Xie et al. Journal of Cardiothoracic Surgery (2025) 20:227
https://doi.org/10.1186/s13019-025-03416-8

Journal of
Cardiothoracic Surgery

REVIEW

Open Access

The association of pulmonary artery catheterization utilization and surgical patients' outcomes: a PRISMA-compliant systematic review and meta-analysis

Chun-mei Xie[1], Li-xian He[1], Meng-qi Shen[1], Yun-tai Yao[2*] and The Evidence in Cardiovascular Anesthesia (EICA) Group

Abstract

Background The utilization of pulmonary artery catheterization (PAC) in surgical patients remains controversial. This study aims to assess the impact of PAC utilization on surgical patient outcomes.

Methods Electronic databases were searched for studies comparing PAC with no-PAC in surgical patients. The primary outcome was short-term mortality. Secondary outcomes included the incidence of postoperative complications, postoperative recovery indicators, and hospitalization costs.

Results Ten randomized controlled trials (n = 2,889) and sixteen observational studies (n = 2,221,917) were included. Among these studies, fifteen involved cardiac surgical patients (n = 2,217,736), and eleven involved non-cardiac surgical patients (n = 7,070). The present study demonstrated PAC utilization did not affect short-term mortality in cardiac surgical patients [odds ratio (OR) 1.20, 95% confidence interval (CI) 0.79–1.82, *p* 0.40], and was associated with a higher incidence of postoperative chronic heart failure, acute renal failure, cerebrovascular events, infectious complications, and longer length of stay (LOS) in intensive care unit (ICU) or hospital. Moreover, PAC utilization was not associated with short-term mortality (OR 0.40, 95% CI 0.16–1.02, p 0.06) and other outcomes for non-cardiac surgical patients.

Conclusions This meta-analysis suggested PAC utilization was not associated with short-term mortality in surgical patients but with a higher incidence of major complications and longer LOS in the ICU or hospital in cardiac surgical patients.

Keywords Cardiac surgery, Non-cardiac surgery, Outcomes, Pulmonary artery catheterization, Meta-analysis

Introduction

For five decades, pulmonary artery catheterization (PAC) has been used for preoperative hemodynamic optimization, intraoperative monitoring, and postoperative management in surgical patients [1–9]. PAC provides vital parameters, including cardiac output (CO), mixed venous oxygen saturation ($SmvO_2$), pulmonary artery pressure (PAP), and pulmonary capillary wedge pressure (PCWP). Additional derived data could be calculated from these measurements, including pulmonary

*Correspondence:
Yun-tai Yao
yuntaiyao@126.com
[1] Department of Anesthesiology, Fuwai Yunnan Hospital, Chinese Academy of Medical Sciences, Affiliated Cardiovascular Hospital of Kunming Medical University, Kunming 650102, China
[2] Department of Anesthesiology, Fuwai Hospital, National Center for Cardiovascular Diseases, Peking Union Medical College and Chinese Academy of Medical Sciences, Beijing 100037, China

and systemic vascular resistance (PVR, SVR), cardiac index (CI), stroke volume (SV), right and left ventricular end-systolic and end-diastolic volume, right ventricular ejection fraction (RVEF), oxygen delivery, and oxygen consumption. PAC utilization could be valuable in guiding treatment in high-risk surgical patients.

Since the adoption of PAC into clinical practice, studies of PAC in surgical patients have yielded inconsistent results. Studies reported that PAC utilization in coronary artery bypass graft (CABG) [10] and in hip surgery [11] had reduced mortality; another study suggested that the benefit of PAC utilization outweighed the risk in cardiovascular surgical patients [12]. However, several studies found no benefit for PAC utilization [13–16] and reported that PAC utilization in cardiac surgical patients was associated with greater mortality, prolonged mechanical ventilation duration (MVD), and length of stay (LOS) in hospital [17]. These findings were consistent with an international prospective observational study in 5,065 patients undergoing CABG [18], and PAC's benefit had not been reported in the most recent studies [5, 8, 19]. Therefore, the authors conducted the current study to investigate whether PAC utilization affects the outcomes of cardiac and non-cardiac surgical patients.

Methods

The current study sought to include all relevant studies based on recently published guidelines [20] and the Cochrane Handbook for Systematic Reviews of Interventions [21]. Findings were reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement [22] (Supplementary files Table 1). The study was registered on the International Prospective Register of Systematic Reviews PROSPERO: CRD42022374726.

Search strategy and study selection

Two authors (XCM and HLX) independently retrieved published studies [8] in PubMed, Embase, Cochrane Library, Web of Science, and Scopus databases from inception until 5 January 2025, using different combinations of search words as follows: (pulmonary artery catheter OR right heart catheter OR Swan-Ganz catheter) AND (surgery OR operation) AND clinical trial (Supplementary files Table 2). The language was restricted to English. Moreover, additional relevant studies were searched manually by checking references of the retrieved articles and relevant reviews.

Inclusion criteria: ① Study population: cardiac and non-cardiac surgical patients. ② Intervention measure: PAC utilization. ③ Control group: no-PAC utilization. ④ Outcomes: the primary outcome was short-term mortality; secondary outcomes included composite and individual incidences of postoperative complications, hospitalization costs, and postoperative recovery (MVD, LOS in ICU and hospital). ⑤ Study design: randomized controlled trials (RCTs), cohort studies, and case–control studies. Exclusion criteria: duplicate publications, reviews, case reports, abstracts, letters, comments, animal or cell studies, and studies lacking information about outcomes of interest.

Data abstraction

Three authors (CMX, MQS, LXH) independently extracted data from the selected articles strictly following the inclusion and exclusion criteria. The following information was recorded: (1) author, country and publication year, duration of included studies; (2) type of surgical procedure; (3) total number of patients, number of patients in PAC and no-PAC groups; (4) data regarding outcomes of interest in both groups. Disagreements were resolved by discussion among all authors during the process of data abstraction.

Outcome

The primary outcome was short-term mortality from any cause. Short-term mortality defined as in-hospital and 30-day post-operative mortality. Secondary outcomes included the incidence of postoperative complications, postoperative recovery indicators, and hospitalization costs. The composite postoperative outcomes consisted of fatal and nonfatal in-hospital outcomes classified as cardiac (arrhythmia, myocardial infarction, congestive heart failure), cerebrovascular events (stroke, encephalopathy), renal (dysfunction or failure), pulmonary complications, and infectious morbidities. The composite postoperative outcomes are mostly based on the data presented in the original study, rather than the authors simply adding up individual outcome measures.

In addition, the definition of individual outcomes, such as myocardial infarction or renal insufficiency, refers to the definition in the original study and the presented data.

Evaluation of the quality of studies

Two authors (CMX, MQS) independently assessed the quality of the included studies. The risk of bias assessment was conducted using the Cochrane Risk of Bias Tool [23]. Also, the modified 7-point *Jadad* score [24] was used to evaluate the methodological quality of included RCTs. Trials with 1–3 points were deemed low quality, and those with 4–7 points were deemed high quality. Additionally, the Newcastle–Ottawa Scale (NOS) was used to assess the methodological quality of included observational studies [25]. The NOS scale evaluated three aspects of study methods: selection of study groups (range 0–4), comparability of groups (range 0–2), and quality of outcome or exposure ascertainment (range 0–3). The total score ranged from 0 to 9, and a score > 5 reflected an acceptable methodological design.

Subgroup analysis

The present study assessed the effect of PAC utilization in different subgroups, including whether goal-directed therapy (GDT) was employed in the original article and whether the trial was conducted before/after the SUPPORT study (1996). The SUPPORT study involved medical and surgical patients and showed PAC utilization had increased mortality, LOS in ICU, and costs [2]. Hence, subsequent consensus statements recommended redoubled efforts at education regarding the use of pulmonary-artery catheters and randomized, controlled clinical trials of their service. Therefore, the current study conducted a subgroup analysis before/after the SUPPORT study (1996).

Statistical analyses

All data were analyzed using RevMan 5.4 (Cochrane Collaboration, Oxford, UK). Pooled odds ratio (OR) and 95% confidence interval (CI) were estimated for dichotomous data, and weighted mean difference (WMD) and 95% CI were for continuous data. Heterogeneity was assessed by I^2 statistic, with statistics of < 25%, 25–50%, and > 50% as thresholds for low, moderate, and high heterogeneity, respectively [26, 27]. Each outcome was tested for heterogeneity, and a randomized-effects or fixed-effects model was used in the presence or absence of significant heterogeneity. Potential publication bias was explored through visual inspection of funnel plots of outcomes. Sensitivity analyses were done by examining the influence of the statistical model on estimated treatment effects, and analyses that adopted the fixed-effects model were repeated using the randomized-effects model and vice versa. In addition, it also evaluated the influence of individual studies on the overall effects. All *p*-values were two-sided, and statistical significance was defined as $p < 0.05$.

Results

Characteristics of included studies

The search initially retrieved 719 citations. Finally, twenty-six studies (n = 2,224,806) were included in qualitative synthesis (Fig. 1) [4–11, 13–19, 28–38]. One study did not report extractable outcomes and was not pooled for meta-analysis [30]. Characteristics of the included studies were summarized in Table 1 and Table 2, ten studies were RCTs (n = 2,889), and sixteen were observational cohort studies (n = 2,221,917). Also, fifteen involved cardiac surgical patients (only one was RCT [29]), and eleven studies included non-cardiac surgical patients (only two were cohort studies [8, 30]).

Study quality and risk bias

The risk of bias analysis of the ten RCTs was shown in Supplementary files Fig. 1. Four RCTs [9, 15, 34, 37] scored as “high quality” according to the modified *Jadad* score, and the other RCTs as “low quality” (Supplementary files Table 3). Details of the methodological quality of the included observational cohort studies according to the NOS were provided in Supplementary files Table 3. The median NOS rating for the 16 studies reviewed was 6 (range: 5–8). Therefore, all were considered to be of high quality.

Short-term mortality

Data on the outcome of short-term mortality were available from twenty-four studies (three studies [6, 8, 28] reported 30-day mortality, seventeen reported in-hospital mortality, two [7, 16] reported zero death, one [33] reported overall mortality, and one did not provide available data). As shown in Fig. 2A, twelve observational cohort studies (n = 2,127,113) reported short-term mortality in cardiac surgical patients, and meta-analysis showed PAC was not associated with short-term mortality (OR 1.20, 95% CI 0.79–1.82, *p* 0.40) with high heterogeneity ($I^2 = 90\%$, $p < 0.00001$). The results of subgroup analysis (before/after the SUPPORT study) showed PAC did not affect short-term mortality (Supplementary files Fig. 2). As shown in Fig. 3A, eight RCTs (n = 2,711) and one observational cohort study (n = 200) reported short-term mortality in non-cardiac surgical patients, and meta-analysis results of RCTs showed PAC utilization was not associated with short-term mortality (OR 0.40, 95% CI 0.16–1.02, *p* 0.06) with high heterogeneity ($I^2 = 60\%$, $p = 0.01$). The results of the subgroup analysis (before/after the SUPPORT study) showed that PAC utilization did not affect short-term mortality (the group before the SUPPORT study) (Supplementary files Fig. 3). Another subgroup analysis was performed based on whether goal-directed therapy (GDT) was employed or not, and the results of the GDT group showed that PAC utilization did not affect short-term mortality (Supplementary files Fig. 4).

The incidence of composite postoperative complications

As shown in Fig. 2B, three observational studies (n = 9,524) reported the incidence of composite postoperative complications in cardiac surgical patients, and meta-analysis showed PAC utilization did not affect the incidence of composite postoperative complications (OR 1.44, 95% CI 0.85–2.45, *p* 0.18) with high heterogeneity ($I^2 = 94\%$, $p < 0.00001$). Figure 3B showed that six

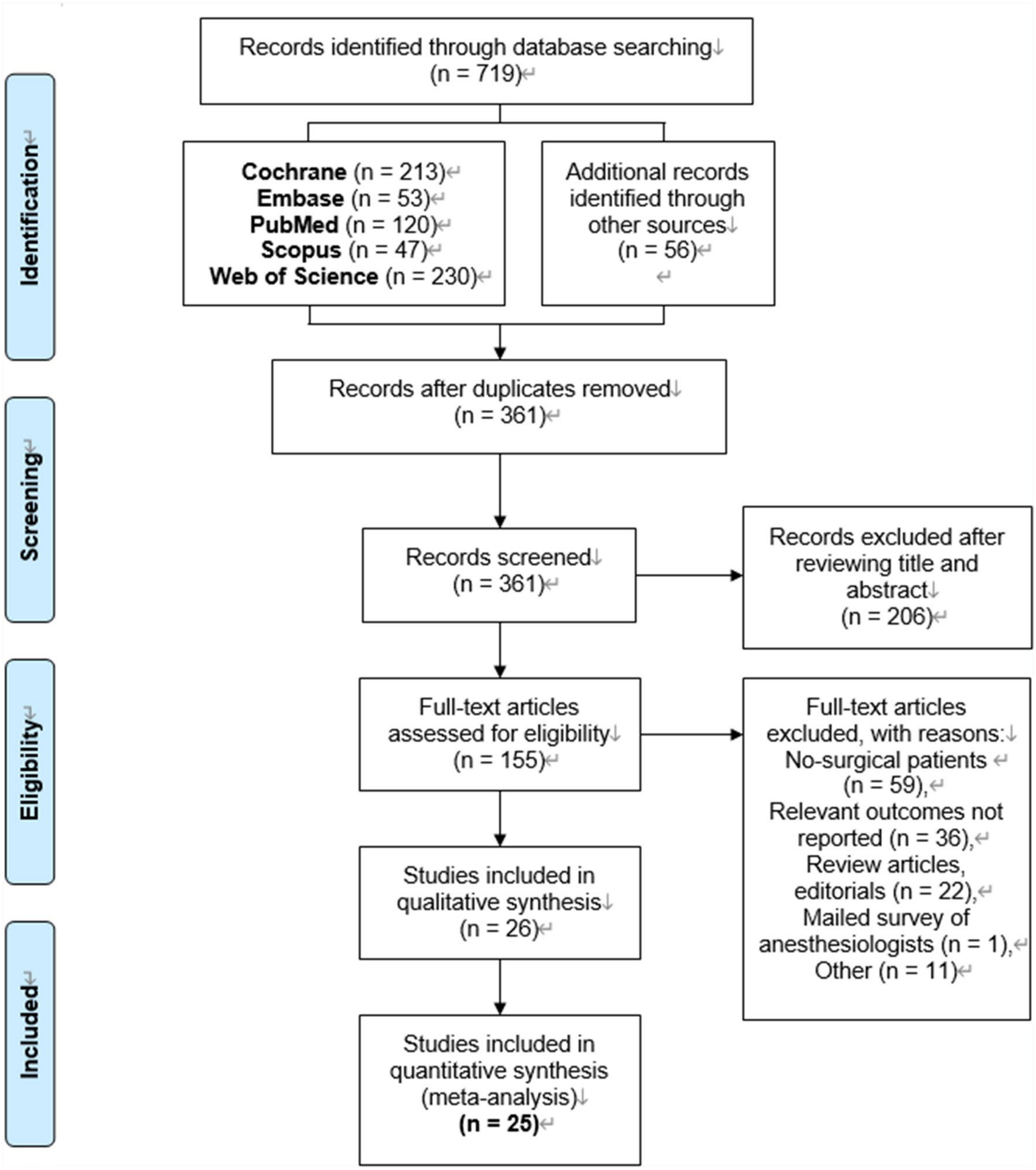

Fig. 1 Flow diagram of study selection

RCTs ($n=577$) and one observational study ($n=4,059$) reported the incidence of composite postoperative complications in non-cardiac surgical patients. All the included RCTs performed goal-directed therapy, and meta-analysis results of RCTs showed PAC utilization did not affect the incidence of composite postoperative complications (OR 0.48, 95% CI 0.19–1.25, p 0.13) with high heterogeneity ($I^2=77\%$, $p=0.0007$).

The incidence of other major complications

Meta-analysis of the incidence of various complications was presented in Supplementary files Table 4, all the included studies in cardiac surgical patients were observational cohort studies, while all the included studies in non-cardiac surgical patients were RCTs. These results showed that PAC utilization was associated with higher incidence of postoperative chronic

Table 1 Characteristics of the included studies

Study	Country	Design	Period time	Surgery	PAC insertion		Sample size (n)		Major findings (PAC vs no-PAC)					
					Settings	Timing	PAC	no-PAC	Mortality	Morbidities	MVD	ICU LOS	Hospital LOS	Cost
Schultz 1985	US	RCT	?	Hip surgery	ICU	Pre-op	35	35	↓	(–)	?	?	?	?
Isaacson 1990	US	RCT	(1987.1–1989.1)	Abdominal aortic surgery	OR	Intra-op	49	53	(–)	(–)	(–)	(–)	(–)	(–)
Shoemaker 1990	US	RCT	(1983.5–1984.5)	Major non-cardiac surgery	ICU	Pre-op	30	28	↓	③(–), ④⑤↓	?	↓	?	↓
Berlauk 1991	US	RCT	(1986.10–1990.1)	Lower limb revascularization	ICU	Pre-op	66	21	(–)	%1 ↓	?	(–)	(–)	(–)
Bender 1997	US	RCT	(1992.4–1995.5)	Lower limb revascularization, AAS	ICU	Pre-op	51	53	(–)	①③(-)	?	(–)	?	(-)
Valentine 1998	US	RCT	(1994.3–1997.3)	Abdominal aortic surgery	ICU	Pre-op	60	60	(–)	①②③④(–)	?	(–)	(–)	?
Wilson 1999	UK	RCT	?	Major non-cardiac surgery	ICU	Pre-op	92	46	↓	?	?	?	?	?
Polanczyk 2001	US	Cohort	(1989.7–1994.2)	Major non-cardiac surgery	?	?	215	215		①②③④↑	?	?	?	?
Bonazzi 2002	Italy	RCT	(1996.4–2000.4)	Abdominal aortic surgery	ICU	Pre-op	50	50	(–)	①④(-)	?	?	(–)	?
Sandham 2003	Canada	RCT	(1990.3–1999.7)	Major non-cardiac surgery	?	?	997	997	(–)	↑	?	?	(–)	?
Hofer 2020	US	Cohort	(2015.1–2018.4)	Liver transplantation	?	?	200	38	↑	④↑	(–)	(–)	↓	?
Moore 1978	US	Cohort	(1976–1977)	On-pump CABG	OR	Intra-op	28	20	↓	?	?	?	?	?
Pearson 1989	US	RCT	(9 months)	Cardiac surgery	?	?	28	86	(–)	(–)	(–)	(–)	?	↑
Tuman 1989	US	Cohort	?	On-pump CABG	OR	Intra-op	537	557	(–)	①②③④(-)		(–)	?	
Stewart 1998	US	Cohort	(1996.4–1996.10)	On-pump CABG	?	?	61	133	(–)	↑	↑	↑	↑	↑
Ramsey 2000	US	Cohort	(1997.1–1997.12)	Off-pump CABG	?	?	8,064	5,843	↑	?	?	↑	↑	↑
Schwann 2002	US	Cohort	(1994–1998)	On-pump CABG	?	?	242	2,443	?	↓	?	?	?	?
Djaiani 2006	Canada	Cohort	?	On-pump CABG	OR	Intra-op	46	154	(–)	②④(–)	↑	↑	↑	?
Resano 2006	US	Cohort	(2000.1–2003.12)	Off-pump CABG	?	?	1,617	743	(-)	①②④(–)	(–)	(–)	(–)	?
Schwann 2011	US	Cohort	(1996.12–2000.6)	On-pump CABG	?	?	1,273	1,273	↑	①②④↑	↑	↑	?	?
Chiang 2015	US	Cohort	(2000.1–2010.12)	Cardiac surgery	?	?	1,605,697	412,640	↑	?	↑	↑	?	(-)
Xu 2015	China	Cohort	(2012.6–2012.12)	On and off-pump CABG	OR	Intra-op	424	424	(–)	①②④⑤(-)	?	?	?	↑
Brovman 2016	US	Cohort	(2010.1–2014.12)	Cardiac surgery	OR	Intra-op	40,036	76,297	(–)	⑥↓	?	?	?	?
Shaw 2018	US	Cohort	(2011.1–2015.6)	Cardiac surgery	?	?	3,422	3,422	(–)	①③↓, ④⑤↑	?	?	↓	?
Pasquier 2020	France	Cohort	(2012–2019)	Bentall procedure	?	?	59	75	(–)	①②↑, ③(-)	?	↑	↑	?
Brown 2022	US	Cohort	(2010–2018)	On-pump CABG, VS	?	?	3,519	3,519	(–)	②④⑤(–), ⑥↑	?	↑	?	?

AAS Abdominal aortic surgery, *CABG* coronary artery bypass graft, *ICU* intensive care unit, *Intra-op* intra-operative, *LOS* length of stay, *MVD* mechanical ventilation duration, *OR* operating room, *PAC* pulmonary artery catheter, *Pre-op* Pre-operative, *RCT* randomized controlled trial, *UK* United Kingdom, *US* United States, *VS* valve surgery. ① post-operative cardiac complications (myocardial infarction, new-onset arrhythmia, new-onset heart failure). ② post-operative cerebrovascular events (stroke, encephalopathy, transient ischemic attack). ③ postoperative pulmonary complications (pneumonia, pulmonary edema, acute respiratory distress syndrome, pulmonary embolism). ④ renal dysfunction or need for renal replacement therapy. ⑤ infectious complications (bacteremia/sepsis, urinary tract infection, catheter-related infection, wound infection). ⑥ red blood cell transfusion. ? = not mentioned

Table 2 Summary of the effect of PAC utilization on outcomes of included studies

Study	Patients		PAC insertion		Goal-directed therapy by PAC?	PAC effects on patients' outcomes	
	Inclusion criteria	Exclusion criteria	PAC-related complications	Personnel		Benefit	Harm
Schultz 1985	Hip fracture surgery	?	?	?	Yes, but not described in detail	+	–
Isaacson 1990	Pre-op LVEF ≧ 40%	Coronary artery diseases, valvular disease, CHF, RF, FEV_1/FVC < 50%	?	Anesthesiologist	×	–	–
Shoemaker 1990	High-risk general surgery	?	Transient arrhythmia (12%), catheter infection (5%)	?	CI > 4.5 L/min/m^2, DO_2 > 600 mL/min/m^2, VO_2 > 170 mL/min/m^2	+	–
Berlauk 1991	Vascular surgery by one surgeon	MI ≦ 3 months, CABG ≦ 6 weeks, unstable angina, valvular disease, CHF	?	Intensivist	PCWP: 8–14 mmHg, CI ≧ 2.8 L/min/m^2, SVR ≦1100 dyne-second/cm^5	+	–
Bender 1997	Vascular surgery by one surgeon	MI ≦ 3 months, CABG ≦ 6 weeks, valvular disease, CHF	Transient arrhythmia (6%)	Intensivist	PCWP: 8–14 mmHg, CI ≧ 2.8 L/min/m^2, SVR ≦1100 dyne-second/cm^5	+	–
Valentine 1998	Abdominal aortic surgery	MI ≦ 3 months, CABG ≦ 6 weeks, unstable angina, valvular disease, RF, CHF	Transient arrhythmia (8%), paroxysmal supraventricular tachycardia (3%)	?	PCWP: 8–15 mmHg, CI ≧ 2.8 L/min/m^2, SVR ≦1100 dyne-second/cm^5	–	–
Wilson 1999	Major general, vascular surgery, urology	?	?	?	PCWP: 12 mmHg, DO_2 > 600 mL/min/m^2	+	–
Polanczyk 2001	Aged ≥ 50 yr, LOS ≥ 2 days	Abdominal aortic surgical patients	?	?	×	–	+
Bonazzi 2002	Aged < 75 yr, pre-op LVEF ≦ 50%	Chronic obstructive pulmonary disease, RF	Transient arrhythmia (18%), paroxysmal supraventricular tachycardia (4%)	?	PCWP: 10–18 mmHg, CI ≧ 3.0 L/min/m^2, SVR ≦ 1450 dyne-second/cm^5, DO_2 > 600 mL/min/m^2	–	–
Sandham 2003	Aged ≧ 60 yr, ASA III or IV	?	Hemothorax (0.2%), pneumothorax (0.9%), pulmonary hemorrhages (0.3%), pulmonary infarction (0.1%)	?	PCWP: 12 mmHg, CI: 3.5–4.5 L/min/m^2, DO_2: 550–600 mL/min/m^2, HR < 120 bpm, Hct > 27%, MAP: 70 mmHg	–	+
Hofer 2020	Aged ≧ 18 yr	Combined heart-liver transplantation, patients had orthotopic liver transplantation without TEE or PAC	?	Anesthesiologist	×	+	+
Moore 1978	LM stenosis ≧ 70%	?	?	Anesthesiologist	CI: 2.5–4.5 L/min/m^2, SVR < 35 Wood, LVFP: 5–15 mmHg, MAP: 80–90 mmHg, HR: 70–90 bpm, RPP ≦ 12000	+	–
Pearson 1989	Aged ≧ 18 yr	?	?	?	Yes, but not described in detail	–	+
Tuman 1989	Aged ≧ 18 yr	?	?	Anesthesiologist	×	–	–
Stewart 1998	Pre-op LVEF ≧ 40%, Scr < 2.0 mg/dL	Chronic obstructive pulmonary disease, unstable angina, pre-op IABP	?	Anesthesiologist	×	–	+
Ramsey 2000	Elective CABG patients at community-based medical centers	?	?	?	×	–	+

Table 2 (continued)

Study	Patients		PAC insertion		Goal-directed therapy by PAC?	PAC effects on patients' outcomes	
	Inclusion criteria	Exclusion criteria	PAC-related complications	Personnel		Benefit	Harm
Schwann 2002	Elective CABG	?	?	?	×	+	–
Djaiani 2006	Elective CABG	Valvular disease, pre-op LVEF < 20%, LM stenosis > 70%, pre-op IABP, LBBB, RF	Transient arrhythmia (42%)	Anesthesiologist	×	–	+
Resano 2006	Low-risk off-pump CABG	Aged > 75 yr, pre-op LVEF < 35%, emergent or salvage operations, minimally invasive	?	Anesthesiologist	×	–	–
Schwann 2011	Aged ≧ 18 yr	?	?	?	×	–	+
Chiang 2015	Elective CABG	?	?	?	×	–	+
Xu 2015	Elective CABG	?	?	Anesthesiologist	×	–	+
Brovman 2016	Elective CABG and VS	Missing data	?	Anesthesiologist	×	+	-
Shaw 2018	Aged ≧ 18 yr	Prior PCI, missing data, hospital LOS < 48 h or > 6 months	?	?	×	+	+
Pasquier 2020	Pre-op LVEF > 40%	Pulmonary artery hypertension, CS history	?	?	×	–	+
Brown 2022	Elective-isolated CABG/VS	?	?	?	×	–	+

ASA American Society of Anesthesiologists, *bpm* beats per minute, *CABG* coronary artery bypass graft, *CHF* chronic heart failure, *CI* cardiac index, *COPD* chronic obstructive pulmonary disease, *CS* cardiac surgery, DO_2 oxygen delivery, FEV_1 forced expiratory volume in one second, *FVC* forced vital capacity, *Hct* hematocrit, *HR* heart rate, *ICU* intensive care unit, *LBBB* left bundle-branch block, *LM* left main coronary artery, *LOS* length of stay, *LVEF* left ventricular eject fraction, *LVFP* left ventricular filling pressure, *MAP* mean artery pressure, *MI* myocardial infarction, *PCI* percutaneous coronary intervention, *PCWP* pulmonary capillary wedge pressure, *RF* renal failure, *RPP* rate-pressure product, *Scr* serum creatinine, *SVR* systemic vascular resistance, *TEE* transesophageal echocardiography, VO_2 oxygen consumption, *VS* valve surgery, ? not mentioned

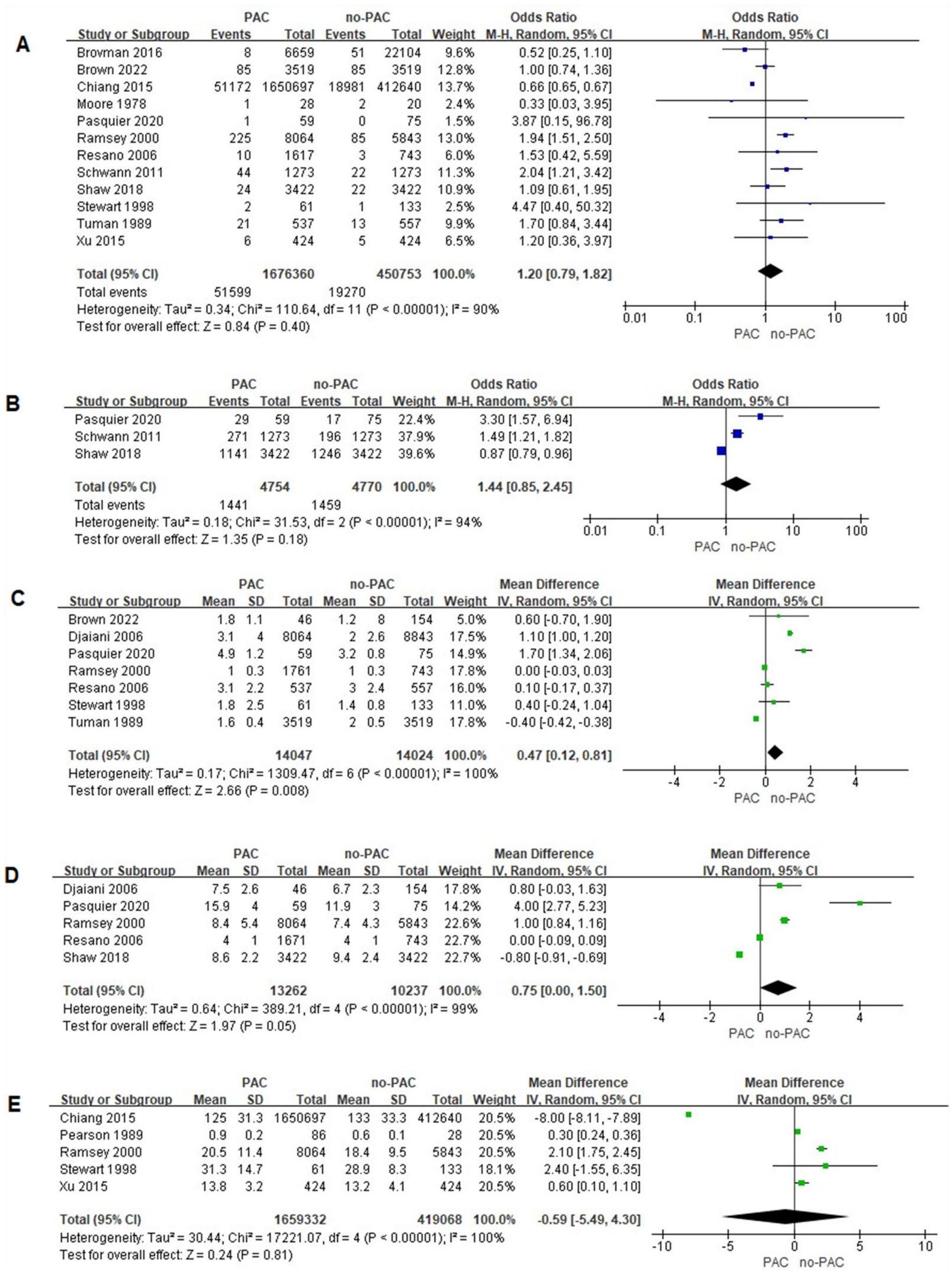

Fig. 2 Meta-analysis results in cardiac surgical patients **A** Short-term mortality **B** The incidence of composite postoperative complications **C** LOS in ICU **D** LOS in hospital E. Hospitalization costs

cardiac failure (CHF) (OR 3.14, 95% CI 0.99–10.00, p 0.05), acute renal failure (ARF) (OR 1.56, 95% CI 1.07–2.26, p 0.02), cerebrovascular events (OR 1.41, 95% CI 1.13–1.78, p 0.003), and infectious complications (OR 1.25, 95% CI 1.08–1.46, p 0.003) in cardiac surgical patients. The forest figures are shown in Supplementary files Fig. 5. Supplementary files Fig. 6 showed that six RCTs (n = 2,411) and one observational study (n = 4,059) reported the incidence of postoperative ARF in non-cardiac surgical patients, and

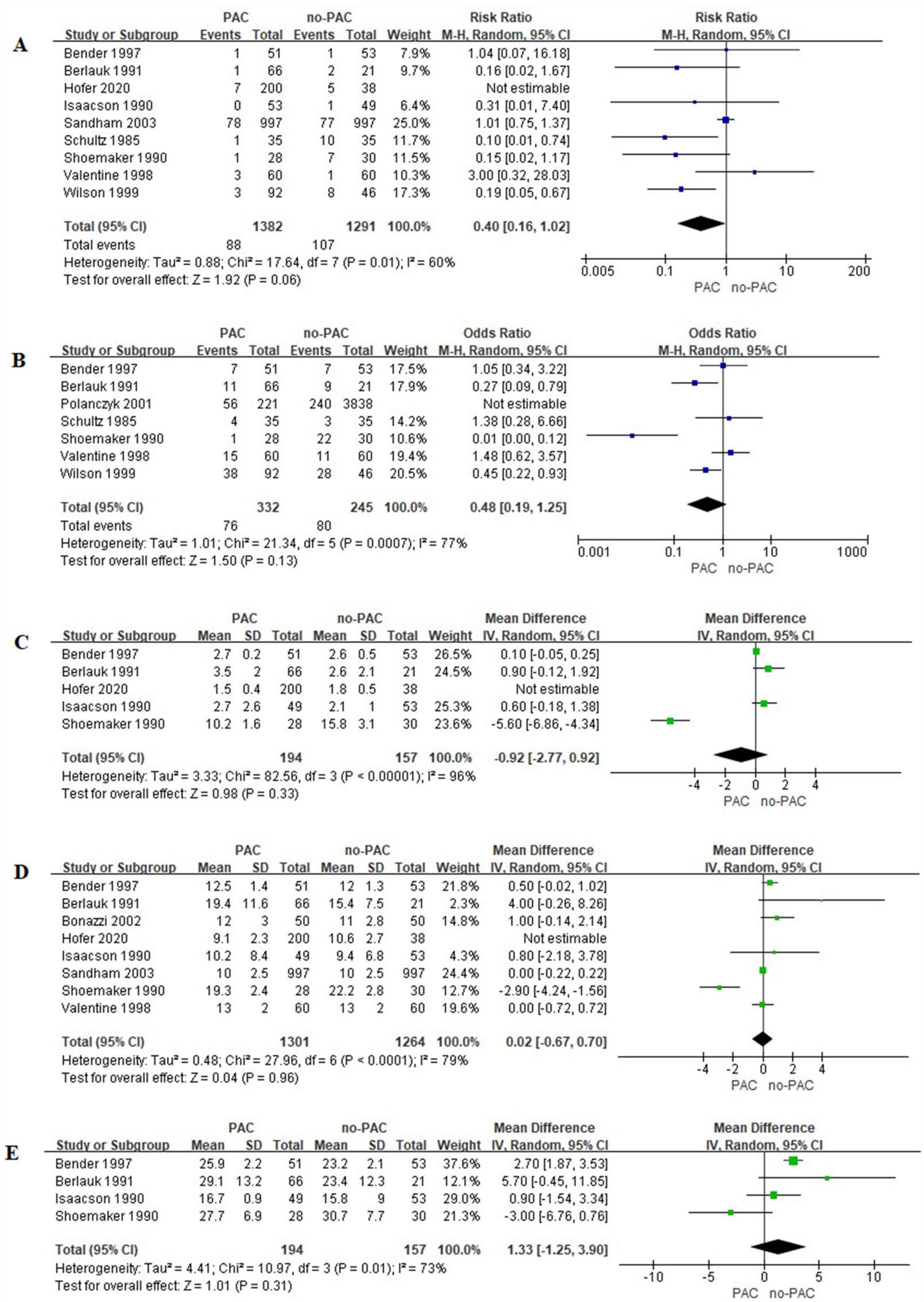

Fig. 3 Meta-analysis results in non-cardiac surgical patient. **A** Short-term mortality **B** The incidence of composite postoperative complications **C** LOS in ICU **D** LOS in hospital E. Hospitalization costs

meta-analysis result of 6 RCTs showed that PAC utilization was associated with lower incidence of postoperative ARF (OR 0.71, 95% CI 0.52–0.96, *p* 0.03).

LOS in ICU

As shown in Fig. 2C, seven observational studies (n = 28,071) reported LOS in ICU in cardiac surgical patients, and meta-analysis showed PAC utilization was associated with longer LOS in ICU (WMD 0.47, 95% CI 0.12–0.81, p 0.008) with high heterogeneity (I^2 = 99%, $p < 0.00001$). Additionally, we conducted a subgroup analysis before/after the SUPPORT study, and the results of the group before the SUPPORT study showed PAC utilization did not affect LOS in the ICU (Supplementary files Fig. 7). Figure 3C showed that four RCTs (n = 351) and one observational study (n = 238) reported LOS in ICU in non-cardiac surgical patients. All the included RCTs performed GDT, and meta-analysis results of RCTs showed PAC utilization did not affect LOS in ICU (WMD −0.92, 95% CI −2.77–0.92, p 0.33) with high heterogeneity (I^2 = 96%, $p < 0.00001$).

LOS in hospital

As shown in Fig. 2D, five observational studies (n = 28,071) reported hospital LOS in cardiac surgical patients, and meta-analysis showed PAC utilization was associated with longer LOS in hospital (WMD 0.75, 95% CI 0.00–1.50, p 0.05) with high heterogeneity (I^2 = 99%, $p < 0.00001$). Figure 3D showed that seven RCTs (n = 2,566) and one observational study (n = 238) reported hospital LOS in non-cardiac surgical patients, and a meta-analysis of seven RCTs showed PAC did not affect hospital LOS (WMD 0.02, 95% CI −0.67–0.70, p 0.96) with high heterogeneity (I^2 = 79%, $p < 0.0001$). The subgroup analysis results (whether GDT was employed) showed PAC utilization did not affect hospital LOS (Supplementary files Fig. 8).

MVD

Three studies reported MVD, two observational cohort studies in cardiac surgical patients, and a meta-analysis showed PAC utilization did not affect MVD (OR 0.85, 95% CI 0.56–1.29, p 0.46) (Supplementary files Fig. 9). In non-cardiac surgical patients, only one study reported that PAC utilization did not influence MVD.

Hospitalization costs

As shown in Fig. 2E (the units shown were 1000 USD), five observational studies (n = 2,078,400) reported hospitalization costs in cardiac surgical patients, and meta-analysis results showed PAC utilization did not affect hospitalization costs (WMD −0.59, 95% CI −5.49–4.30, p 0.81) with high heterogeneity (I^2 = 100%, $p < 0.00001$). The results of subgroup analysis (before/after the SUPPORT study) showed that PAC utilization was associated with higher hospitalization costs (the group before 1996) (Supplementary files Fig. 10). Figure 3E showed that four RCTs (n = 351) reported hospitalization costs in non-cardiac surgical patients, and meta-analysis showed PAC utilization did not affect hospitalization costs (WMD 1.33, 95% CI −1.25–3.90, p 0.31) with high heterogeneity (I^2 = 73%, p = 0.01).

Sensitivity analyses and publication bias

First, by examining the influence of the statistical model on estimated treatment effects, as shown in Supplementary files Table 5, results of short-term mortality in non-cardiac surgical patients, LOS in ICU of cardiac surgical patients, and postoperative cerebrovascular events, ARF, CHF, infectious complications in cardiac and non-cardiac surgical patients essentially did not change, indicating that these results were reliable. Second, sensitivity tests were performed by removal of each study to evaluate the influence of individual studies on the overall effects (Supplementary files Table 6). The meta-analysis results of short-term mortality and hospitalization costs in non-cardiac surgical patients, cerebrovascular events, ARF and LOS in hospital in cardiac surgical patients changed after the sensitivity test described above. Third, the funnel plot suggested moderate publication bias in studies reporting short-term mortality (Fig. 4).

Discussion

The invention of PAC has a long and distinguished history. Professor Werner Forssmann first performed the human right heart catheter in 1929. In the 1940s, Richards and colleagues [39] developed a catheter that could be inserted in the pulmonary artery to study hemodynamics in patients using fluoroscopy guidance. The introduction of PAC by professors Jeremy Swan and William Ganz in 1970 [1] allowed the insertion of the catheter at the bedside. Following the work of Swan/Ganz, PAC has begun to be routinely used in critically ill patients as a diagnostic tool and monitoring device, particularly for those with myocardial infarction, cardiogenic shock,

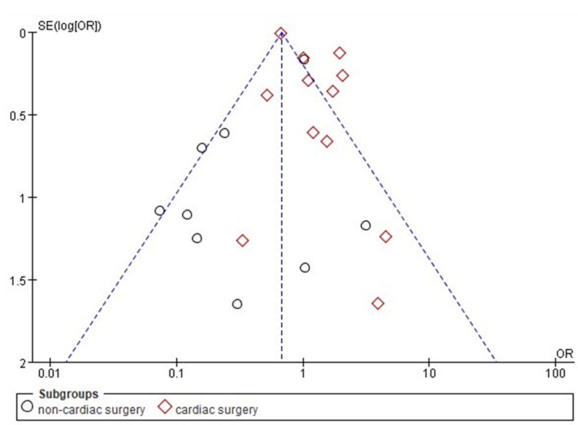

Fig. 4 Funnel plot of short-time mortality in cardiac and non-cardiac surgical patients

and CHF. However, the SUPPORT trial conducted in 1996 revealed that PAC utilization was associated with increased 30-day mortality, LOS in the ICU, and costs [2]. These findings raised concerns regarding the risk–benefit profile of PAC utilization. Conversely, a study called PAC-man enrolled 1,041 ICU patients from the UK and reported no significant difference in in-hospital mortality between patients managed with or without PAC [40]. Several studies including high-risk surgical patients also showed that the benefit of PAC utilization was modest [4, 9, 18]. Concerns about the safety and efficacy of PAC, alternative less invasive or noninvasive hemodynamic monitoring devices emerged [41]. Although many technologies have sought to supplant PAC, none has been subjected to as much clinical use and scrutiny. PAC remains the gold standard for CO/CI, $SmvO_2$, PAP, blood temperature, and all in one piece. Transesophageal echocardiography (TEE) has been increasingly used in noncardiac and cardiac surgical patients. TEE could detect wall motion abnormalities, which are early signs of acute myocardial ischemia. Moreover, TEE could provide live information regarding valvular structures and function, and detect intracardiac air [42]. However, TEE use needs a skilled operator, and the standard TEE probes cannot be kept in the patient for too long. Therefore, TEE and PAC were complementary to each other. Combined use of PAC and TEE may be more helpful than alone.

The present study demonstrated PAC utilization did not affect short-term mortality in cardiac surgical patients and was associated with a higher incidence of postoperative CHF, ARF, cerebrovascular events, infectious complications, and LOS in the ICU or hospital. It is plausible to hypothesize that this observation results reflect the practice of escalating monitoring to include PAC placement in the face of clinical deterioration in patients who ultimately suffer a complication could be reasonable. To our knowledge, many factors may affect surgical patients' outcomes, for example, patients' preoperative conditions, comorbidities, surgery risks, etc. As far as PAC is concerned, the indications of PAC utilization, clinicians' proficiency and experience, whether GDT was employed, and the timing of PAC insertion could all affect the patients' outcomes. However, early PAC insertion was not associated with survival benefits in critically ill patients with cardiac diseases, either in surgical or non-surgical patients [43].

In 2003, the American Society of Anesthesiologists (ASA) updated the practice guidelines for PAC utilization, recommending that appropriate PAC use should be determined based on three key factors: patient characteristics, surgical considerations, and clinical practice variables [44]. Firstly, PAC utilization was appropriate in high-risk surgical patients (ASA grade 4/5, hemodynamic disturbances with high possibility of organ dysfunction or death) undergoing high-risk procedures (a great chance of fluid change or hemodynamic disturbances or other factors with high risk of morbidity and mortality). Secondly, the low-risk practice settings (good catheter-use skills and technical support, training, and experience of nursing staff in the recovery room and ICU, technical support for ancillary services, and availability of specialists and equipment to manage complications), as well as the proficiency and experience of clinicians in PAC utilization, must be taken into account. Finally, the risk degree of patients and the risk posed by the procedure itself should influence the decision whether or not a PAC is used [44]. It is noteworthy that this latest PAC guideline was published 20 years ago. One non-cardiac surgery study (liver transplantation) and seven cardiac surgery studies included in the present study were conducted after 2003. However, the enrolled patients did not reach ASA grade 4/5 and mainly underwent CABG or VS. In 2021, the Chinese Society of Anesthesiology (CSA) issued recommendations for utilizing PAC in cardiac surgical patients with specific conditions such as left ventricular systolic dysfunction (ejection fraction $<30\%$), right ventricular systolic dysfunction, left ventricular diastolic dysfunction, acute ventricular septal perforation and left ventricular assist device. Consequently, judicious employment of PAC in this patient population is advised primarily for individuals experiencing persistent hemodynamic instability or at high risk of developing such circumstances intraoperatively or shortly after surgery.

The clinicians' expertise and extensive experience with PAC are indispensable. Professor Jeremy Swan, the pioneer of PAC, recommended that physicians should perform a minimum of 50 PAC procedures annually to uphold their proficiency [45]. The latest review concluded that a thorough understanding of measurements (e.g., CO, PAWP, $SmvO_2$) obtained from PAC was the first step in the successful application of PAC in clinical practice [46]. In some patients, CO measurement was indicated as an aid to diagnosis, to monitor the adequacy of therapy, and to prognosis [47]. Critically-ill patients who could not sustain a CI in excess of 2 $L/min/m^2$, despite aggressive therapy, had a very high mortality rate [48]. For CHF patients, $PCWP < 15$ mmHg was an indicator of remission of HF [49]. Maintaining $SmvO_2 > 70\%$ during cardiac surgery correlates with a better postoperative outcome [50]. Pinsky and colleagues pointed out that the monitoring device could only improve outcomes if coupled with a specific treatment plan known to improve outcomes [51]. However, several surveys [52–55] identified that many physicians and nurses could not correctly measure or interpret even the most basic information provided by PAC. If future generations of physicians and nurses receive less training in PAC than their predecessors, these deficiencies will likely worsen, which may further decrease the effectiveness of PAC utilization in clinical situations. Correspondingly, educational modalities for learning PAC would like to be relied upon more broadly, such as simulation, similar to the high-fidelity mannequins in central venous catheter insertion [56]. Expansion of high-fidelity simulation to include waveform interpretation and identification and management of complications of PAC (e.g., arrhythmias) could supplement hands-on training [57].

In the present study, PAC-guided GDT was employed in only two cardiac surgical studies, one described PAC-guided GDT reduced mortality [10], and another study described PAC-guided GDT did not affect mortality and morbidity [29]. PAC was inserted and guided for GDT in eight non-cardiac surgical studies, and four studies showed benefit [11, 14, 34, 37], three studies showed no effect [16, 28, 36], and one study showed harm [9]. As shown in Table 2, four GDT parameters (CI, PCWP, SVR, oxygen delivery) were used in seven [9, 10, 14, 16, 28, 34, 36], six [9, 14, 16, 28, 36, 37], five [10, 14, 16, 28, 36], and four [9, 16, 34, 37] included PAC-guided GDT studies in the current study, respectively. However, there were few definitive data to support the use of any hemodynamic target. The benefit of GDT seemed to rely on the use of vasoactive agents, and the mortality was not statistically significant in cardiac surgical patients. Nonetheless, the results were relevant to anesthetic practice, the performance of intra-operatively initiated GDT still yielded clinically important benefit [58].

In the present study, two [15, 18], five [8, 14, 15, 28, 36], four [9, 14–16] non-cardiac surgical studies showed that PAC utilization did not affect MVD, LOS in ICU, and hospital LOS, respectively. For cardiac surgical patients, four [7, 17, 18, 35], seven [5, 7, 17–19, 31, 35], four [5, 7, 31, 35] studies showed that PAC utilization was associated with longer MVD, LOS in ICU, and hospital LOS, respectively. And two [29, 32], three [13, 29, 32], one [32] studies showed no effect on MVD, LOS in ICU, and hospital LOS, respectively. Only one study showed that PAC utilization was associated with shorter hospital LOS. As mentioned above, many factors affected the mortality and morbidity of surgical patients using PAC. Similarly, postoperative recovery was also influenced by many factors (patients' condition, doctors' preferences, and institutions' clinical routines).

The results showed that PAC utilization did not affect hospitalization costs in cardiac and non-cardiac surgical patients in the current study. In the original studies, four non-cardiac surgical studies [14, 15, 28, 34, 36] and one cardiac surgical study [17] showed that PAC utilization did not affect hospitalization costs, and one non-cardiac surgical study [34] showed PAC utilization had reduced costs. On the contrary, four cardiac surgical studies [29, 31, 35, 38] showed higher hospitalization costs with PAC utilization. Hospitalization costs were also influenced by many factors. Clermont et al. reported that PAC utilization had increased costs for routine PAC utilization in acute lung injury patients [59]. A retrospective cohort study reported that PAC utilization had increased hospitalization costs in HF patients [60]. When PAC utilization reduced mortality and improved outcomes, it was a benefit despite the increased costs. An economic calculating model-based study [61] reported that for an acute care hospital with 500 procedures/year and 34% PAC adoption (It is based PAC utilization was approximately 34% of the US cardiac surgical procedures), annualized savings were $61,806 versus no PAC utilization, and for an integrated payer-provider health system with the base-case scenario of 3845 procedures/year and 34% PAC adoption, estimated savings were $596,637 for the combined surgical index admission and treatment for related complications over the following year.

In general, the evidence of effectiveness and safety for PAC utilization was still lacking, and it wasn't easy to draw definitive conclusions from accumulated evidence. PAC, while a valuable diagnostic and monitoring tool, is not without risks. Common complications include arrhythmias, rare but severe complications include pulmonary artery rupture and catheter-related infections. Thrombotic complications, mechanical complications such as catheter knotting, can lead to significant morbidity. The overall mortality rate associated with PAC, these potential adverse outcomes underscore the importance of careful patient selection, skilled catheter placement, and judicious use of this invasive monitoring technique. Based on the current study's findings, routine use of PAC in low-risk patients had not reduced mortality or hospital LOS. For patients with relative contraindications, the harm of PAC utilization may outweigh its benefit, and for patients with indications, PAC utilization may improve prognosis. Although clinical trials could not reach consistent conclusions, there were a large number of patients in clinical practice who needed PAC utilization and benefited from it. Future studies should focus on defining subgroups of patients who might benefit from PAC utilization and defining effective therapeutic interventions according to the hemodynamic information gained from PAC.

Limitations

The limitations of this study should be acknowledged, which are characteristics of all aggregate data meta-analyses [62, 63]. First, the authors included several studies performed in different settings with different aims, and simultaneously these data were not suitable for subgroup analysis, which may be the source of heterogeneity [64]. Second, the present study included both RCTs and observational studies, the period of inclusion was large, and the sample size of four RCTs was less than 100, therefore may reduce the quality of evidence of the present study. Third, the authors focused on surgical patients, which did not include studies of PAC utilization in other settings such as in HF patients and coronary care units. Fourth, the current study had limitations in analyzing the secondary outcomes (complications, LOS in ICU and hospital, hospitalization costs), because only some of the included studies reported these outcomes. In addition, the diagnostic criteria of complications in each study were not unified. Finally, the postoperative recovery of surgical patients was complex and could be affected by many factors, however, the present study only analyzed the effect of PAC utilization.

Conclusions

This meta-analysis suggested that PAC utilization was not associated with short-term mortality in surgical patients but with a higher incidence of major complications and longer LOS in the ICU or hospital in cardiac surgical patients.

Abbreviations

PAC	Pulmonary artery catheterization
OR	Odds ratio
CI	Confidence interval
LOS	Length of stay
ICU	Intensive care unit
CO	Cardiac output
$SmvO_2$	Mixed venous oxygen saturation
PAP	Pulmonary artery pressure
PCWP	Pulmonary capillary wedge pressure
PVR	Pulmonary vascular resistance
SVR	Systemic vascular resistance
CI	Cardiac index
SV	Stroke volume
RVEF	Right ventricular ejection fraction
CABG	Coronary artery bypass graft
MVD	Mechanical ventilation duration
RCTs	Randomized controlled trials
NOS	Newcastle–Ottawa scale
GDT	Goal-directed therapy
WMD	Weighted mean difference
CHF	Chronic cardiac failure
ARF	Acute renal failure
PiCCO	Pulse index continuous cardiac output
LiDCO	Lithium dilution cardiac output
NICO	Noninvasive cardiac output
TEE	Transesophageal echocardiography
HF	Heart failure
SCA	Society of cardiovascular anesthesiologists
ASA	American society of anesthesiologists
CSA	Chinese society of anesthesiology

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13019-025-03416-8.

Supplementary file 1.
Supplementary file 2.
Supplementary file 3.
Supplementary file 4.
Supplementary file 5.
Supplementary file 6.
Supplementary file 7.
Supplementary file 8.
Supplementary file 9.
Supplementary file 10.
Supplementary file 11.
Supplementary file 12.
Supplementary file 13.
Supplementary file 14.
Supplementary file 15.
Supplementary file 16.

Acknowledgements
None.

Author contributions
Chun-Mei Xie, Li-Xian He: conceptualization, software, methodology, data collection, data analysis/interpretation, statistics, and writing-original draft. Meng-Qi Shen: data collection, formal analysis, software, and critical revision of the article. Yun-Tai Yao: conceptualization, data collection, data analysis/interpretation, statistics, formal analysis, supervision, and critical revision of the article.

Funding
This work was supported by the National Key Research and Development Program (2022YFC2503400), the Yunnan Provincial Clinical Medicine Research Special Program (202405AJ310003), and the Major Science and Technology Special Plan Project of Yunnan Province (202302AA310045).

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 6 January 2025 Accepted: 6 April 2025
Published online: 06 May 2025

References

1. Swan HJ, Ganz W, Forrester J, Marcus H, Diamond G, Chonette D. Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. N Engl J Med. 1970;283:447–51.
2. Connors AF Jr, Speroff T, Dawson NV, Thomas C, Harrell FE Jr, Wagner D, et al. The effectiveness of right heart catheterization in the initial care of critically ill patients. Support Investigators JAMA. 1996;276:889–97.
3. Rajaram SS, Desai NK, Kalra A, Gajera M, Cavanaugh SK, Brampton W, et al. Pulmonary artery catheters for adult patients in intensive care. Cochrane Database Syst Rev. 2013;2013:CD003408.
4. Brovman EY, Gabriel RA, Dutton RP, Urman RD. Pulmonary artery catheter use during cardiac surgery in the united states, 2010 to 2014. J Cardiothorac Vasc Anesth. 2016;30:579–84.
5. Pasquier V, Deletombe B, Bedague D, Albaladejo P, Durand M. Impact of pulmonary artery catheter hemodynamic monitoring on post-operative morbidity and mortality in elective Bentall procedures. Journal of Cardiothoracic and Vascular Anesthesia. 2020;34.
6. Shaw AD, Mythen MG, Shook D, Hayashida DK, Zhang X, Skaar JR, et al. Pulmonary artery catheter use in adult patients undergoing cardiac surgery: a retrospective, cohort study. Perioper Med (Lond). 2018;7:24.
7. Djaiani G, Karski J, Yudin M, Hynninen M, Fedorko L, Carroll J, et al. Clinical outcomes in patients undergoing elective coronary artery bypass graft surgery with and without utilization of pulmonary artery catheter-generated data. J Cardiothorac Vasc Anesth. 2006;20:307–10.
8. Hofer RE, Vogt MNP, Taner T, Findlay JY. Influence of intraoperative transesophageal echocardiography and pulmonary artery catheter monitoring on outcomes in liver transplantation. Transplant Direct. 2020;6: e525.
9. Sandham JD, Hull RD, Brant RF, Knox L, Pineo GF, Doig CJ, et al. A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients. N Engl J Med. 2003;348:5–14.
10. Moore CH, Lombardo TR, Allums JA, Gordon FT. Left main coronary artery stenosis: hemodynamic monitoring to reduce mortality. Ann Thorac Surg. 1978;26:445–51.
11. Schultz RJ, Whitfield GF, LaMura JJ, Raciti A, Krishnamurthy S. The role of physiologic monitoring in patients with fractures of the hip. J Trauma. 1985;25:309–16.
12. Davies MJ, Cronin KD, Domaingue CM. Pulmonary artery catheterisation. An assessment of risks and benefits in 220 surgical patients. Anaesth Intensive Care. 1982;10(1):9–14. https://doi.org/10.1177/0310057X8201000103.
13. Tuman KJ, McCarthy RJ, Spiess BD, DaValle M, Hompland SJ, Dabir R, et al. Effect of pulmonary artery catheterization on outcome in patients undergoing coronary artery surgery. Anesthesiology. 1989;70:199–206.
14. Berlauk JF, Abrams JH, Gilmour IJ, O'Connor SR, Knighton DR, Cerra FB. Preoperative optimization of cardiovascular hemodynamics improves outcomes in peripheral vascular surgery. A prospective, randomized clinical trial. Ann Surg. 1991;214:289–97.
15. Isaacson IJ, Lowdon JD, Berry AJ, Smith RB 3rd, Knos GB, Weitz FI, et al. The value of pulmonary artery and central venous monitoring in patients undergoing abdominal aortic reconstructive surgery: a comparative study of two selected, randomized groups. J Vasc Surg. 1990;12(6):754–60.
16. Bonazzi M, Gentile F, Biasi GM, Migliavacca S, Esposti D, Cipolla M, Marsicano M, Prampolini F, Ornaghi M, Sternjakob S, Tshomba Y. Impact of perioperative haemodynamic monitoring on cardiac morbidity after major vascular surgery in low risk patients. A randomised pilot trial. Eur J Vasc Endovasc Surg. 2002;23(5):445–51. https://doi.org/10.1053/ejvs.2002.1617.
17. Chiang Y, Hosseinian L, Rhee A, Itagaki S, Cavallaro P, Chikwe J. Questionable benefit of the pulmonary artery catheter after cardiac surgery in high-risk patients. J Cardiothorac Vasc Anesth. 2015;29:76–81.
18. Schwann NM, Hillel Z, Hoeft A, Barash P, Möhnle P, Miao Y, et al. Lack of effectiveness of the pulmonary artery catheter in cardiac surgery. Anesth Analg. 2011;113:994–1002.
19. Brown JA, Aranda-Michel E, Kilic A, Serna-Gallegos D, Bianco V, Thoma FW, et al. The impact of pulmonary artery catheter use in cardiac surgery. J Thorac Cardiovasc Surg. 2022;164(1965–1973): e6.
20. Muka T, Glisic M, Milic J, Verhoog S, Bohlius J, Bramer W, et al. A 24-step guide on how to design, conduct, and successfully publish a systematic review and meta-analysis in medical research. Eur J Epidemiol. 2020;35:49–60.
21. Cumpston M, Li T, Page MJ, Chandler J, Welch VA, Higgins JP, et al. Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. Cochrane Database Syst Rev. 2019;10:ED000142.
22. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372: n71.
23. Corbett MS, Higgins JP, Woolacott NF. Assessing baseline imbalance in randomised trials: implications for the Cochrane risk of bias tool. Res Synth Methods. 2014;5(1):79–85.
24. Luo X, Jiang L, Du B, Wen Y, Wang M, Xi X, et al. A comparison of different diagnostic criteria of acute kidney injury in critically ill patients. Crit Care. 2014;18:R144.
25. Stang A. Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. Eur J Epidemiol. 2010;25:603–5.
26. Fleiss JL. Analysis of data from multi-clinic trials. Control Clin Trials. 1986;7:267–75.
27. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ. 2003;327:557–60.
28. Bender JS, Smith-Meek MA, Jones CE. Routine pulmonary artery catheterization does not reduce morbidity and mortality of elective vascular surgery: results of a prospective, randomized trial. Ann Surg. 1997;226:229–36.
29. Pearson KS, Gomez MN, Moyers JR, Carter JG, Tinker JH. A cost/benefit analysis of randomized invasive monitoring for patients undergoing cardiac surgery. Anesth Analg. 1989;69:336–41.
30. Polanczyk CA, Rohde LE, Goldman L, Cook EF, Thomas EJ, Marcantonio ER, et al. Right heart catheterization and cardiac complications in patients undergoing noncardiac surgery: an observational study. JAMA. 2001;286:309–14.
31. Ramsey SD, Saint S, Sullivan SD, Dey L, Kelley K, Bowdle A. Clinical and economic effects of pulmonary artery catheterization in nonemergent coronary artery bypass graft surgery. J Cardiothorac Vasc Anesth. 2000;14:113–8.
32. Resano FG, Kapetanakis EI, Hill PC, Haile E, Corso PJ. Clinical outcomes of low-risk patients undergoing beating-heart surgery with or without pulmonary artery catheterization. J Cardiothorac Vasc Anesth. 2006;20:300–6.
33. Schwann TA, Zacharias A, Riordan CJ, Durham SJ, Engoren M, Habib RH. Safe, highly selective use of pulmonary artery catheters in coronary artery bypass grafting: an objective patient selection method. Ann Thorac Surg. 2002;73:1394–401.
34. Shoemaker WC, Kram HB, Appel PL, Fleming AW. The efficacy of central venous and pulmonary artery catheters and therapy based upon them in reducing mortality and morbidity. Arch Surg. 1990;125:1332–7.
35. Stewart RD, Psyhojos T, Lahey SJ, Levitsky S, Campos CT. Central venous catheter use in low-risk coronary artery bypass grafting. Ann Thorac Surg. 1998;66:1306–11.
36. James Valentine R, Duke ML, Inman MH, Grayburn PA, Hagino RT, Kakish HB, Patrick Clagett G. Effectiveness of pulmonary artery catheters in aortic surgery: a randomized trial. J Vasc Surg. 1998;27(2):203–12. https://doi.org/10.1016/S0741-5214(98)70351-9.
37. Wilson J, Woods I, Fawcett J, Whall R, Dibb W, Morris C, et al. Reducing the risk of major elective surgery: randomised controlled trial of preoperative optimisation of oxygen delivery. BMJ. 1999;318:1099–103.
38. Xu F, Wang Q, Zhang H, Chen S, Ao H. Use of pulmonary artery catheter in coronary artery bypass graft. Costs Long-Term Outcomes PLoS One. 2015;10: e0117610.
39. Bloomfield RA, Lauson HD, Cournand A, Breed ES, Richards DW. Recording of right heart pressures in normal subjects and in patients with chronic pulmonary disease and various types of cardio-circulatory disease. J Clin Invest. 1946;25:639–64.
40. Harvey S, Harrison DA, Singer M, Ashcroft J, Jones CM, Elbourne D, et al. Assessment of the clinical effectiveness of pulmonary artery catheters in management of patients in intensive care (PAC-Man): a randomized controlled trial. Lancet. 2005;366:472–9.

41. Rozental O, Thalappillil R, White RS, Tam CW. To swan or not to swan: indications, alternatives, and future directions. J Cardiothorac Vasc Anesth. 2020;35:600–15.
42. Youssef N, Whitlock RP. The routine use of the pulmonary artery catheter should be abandoned. Can J Cardiol. 2017;33:135–41.
43. Wu J, Liang Q, Hu H, Zhou S, Zhang Y, An S, et al. Early pulmonary artery catheterization is not associated with survival benefits in critically ill patients with cardiac disease: an analysis of the MIMIC-IV database. Surgery. 2022;172:1285–90.
44. American Society of Anesthesiologists Task Force on Pulmonary Artery C. Practice guidelines for pulmonary artery catheterization: an updated report by the American Society of Anesthesiologists Task Force on Pulmonary Artery Catheterization. Anesthesiology. 2003;99:988-1014. https://doi.org/10.1097/00000542-200310000-00036
45. Swan HJ. What role today for hemodynamic monitoring? When is this procedure indicated? How much training is required? J Crit Illn. 1993;8:1043–50.
46. Bootsma IT, Boerma EC, Scheeren TWL, de Lange F. The contemporary pulmonary artery catheter. Part 2: measurements, limitations, and clinical applications. J Clin Monit Comput. 2022;36(1):17–31. https://doi.org/10.1007/s10877-021-00673-5.
47. Tuchschmidt J, Fried J, Astiz M, Rackow E. Elevation of cardiac output and oxygen delivery improves outcome in septic shock. Chest. 1992;102:216–20.
48. Rivers E, Nguyen B, Havstad S, Ressler J, Muzzin A, Knoblich B, et al. Early goal-directed therapy in the treatment of severe sepsis and septic shock. N Engl J Med. 2001;345:1368–77.
49. Binanay C, Califf RM, Hasselblad V, O'Connor CM, Shah MR, Sopko G, et al. Evaluation study of congestive heart failure and pulmonary artery catheterization effectiveness: the ESCAPE trial. JAMA. 2005;294:1625–33.
50. Pölönen P, Ruokonen E, Hippeläinen M, Pöyhönen M, Takala J. A prospective, randomized study of goal-oriented hemodynamic therapy in cardiac surgical patients. Anesth Analg. 2000;90:1052–9.
51. Pinsky MR, Vincent JL. Let us use the pulmonary artery catheter correctly and only when we need it. Crit Care Med. 2005;33:1119–22.
52. Marik P, Heard SO, Varon J. Interpretation of the pulmonary artery occlusion (wedge) pressure: physician's knowledge versus the experts' knowledge. Crit Care Med. 1998;26:1761–4.
53. Jacka MJ, Cohen MM, To T, Devitt JH, Byrick R. The appropriateness of the pulmonary artery catheter in cardiovascular surgery. Can J Anaesth. 2002;49:276–82.
54. Johnston IG, Jane R, Fraser JF, Kruger P, Hickling K. Survey of intensive care nurses' knowledge relating to the pulmonary artery catheter. Anaesth Intensive Care. 2004;32:564–8.
55. Parviainen I, Jakob SM, Suistomaa M, Takala J. Practical sources of error in measuring pulmonary artery occlusion pressure: a study in participants of a special intensivist training program of The Scandinavian Society of Anaesthesiology and Intensive Care Medicine (SSAI). Acta Anaesthesiol Scand. 2006;50(5):600–3. https://doi.org/10.1111/j.1399-6576.2006.001008.x.
56. Evans LV, Dodge KL, Shah TD, Kaplan LJ, Siegel MD, Moore CL, et al. Simulation training in central venous catheter insertion: improved performance in clinical practice. Acad Med. 2010;85:1462–9.
57. Tukey MH, Wiener RS. The current state of fellowship training in pulmonary artery catheter placement and data interpretation: a national survey of pulmonary and critical care fellowship program directors. J Crit Care. 2013;28:857–61.
58. Chong MA, Wang Y, Berbenetz NM, McConachie I. Does goal-directed haemodynamic and fluid therapy improve peri-operative outcomes?: a systematic review and meta-analysis. Eur J Anaesthesiol. 2018;35:469–83.
59. Clermont G, Kong L, Weissfeld LA, Lave JR, Rubenfeld GD, Roberts MS, et al. The effect of pulmonary artery catheter use on costs and long-term outcomes of acute lung injury. PLoS ONE. 2011;6: e22512.
60. Gabriel A, Hernandez AL, Blumer V, Rueda CA, Zalawadiya S, Stevenson LW, Lindenfeld J. Trends in utilization and outcomes of pulmonary artery catheterization in heart failure with and without cardiogenic shock. J Cardiac Failure. 2019;25(5):364–71. https://doi.org/10.1016/j.cardfail.2019.03.004.
61. Stevens M, Davis T, Munson SH, Shenoy AV, Gricar BLA, Yapici HO, et al. Short and mid-term economic impact of pulmonary artery catheter use in adult cardiac surgery: a hospital and integrated health system perspective. Clinicoecon Outcomes Res. 2021;13:109–19.
62. Greco T, Zangrillo A, Biondi-Zoccai G, Landoni G. Meta-analysis: pitfalls and hints. Heart Lung Vessel. 2013;5:219–25.
63. Frieden TR. Evidence for health decision making - beyond randomized. Controlled Trials N Engl J Med. 2017;377:465–75.
64. Xie CM, Yao YT, Yang K, Shen MQ, He LX, Dai Z, et al. Furosemide does not reduce the incidence of postoperative acute kidney injury in adult patients undergoing cardiac surgery: a PRISMA-compliant systematic review and meta-analysis. J Card Surg. 2022;37:4850–60.

Publisher's Note