length of stay (LOS). Data were pooled using a random-effects model with the Hartung–Knapp adjustment. Risk ratios (RR) were calculated for dichotomous outcomes, and mean differences (MD) were calculated for continuous outcomes. Trial sequential analysis (TSA) was performed to control for random error and assess the conclusiveness of the available evidence.

Results Eighteen RCTs involving 16,573 patients were included. Compared with standard management, intensive management was associated with lower risks of POD (10 studies; RR = 0.72, 95% CI [0.55, 0.93]; $P = 0.019$; moderate-certainty evidence) and SSI (5 studies; RR = 0.64, 95% CI [0.53, 0.76]; $P = 0.002$; moderate-certainty evidence). However, no significant between-group differences were observed in postoperative myocardial injury (9 studies; RR = 1.02, 95% CI [0.92, 1.13]), AKI (13 studies; RR = 0.92, 95% CI [0.79, 1.06]), or mortality (13 studies; RR = 0.99, 95% CI [0.83, 1.17]). TSA supported a beneficial effect of intensive management on POD, and indicated that a clinically meaningful benefit of the prespecified magnitude was unlikely for myocardial injury and AKI. No significant between-group differences were observed in postoperative stroke, pneumonia, heart failure, ICU admission, or hospital LOS.

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Conclusions In this systematic review and meta-analysis, intensive intraoperative blood pressure management may reduce the risks of POD and SSI in adults undergoing noncardiac surgery. However, it was not associated with significant differences in postoperative myocardial injury, AKI or mortality.

Protocol registration PROSPERO: CRD420261323873.

Keywords Intraoperative blood pressure management, Meta-analysis, Noncardiac surgery, Postoperative outcomes, Systematic review, Trial sequential analysis

1 Introduction

Intraoperative blood pressure management is a key part of anaesthesia and perioperative care, and is closely associated with postoperative outcomes [1, 2]. A primary concern is intraoperative hypotension, a condition that occurs frequently in noncardiac surgery and linked to major postoperative complications [3, 4]. Consequently, determining the optimal intraoperative blood pressure management strategy has become a focal point in perioperative medicine. Current guidelines and the standard of clinical practice recommend maintaining mean arterial pressure (MAP) ≥ 60 mmHg [5]. However, controversy persists regarding whether targeting higher intraoperative MAP thresholds can improve postoperative outcomes in surgical patients. Although previous observational studies [6–9] and some randomized controlled trials (RCTs) [10, 11] suggested that intensive intraoperative blood pressure management could improve organ perfusion and reduce postoperative complications, an increasing number of high-quality, large-sample RCTs have not yielded conclusions consistent with these earlier findings [12–14]. Therefore, it is necessary to further synthesize current RCTs to clarify the effect of intraoperative blood pressure management strategy on postoperative outcomes [2].

Intraoperative blood pressure management strategies in clinical practice are primarily categorized into standard and intensive management. Standard management typically aims to maintain MAP ≥ 60 –65 mmHg [15, 16]. Intensive management establishes higher MAP targets and includes two types: a fixed or an individualized higher-target strategy. The fixed higher-target strategy sets a uniform elevated MAP threshold (e.g., ≥ 75 –80 mmHg) or systolic blood pressure (SBP) ≥ 100 mmHg, for all patients [10, 17–19]. The individualized higher-target strategy tailors the blood pressure target based on each patient's characteristics, such as preoperative baseline blood pressure, preoperative mean nighttime MAP or preoperatively predicted risk of hypotension [11, 20, 21].

A previously published meta-analysis, which included five RCTs involving 1,485 patients, indicated that intensive intraoperative blood pressure management significantly reduces the incidence of postoperative acute

kidney injury (AKI) [22]. However, its conclusions conflict with the results of several recently published high-quality, large-sample RCTs [12–14]. Furthermore, a concurrent meta-analysis published online by Shalabi and colleagues explored a similar topic [23]. Based on ten RCTs involving 5,842 patients, they found that individualized intraoperative blood pressure management did not significantly reduce postoperative AKI, although they reported a potential reduction in postoperative delirium (POD) based on a limited subset of four trials. Crucially, their trial sequential analysis (TSA), which was restricted to AKI, remained underpowered, precluding a definitive conclusion. Moreover, their synthesis focused exclusively on individualized targets, leaving the clinical value of fixed higher-target strategy and their comparative efficacy unaddressed.

To update the current evidence and resolve these conflicting findings, we conducted a systematic review and meta-analysis with the following objectives: (1) to systematically evaluate the effect of intensive intraoperative blood pressure management on postoperative outcomes, including myocardial injury, delirium, AKI, and others; (2) to compare a fixed versus an individualized higher-target strategy; and (3) to apply TSA across these critical outcomes to assess whether the accumulated evidence is sufficiently powered to yield reliable conclusions. Through these efforts, our study expands upon earlier findings, aiming to provide comprehensive, evidence-based insights to guide optimal intraoperative blood pressure management and clinical decision-making.

2 Methods

This systematic review was performed on the basis of the criteria of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [24]. This meta-analysis was registered prospectively in the PROSPERO database (CRD420261323873).

2.1 Search strategy and study selection

A comprehensive search was conducted in PubMed, Embase, the Cochrane Library (CENTRAL), and Web of Science (Core Collection) from inception to November 4, 2025. Additionally, the references of relevant reviews and included studies were scanned to identify other eligible

trials. We adopted a search strategy combining three groups of terms: blood pressure or hypertension, perioperative or intraoperative, and RCT. The detailed search strategy is available in Supplementary Material 1. The literature search and screening were performed independently by two investigators (ZXZ and YH), and any disagreement in opinions was resolved through discussion with a third investigator (CC). An updated search was conducted on May 15, 2026, using the original search strategy to capture any new trials.

2.2 Eligibility criteria

We included only RCTs conducted in adult patients undergoing noncardiac surgery. Eligible studies were required to investigate the effects of either fixed or individualized higher-target intraoperative blood pressure management strategy, using standard management strategy (MAP $\geq$ 60–65 mmHg) as the comparator. Studies were excluded if they were not published in the English language or did not employ a clearly defined intensive intraoperative blood pressure management.

2.3 Outcomes

The primary outcomes were postoperative myocardial injury, delirium, and AKI. The secondary outcomes included postoperative mortality, stroke, heart failure, acute respiratory distress syndrome (ARDS), pneumonia, admission to Intensive Care Unit (ICU), surgical site infection (SSI), and hospital length of stay (LOS). Definitions of all outcomes were summarised in Supplementary Tables S1 and S2 (Supplementary Material 2).

2.4 Data extraction

The following data were extracted from each trial: author, year of publication, country where the study was conducted, trial design and methodology, sample size, basic information of the patients (age, gender, type of surgery, American Society of Anesthesiologists [ASA] physical status, baseline MAP, comorbidities), blinding, intervention strategy type, and outcomes. In addition to the aforementioned outcomes, data pertaining to delayed neurocognitive recovery (dNCR), postoperative cognitive dysfunction (POCD) and LOS in ICU were also extracted. However, owing to the limited number of RCTs reporting these outcomes, quantitative synthesis was not undertaken. When multiple reports from the same trial were identified, outcome data were extracted from the most relevant publication for each endpoint, and all reports were treated as a single study according to Cochrane Handbook guidance. Two investigators extracted the data independently, and any discrepancies were resolved through discussion and consensus.

2.5 Risk of bias assessment

Risk of bias was assessed using the Cochrane Risk of Bias 2 (RoB2) tool [25], which evaluates bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in the measurement of the outcome, and bias in selection of the reported result. The impact of study quality on the pooled estimates was further assessed via sensitivity analyses. Any disagreements during the assessment were resolved by consensus among the three study team members.

2.6 Statistical analysis

For dichotomous outcomes, pooled risk ratios (RR) with their corresponding 95% confidence intervals (CIs) were calculated as the summary effect size using the Mantel–Haenszel (MH) method. For continuous outcomes, treatment effects were expressed as mean differences (MD) with 95% CIs, synthesized using the inverse-variance method. To account for potential clinical and methodological diversity, a random-effects model was pre-specified for all analyses. The Hartung–Knapp (HK) adjustment was applied to the random-effects model to yield more conservative 95% CIs and reduce the risk of Type I errors. Between-study heterogeneity was assessed using the Cochran's Q test (significance set at $P < 0.10$) and the inconsistency index ($I^2 > 50\%$ indicating substantial heterogeneity).

For two multi-arm trials [10, 11], the intervention arms representing higher MAP targets were combined into a single intensive-management group to permit one pairwise comparison with the standard-management group and thereby avoid a unit-of-analysis error. In the trial by Wu et al. [10], Level II (MAP, 80–95 mmHg) and Level III (MAP, 96–110 mmHg) were combined as the intensive-management group, whereas Level I (MAP, 65–79 mmHg) served as the standard-management group. In the trial by Xu et al. [11], groups M (MAP maintained between baseline and 10% below baseline) and H (MAP maintained between baseline and 10% above baseline) were combined as the intensive-management group, whereas group D (MAP maintained at 10%–20% below baseline) served as the standard-management group. For dichotomous outcomes, the numbers of events and participants in the relevant intervention arms were summed. For continuous outcomes, the means and standard deviations were combined using the formulas recommended in the Cochrane Handbook for Systematic Reviews of Interventions [26].

Potential sources of heterogeneity were explored through predefined subgroup analyses based on the higher-target strategy, provided that at least three

studies were available per subgroup. To assess the robustness of our findings, two types of sensitivity analyses were conducted: a leave-one-out analysis to evaluate the influence of individual studies on the overall estimate, and a high-risk-of-bias filtration by re-running the meta-analysis after excluding studies with a high risk of bias.

TSA was conducted to control for the risks of random errors and to evaluate whether the accumulated information size was sufficient for robust conclusions. We performed TSA using an alpha error of 5% and a beta error of 20% (80% power) applying the O'Brien-Fleming spending function to construct the alpha boundaries, and calculated the required information size (RIS) and heterogeneity-adjusted required information size (HARIS) [27, 28]. For POD, an anticipated relative risk reduction (RRR) of 30% was specified, consistent with the effect size used in the sample-size calculation for the cogPOISE-3 substudy, the largest trial contributing data for this outcome [29]. For all other outcomes, an anticipated RRR of 20% was specified, consistent with the effect size used in the sample-size calculation for the POISE-3 trial and its prespecified kidney substudy [13, 30]. Evidence was considered inconclusive when the cumulative Z-curve crossed neither the trial sequential monitoring boundary nor the futility boundary and the accrued information size (AIS) remained below the HARIS, indicating that the available sample size was insufficient to draw a definitive conclusion. When the AIS reached or exceeded the HARIS without the cumulative Z-curve crossing the trial sequential monitoring boundary, a beneficial intervention effect of at least the prespecified magnitude was considered unlikely. When the Z-curve crossed the trial sequential monitoring boundary for benefit or harm, the evidence was considered sufficient to support an intervention effect of at least the prespecified magnitude in the corresponding direction. We also performed sensitivity TSAs using smaller but still clinically meaningful anticipated RRRs: 10% and 15% for myocardial injury and AKI, respectively, and 20% and 25% for POD (Supplementary Table S3).

Publication bias was assessed for the primary outcomes by visual inspection of contour-enhanced funnel plots. Following Cochrane Handbook guidance, Egger's linear-regression test was applied only to outcomes with at least ten contributing studies, as asymmetry tests are underpowered and unreliable with fewer studies. A P value < 0.05 was considered statistically significant.

All statistical analyses were conducted using R statistical software (version 4.5.2; R Foundation for Statistical Computing, Vienna, Austria), using the 'meta' and 'dplyr' packages [31]. The TSA was performed using the 'RTSA' package. The risk of bias plots were generated using the

'robvis' package [32], and other plots were constructed using the 'ggplot2' package.

2.7 Certainty of evidence

The certainty of evidence for each outcome was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach [33], categorizing it into four levels (high, moderate, low, or very low) based on five domains: risk of bias, inconsistency, indirectness, imprecision, and publication bias.

3 Results

3.1 Characteristics of included studies

Our study selection process is shown in the PRISMA flow diagram (Fig. 1). We initially searched 35,861 records. After screening and exclusion, we finally included 18 trials [10–14, 17–21, 29, 34–43] published between 2017 and 2026 involving 16,573 patients.

Geographically, the trials were widely distributed, with ten studies conducted in China [10, 11, 17, 19, 37–40, 42, 43], three in Germany [12, 34, 36], and one each in France [20], Italy [21], the Netherlands [14], and Switzerland [18]. In addition, the POISE-3 trial was large-scale multinational trials, and three publications were identified from the same randomized population [13, 29, 35]. The sample sizes of the included studies varied, ranging from 98 to 7,490 patients. The study populations primarily consisted of elderly patients undergoing noncardiac surgeries. Notably, a substantial proportion of the enrolled patients were classified as having an ASA physical status of III or IV, indicating a high baseline clinical risk profile. In addition, many patients had hypertension before surgery, and other preoperative comorbidities were listed in the Supplementary Table S4.

Regarding the intensive strategies, seven trials utilized a fixed higher-target strategy [10, 13, 17–19, 38, 42], and the other eleven trials used an individualized higher-target strategy [11, 12, 14, 20, 21, 34, 36, 37, 39–41]. Detailed characteristics, baseline demographics, and specific outcomes reported for each included trial are summarized in Table 1.

3.2 Risk of bias assessment

The RoB2 assessment revealed a low risk of bias in 12 included articles, some concerns regarding the risk of bias in three articles and a high risk of bias in three articles (Fig. 2).

Regarding bias arising from the randomization process, most studies were rated as low risk, with three trials showing some concerns [36, 39, 40]. Due to the nature of intraoperative hemodynamic interventions, double-blinding was not feasible in most trials, which could theoretically lead to bias due to deviations from intended

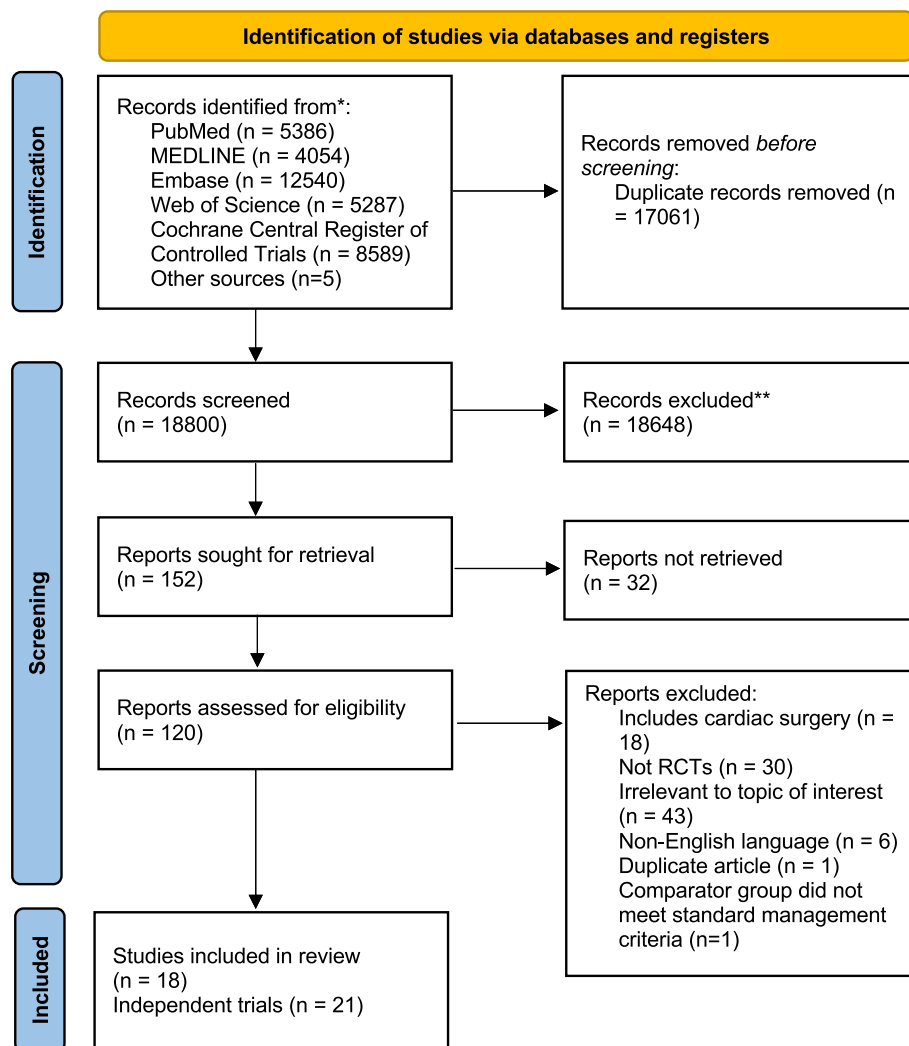


Fig. 1 The PRISMA flow diagram. Three reports, two by Marcucci et al. [29, 35] and one by Khader et al. [41], were prespecified secondary publications of included parent trials and were therefore not counted as separate trials. Data from these reports were included only for the relevant outcomes

interventions. However, the majority of studies mitigated bias in measurement of the outcome by implementing blinded outcome assessment. Only two trials were rated as high risk in this domain because assessors were potentially aware of the assigned interventions [19, 43]. Regarding bias due to missing outcome data, three trials were rated as high risk [19, 34, 43].

3.3 Primary outcomes

3.3.1 The incidence of postoperative myocardial injury

A total of 9 studies including 14,606 patients (7,297 in the intensive group and 7,309 in the standard group) reported data on the incidence of postoperative myocardial injury [12–14, 18, 20, 34, 36, 38, 42]. There was no statistically significant difference in the incidence of

myocardial injury between the intensive and standard groups (RR=1.02, 95% CI [0.92, 1.13]; $P=0.676$), with no heterogeneity ($I^2=0\%$, $P=0.481$) (Fig. 3A).

Subgroup analyses showed no significant difference in myocardial injury risk within either the fixed (4 studies [13, 18, 38, 42]; RR=0.99, 95% CI [0.84, 1.17]; $I^2=0\%$) or individualized (5 studies [12, 14, 20, 34, 36]; RR=1.09, 95% CI [0.87, 1.36]; $I^2=0\%$) subgroup.

To detect the effect of each study on outcomes, sensitivity analysis was performed by deleting a study one by one, and the combined results showed no significant changes, denoting that the results were relatively steady (Supplementary Fig. 1A, Supplementary Material 3). Furthermore, following the exclusion of one study identified with a high risk of bias (2024-Nicklas) [34], the

Table 1 Characteristics of the included studies

References	Country	Sample size(n, male/female)	Age (years), Mean $\pm$ SD or Median (IQR)		Type of surgery	ASA physical status $\geq$ III, n/N		Intensive Strategy Type	Intensive- management strategy	Standard- management strategy	Outcomes
			Intensive	Standard		Intensive	Standard				
2017-Futier [20] (INPRESS trial) ^s	France	292 (248/44)	69.7 $\pm$ 7.1	70.0 $\pm$ 7.5	surgery under general anesthesia	85/147	91/145	Individualized higher-target strategy	SBP was targeted to remain within $\pm$ 10% of the reference value	received intravenous ephedrine administered, if SBP below 80 mmHg or lower than 40% from the patient's reference value	a, c–k
2017-Wu [10] (Multi-arm trials) [†]	China	646 (424/222)	73.5 $\pm$ 5.5	73 $\pm$ 7	elective major gastrointestinal surgery	62/416	32/230	Fixed higher-target strategy	80 to 110 mmHg	65–79 mmHg	c–e, h–j
2018-Langer [21]	Italy	101 (53/48)	80 $\pm$ 4	80 $\pm$ 4	elective noncardiac surgery	19/51	17/50	Individualized higher-target strategy	90% of baseline MAP	no target was specified	b, d, i, k
2020-Xu [11]	China	150 (60/90)	68.5 $\pm$ 7.1	69 $\pm$ 8	hip arthroplasty	26/100	12/50	Individualized higher-target strategy	10% below the baseline to 10% above the baseline	10% to 20% below the baseline	b, k
2021-Hu [17]	China	298 (124/174)	72 (68–77)	73 (68–77)	non-cardiothoracic surgery	NA	NA	Fixed higher-target strategy	90–100 mmHg	60–70 mmHg	b, d, f, k
2021-Wanner [18]	Switzerland	451 (368/83)	70 $\pm$ 8	69 $\pm$ 10	major noncardiac surgery	149/225	145/226	Fixed higher-target strategy	MAP $\geq$ 75 mmHg	MAP $\geq$ 60 mmHg	a, c–f
2022-Zhang [19]	China	108 (71/37)	71 (67.5–76)	70 (68–75)	gastrointestinal laparoscopic surgery	12/53	11/55	Fixed higher-target strategy	86–100 mmHg	65–85 mmHg	b, k
2023-Marcucci [13, 29, 35] [*] (POISE-3 trial)	Multiple countries	7490 (4,171/3,319)	69.8 $\pm$ 9.3	69.8 $\pm$ 9.3	inpatient noncardiac surgery	NA	NA	Fixed higher-target strategy	MAP $\geq$ 80 mmHg	MAP $\geq$ 60 mmHg	a–e, k
2024-Nicklas [34]	Germany	328 (206/122)	66 (58–72)	66 (60–73)	elective major noncardiac surgery	67/166	79/162	Individualized higher-target strategy	a range of the preoperative baseline MAP + 10 mmHg	above 65 mmHg	a–d, i, k
2024-Berg-holz [36, 41] [#] (IMPROVE-pilot)	Germany	98 (44/54)	69 (57, 78)	69 (55, 77)	elective major non-cardiac surgery	31/53	24/45	Individualized higher-target strategy	maintaining intraoperative MAP above the pre-operative mean nighttime MAP	maintaining intraoperative MAP above 65 mmHg	a–c, i

Table 1 (continued)

References	Country	Sample size(n, male/female)	Age (years), Mean $\pm$ SD or Median (IQR)		Type of surgery	ASA physical status $\geq$ III, n/N		Intensive Strategy Type	Intensive management strategy	Standard management strategy	Outcomes
			Intensive	Standard		Intensive	Standard				
2025-Pang [37]	China	179 (115/64)	69 $\pm$ 6	68 $\pm$ 5	elective laparoscopic gastric and intestinal tumor resection surgery	52/89	46/90	Individualized higher-target strategy	SBP within -20% and $+10\%$ if baseline SBP was ≥ 130 mmHg or diastolic blood pressure was ≥ 80 mmHg, or otherwise, to target SBP within $\pm 10\%$ of the baseline value	SBP ≥ 90 mmHg and MAP ≥ 65 mmHg	b–d, i, k
2025-Zhao [38]	China	1,477 (1,086/391)	68.9 $\pm$ 8.2	68.2 $\pm$ 8.2	elective major inpatient abdominal surgery	454/739	417/738	Fixed higher-target strategy	MAP ≥ 80 mmHg	MAP ≥ 65 mmHg or 60% of preoperative baseline pressure	a–h, j
2025-Fang [39]	China	100 (64/36)	67.0 (63.0–70.0)	69.0 (64.2–73.0)	major surgery	29/50	26/50	Individualized higher-target strategy	MAP was targeted to remain within $\pm 20\%$ of the reference value	MAP ≥ 65 mmHg	c, h, j, k
2025-Kant [14]	The Netherlands	3,247 (1,509/1,738)	59 (44–69)	59 (45–69)	elective noncardiac surgery	409/1,618	413/1,629	Individualized higher-target strategy	low risk ≥ 70 mmHg; intermediate risk ≥ 80 mmHg; high risk ≥ 90 mmHg	avoid sustained MAP values lower than 65 mmHg	a, c, d, i, k
2025-Saugel [12] (IMPROVE-multi)	Germany	1,134 (747/387)	67 (59–73)	66 (59–73)	elective major abdominal surgery	320/567	323/567	Individualized higher-target strategy	keep MAP at least at the individual preoperative mean nighttime MAP	the target MAP was 65 mmHg or higher	a, c, d, i, j
2025-Wang [42]	China	142 (33/109)	70 (68–74)	69 (67–74)	elective unilateral total knee arthroplasty	28/71	25/71	Fixed higher-target strategy	MAP: 85–100 mmHg	MAP: 65–85 mmHg	a, c, d, k
2025-Huang [40]	China	188 (48/140)	81 $\pm$ 7	83 $\pm$ 7	hip fracture repair surgery	11/94	6/94	Individualized higher-target strategy	Blood pressure $> 80\%$ of preoperative value	avoiding hypotension, i.e. 90/60 mm Hg	b, d, i, k

Table 1 (continued)

References	Country	Sample size(<i>n</i> , male/female)	Age (years), Mean ± SD or Median (IQR)		Type of surgery	ASA physical status ≥III, <i>n</i> / <i>N</i>		Intensive Strategy Type	Intensive-management strategy	Standard-management strategy	Outcomes
			Intensive	Standard		Intensive	Standard				
2026-Li [43]	China	144 (91/53)	70.4 ± 6.3	69.4 ± 6.3	radical gastrectomy or colorectal cancer resection	5/74	5/70	Individualized higher-target strategy	systolic blood pressure or MAP was maintained within ±10% and ±20% of baseline	MAP was maintained at ≥ 65 mmHg	c, e, g–i, k

Note: Outcomes were coded as follows: *a* myocardial injury, *b* postoperative delirium, *c* acute kidney injury, *d* mortality, *e* stroke, *f* heart failure, *g* acute respiratory distress syndrome, *h* pneumonia, *i* intensive care unit admission, *j* surgical site infection, and *k* hospital length of stay

Unless otherwise specified, the sample sizes shown represent the numbers of participants randomized in each trial. When the denominators in the forest plots differ from those presented here, the forest-plot denominators represent the outcome-specific populations included in the respective analyses. “Enrolled” refers to participants who provided informed consent and entered the study; “randomized” refers to participants who were formally assigned to treatment groups; and “analyzed” or “available” refers to participants whose data were included in the analysis of a specific outcome.

* POISE-3 trial (2023-Marcucci, *n* = 7,490) [13]. Three publications arose from the same randomized population. Cardiovascular outcome data were obtained from the parent POISE-3 trial report (2023-Marcucci, *n* = 7,490) [13]; acute kidney injury data were obtained from the prespecified kidney substudy (2024-Marcucci, *n* = 7,307) [35]; and postoperative delirium data were obtained from the prespecified cogPOISE-3 substudy (2025-Marcucci, *n* = 2,603) [29]. In accordance with guidance in the Cochrane Handbook for Systematic Reviews of Interventions regarding multiple reports of the same study, the three reports were treated as one trial. The sample size shown in this table reflect the parent trial population (*n* = 7,490), whereas each outcome-specific meta-analysis used data from the relevant report. Each participant was counted only once within any individual outcome-specific meta-analysis

IMPROVE-pilot trial (2024-Bergholz, 105 participants were enrolled) [36]. Postoperative delirium data were obtained from the prespecified single-center substudy, which included 49 participants in the final analysis (2025-Khader, *n* = 49) [41]; data for all other eligible outcomes were obtained from the parent trial report. The two reports were treated as one trial in accordance with guidance in the Cochrane Handbook for Systematic Reviews of Interventions. Each participant was counted only once within any individual outcome-specific meta-analysis. The IMPROVE-multi trial (2025-Saugel, *n* = 1,134) [12] enrolled an independent, nonoverlapping population and was therefore treated as a separate trial

† Multi-arm trials. For the study... by 2017-Wu [10], participants were randomized to three intraoperative MAP target groups: Level I, 65–79 mmHg; Level II, 80–95 mmHg; and Level III, 96–110 mmHg. For the meta-analysis, Levels II and III were combined as the intensive-management group, whereas Level I served as the standard-management group. For the study by 2020-Xu [11], participants were randomized to three groups defined relative to baseline MAP: group D, 10%–20% below baseline; group M, from 10% below baseline to baseline; and group H, from baseline to 10% above baseline. Groups M and H were combined as the intensive-management group, whereas group D served as the standard-management group. For both trials, patient characteristics in this table are presented by original randomization arm; the statistical methods used to combine arms for pooled analyses are described in the Statistical Analysis section

§ INPRESS trial. For the study by 2017-Futier [20], the resting blood pressure recorded during the preoperative anesthesiology consultation was retrieved from the patient’s medical record and used as the reference value. ASA American Society of Anesthesiologists, ICU intensive care unit, MAP mean arterial pressure, SBP systolic blood pressure

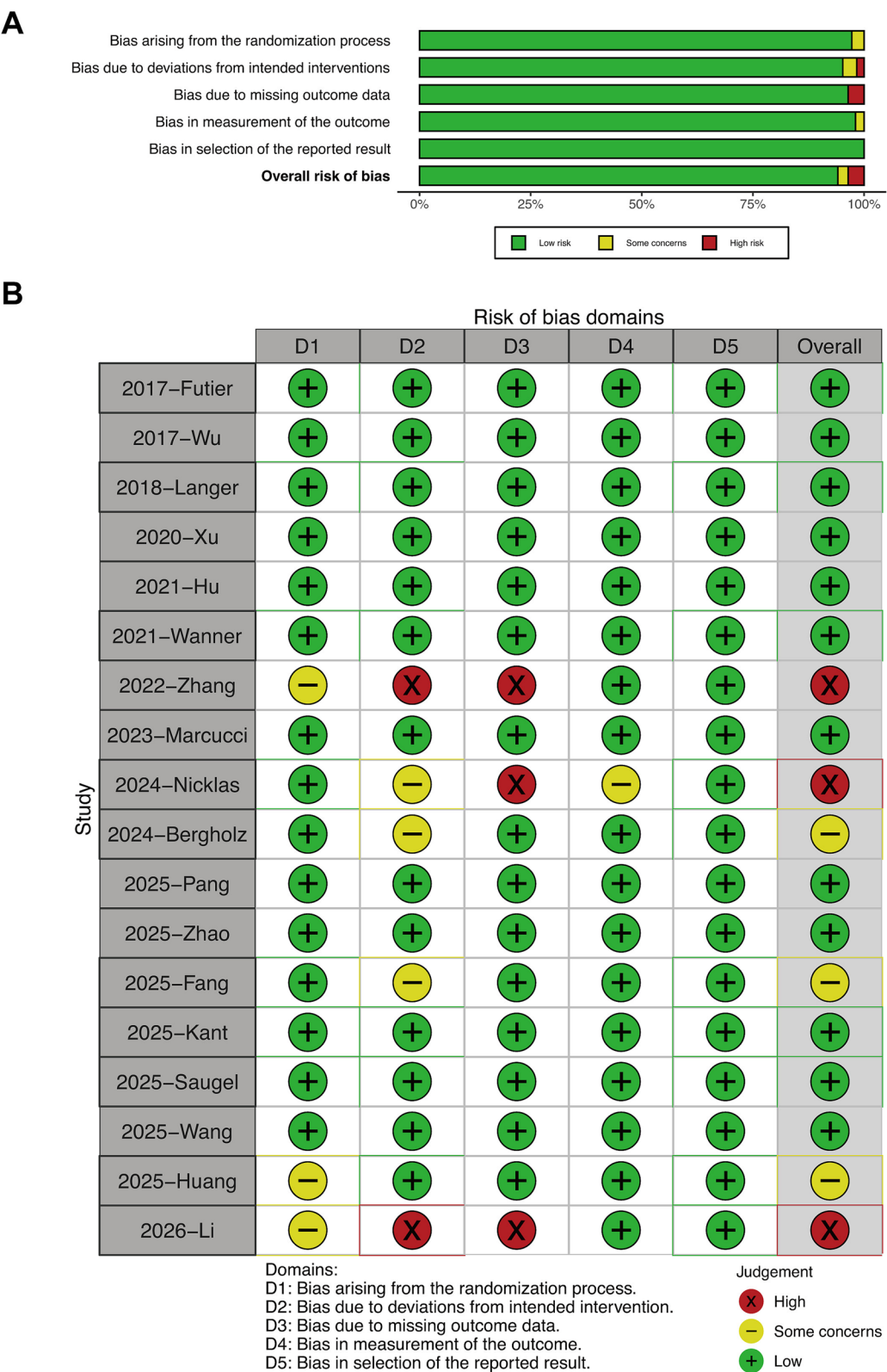


Fig. 2 Risk-of-bias assessment of the included randomized controlled trials. **A** Risk-of-bias summary; **B** Traffic-light plot

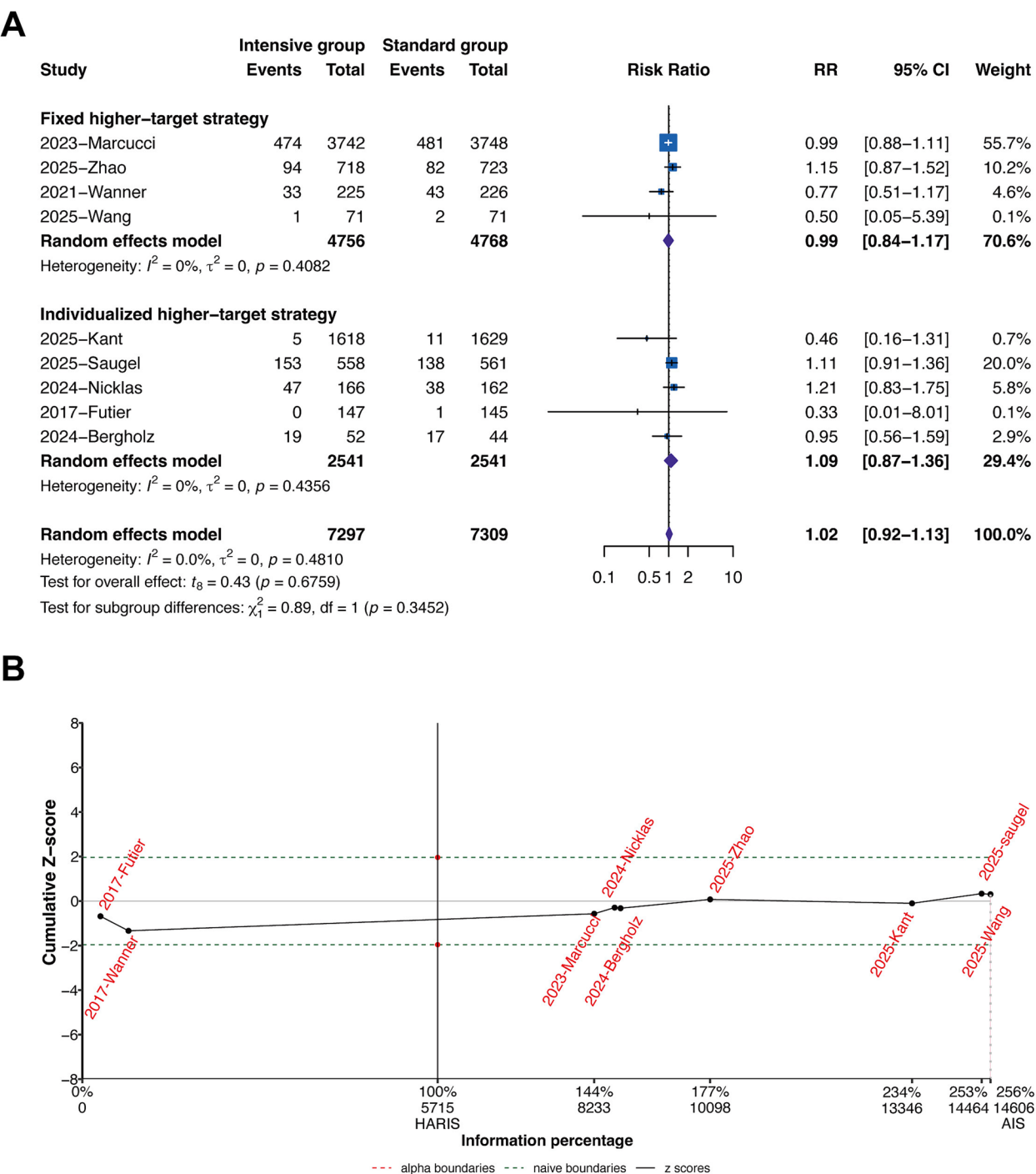


Fig. 3 Forest plot and trial sequential analysis of the effect of intensive intraoperative blood pressure management on postoperative myocardial injury. **A** Forest plot stratified by target strategy. Squares represent the RRs for individual studies, with the size of each square proportional to the study's statistical weight. The solid vertical line indicates no effect ($RR = 1.0$), and the diamonds represent the pooled subgroup and overall estimates. **B** Trial sequential analysis. The cumulative Z-curve (solid black line) represents the accumulation of evidence as trials are sequentially included. The horizontal green dashed lines indicate the conventional unadjusted significance boundaries ($Z = \pm 1.96$; two-sided $P = 0.05$). The outward-sloping red dashed curves indicate the trial sequential monitoring boundaries. The solid vertical black line indicates the HARIS. AIS accrued information size, CI confidence interval, HARIS heterogeneity-adjusted required information size, RR risk ratio

summarized estimate remained highly stable and non-significant ($RR=1.01$, 95% CI [0.91, 1.12]; $P=0.854$), with no heterogeneity ($I^2=0\%$, $P=0.465$) (Supplementary Fig. 1B).

Visual inspection of the contour-enhanced funnel plot revealed a symmetrical distribution of the study effect sizes around the pooled estimate (Supplementary Fig. S2A). Due to the limited number of included trials ($n=9$), formal statistical assessment for publication bias via Egger's test was not performed.

TSA analysis showed that the cumulative Z-curve remained within the conventional unadjusted significance boundaries and never approached the alpha boundaries, while the AIS reached 256% of the HARIS (Fig. 3B). These findings indicate that intensive intraoperative blood pressure management does not reduce the incidence of postoperative myocardial injury.

3.3.2 The incidence of postoperative delirium

Data on the incidence of POD were extracted from 10 studies [11, 17, 19, 21, 29, 34, 37, 38, 40, 41], which included a total of 5,478 patients (2,785 in the intensive group and 2,693 in the standard group). The pooled RR showed that the intensive group had a lower risk of POD compared to the standard group ($RR=0.72$, 95% CI [0.55, 0.93]; $P=0.019$), with low heterogeneity ($I^2=27.7\%$, $P=0.19$) (Fig. 4A).

Subgroup analysis based on higher-target strategy revealed that the individualized higher-target strategy decreased the incidence of POD (6 studies [11, 21, 34, 37, 40, 41]; $RR=0.62$, 95% CI [0.46, 0.84]; $I^2=0\%$), whereas the fixed higher-target group showed no difference compared to the standard group (4 studies [17, 19, 29, 38]; $RR=0.79$, 95% CI [0.42, 1.48]; $I^2=59.5\%$). However, the test for subgroup differences indicated no significant interaction ($P=0.314$).

Leave-one-out sensitivity analysis revealed that while the direction of the protective effect generally persisted, the statistical significance of the overall estimate exhibited fragility (Supplementary Fig. S3A). Specifically, exclusion of the study by Hu et al. [17] resulted in a pooled effect estimate that was not statistically significant ($RR=0.85$, 95% CI [0.67, 1.07]; $P=0.139$). An additional sensitivity analysis was performed after excluding two studies judged to be at high risk of bias: those by Zhang et al. [19] and Nicklas et al. [34]. The pooled analysis of the remaining 8 studies maintained a significant difference in the incidence of POD between the two groups ($RR=0.68$, 95% CI [0.49, 0.95]; $P=0.029$), with a moderate heterogeneity ($I^2=41.6\%$, $P=0.101$) (Supplementary Fig. S3B).

Visual inspection of the contour-enhanced funnel plot for POD suggested slight asymmetry in the distribution

of the included studies (Supplementary Fig. S2B). However, Egger's linear regression test indicated no statistically significant evidence of publication bias ($P=0.211$).

TSA results indicated the cumulative Z-curve crossed the alpha boundary for benefit, and the AIS reached the HARIS (Fig. 4B). These findings suggest that, under the prespecified 30% RRR assumption, the accumulated evidence is consistent with a reduction in POD.

3.3.3 The incidence of postoperative AKI

Thirteen studies (involving 15,143 patients, including 7,670 in the intensive group and 7,473 in the standard group) reported data on the incidence of AKI [10, 12, 14, 18, 20, 34–39, 42, 43]. A meta-analysis showed no statistically significant difference in the incidence of AKI between the intensive and standard groups ($RR=0.92$, 95% CI [0.79%, 1.06%]; $P=0.210$), with low heterogeneity ($I^2=35.7\%$, $P=0.097$) (Fig. 5A).

No significant difference was observed in both the fixed (5 studies [10, 18, 35, 38, 42]; $RR=1.00$, 95% CI [0.87, 1.16]; $I^2=4.1\%$) and individualized higher-target groups (8 studies [12, 14, 20, 34, 36, 37, 39, 43]; $RR=0.84$, 95% CI [0.63, 1.10]; $I^2=38.6\%$).

Sensitivity analysis by eliminating studies one by one showed no significant change in the pooled results (Supplementary Fig. S4A). Furthermore, after excluding two studies with high risk of bias—those by Nicklas et al. [34] and Li et al. [43]—the pooled estimate remained similar and was not statistically significant ($RR=0.91$, 95% CI [0.76, 1.08]; $P=0.230$), with moderate heterogeneity ($I^2=46.4\%$, $P=0.045$; Supplementary Fig. S4B).

Visual examination of the contour-enhanced funnel plot revealed a symmetrical distribution of effect sizes across studies around the pooled estimate (Supplementary Fig. S2C), and the Egger's linear regression test showed no statistically significant difference ($P=0.059$).

For postoperative AKI, the cumulative Z-curve initially crossed the conventional unadjusted significance boundary, suggesting a possible early benefit with limited evidence. However, with the sequential inclusion of subsequent trials, the curve returned to and remained within the naive significance boundaries, never approaching the trial sequential monitoring boundaries (Fig. 5B). Importantly, the AIS exceeded the HARIS, indicating that a benefit of the prespecified magnitude (20% RRR) can be excluded, although a smaller benefit cannot be ruled out. These findings suggest that intensive management is unlikely to reduce postoperative AKI by the prespecified magnitude.

3.4 Secondary outcomes

There were no significant differences between the intensive and standard groups in most secondary outcomes

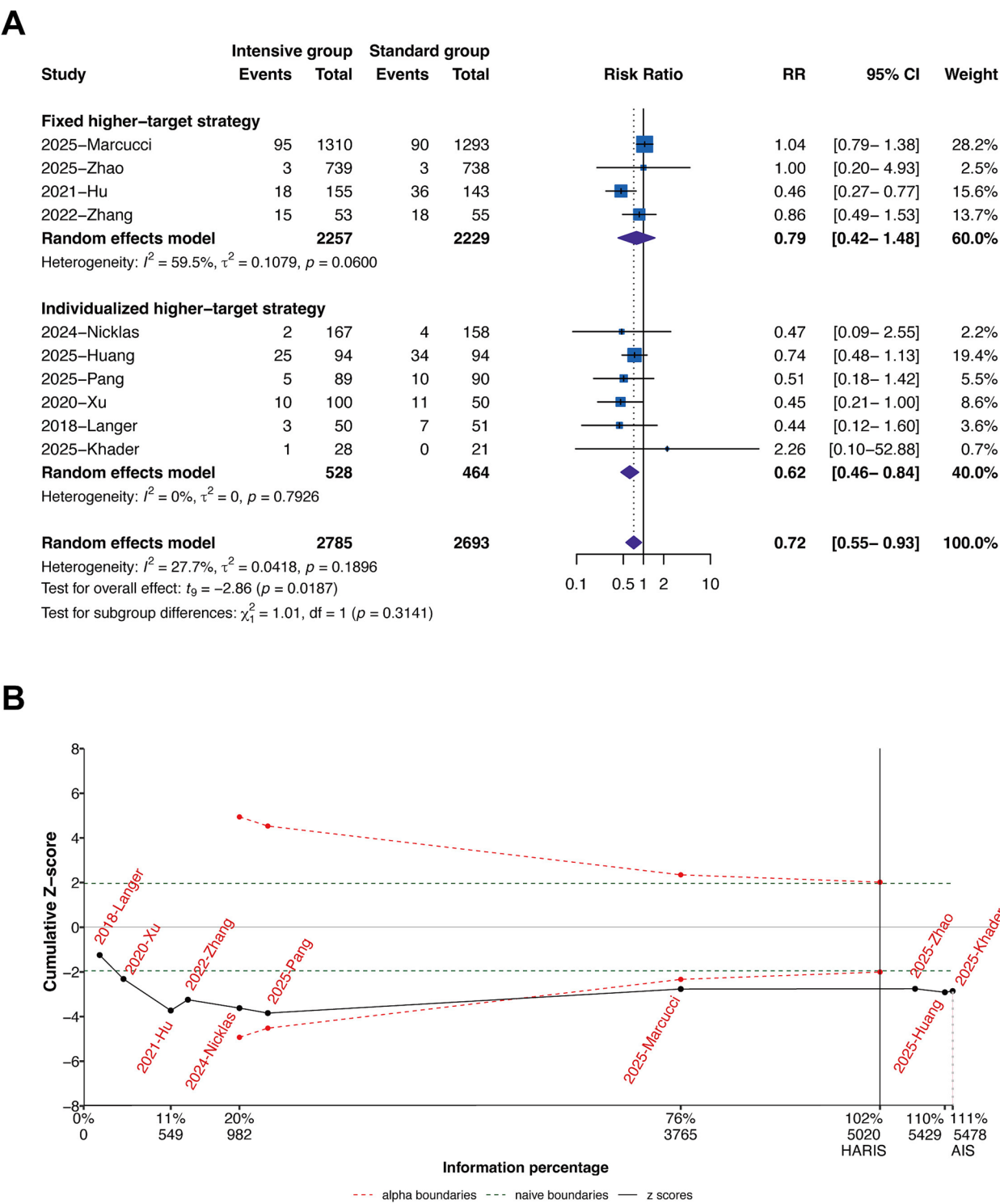


Fig. 4 Forest plot and trial sequential analysis of the effect of intensive intraoperative blood pressure management on the risk of POD. **A** Forest plot stratified by target strategy. Squares represent the RRs for individual studies, with the size of each square proportional to the study's statistical weight. The solid vertical line indicates no effect (RR=1.0), and the diamonds represent the pooled subgroup and overall estimates. **B** Trial sequential analysis. The cumulative Z-curve (solid black line) represents the accumulation of evidence as trials are sequentially included. The horizontal green dashed lines indicate the conventional, unadjusted significance boundaries ($Z = \pm 1.96$, two-sided $P=0.05$). The outward-sloping red dashed curves indicate the trial sequential monitoring boundaries. The solid vertical black line indicates the HARIS. *POD* postoperative delirium

(Fig. 6). Specifically, intensive management did not affect postoperative mortality (RR=0.99, 95% CI [0.83, 1.17]; $P=0.862$; $I^2=0\%$; 13 studies [10, 12–14, 17, 18, 20, 21, 34, 37, 38, 40, 42], 15,989 patients), stroke (RR=1.04, 95% CI [0.74, 1.47]; $P=0.729$; $I^2=0\%$; 6 studies [10, 13, 18, 20, 38, 43], 10,500 patients), heart failure (RR=1.03, 95% CI [0.27, 3.91]; $P=0.943$; $I^2=13.6\%$; 4 studies [17, 18, 20, 38], 2,518 patients), ARDS (RR=0.94, 95% CI [0.46, 1.94]; $P=0.766$; $I^2=0\%$; 3 studies [20, 38, 43], 1,913 patients), and pneumonia (RR=0.72, 95% CI [0.49, 1.08]; $P=0.090$; $I^2=6.9\%$; 5 studies [10, 20, 38, 39, 43], 2,659 patients). Similarly, no significant differences were observed in the rates of admission to the ICU (RR=1.01, 95% CI [0.90, 1.14]; $P=0.853$; $I^2=5.5\%$; 10 studies [10, 12, 14, 20, 21, 34, 36, 37, 40, 43], 6,357 patients) or hospital LOS (MD=−0.10 days, 95% CI [−0.50, 0.30] days; $P=0.585$; $I^2=49.7\%$; 13 studies [11, 13, 14, 17, 19–21, 34, 37, 39, 40, 42, 43], 12,767 patients, Supplementary Fig. 5). However, the incidence of SSI was significantly lower in the intensive group (RR=0.64, 95% CI [0.53, 0.76]; $P=0.002$; $I^2=0\%$; 5 studies [10, 12, 20, 38, 39], 3,649 patients). This reduction remained stable in the leave-one-out sensitivity analysis, in which no single trial materially altered the pooled estimate (Supplementary Fig. 6).

3.5 GRADE assessment

The certainty of evidence for each predefined outcome was rated with the GRADE framework and was summarised, together with anticipated absolute effects per 1,000 patients, in the summary of findings table (Table 2). Since all included studies were RCTs, each outcome started at high certainty, and was assessed across five domains (risk of bias, inconsistency, indirectness, imprecision, and publication bias).

Regarding the primary outcomes, the certainty of evidence for postoperative myocardial injury and AKI was maintained at high. Although trials with a high risk of bias were included in these analyses, we did not downgrade for this domain. These high-risk trials contributed minimal statistical weight, and the pooled estimates were overwhelmingly driven by low-risk trials. Our sensitivity analyses showed that excluding these high-risk trials had a negligible impact on robust null effects. Conversely, the certainty of evidence for POD was downgraded by

one level to moderate due to imprecision. Although the primary pooled estimate indicated a beneficial effect and was based on a large accrued sample size, the certainty of the evidence was downgraded because of fragility in the leave-one-out sensitivity analysis: exclusion of the small study by Hu et al. [17] resulted in an effect estimate that was no longer statistically significant.

Among the secondary outcomes, the certainty of evidence for mortality, admission to ICU and hospital LOS was rated as high, as high-risk trials had a negligible impact on these null estimates. The certainty of evidence for postoperative stroke and pneumonia was downgraded to moderate due to imprecision, driven by the low total number of events resulting in wide CIs that cross the line of no effect. The evidence for postoperative heart failure was downgraded to low due to serious imprecision, characterized by an exceptionally low event rate and an extremely wide CI crossing the line of no effect. For ARDS, the certainty of evidence was graded as low due to a combination of risk of bias and imprecision. The trial reported by Li et al. [43], which was judged to be at high risk of bias, contributed substantial weight to this analysis (21.5%). In addition, the small total number of surgical site infection (SSI) events resulted in a wide confidence interval. The certainty of the evidence for SSI was downgraded by one level to moderate. Although the pooled estimate was statistically robust with no heterogeneity ($I^2=0\%$), SSI was a secondary outcome derived from only five trials. Its ascertainment is likely to have varied across studies, and it is strongly influenced by perioperative factors other than blood pressure.

4 Discussion

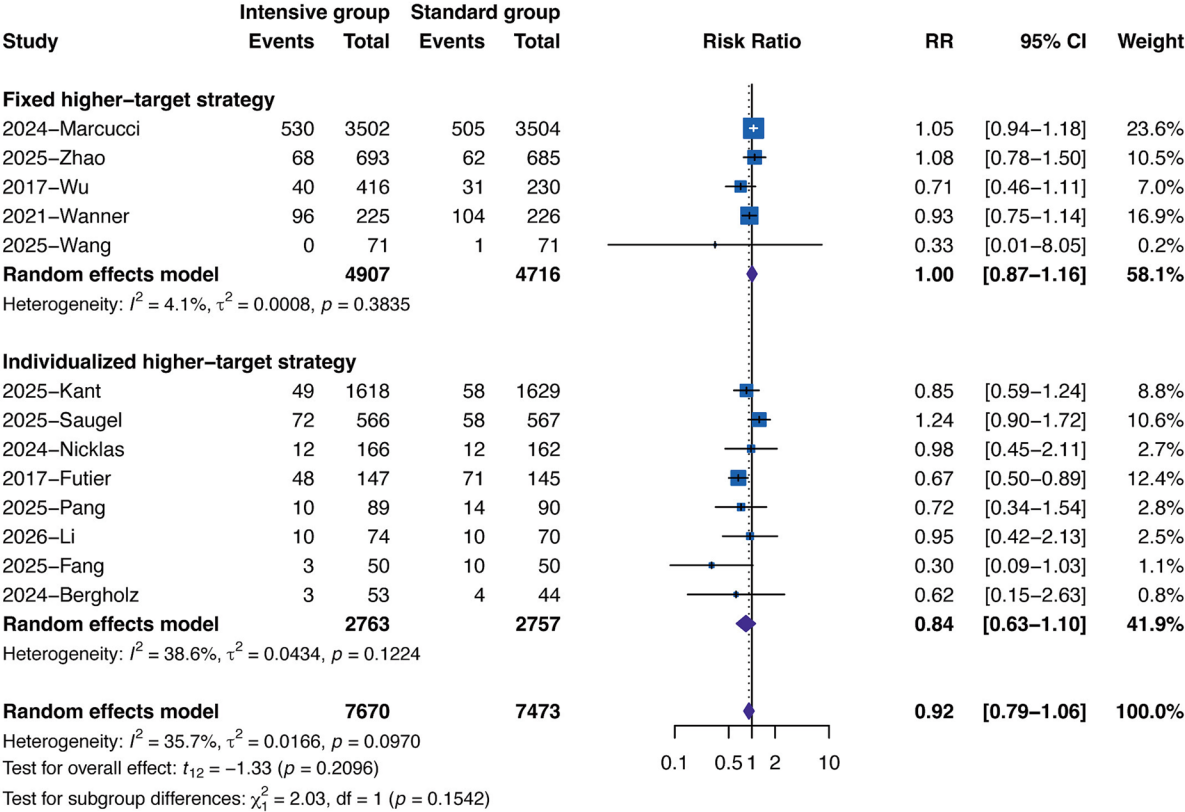
4.1 Principal findings

To our knowledge, this is the most comprehensive systematic review and meta-analysis to date evaluating this intervention. In this meta-analysis of 18 RCTs involving 16,573 patients undergoing noncardiac surgery, we found that intensive management was associated with lower risks of POD and SSI, but had no significant effect on myocardial injury, AKI and other outcomes. Furthermore, our subgroup analyses indicated that a reduction in POD was observed within the individualized subgroup,

(See figure on next page.)

Fig. 5 Forest plot and trial sequential analysis of the effect of intensive intraoperative blood pressure management on the risk of AKI. **A** Forest plot stratified by target strategy. Squares represent the RRs for individual studies, with the size of each square proportional to the study's statistical weight. The solid vertical line indicates no effect (RR = 1.0), and the diamonds represent the pooled subgroup and overall estimates. **B** Trial sequential analysis. The cumulative Z-curve (solid black line) represents the accumulation of evidence as trials are sequentially included. The horizontal green dashed lines indicate the conventional unadjusted significance boundaries ($Z = \pm 1.96$, two-sided $P = 0.05$). The outward-sloping red dashed curves indicate the trial sequential monitoring boundaries. The solid vertical black line indicates the HARIS

A



B

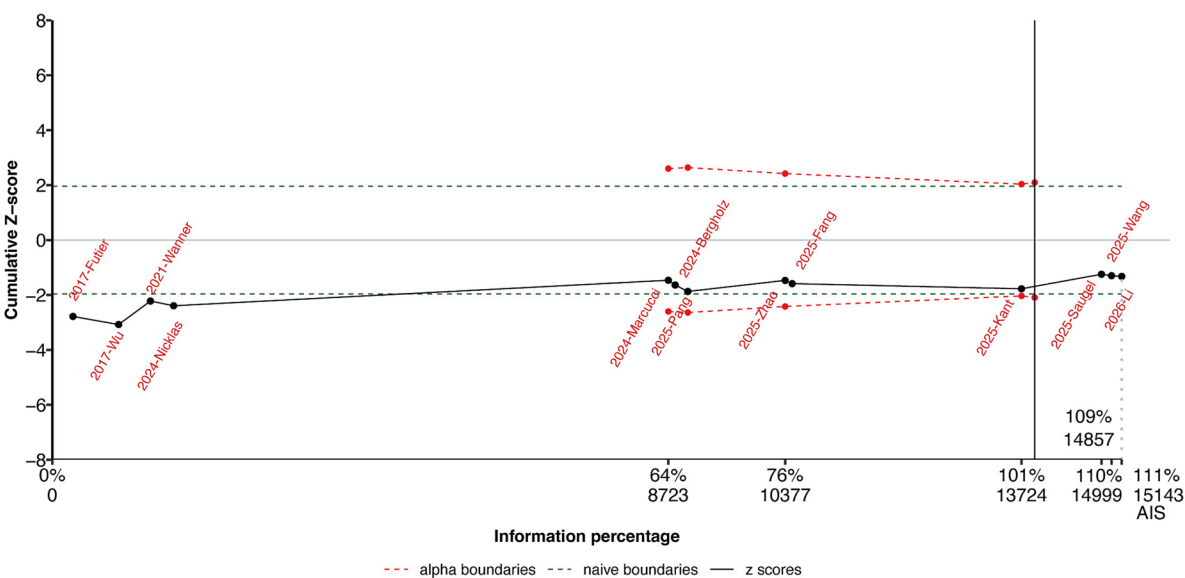


Fig. 5 (See legend on previous page.)

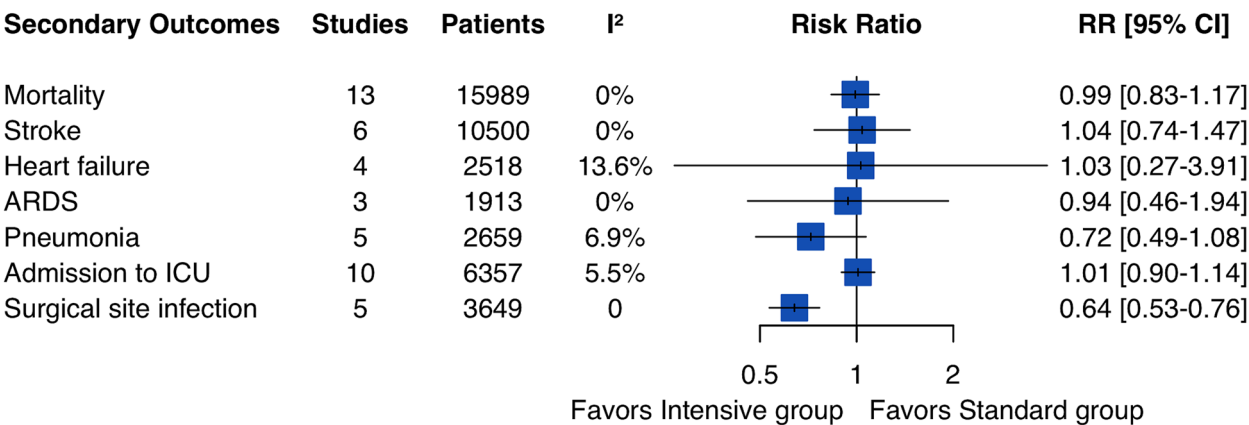


Fig. 6 Summary forest plots of the predefined binary secondary outcomes. Pooled RRs and 95% CIs compare intensive intraoperative blood pressure management with standard management

although the test for subgroup differences was not statistically significant.

Regarding postoperative myocardial injury and AKI, our meta-analysis found that intensive management did not reduce their risks. TSA further corroborated this neutral finding, suggesting that additional trials are unlikely to alter this conclusion. For the majority of patients undergoing noncardiac surgery, the standard target (MAP $\geq$ 65 mmHg) is sufficiently safe and effective.

Several factors may explain these neutral results. First, through a review of the hemodynamic data from the included trials, we found a lack of substantial hemodynamic separation between the two groups (Table 3). Despite substantial differences in the protocol-defined intraoperative blood pressure targets, the between-group differences in the achieved MAP were only 6 mmHg in the trial by Futier et al. [20] and 7 mmHg in the trial by Langer et al. [21]). Moreover, patients in the standard-management groups received closely monitored care and had limited exposure to severe intraoperative hypotension. For instance, in the BP-CARES trial, the median duration of MAP < 65 mmHg in the standard group was only 8 min [38]. Because myocardial injury and AKI are related to intraoperative hypotension, they are affected by this lack of separation. This insufficient difference in achieved blood pressure levels likely diluted the potential treatment effect, making it difficult to detect differences in clinical outcomes. The neutral results for these two outcomes may therefore reflect the small achieved difference rather than a true absence of effect. Second, inconsistencies in preoperative antihypertensive management and the lack of comprehensive postoperative blood pressure management may have obscured benefits. Furthermore, our meta-analysis focused exclusively on intraoperative interventions due to the inherent design of the

included RCTs. Indeed, evidence from a VISION sub-study showed that the association between postoperative hypotension and myocardial injury was stronger than that of intraoperative hypotension [44]. The lack of comprehensive postoperative blood pressure management might have masked the potential benefits of the intensive management. Third, elevating blood pressure does not necessarily equate to improving tissue perfusion. Pursuing a higher MAP target often requires increased exposure to vasopressors (Supplementary Table 5), which may induce microcirculatory vasoconstriction and offset the benefit of improved perfusion pressure [45]. Therefore, simply raising blood pressure without correcting the underlying pathophysiology, such as using vasopressors for vasodilation and fluid optimization for hypovolemia, may fail to interrupt the injury process [2].

Importantly, our meta-analysis showed that the intensive strategy was associated with a lower POD risk in elderly patients undergoing noncardiac surgery. The aging brain is highly susceptible to hypoperfusion due to microvascular fragility. Furthermore, in those with chronic vascular comorbidities, adaptive remodeling frequently shifts the cerebral autoregulation curve to the right and elevates its lower limit. Consequently, standard intraoperative MAP targets may be insufficient, exposing these patients to masked cerebral ischemia. Maintaining a higher intraoperative MAP theoretically accommodates this altered autoregulatory range, ensures adequate cortical microperfusion, and prevents the secondary cascade of neuroinflammation and blood–brain barrier breakdown, thereby exerting a neuroprotective effect [46]. The brain, unlike the kidneys or myocardium, benefits from this strategy because the blood–brain barrier protects cerebral microvasculature from alpha-agonist vasoconstriction. Consequently, elevating MAP improves

Table 2 Summary of findings for postoperative outcomes comparing intensive with standard intraoperative blood pressure management

Outcome	No. of participants (studies)	Relative effect, RR/MD (95% CI)	Assumed risk with standard care (per 1,000)	Corresponding risk with intensive management (per 1,000) (95% CI)	Risk difference (per 1,000) (95% CI)	Heterogeneity (I ²)	Certainty of the evidence (GRADE)
Myocardial Injury	14,606 (9)	RR 1.02 (0.92–1.13)	111	113 (102–126)	+ 2 (–9 to +15)	0%	⊕⊕⊕⊕ High ^{a,b}
Delirium	5,478 (10)	RR 0.72 (0.55–0.93)	79	57 (44–74)	– 22 (–35 to –5)	27.7%	⊕⊕⊕⊖ Moderate ^f
Acute Kidney Injury	15,143 (13)	RR 0.92 (0.79–1.06)	126	116 (99–133)	– 10 (–27 to +7)	35.7%	⊕⊕⊕⊕ High ^{a,b}
Mortality	15,989 (13)	RR 0.99 (0.83–1.17)	20	20 (17–24)	0 (–3 to +4)	0%	⊕⊕⊕⊕ High ^{a,b}
Stroke	10,500 (6)	RR 1.04 (0.74–1.47)	4	4 (3–6)	0 (–1 to +2)	0%	⊕⊕⊕⊖ Moderate ^c
Heart Failure	2,518 (4)	RR 1.03 (0.27–3.91)	15	16 (4–59)	+ 1 (–11 to +44)	13.6%	⊕⊕⊖⊖ Low ^d
ARDS	1,913 (3)	RR 0.94 (0.46–1.94)	23	22 (11–45)	– 1 (–12 to +22)	0%	⊕⊕⊖⊖ Low ^e
Pneumonia	2,659 (5)	RR 0.72 (0.49–1.08)	88	64 (43–95)	– 24 (–45 to +7)	6.9%	⊕⊕⊕⊖ Moderate ^c
Admission to ICU	6,357 (10)	RR 1.01 (0.90–1.14)	163	165 (147–186)	+ 2 (–16 to +23)	5.5%	⊕⊕⊕⊕ High ^{a,b}
Surgical Site Infection	3,649 (5)	RR 0.64 (0.53–0.76)	60	38 (32–46)	– 22 (–28 to –14)	0%	⊕⊕⊕⊖ Moderate ^g
Hospital LOS	12,767 (13)	MD –0.10 days (–0.50 to 0.30)	—	—	MD –0.10 days (–0.50 to 0.30)	49.7%	⊕⊕⊕⊕ High ^{a,b}

Anticipated absolute effects are expressed per 1,000 patients. The assumed risk with standard care is the pooled control-group event rate across contributing trials; the corresponding risk with intensive management is the assumed risk multiplied by the relative risk (RR), with the 95% CI derived from the 95% CI of the RR. For hospital length of stay, a continuous outcome, the effect is expressed as a mean difference (MD) in days

Note: The level of evidence was assessed by the GRADE method, from very low to high certainty: ⊕⊕⊕⊕ High certainty: we are very confident that the true effect lies close to that of the estimate of the effect; ⊕⊕⊕⊖ Moderate certainty: we are moderately confident in the effect estimate, the true effect is likely to be close to the estimate of the effect, but there is a possibility for substantial difference; ⊕⊕⊖⊖ Low certainty: our confidence in the effect estimate is limited, the true effect may be substantially different from the estimate of the effect; ⊕⊖⊖⊖ Very low certainty: we have very little confidence in the effect estimate, the true effect is likely to be substantially different from the estimate of effect

^a Not downgraded for risk of bias: although high-risk trials were included, they contributed minimal statistical weight and sensitivity analyses confirmed they had a negligible impact on the robust pooled estimates

^b Not downgraded for imprecision: the 95% confidence interval was narrow and excluded an appreciable effect, and for the primary outcomes the accrued information size exceeded the heterogeneity-adjusted required information size in the trial sequential analysis

^c Downgraded by one level for imprecision: insufficient optimal information size, with few events and a wide confidence interval crossing the line of no effect

^d Downgraded by two levels for serious imprecision: low event rate and a wide confidence interval crossing the line of no effect

^e Downgraded by two levels for a combination of risk of bias and imprecision: a high-risk trial (2026-Li) carried substantial weight (21.5%) and the limited event count produced a wide confidence interval

^f Downgraded by one level for imprecision: fragility observed in the leave-one-out sensitivity analysis, in which exclusion of the small 2021-Hu trial rendered the pooled estimate non-significant

^g Downgraded by one level for indirectness: a secondary outcome from only five trials, with likely variation in outcome ascertainment across studies and a strong influence of perioperative factors other than blood pressure; vulnerable to multiplicity and regarded as hypothesis-generating

Publication bias: not downgraded. Funnel-plot asymmetry was formally assessable only for outcomes with at least ten studies (symmetrical contour-enhanced funnel plots; non-significant Egger's test); for outcomes with fewer trials it could not be reliably evaluated, as acknowledged in the Limitations

cerebral driving pressure. Furthermore, the aging brain remains vulnerable to even minor MAP excursions below its individualized ischemic threshold. A reduction was observed within the individualized subgroup, but the subgroup difference was not statistically significant ($P=0.314$). Physiologically, the lower limit of cerebral

autoregulation varies significantly among individuals. A fixed higher-target might still fall below the ischemic threshold for elderly patients with hypertension. For instance, the 2021-Hu trial enrolled normotensive elderly patients [17]. This highly selected cohort, lacking the chronic rightward shift of autoregulation, may respond

Table 3 Differences in intraoperative blood pressure between the intensive- and standard-management groups

Reference	Intensive-management group	Standard-management group
Achieved MAP, mmHg		
2017-Futier [20]	81 ± 14	75 ± 13
2018-Langer [21]	92 ± 9	85 ± 11
2020-Xu [11]	<i>Reported graphically only (MAP by timepoint)</i>	
2022-Zhang [19]	<i>Reported per patient by timepoint only</i>	
2024-Bergholz [36]	<i>Reported as boxplots (every 30 min)</i>	
2025-Pang [37]	86 ± 10	76 ± 12
2025-Kant [14]	86.9 (82.0–92.9)	81.1 (75.3–87.1)
Time-weighted average MAP (TWA-MAP), mmHg		
2017-Wu [10]	II: 88 ± 7; III: 100 ± 6	I: 72 ± 5
2025-Zhao [38]	87 ± 6	82 ± 7
2025-Wang [42]	93.1 ± 2.29	78.6 ± 2.97
Time-weighted average MAP < 65 mmHg, mmHg		
2024-Bergholz [36]	0.07 (0.01–0.27)	0.47 (0.17–0.87)
2025-Kant [14]	0 (0–0.4)	0.1 (0–0.5)
2025-Saugel [12]	0.02 (0.00–0.13)	0.12 (0.02–0.36)
2025-Khader [41]	0.07 (0.02–0.22)	0.45 (0.11–1.22)
2026-Li [43]	0.07 (0.00–0.25)	0.14 (0.01–0.64)
Area under a MAP of 65 mmHg, mmHg × min		
2024-Nicklas [34]	0 (0–35)	35 (0–138)
2024-Bergholz [36]	20 (4–54)	143 (34–191)
2025-Pang [37]	0 (0–1.88)	41.2 (16.5–80.6)
2025-Zhao [38]	3 (0–25)	23 (0–87)
2025-Saugel [12]	6 (0–54)	48 (7–151)
2025-Kant [14]	0 (0–24.9)	23.7 (0–81.8)
2026-Li [43]	3.4 (0.34–15.2)	24.1 (0.87–76.5)
Area under the preoperative baseline MAP, mmHg × min		
2024-Nicklas [34]	563 (245–1408)	2620 (1330–5204)
2025-Saugel [12]	454 (159–1137)	1306 (394–3198)
Cumulative duration with MAP < 75 mmHg, min		
2021-Wanner [18]	72 (41–138)	121 (70–210)
2025-Pang [37]	11.5 (3.1–28.2)	112 (81–140)
Cumulative duration with MAP < 60 mmHg, min		
2023-Marcucci [13]	0.0 (0.0–0.0)	0.0 (0.0–2.2)
2024-Marcucci [35]	0.0 (0.0–0.0)	0.0 (0.0–5.0)
2025-Pang [37]	0.0 (0.0–0.0)	2.08 (0.625–5.67)
2025-Marcucci [29]	0.0 (0.0–0.0)	0.0 (0.0–3.0)
2026-Li [43]	1.1 (0–5.2)	2.2 (0.1–11)
Cumulative duration with MAP < 65 mmHg, min		
2021-Wanner [18]	9 (3–24)	23 (8–49)
2025-Pang [37]	0 (0–0.76)	16.7 (8.04–26.3)
2025-Zhao [38]	1 (0–7)	8 (0–20)
2026-Li [43]	2.1 (0.4–5.2)	4.5 (0.3–15)

Note: Values are mean ± SD or median (IQR). For 2017-Wu [10], participants were assigned to three groups (I, II, III); groups II and III were merged as the intensive group and group I served as the standard group. For 2020-Xu [11], participants were assigned to three groups (D, M, H); groups M and H were merged as the intensive group and group D served as the standard group. All data were extracted and sorted according to this grouping. MAP mean arterial pressure, IQR interquartile range, TWA-MAP time-weighted average mean arterial pressure

better to a fixed higher-target strategy. In contrast, an individualized strategy tailored to the patient's preoperative baseline blood pressure, more accurately preserves patient-specific cerebral perfusion.

Although TSA provided statistical support for a beneficial effect of intensive management on POD, this finding should be interpreted with caution. Leave-one-out sensitivity analysis revealed that the statistical significance of the pooled estimate was dependent on the inclusion of the small 2021-Hu trial [17], whose removal rendered the overall effect non-significant. This fragility, attributable to the limited sample size and event count of this single study, introduces imprecision and precludes a high certainty of evidence. Consequently, the certainty of evidence for POD was downgraded to moderate. Taken together, while intensive intraoperative blood pressure management may reduce the risk of POD, the moderate certainty of evidence precludes a routine clinical recommendation. Further well-designed, adequately powered studies are required to confirm these findings, particularly in aging patients and those with preoperative hypertension, impaired cerebral perfusion, or other baseline risk factors for POD.

Among the secondary outcomes, our analysis revealed that the occurrence of SSI was lower in the intensive group (moderate certainty of evidence). This benefit can be explained by improved peripheral tissue perfusion and oxygenation, which enhance wound healing, alleviate tissue hypoxia, and inhibit bacterial colonization [47]. Although the result was statistically robust and homogeneous, SSI is a secondary outcome influenced by many perioperative factors other than blood pressure, and we therefore regard it as a hypothesis-generating finding. Conversely, intensive intraoperative blood pressure management did not alter postoperative overall mortality, stroke, ICU admission rates, and hospital LOS.

These findings should also be weighed against the treatment burden required to achieve the higher targets. Beyond the mechanistic considerations discussed above, the intensive strategy was delivered chiefly through greater vasopressor exposure, and in some trials through withholding of renin-angiotensin inhibitors, rather than through greater fluid administration (Supplementary Table 5). This greater treatment intensity was accompanied by more intraoperative hypertension in a minority of trials, but not by a consistent excess of arrhythmia, bradycardia, major bleeding, or fluid overload. Set against benefits limited to POD and SSI, both of moderate certainty, and no effect on myocardial injury, AKI, or mortality, intensive targets increase treatment burden for an uncertain net benefit, and the decision to pursue higher targets is better individualized to the patient and the hemodynamic context than applied uniformly.

4.2 Comparison with previous evidence and interpretation

Hitherto, only one previous meta-analysis evaluated the effect of intensive intraoperative blood pressure management, which focused solely on AKI based on five relatively small RCTs [22]. That analysis did not incorporate the recent large-scale trials and omitted other critical postoperative outcomes. While diverging from that earlier analysis, our results align with recent large-scale RCTs, including the POISE-3 [13], IMPROVE-multi [12] and PRETREAT [14], providing an updated conclusion that more accurately reflects the current evidence landscape. Furthermore, no prior meta-analysis has provided a subgroup analysis comparing the fixed and individualized higher-target strategies. By addressing these critical evidence gaps, our study provides an updated comprehensive synthesis of the current literature.

During the final preparation of this manuscript, two contemporaneous meta-analysis one by Shalabi and colleagues and another by Chiou et al. [23, 48]. Their findings aligned with ours, demonstrating that individualised intraoperative blood pressure management reduced POD but did not significantly improve postoperative AKI or myocardial injury. This concordance underscores the clinical importance of this question and supports the consistency of these findings.

However, our review expands the scope and statistical certainty of the evidence base. Shalabi et al. restricted their analysis to individualised strategies versus routine management, thereby excluding trials employing fixed higher-target protocols. Consequently, their findings cannot inform whether fixed higher-target strategies confer similar or different benefits compared with individualised approaches. Chiou et al., in contrast, included both fixed and individualised higher targets across 15 trials (15,603 patients), but their TSA applied a uniform 20% RRR for all outcomes, which rendered their delirium TSA inconclusive. Furthermore, their evidence base comprised 5,842 and 15,603 patients, respectively, with myocardial injury and delirium informed by just three or four trials in Shalabi et al. In Shalabi et al., the neutral AKI estimate was fragile, becoming statistically significant when the single highest-weight trial was removed, and their TSA did not reach the RIS, in contrast, in our synthesis the AKI estimate was more stable and the RIS was reached. Notably, even the Bayesian analysis reported by Shalabi et al. estimated only a 39% probability that any AKI benefit reached a clinically meaningful threshold. In Chiou et al., TSA confirmed firm evidence against a clinically meaningful benefit for AKI and myocardial injury, whereas the evidence for mortality remained insufficient.

In contrast, by encompassing both fixed and individualised higher-target strategies across 16,573 patients, our study, with the largest sample among the three reviews,

allows an assessment of intensive management across a wider evidence base. We also evaluated several clinically important outcomes not assessed in either prior work, including SSI, pneumonia, and heart failure; the reduction we observed in SSI, in particular, adds information not previously available. Both prior analyses found a lower incidence of POD, but our broader set of trials yielded a more conservative estimate than Shalabi et al. (RR 0.72 versus RR 0.46). For POD, our TSA reached the RIS and supported a beneficial effect. The apparent difference from the findings of Chiou et al. was attributable to our use of a delirium-specific RRR of 30%, based on the cogPOISE-3 design, rather than to a genuine discrepancy in the evidence, as sensitivity TSAs using a 20% RRR likewise yielded inconclusive results. For myocardial injury and AKI, our TSA also reached the RIS and indicated that a clinically meaningful benefit of the pre-specified magnitude is unlikely, consistent across all three reviews, although smaller effects cannot be excluded. Taken together, these three analyses provide complementary and largely concordant evidence, with the present work offering the most comprehensive outcome assessment to date.

4.3 Strengths and limitations

This meta-analysis possesses several strengths. First, it included only RCTs and incorporated the recent high-quality trials [12–14, 38], with a total sample size of 16,573 patients, making the conclusions timely and statistically powerful. Second, the included trials were geographically diverse, covering China, Germany, France, Italy, Switzerland, the Netherlands, and multiple national multicentre studies, providing good population representativeness and enhancing the generalizability of the findings. Third, the outcomes were comprehensive, simultaneously evaluating multiple clinically important endpoints including cardiovascular (myocardial injury, heart failure), neurocognitive (POD, stroke), renal (AKI), infection (SSI, pneumonia), mortality, admission to ICU, and hospital LOS. Importantly, this is the first meta-analysis to systematically provide subgroup comparisons between the fixed and individualized higher-target strategies. Finally, this study used the GRADE system to assess the certainty of evidence and performed extensive sensitivity analyses, TSA, and publication bias assessments to further reinforce the robustness of our conclusions. These strengths allow this analysis to provide a more reliable basis for clinical decision-making.

However, several limitations must be acknowledged. First, due to the inherent nature of intraoperative hemodynamic management, double-blinding of the participating anaesthesiologists in the included trials is difficult, introducing an unavoidable risk of bias. Second, the

included trials were heterogeneous in both outcome assessment and protocol thresholds, which may have contributed to the observed statistical heterogeneity. Third, determinants of intervention intensity beyond achieved MAP, including vasopressor and fluid use, antihypertensive management, and postoperative blood pressure control, were reported too sparsely to be synthesized. Fourth, several secondary outcomes were informed by few trials and events, yielding imprecise estimates, and publication bias could be formally assessed only for outcomes with at least 10 trials. We did not search conference abstracts, preprint servers, or other grey-literature sources, so unpublished data may not have been fully captured. Fifth, our neurocognitive analysis was restricted to POD, and longer-term cognitive outcomes could not be evaluated. Finally, only English-language studies were included.

4.4 Implications for future research

Our TSA provides clear but divergent directions for future research. For both postoperative myocardial injury and AKI, the TSA suggests that intensive management does not meaningfully reduce incidence of them. Future research should evaluate complementary approaches, including biomarker-guided care, goal-directed hemodynamic therapy, and postoperative pharmacological interventions. For example, the MANAGE trial [49] evaluated dabigatran for preventing major vascular complications in patients who had developed myocardial injury after noncardiac surgery. Nevertheless, trial sequential analysis suggested a potential benefit of intensive blood pressure management for POD, although recent trials, including cogPOISE-3 [29] and BP-CARES [38], reported null findings. The present results highlight the need for definitive, large-scale RCTs with postoperative neurocognitive outcomes as the primary endpoint, including POD, dNCR and POCD. Such a trial would validate the effect and provide the evidence base for clinical recommendations. Several ongoing registered trials (Supplementary Table 6) are expected to provide further evidence. Some are evaluating composite cardiovascular and renal outcomes (NCT04884802, NCT06225453), whereas others are specifically evaluating neurocognitive outcomes, including POD and cognitive impairment (NCT06711432).

For intraoperative blood pressure management, current evidence suggests that intensive management alone offers limited benefit. In clinical practice, greater emphasis should be placed on holistic perioperative care, including the judicious continuation or withholding of preoperative antihypertensive agents and the vigilant control of postoperative hypotension. At the same time, it is essential to recognize the distinct endotypes of intraoperative hypotension, such as vasodilation, hypovolemia, myocardial depression, and bradycardia and to implement

mechanism-directed, precision interventions guided by real-time hemodynamic monitoring. Given the complex relationship between MAP and organ perfusion, together with the current lack of reliable tools to precisely monitor organ-level perfusion at the bedside [50], the optimal individualized management strategy remains elusive. Future studies should therefore seek to identify more precise markers of organ perfusion to enable truly precision-based care. Moreover, we call for future trials to place greater emphasis on postoperative long-term outcomes, including POCD, long-term renal outcomes, and health-related quality of life, in order to achieve meaningful and lasting improvements in patient prognosis.

4.5 Conclusion

In adults undergoing noncardiac surgery, intensive intraoperative blood pressure management may reduce the risk of POD and SSI compared with standard management, with moderate-certainty evidence for both outcomes. However, it was not associated with reductions in postoperative myocardial injury, acute kidney injury, or mortality.

Abbreviations

AIS	Accrued information size
ARDS	Acute respiratory distress syndrome
ASA	American Society of Anesthesiologists
AKI	Acute kidney injury
CI	Confidence interval
dNCR	Delayed neurocognitive recovery
GRADE	The Grading of Recommendations Assessment, Development and Evaluation
HARIS	Heterogeneity-adjusted required information size
HK	Hartung-Knapp adjustment
I ²	Inconsistency
ICU	Intensive Care Unit
LOS	Length of stay
MAP	Mean arterial pressure
MD	Mean difference
MH	Mantel-Haenszel method
POD	Postoperative delirium
POCD	Postoperative cognitive dysfunction
RAS	Renin-angiotensin system
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT	Randomized controlled trial
RIS	Required information size
RoB2	Risk of Bias 2 tool
RR	Risk ratio
RRR	Relative risk reduction
SBP	Systolic blood pressure
SSI	Surgical site infection
TSA	Trial sequential analysis

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44254-026-00188-9>.

Supplementary Material 1: Search strategy
 Supplementary Material 2: Supplementary Tables
 Supplementary Material 3: Supplementary Figures

Acknowledgements

Not applicable.

Authors' contributions

ZXZ: Conceptualization, data curation, formal analysis, writing – original draft, writing – review & editing. YH: Conceptualization, data curation, formal analysis, writing – original draft, writing – review & editing. CC: Conceptualization, data curation, formal analysis, writing – review & editing. QRS: Data curation, formal analysis. HJZ: Data curation, formal analysis. TXL: Data curation, formal analysis. HY: Conceptualization, supervision, writing – original draft, writing – review & editing.

Funding

None.

Data availability

All data generated or analyzed during this study are included in this article and its supplementary information files.

Declarations

Competing interests

Professor Hai Yu is a member of the Editorial Board, and Professor Chan Chen is a Scientific Editor for *Anesthesiology and Perioperative Science*. Both authors have recused themselves from all editorial procedures regarding this submission, including peer review and academic decision-making.

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Received: 17 May 2026 Revised: 23 July 2026 Accepted: 28 July 2026
 Published online: 14 September 2026

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