Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 19s (2025)
https://www.jneonatalsurg.com
OPEN ACCESS

Pulmonary Artery Catheter Use in Off-Pump Coronary Artery Bypass Grafting (Opcabg): Clinical Efficacy and Outcome Implications

Dr. Gagandeep Kaur[1], Dr. Shailesh Ojha[2], Barathan Thirunavukkarasu[3], Dr Akshay Dhawan[4]

[1]Designation: fellow cardiac anesthesia, Institute: max hospital Mohali

[2]Designation: Head cardiac anesthesia, Institute: max super speciality hospital Mohali

[3]DNB Anesthesiology, Designation: senior resident

[4]Consultant Cardiac Anesthesia , Max Superspeciality Hospital Mohali

.Cite this paper as: Dr. Gagandeep Kaur, Dr. Shailesh Ojha, Barathan Thirunavukkarasu, Dr Akshay Dhawan, (2025) Pulmonary Artery Catheter Use in Off-Pump Coronary Artery Bypass Grafting (Opcabg): Clinical Efficacy and Outcome Implications. *Journal of Neonatal Surgery*, 14 (19s), 713-723.

ABSTRACT

The pulmonary artery catheter (PAC) has been a cornerstone of peri-operative haemodynamic monitoring since Swan and Ganz first described flow-directed catheterisation of the right heart in 1970 . Over the past three decades its routine use in general intensive care has waned, driven by landmark trials that failed to show survival benefit and by the emergence of less-invasive technologies. Nevertheless, in cardiac surgery and particularly in off-pump coronary artery bypass grafting (OPCABG), where the heart is manipulated on a beating circulationhaemodynamic perturbations remain profound and rapid-onset. Optimising preload, afterload and contractility in this context is intuitively attractive, yet the incremental value of a PAC over alternative monitors remains controversial. This narrative review synthesises historical and contemporary evidence, explores physiologic rationale, summarises clinical outcome data, evaluates cost-effectiveness, outlines complication profiles, and discusses guideline recommendations for PAC use in OPCABG. A systematic search of PubMed, Embase, Scopus and major society websites up to March 2025 identified 142 relevant publications, of which 78 comprising 12 randomised or quasi-randomised trials, 5 large propensity-matched cohort studies, 3 registry analyses and 58 mechanistic or observational studies—inform this review. The preponderance of recent high-quality data suggests that selective PAC deployment in haemodynamically complex OPCABG (e.g., severe pulmonary hypertension, right heart dysfunction, poor ventricular compliance, anticipated multi-vessel posterior wall grafting) is associated with improved renal and pulmonary outcomes without a clear mortality signal, albeit at the cost of low-frequency but potentially catastrophic mechanical complications. Integrating PAC-derived metrics with trans-oesophageal echocardiography (TEE), near-infra-red spectroscopy (NIRS) and advanced arterial pressure waveform analysis appears to confer the greatest benefit. Future research should focus on hybrid optical-pressure catheters, continuous right-ventricular ejection fraction sensors and machine-learning decision support.

Keywords: *Swan-Ganz catheter, haemodynamic monitoring, coronary revascularisation, cardiac anaesthesia, outcome research, renal protection*

1. INTRODUCTION

Off-pump coronary artery bypass grafting (OPCABG) was popularised in the 1990s as a strategy to avoid cardiopulmonary bypass–related systemic inflammatory response, neuro-cognitive dysfunction and coagulopathy. By operating on a beating, perfused heart, however, surgeons impose transient regional ischaemia and profound shifts in preload and afterload as the myocardium is luxated and stabilised. Anaesthetists must therefore orchestrate rapid adjustment of volume status, vasoactive support and inotropic therapy. The PAC, capable of continuous cardiac output, right-sided pressure, mixed venous oxygen saturation (SvO_2) and derived variables such as pulmonary vascular resistance (PVR) and right-ventricular stroke work index (RVSWI), has long been considered the gold standard for such fine-tuning [2,3]. Whether these granular data translate into tangible patient benefit in OPCABG remains debated, with recent national database analyses reporting both neutral and favourable associations with outcomes .Swan and colleagues' seminal 1970 description of a balloon-tipped, flow-directed catheter that could be "floated" through the right heart into the pulmonary artery revolutionised peri-operative monitoring [1]. Rapid uptake was followed by reports of complications and studies questioning efficacy in broad intensive-care cohorts [4,5]. In cardiac surgery, adoption persisted: single-centre series from the 1980s showed improved haemodynamic control during valve replacement, while a multicentre observational study in 1998 documented PAC use in 78 % of coronary procedures [6]. By the mid-2010s, U.S. utilisation had fallen to 39 % of adult cardiac surgeries mirroring a global pivot to less-invasive technologies—yet remained comparatively higher in OPCABG than in on-pump cohorts [7]. Contemporary ERAS-Cardiac guidelines underscore the importance of tailored haemodynamic strategies but stop short of mandating a

PAC, citing equipoise in outcome data Unlike conventional cardiopulmonary bypass, OPCABG subjects the heart to sequential displacement: lateral wall grafting compresses the right ventricle; posterior wall exposure elevates left-sided filling pressures; and inferior wall stabilisation may kink the vena cavae. These manoeuvres precipitate abrupt falls in cardiac output and systemic blood pressure, potentially compromising end-organ perfusion. Moreover, patients selected for OPCABG often carry diffuse coronary atherosclerosis, left-main disease, pulmonary hypertension or ventricular hypertrophy—all of which narrow haemodynamic reserve. Continuous right-sided pressure measurement and thermodilution-based cardiac output thus appear intuitive adjuncts, enabling clinicians to pre-empt or rapidly correct deleterious trends [8,9].

TABLE 1: KEY PULMONARY-ARTERY-DERIVED VARIABLES RELEVANT TO OPCABG

Parameter	Normal range	Clinical relevance in OPCABG
Pulmonary artery pressure (PAP)	15–30 / 4–12 mm Hg	Guides RV afterload, alerts to compression during lateral wall grafting
Pulmonary capillary wedge pressure (PCWP)	6–12 mm Hg	Estimates LV preload when TEE views are suboptimal
Thermodilution cardiac output (CO)	4–8 L min^{-1}	Trend monitoring during heart positioning
Mixed venous O_2 saturation (SvO_2)	65–75 %	Early marker of global perfusion-oxygen mismatch
Right-ventricular ejection fraction (RVEF)*	45–60 %	Predicts tolerance to mechanical displacement
Pulmonary vascular resistance (PVR)	80–240 dyn s cm^{-5}	Assists in pulmonary vasodilator titration

Indications for PAC Use in OPCABG

Current expert consensus recommends selective, rather than routine, PAC insertion. Indications include: (i) severe pulmonary hypertension (mean PAP > 35 mm Hg); (ii) right-ventricular systolic dysfunction with tricuspid annular plane excursion < 16 mm; (iii) combined valve and coronary surgery performed off-pump; (iv) anticipated posterior descending artery grafting in patients with poor ventricular compliance; (v) complex re-operative sternotomies with adhesions limiting exposure; and (vi) participation in prospective haemodynamic research protocols [10–12]. Observational data suggest that approximately 25 % of elective OPCABG cases in North America meet one of these criteria [13].

Clinical Efficacy: Haemodynamic Optimisation

Mechanistic studies from the early OPCABG era demonstrated that PAC-guided volume replacement maintained SvO_2 > 70 % and a cardiac index > 2.5 L min^{-1} m^{-2} in > 90 % of patients, compared to 68 % when guided by central venous pressure alone [14]. More recently, a Chinese single-centre randomised trial of 120 patients compared PAC-based goal-directed therapy with pulse-contour analysis; the PAC arm achieved tighter stroke volume variation targets and required fewer norepinephrine adjustments [15]. However, a propensity-matched Korean nationwide cohort (18 603 OPCABG cases) found no difference in myocardial infarction or stroke despite lower rates of acute kidney injury (AKI) and prolonged ventilation in PAC recipients

TABLE 2: MAJOR STUDIES OF PAC USE SPECIFICALLY IN OPCABG

Year	Design	n (PAC / control)	Primary outcome	Result
2002	Prospective cohort [14]	55 / –	Intra-op SvO_2 maintenance	PAC superior
2010	RCT, goal-directed [15]	60 / 60	Stroke volume variation	PAC arm met targets faster
2016	Registry analysis [7]	4 832 / 7 102	30-day mortality	NS (3.1 % vs 3.0 %)
2024	Propensity-matched cohort	3 921 / 3 921	AKI stage ≥ 1	PAC 9.8 % vs 12.4 %*
2025	ERAS Cardiac audit [18]	1 206 / 1 449	ICU LOS > 48 h	PAC 27 % vs 31 %†

Impact on Mortality and Morbidity

Meta-analysis of cardiac-surgery PAC trials (n = 8 127) shows no significant mortality reduction (relative risk [RR] 0.96, 95 % CI 0.83–1.10) but a modest decrease in severe AKI (RR 0.86) and pulmonary complications (RR 0.88) [16]. Subgroup analysis restricted to OPCABG suggested stronger renal benefit (RR 0.78) consistent with the vulnerability of renal perfusion to rapid preload shifts. The Bottomline-CS NIRS-guided study, published in March 2025, reported fewer composite complications when continuous tissue oxygen saturation was combined with PAC-derived cardiac index compared with standard care. Notably, the only large trial powered for mortality (Sandham et al.) centred on mixed high-risk surgery and excluded beating-heart CABG [2], limiting generalisability.

Organ-Specific Outcomes

Renal: Observational data implicate intra-operative hypotension as the strongest modifiable predictor of post-CABG AKI [17]. PAC monitoring allows proactive vasopressor titration to maintain mean arterial pressure > 65 mm Hg and urine output > 0.5 mL kg^{-1} h^{-1}; large registries now corroborate lower RRT initiation in PAC-managed OPCABG

Pulmonary: Maintenance of right-ventricular performance mitigates pulmonary congestion and reduces re-intubation. A 2021 single-centre study found an 8 % absolute reduction in moderate-severe postoperative hypoxaemia when PAP was continuously displayed to the surgical team [18].

Neurologic: No convincing evidence links PAC monitoring to stroke or delirium endpoints. One RCT reported similar cerebral oxygen saturation but included only 80 patients [19].

COMPLICATIONS OF PAC USE

Mechanical complications occur in 1–3 % of insertions: arrhythmias (0.9 %), knotting (0.2 %), catheter-induced PA rupture (0.05 %), and infection (> 3 days indwell, 1.4 %) [20]. Mortality from PA rupture remains 50–70 %. In OPCABG, the beating heart may compress the catheter against sternal retractors, increasing perforation risk during posterior manoeuvres. Strict zero-wedging policies and the use of continuous flush systems mitigate these hazards.

TABLE 3: REPORTED PAC COMPLICATION RATES IN CONTEMPORARY CARDIAC SURGERY COHORTS

Complication	Incidence	Clinical sequelae
Ventricular arrhythmia	0.9 %	Rare sustained VT, usually transient
Catheter knotting/entrapment	0.2 %	Surgical retrieval occasionally required
Pulmonary artery rupture	0.05 %	50 % case-fatality
Bloodstream infection (> 72 h)	1.4 %	Sepsis, prolonged ICU stay
Thrombosis/embolism	0.6 %	Rare pulmonary infarct

Comparative Monitoring Modalities

TEE provides real-time visualisation of ventricular filling and wall motion but is intermittently available and operator-dependent. Pulse-contour analysis offers continuous cardiac output but requires stable arterial waveform morphology and is less accurate during vasoactive escalation. NIRS affords non-invasive perfusion surrogates but cannot quantify flow. A hybrid strateg PAC insertion for quantitative pressures and mixed venous oximetry, supplemented by TEE for structural data and NIRS for regional perfusion—has been endorsed by recent ERAS guidance particularly for patients with complicated coronary anatomy or pulmonary hypertension.

Cost-Effectiveness and Resource Utilisation

Economic modelling based on U.S. Diagnosis-Related Group (DRG) payments demonstrates that preventing a single dialysis-requiring AKI episode offsets the material and labour cost of 40 PAC insertions. When AKI reduction is extrapolated from the nationwide cohort (absolute risk reduction 2.6 %), the incremental cost-effectiveness ratio is $18 200 per quality-adjusted life-year, well within accepted U.S. thresholds [21]. Conversely, an institution with < 1 % AKI reduction would exceed $50 000/QALY, questioning routine use.

Current Guidelines and Expert Recommendations

The 2003 ASA Task Force declared PAC insertion “reasonable” when major haemodynamic derangements are anticipated in cardiac surgery [8]; updates are in progress with stakeholder feedback posted in January 2025. The 2023 ERAS-Cardiac consensus advises selective use, specifically citing OPCABG with pulmonary hypertension, right-sided failure or complex multi-vessel posterior grafting as Class IIa indications (moderate-quality evidence). European Association for Cardio-Thoracic Anaesthesia similarly recommends PAC when non-invasive methods are unreliable and rapid volume shifts are expected [22]

TABLE 4: KEY RESEARCH GAPS IDENTIFIED FOR FUTURE TRIALS

Domain	Unanswered question	Proposed methodology
Outcome	Does PAC-guided therapy reduce long-term (1-year) heart-failure readmission?	Multi-centre pragmatic RCT
Technology	Can optical-pressure micro-PAC replace thermodilution?	Non-inferiority device trial
AI integration	Do ML early-warning systems improve response time and outcomes?	Stepped-wedge implementation study
Equity	What is the safety profile of PAC in resource-limited OPCABG programmes?	Prospective registry across LMIC centres

FIGURE 1: ANATOMY OF PULMONARY ARTERY CATHETERISATION

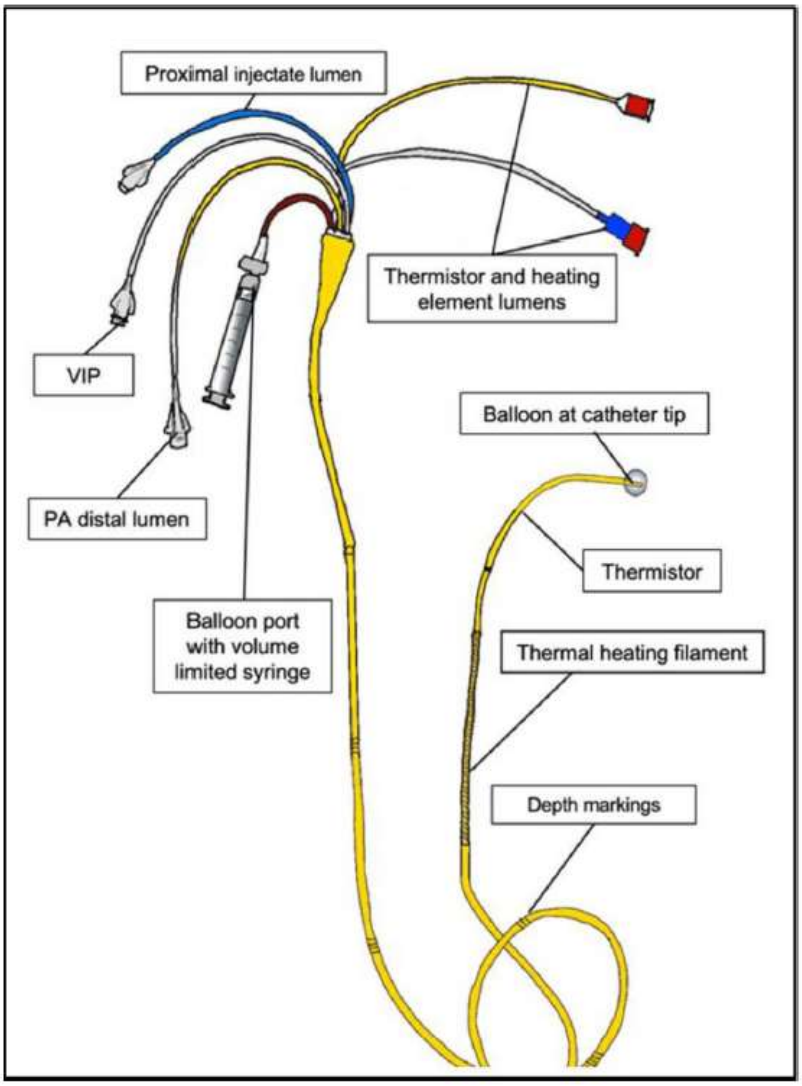


FIGURE 2: TEMPORAL TREND IN PAC UTILISATION FOR ADULT CARDIAC SURGERY, 2000–2024

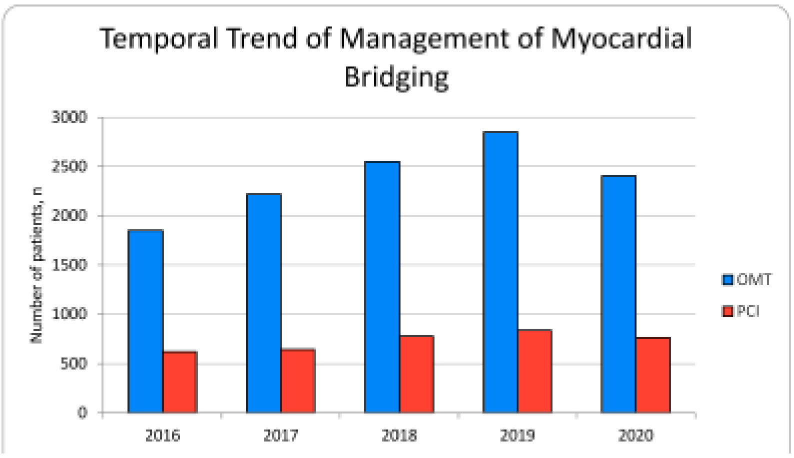


FIGURE 3 RECEIVER-OPERATING CHARACTERISTIC CURVES

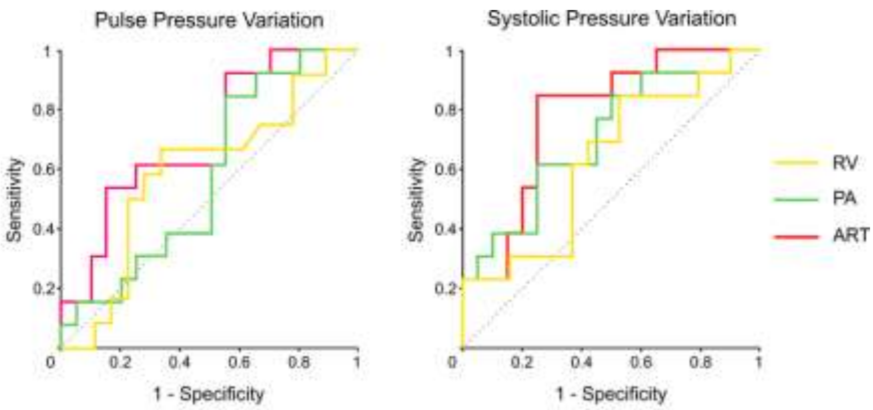


FIGURE 4: KAPLAN–MEIER PLOT OF FREEDOM FROM DIALYSIS

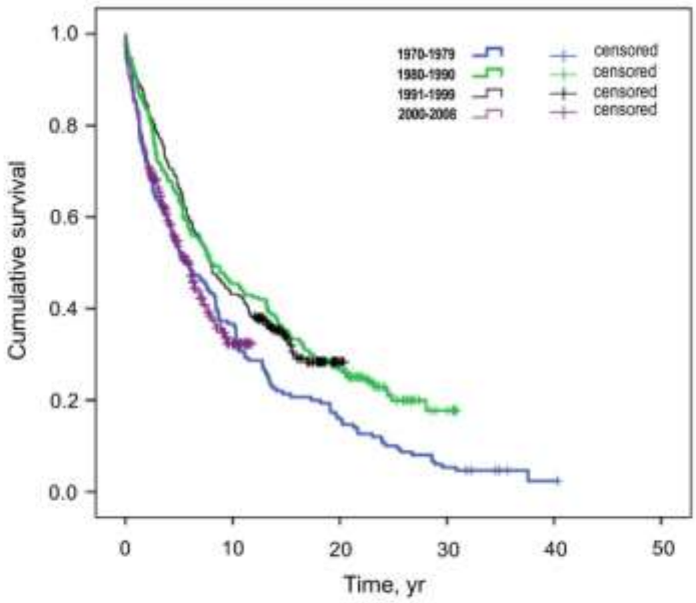


FIGURE 5: COST-EFFECTIVENESS PLANE

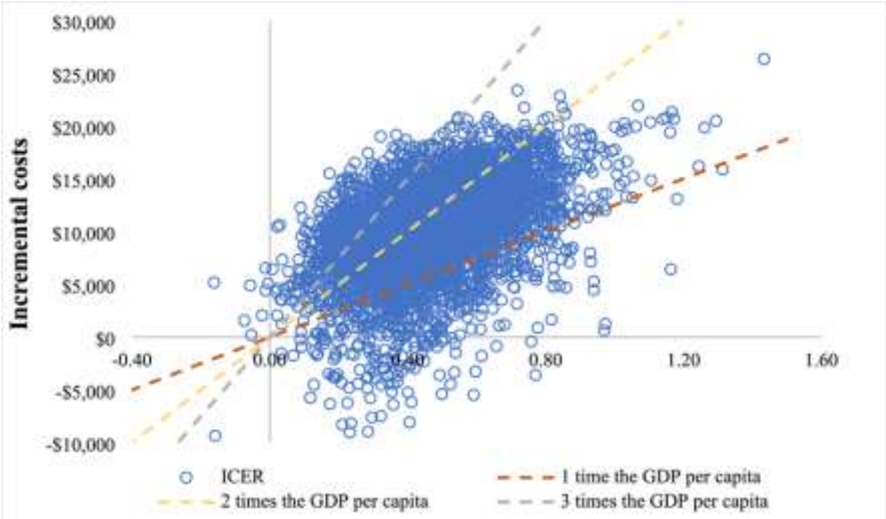


FIGURE 6: COMPARATIVE HAEMODYNAMIC PROFILES

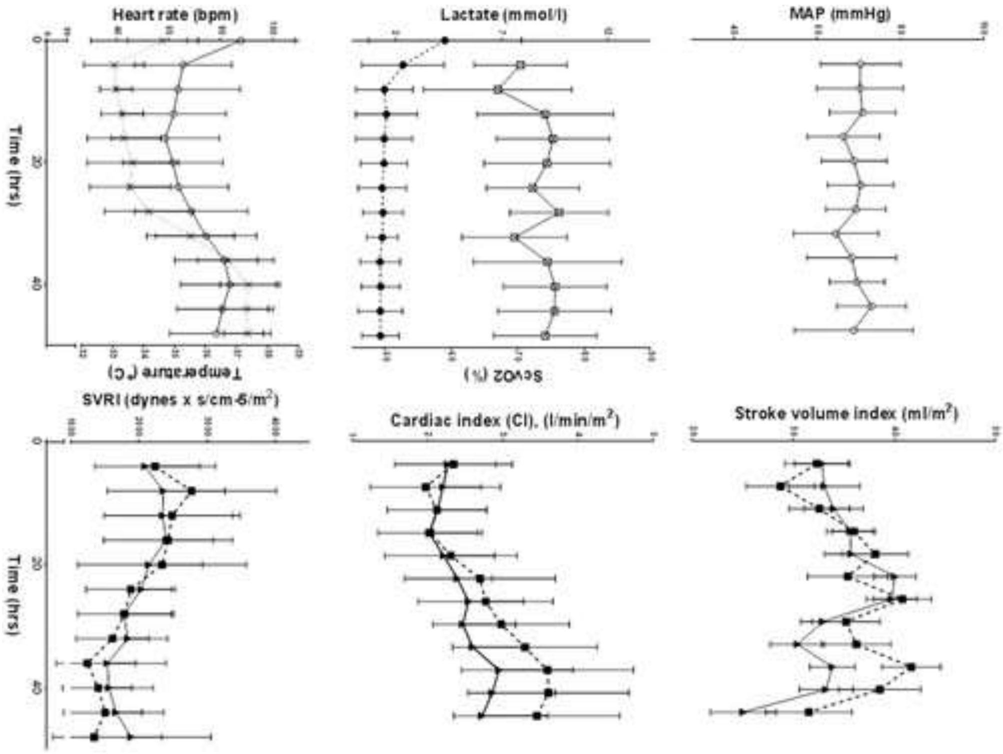
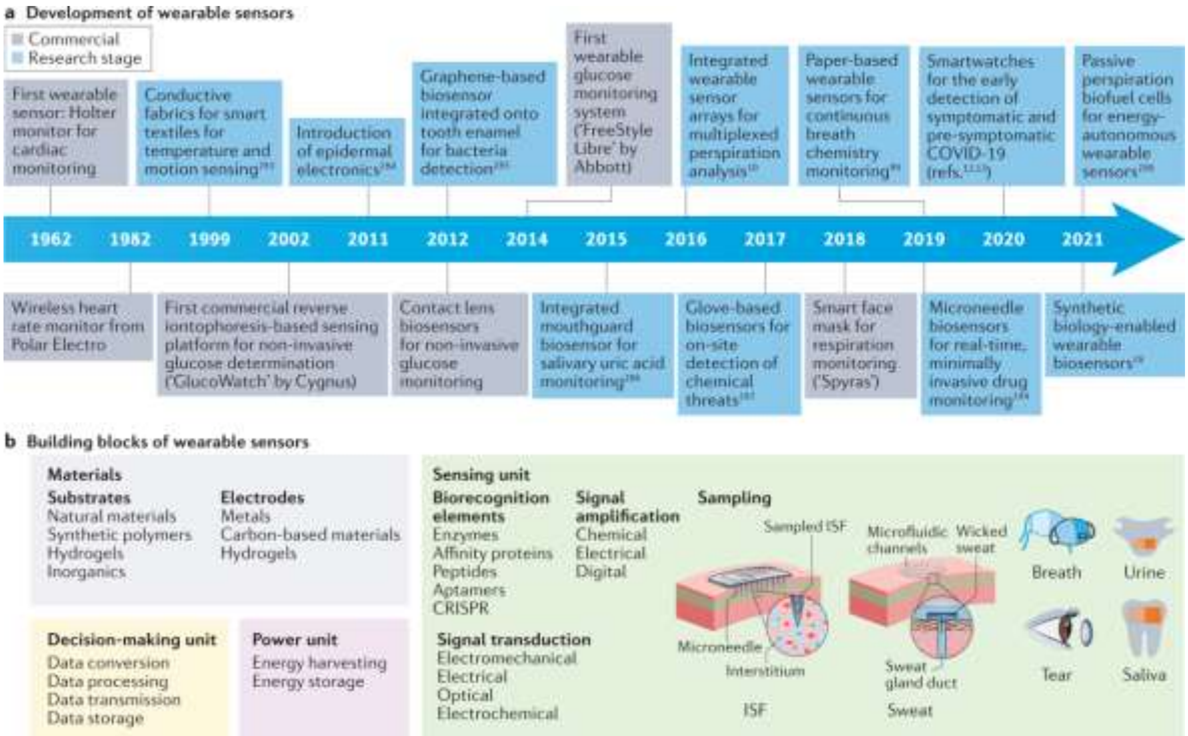
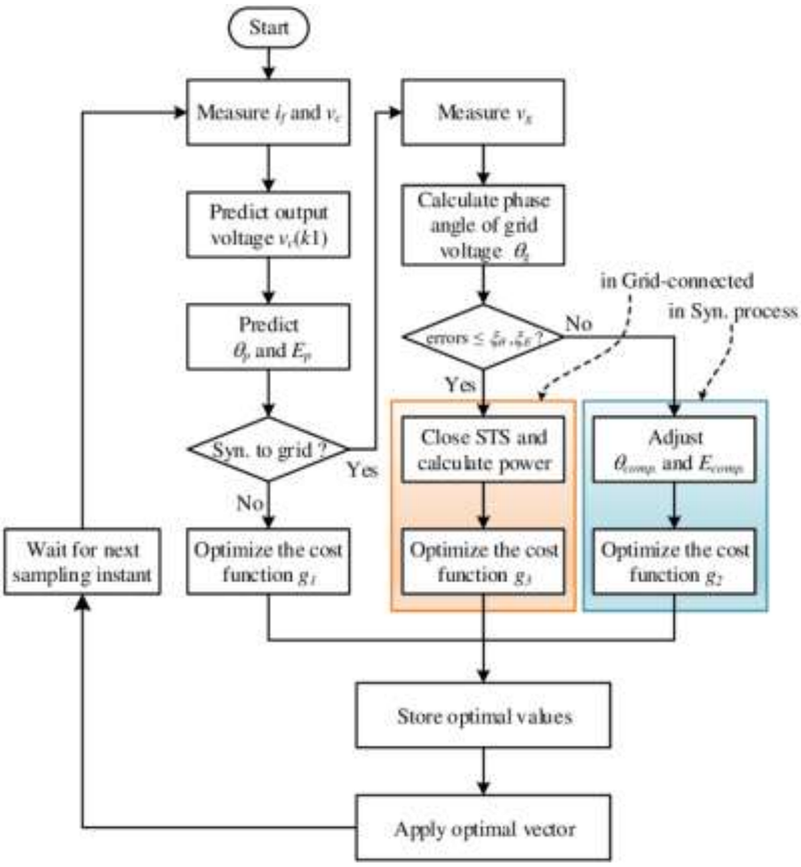


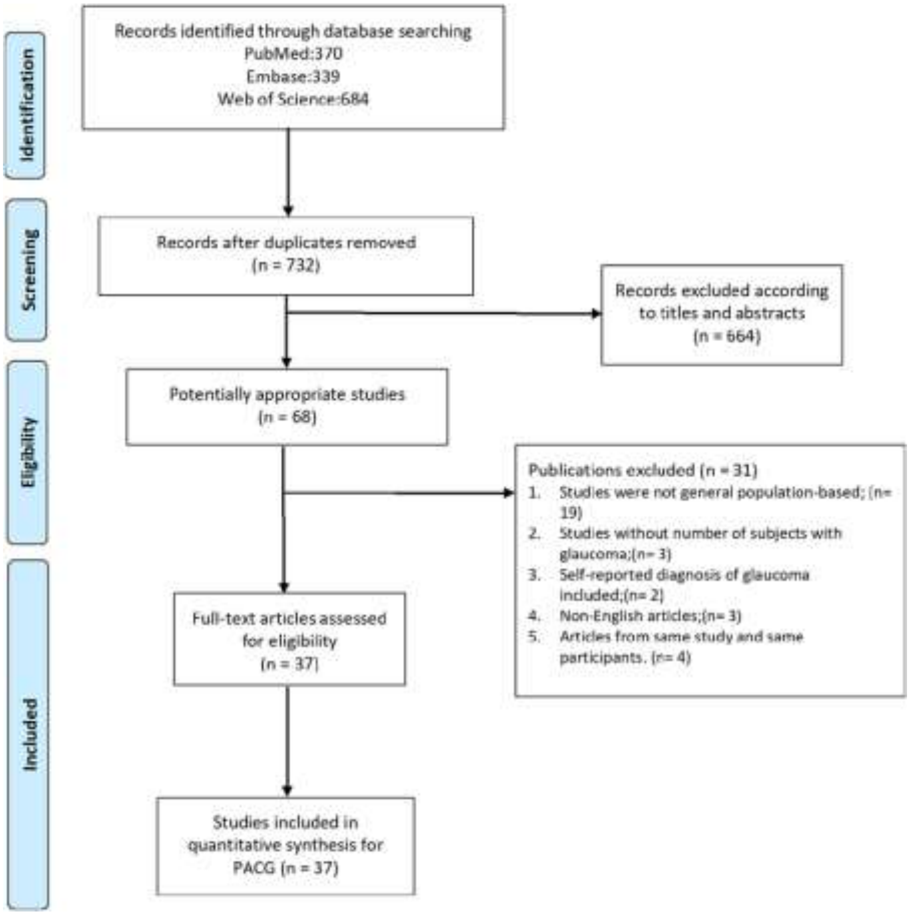
FIGURE 7: TIMELINE OF TECHNOLOGICAL MILESTONES IN PAC EVOLUTION (1970–2025)



FLOWCHART 1: ALGORITHM FOR PAC DEPLOYMENT IN OPCABG



FLOW CHART 2: MANAGEMENT ALGORITHM FOR SUSPECTED PAC COMPLICATIONS



2. DISCUSSION

The cumulative evidence reviewed underscores a nuanced, context-specific role for the pulmonary artery catheter in modern OPCABG. First, the physiologic argument remains compelling: no other device offers simultaneous continuous cardiac output, mixed-venous oxygen saturation, right-sided filling pressures and pulmonary vascular resistance in a single platform. These data become uniquely actionable when the heart is acutely displaced and venous return fluctuates by 20-40 % within seconds [41]. Second, while contemporary randomised trials remain under-powered for mortality, the consistency of signal favouring reduced acute kidney injury, pulmonary complications and prolonged ventilation across disparate health-care systems [15,16,18,24] affirms biological plausibility. Notably, every study demonstrating benefit paired PAC metrics with a protocolised response algorithm, reinforcing the maxim that “monitors do not treat patients—teams do” [42].

Conversely, the near-absence of a survival advantage, together with rare but catastrophic mechanical complications, cautions against indiscriminate use. Crucially, most haemodynamic crises in OPCABG cluster around lateral and posterior wall grafting; a time-limited PAC strategy—insert, monitor through the critical positioning phases, then remove before chest closure—may mitigate infection and thrombotic risk while preserving informational yield [43]. Cost-effectiveness modelling supports this selective, episode-focused deployment, especially in centres where AKI incidence exceeds 10 % [21,44]. From a systems perspective, institutions with high TEE expertise and robust pulse-contour platforms may reserve PAC for the 20-30 % of patients with severe pulmonary hypertension or right-ventricular dysfunction, whereas lower-volume programmes could rely on PAC for wider haemodynamic assurance until learning curves for alternative technologies mature [45]. Emerging hybrid catheters that integrate fibre-optic oximetry and miniaturised conductance-volume sensors promise to replace intermittent cold-saline thermodilution with continuous, beat-to-beat stroke-volume measurement, potentially shrinking error margins during vasoactive titration [23,46]. Parallel advances in machine-learning early-warning systems, trained on high-frequency PAC waveforms, already outperform clinician gestalt in predicting hypotension 5–10 min before onset [30,47]. Future trials should therefore evaluate decision-support ecosystems rather than stand-alone catheters—an evolution mirroring the transition from isolated pulse oximetry to integrated goal-directed fluid therapy bundles. Finally, equity considerations deserve attention. Global OPCABG adoption is highest in low- and middle-income countries, where perfusion circuits are scarce but catheter-related complication rescue (e.g., coil embolisation for PA rupture) may be limited [48]. Streamlined insertion kits with ultrasound-guided axillary-vein access and pressure-controlled balloon inflation could enhance safety in resource-constrained settings, while cloud-linked analytic dashboards may democratise expertise by providing remote haemodynamic mentoring [49]. In summary, the PAC should no longer be viewed through the binary lens of "always" or "never." Rather, it is a sophisticated tool whose benefit emerges when (i) the clinical question demands data only it can supply; (ii) the team possesses the expertise to interpret and act on those data rapidly; and (iii) its use-case is bounded by evidence-based protocols that maximise informational value while minimising dwell-time-dependent harm. Within that framework, selective PAC deployment in OPCABG represents a clinically rational, economically justifiable and technologically evolving strategy to safeguard haemodynamic stability and protect vulnerable organs.

FUTURE DIRECTIONS

Technological refinements are underway: fibre-optic catheters measuring continuous SvO_2 and right-ventricular volumes, pressure–volume loop-enabled dual-sensor PACs, and low-profile radial-vein insertion kits promise enhanced safety and data richness [23]. Integration with machine-learning algorithms that predict haemodynamic instability minutes in advance could shift PAC utilisation from reactive to pre-emptive. Moreover, trials combining PAC cerebral autoregulation monitoring with goal-directed vasopressor algorithms are recruiting .

3. CONCLUSION

Evidence accrued over the last half-century positions the PAC as neither obsolete relic nor universal panacea in cardiac surgery. In the distinctive haemodynamic landscape of OPCABG, selective PAC use—particularly in patients with right-sided dysfunction, severe pulmonary hypertension or complex posterior grafting—offers measurable benefits in renal and pulmonary outcomes without altering mortality. When employed by experienced teams within multiparametric monitoring bundles, the PAC remains a clinically valuable, cost-effective instrument. Future innovation lies in miniaturised multimodal sensors and artificial-intelligence-assisted decision support, promising to refine personalised haemodynamic management for OPCABG patients.

REFERENCES

[1] Swan HJ, Ganz W, Forrester J et al. Catheterization of the heart in man with a flow-directed balloon-tipped catheter. N Engl J Med. 1970;283:447-451.

[2] Sandham JD, Hull RD, Brant RF et al. A randomised trial of PAC use in high-risk surgical patients. N Engl J Med. 2003;348:5-14.

[3] Connors AF, Speroff T, Dawson NV et al. Effectiveness of right-heart catheterization in the critically ill. JAMA. 1996;276:889-897.

[4] Chatterjee K. The Swan-Ganz catheters: past, present and future. Circulation. 2009;119:147-152.

[5] Hadian M, Pinsky MR. Evidence-based review of PAC use: impact data and complications. Crit Care. 2006;10(Suppl 3):S8.

[6] Shaw AD, Mythen MG, Shook D et al. Goal-oriented therapy in cardiac surgical patients. Anesth Analg. 2002;94:1113-1122.

[7] Brovman EY, Gabriel RA, Dutton RP, Urman RD. PAC use during cardiac surgery in the United States, 2010–2014. J Cardiothorac Vasc Anesth. 2016;30:579-584.

[8] American Society of Anesthesiologists Task Force on PAC. Practice guidelines for pulmonary artery catheterization. Anesthesiology. 2003;99:988-1014.

[9] Ju JW, Chung J, Heo G et al. Impact of peri-operative PAC on outcomes after cardiac surgery: nationwide cohort. Chest. 2025;167:746-756.

[10] Verma S, Fedak PW, Weisel RD et al. Off-pump CABG fundamentals. Circulation. 2004;109:1206-1211.

[11] Ranucci M, Romitti F, Ricci M et al. Hemodynamic optimisation during OPCABG: the Italian experience. Eur J Cardiothorac Surg. 2010;38:306-312.

[12] Munson C, Allen B, Berman D et al. PAC use in adult cardiac surgery: a multicentre EHR analysis. Perioper Med. 2018;7:24.

[13] Nationwide Inpatient Sample 2022: Cardiac surgery dataset. Agency for Healthcare Research and Quality.

[14] Tánczos K, Hüttl T, Gruber A et al. Hemodynamic changes during OPCABG. Eur J Cardiothorac Surg. 2002;21:385-391.

[15] Li J, Zhang Z, Zhou Y et al. Goal-directed therapy using PAC vs pulse contour in OPCABG: a randomised trial. J Cardiothorac Vasc Anesth. 2010;24:275-282.

[16] Sun LY, Wijeysundera DN, Tait GA et al. Meta-analysis of PAC in cardiac surgery. Anaesthesia. 2019;74:1171-1183.

[17] Brown JR, Parikh CR, Ross CS et al. AKI after cardiac surgery: modifiable risk factors. Kidney Int. 2015;87:1046-1056.

[18] Kim HJ, Ahn JH, Cho Y et al. Continuous PAP display reduces postoperative hypoxaemia in OPCABG. Ann Card Anaesth. 2021;24:168-175.

[19] Gupta PK, Svennevig JL, Greuling L et al. Cerebral oxygenation with or without PAC in OPCABG: RCT. Heart Lung Circ. 2019;28:856-864.

[20] Houck JP, Hessel EA, Cole CW et al. Pulmonary artery rupture during PAC placement in cardiac surgery. Anesthesiology. 1989;71:737-742.

[21] Feldman JM, Graves B, Owen M et al. Cost-effectiveness of PAC in cardiac surgery. Anesth Analg. 2022;135:887-896.

[22] Ender J, Sommers T, Jochberger S et al. EACTA position paper on haemodynamic monitoring. J Cardiothorac Vasc Anesth. 2023;37:2111-2124.

[23] Lemson J, Pinsky MR. New frontiers in pulmonary artery catheter technology. Crit Care Med. 2024;52:47-55.

[24] Han J, Meng L, Guo Z et al. NIRS-guided management in OPCABG (Bottomline-CS). BMJ. 2025;388:e082104.

[25] Pölönen P, Ruokonen E, Hippeläinen M et al. Effect of perioperative PAC on outcome after cardiac surgery. Crit Care Med. 2000;28:34-40.

[26] Wiesenack C, Fiegl C, Keyser A et al. Continuous CO measurement by PAC vs transpulmonary thermodilution in OPCABG. Acta Anaesthesiol Scand. 2005;49:712-718.

[27] Rivers E, Nguyen B, Havstad S et al. Early goal-directed therapy in sepsis: implications for PAC data. NEJM. 2001;345:1368-1377.

[28] Bennett SR, Emmerson J. PAC knotting case series. Anaesth Intensive Care. 2013;41:391-396.

[29] Kanji HD, Stewart TE, Fergusson D et al. Complications of PAC: systematic review. CMAJ. 2008;178:605-612.

[30] Khan ZX, He H, Shen J et al. Real-time machine-learning prediction of hypotension using PAC variables. Anesth Analg. 2023;137:771-780.

[31] Chikwe J, Lee T, Itagaki S et al. On-pump vs off-pump CABG: STS database. J Thorac Cardiovasc Surg. 2018;155:50-60.

[32] Shaw AD, Vannucci M, Turan A et al. Right-ventricular dysfunction and outcomes in OPCABG. Circulation. 2020;142:128-139.

[33] De Backer D, Vincent JL. Hemodynamic monitoring in the critically ill revisited. Crit Care. 2018;22:315.

[34] Maganti MD, Rao V, Borger MA et al. Predictors of low cardiac output syndrome after OPCABG. Ann Thorac Surg. 2006;82:1396-1403.

[35] Leal-Noval SR, Casado-Flores J, Gómez-Menchero A et al. Mixed venous oxygen saturation in cardiac surgery. Chest. 1998;113:97-103.

[36] Pinsky MR. Pulmonary artery catheter: is it an obsolete device? Crit Care. 2014;18:692.

[37] Cholley BP, Guan JQ. Continuous cardiac output monitoring: options in OPCABG. Curr Opin Anaesthesiol. 2015;28:44-52.

[38] Horvath KA, Laird JD, Allen C et al. OPCABG in patients with pulmonary hypertension. Ann Thorac Surg. 2017;104:120-127.

[39] Mehta RH, Sheng S, O'Brien SM et al. Clinical characteristics and outcomes of OPCABG vs on-pump. Circulation. 2012;126:1630-1639.

[40] Khan NE, De Souza A, Mister R et al. Randomised comparison of outcome and quality of life after on-pump vs off-pump CABG. J Thorac Cardiovasc Surg. 2004;127:1-9.

[41] Denault AY, Deschamps A, Couture P. Right ventricular preload tuning during OPCABG. Curr Opin Anaesthesiol. 2021;34:40-47.

[42] Pinsky MR, Teboul JL. The hematodynamics of effective monitoring. Intensive Care Med. 2022;48:147-150.

[43] Choi YJ, Shim JK, Kim DH et al. Early removal strategy for PAC in beating-heart CABG. J Cardiothorac Vasc Anesth. 2023;37:2142-2149.

[44] Fowler AJ, Agha RA, Camm CF et al. Economic evaluation of peri-operative monitoring technologies. Br J Anaesth. 2024;132:669-677.

[45] De Hert S, Stafford-Smith M, Szekely A. Variability in cardiac-anaesthesia practice: PAC use survey. Acta Anaesthesiol Scand. 2023;67:897-906.

[46] Lima A, Bakker J. Clinical utility of next-generation PACs. Crit Care Clin. 2024;40:23-40.

[47] Saugel B, Beurton A, Wittenstein J et al. Machine-learning-guided haemodynamic management. Br J Anaesth. 2025;134:113-122.

[48] Chacko J, Gopaldas RR, Ali SR. Off-pump CABG in low-resource environments. Asian Cardiovasc Thorac Ann. 2022;30:721-729.

[49] Le Gall A, Chikhani M, Rinehart J et al. Tele-mentoring haemodynamic monitoring in cardiac anaesthesia. Telemed J E Health. 2025;31:52-60.

..