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REVIEW

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Peri-operative goal-directed haemodynamic therapy and high-risk patients: what's going on? A narrative review

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Abstract

Goal-directed haemodynamic therapy (GDHT) is a comprehensive haemodynamic optimisation strategy rather than simple fluid optimisation. It guides peri-operative haemodynamic management towards predefined physiological targets to reduce post-operative complications in high-risk surgical patients. This review asks whether GDHT retains clinical value in 2026, which patients are most likely to benefit, which targets are most appropriate, and what its relationship to Enhanced Recovery After Surgery (ERAS) programmes should be.

The physiological basis of GDHT links surgical injury to an inflammatory cascade that impairs vascular integrity and tissue perfusion and draws on Shoemaker's seminal observation that prompt restoration of oxygen delivery during surgery or in the first post-operative hours predicts survival. RCTs and meta-analyses have reported reductions in post-operative complications, most consistently acute kidney injury, surgical site infections, and gastrointestinal morbidity, with the benefit most consistent in patients at the highest peri-operative risk. Recent evidence has complicated this picture. OPTIMISE II and iPEGASUS, two large pragmatic trials, produced neutral results, and the incorporation of fluid optimisation into ERAS protocols raises a practical question: what does GDHT add when good peri-operative care already includes haemodynamic attention?

These uncertainties converge on a single practical difficulty: there is no universally accepted definition of "high risk", which limits both trial comparability and clinical uptake. Artificial intelligence tools, in particular closed-loop haemodynamic management systems and machine learning models for preoperative risk stratification, are appraised here as potential means of supporting more individualised implementation.

GDHT retains clinical value in 2026, but the benefit appears most evident in patients at the highest peri-operative risk, while in intermediate-risk populations the evidence for added value beyond well-implemented ERAS remains uncertain. The most effective strategy is a multiparameter-based one, combining dynamic preload indices, cardiac output monitoring, and metabolic endpoints rather than fixed single-variable targets. Validated risk stratification is the critical prerequisite for both rational clinical implementation and meaningful future trials.

Keywords Goal-directed haemodynamic therapy, Post-operative complication, High risk, Artificial intelligence

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Background

Post-operative complications in high-risk surgical patients account for the majority of peri-operative mortality and are a persistent clinical problem [1]. Haemodynamic monitoring addresses this by providing physiological signals that, when appropriately interpreted, can guide timely interventions to maintain organ perfusion; it does not, in itself, guarantee those outcomes.

Two physiological observations underpin goal-directed haemodynamic therapy (GDHT). First, surgical injury triggers an inflammatory cascade: damage-associated molecular patterns (DAMPs) activate Toll-like receptors (TLRs), which in turn release cytokines, reactive oxygen species, and nitrogen intermediates that drive endothelial dysfunction, vascular damage, and tissue hypoperfusion [2, 3]. Second, Shoemaker's landmark study in high-risk surgical patients demonstrated that the capacity to restore oxygen delivery after surgery promptly determines survival: patients who repaid their oxygen debt within 6 h had no complications; those who took up to 24 h to repay it developed complications; those who could not repay it died [4]. This oxygen debt model provided the physiological rationale for targeting oxygen delivery as a therapeutic endpoint, the basis of GDHT.

Numerous RCTs and meta-analyses since that study have reported reductions in post-operative morbidity with GDHT [5–8]. Interpretation of this evidence is complicated by substantial heterogeneity across trials in patient selection, surgical procedures, monitoring technologies, and target variables [9, 10]. A separate complication is the widespread adoption of Enhanced Recovery After Surgery (ERAS) protocols: fluid optimisation is a component of virtually all GDHT strategies, and the two approaches overlap considerably; the available evidence suggests that the incremental benefit of GDHT is less clear when an ERAS programme is already in place [11].

Artificial intelligence tools have more recently entered the peri-operative haemodynamic space, with applications in preoperative risk prediction, intraoperative monitoring support, and closed-loop management under active investigation [12, 13]. Whether these tools improve outcomes in the specific context of GDHT remains to be established. Against this background, we address four questions: which patients benefit from GDHT, at what risk threshold the evidence is most robust, which haemodynamic targets are most appropriate, and what role AI-enabled technologies may play.

Materials and methods

This is a narrative review developed in accordance with the Scale for the Assessment of Narrative Review Articles (SANRA) [14]. A structured literature search was performed across MEDLINE/PubMed, the Cochrane Library, and EMBASE. Search terms combined free-text and Medical Subject Headings (MeSH) related to surgery, goal-directed haemodynamic therapy, cardiac output, cardiac index, oxygen delivery, stroke volume, fluid optimisation, fluid loading, haemodynamic monitoring, and high-risk surgical patients. No time restriction was applied.

Accordingly, final article selection was guided by clinical and methodological relevance, as judged by the authors, rather than by exhaustive systematic inclusion criteria. Randomised controlled trials (RCTs), meta-analyses, systematic reviews, consensus statements, and guidelines published in English were considered. Papers from the authors' personal libraries were included where relevant, and priority was given to studies most directly bearing on the clinical questions addressed.

Population definition

High-risk surgical patients represent approximately 12% of the surgical population, yet account for 80% of peri-operative mortality [15, 16]. Peri-operative mortality in this group ranges from 4.5% in elective abdominal surgery to over 25% in emergency procedures [16]. Risk arises from patient comorbidity, surgical complexity, or their combination [17, 18]. Risk thresholds vary across guidelines: the European Society of Anaesthesiology and Intensive Care (ESAIC) defines high risk as a procedure-related mortality exceeding 5% [17], while the 2022 French guidelines stratify patients as high risk (1–3% estimated mortality) or very high risk (>3%) [19]. No universally accepted definition exists, which complicates both trial design and clinical implementation. The main preoperative risk stratification tools, with their recommended use and key limitations, are summarised in Tables 1 and 2 [20–28] (https://riskcalculator.facs.org/RiskCalculator).

Beyond conventional scores, machine learning models applied to large peri-operative databases show promise for risk prediction. Still, most remain at the single-centre validation stage and are not ready for routine clinical use [29, 30]. Biomarker-based sub-phenotyping may identify, within the high-risk group, those patients most likely to benefit from GDHT [31], though this requires prospective validation. Accurate risk stratification is a prerequisite for GDHT implementation: the evidence is strongest in patients at highest baseline risk, making the choice of risk tool a direct determinant of GDHT eligibility.

GDHT: from physiology to evidence

GDHT targets predefined haemodynamic endpoints [32–34], including cardiac output (CO), stroke volume (SV), oxygen delivery (DO2), fluid responsiveness parameters, and metabolic markers such as central venous oxygen

Table 1 Validated preoperative risk scoring tools for identification of high-risk surgical patients. ASA: American Society of Anaesthesiologists; RCRI: Revised Cardiac Risk Index; NSQIP: National Surgical Quality Improvement Program; MACE: major adverse cardiovascular events; AUC: area under the curve; ML: machine learning; ESC: European Society of Cardiology; ESAIC: European Society of Anaesthesiology and Intensive Care; GDHT: goal-directed haemodynamic therapy

Tool	Key variables	Risk threshold	Main limitations	Role in GDHT context
ASA classification	Physical status (I–VI)	ASA III-IV used as high-risk proxy	Poor inter-rater reliability; experience-dependent; does not predict surgical mortality reliably	Basic screening; insufficient alone for GDHT selection
Lee Revised Cardiac Risk Index (RCRI)	Type of surgery, ischaemic heart disease, cardiac failure, cerebrovascular disease, insulin therapy, creatinine >2 mg/dL	≥2 points	Low performance in thoracic/vascular surgery; omits age, Peripheral Artery Disease, obesity, functional capacity. MACE prediction only	Recommended by ESC/ESAIC; widely used in trials; best combined with biomarkers
ACS NSQIP calculator	>20 variables including frailty and geriatric factors	Procedure-specific (mortality >5%)	Not validated in European populations; relies on ASA; ignores intraoperative complications	Excellent AUC for mortality and complications (0.88–0.93); preferred in North American centres
DASI questionnaire	12 activity items (functional capacity)	<34 points associated with increased MACE risk	Subjective; requires patient cooperation	Recommended by ESC 2022 to assess cardiac reserve; superior to MET
MET evaluation	Subjective estimate of functional capacity	<4 METs = poor functional reserve	High inter-observer variability; poor correlation with peri-operative morbidity	Discouraged by ESC 2022 guidelines
NT-proBNP/Troponin	Cardiac biomarkers (preoperative measurement)	Elevated values (threshold varies by assay)	Require standardised cutoffs; additive, not standalone	Improve RCRI predictive power; candidate tool for GDHT sub-phenotyping

Table 2 Guideline-based definitions of high peri-operative risk and recommended haemodynamic monitoring thresholds relevant to goal-directed haemodynamic therapy (GDHT). ESAIC: European Society of Anaesthesiology and Intensive Care; SFAR: French Society of Anaesthesiology; ESC: European Society of Cardiology; SV: stroke volume; PPV: pulse pressure variation; SVV: stroke volume variation; CO: cardiac output

Guideline/Society	Year	Definition of high peri-operative risk	Recommended monitoring threshold for GDHT
ESAIC	2025	Procedure-related or patient-related peri-operative mortality risk > 5%	CO or SV monitoring considered in patients at high risk for complications; echocardiography endorsed for haemodynamic instability; continuous invasive arterial pressure monitoring recommended in high-risk patients
SFAR (French guidelines)	2022	High risk: expected mortality 1–3%; Very high risk: expected mortality > 3%	Dynamic preload indices combined with SV monitoring recommended to optimise fluid management and reduce complications in high- and very high-risk patients; CO monitoring in very high-risk patients
ESC/EACTS	2022	Surgical procedure risk classified as low (< 1%), intermediate (1–5%), or high (> 5%) 30-day MACE/mortality; individual patient risk added to procedure risk	Advanced haemodynamic monitoring recommended when combined procedure + patient risk is high; specific monitoring tool at discretion of the anaesthesiologist based on patient profile

MACE major adverse cardiovascular events, *MET* metabolicmetabolic equivalent of task

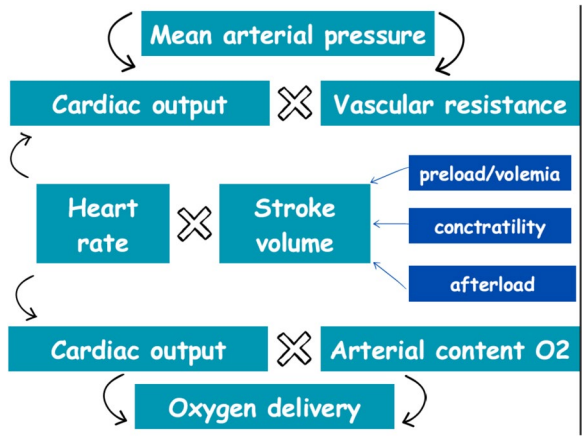


Fig. 1 The link between cardiac output, oxygen delivery and mean arterial pressure and main determinants of cardiac output

saturation (ScvO2), oxygen extraction ratio (O2ER), and lactate. These targets are typically initiated during or after surgery and adjusted according to clinical response [35–37].

These variables are discussed in the subsections below; their physiological interrelationships are illustrated in Fig. 1.

Arterial pressure

Mean arterial pressure (MAP) is the inflow pressure for most organs; its outflow pressure is determined by central venous pressure or extravascular tissue pressure [38, 39]. Multiple studies have linked intraoperative hypotension (variously defined as MAP < 60 mmHg for > 5–10 min, MAP < 55 mmHg for > 1 min, or a > 20% reduction from baseline) to post-operative mortality, myocardial injury, and acute kidney injury (AKI), particularly in high-risk patients [40–43]. However, two recent RCTs testing individualised MAP targets against a standard MAP > 65 mmHg target found no improvement in post-operative outcomes [44, 45]. As the accompanying editorial noted, a higher MAP does not necessarily mean better outcomes, especially when achieved with high-dose vasopressors; the underlying pathophysiological mechanism of hypotension may be more important than the absolute MAP value itself [46].

Current guidelines recommend maintaining MAP > 60–65 mmHg in high-risk surgical patients, with continuous invasive arterial pressure monitoring to allow concomitant assessment of oximetric and metabolic parameters [18, 47, 48]. Non-invasive continuous arterial pressure monitoring remains under evaluation, with accuracy reduced in circulatory shock or high-dose vasopressor states [49].

Not all hypotensive episodes reflect hypoperfusion: the haemodynamic consequences of a fall in MAP depend on the relative contributions of CO, systemic vascular resistance, and organ autoregulation [50]. In high-risk patients, pressure monitoring alone is therefore insufficient, and additional flow-based and metabolic variables are required to guide therapy.

Preload responsiveness

Both hypovolaemia and hypervolaemia impair outcome [51, 52]. In mechanically ventilated patients, dynamic preload indices, pulse pressure variation (PPV), and stroke volume variation (SVV) are more reliable guides to fluid therapy than static parameters such as central venous pressure (CVP) [53, 54]. PPV and SVV quantify the likelihood that CO will increase after a fluid challenge (fluid responsiveness, defined as a > 10–15% CO increase with increased preload) [53]. Both indices are affected by cardiac arrhythmias, tidal volumes < 7–8 ml/kg, and

raised intra-abdominal pressure (e.g., during laparoscopy), and share a grey zone between 9 and 13% where prediction is uncertain [55]. Predictive accuracy varies by surgical context, with area under the curve (AUC) values ranging from 0.80 in open non-laparoscopic surgery to 0.69 in open-chest procedures [56, 57]. Mini fluid challenges (50–100 ml) and end-expiratory occlusion tests can help resolve the grey zone [58].

Fluid responsiveness does not mandate fluid administration: the blood pressure response to volume also depends on vascular tone, and dynamic arterial elastance (eaDyn) can help predict MAP response to a fluid bolus. However, evidence in surgical patients remains limited [59, 60].

GDHT protocols incorporating dynamic preload assessment have been associated with reduced morbidity and shorter ICU stay [61]. Both ERAS pathways and ESAIC guidelines support the use of functional haemodynamic parameters to guide fluid administration [1, 62]. The 2022 French guidelines further recommend combining dynamic preload indices with stroke volume monitoring to optimise fluid management and reduce complications in high-risk and very high-risk patients [19].

Cardiac output

CO is the product of stroke volume and heart rate and, together with arterial oxygen content, determines oxygen delivery (DO2). Monitoring CO during surgery allows detection of the haemodynamic mechanisms underlying instability, reduced flow versus reduced vascular tone, and guides targeted intervention [37]. Current guidelines support CO or SV monitoring in patients at high risk for complications [1, 18, 19, 48], with monitoring tools ranging from invasive (pulmonary artery catheter, transpulmonary thermodilution) to minimally invasive (oesophageal Doppler, pulse wave analysis) and non-invasive (bioreactance, photoplethysmography) systems [63, 64]. Selection should reflect patient and procedural risk, with more advanced systems reserved for the highest-risk cases. Echocardiography is endorsed by recent guidelines for haemodynamic assessment during perioperative instability [1, 48].

Multiple meta-analyses consistently report reductions in post-operative complications with CO- or SV-guided therapy ([65–71], Table 3). A 2019 meta-analysis stratifying trials by control-group mortality risk showed that GDHT significantly reduces mortality when baseline risk exceeds 10% [68]. More recent analyses confirm reductions in surgical site infection (from 13.3% to 9.4%; absolute risk reduction 3.9%) [70] and AKI (OR 0.64, 95% Confidence Interval 0.62–0.87; $p = 0.0003$) [66], with benefit demonstrated across abdominal, orthopaedic, and neurosurgical procedures [71]. Trial sequential analysis in two recent meta-analyses indicates that further RCTs are unlikely to reverse these findings [66, 70].

Oxygen delivery

Oxygen delivery (DO2) and its adequacy at tissue level, assessed via ScvO2, O2ER, and serum lactate, are the ultimate targets of GDHT. DO2 integrates cardiac output with haemoglobin concentration and arterial oxygen saturation, and its optimisation, rather than CO alone, was the original aim of Shoemaker's supranormal strategy [4]. Supranormal targets were subsequently abandoned after larger trials showed they conferred no benefit or caused harm; protocols targeting more physiological values ($CI > 2.5$ l/min/m^2) then demonstrated reductions in post-operative complications [74, 75]. Optimising DO2 within normal ranges, supported by ScvO2 and lactate monitoring, remains a component of multiparameter GDHT protocols in very high-risk patients [4, 48].

Persistently elevated lactate or reduced ScvO2 despite adequate CO suggests impaired oxygen utilisation and may indicate the need for additional interventions beyond fluid loading.

Although limited evidence supports the use of lactate or $ScvO_2$ monitoring in non-cardiac surgery patients to improve post-operative outcome, their incorporation into the haemodynamic evaluation should be considered in very high-risk patients as markers of hypoperfusion [48].

The positive findings about GDHT efficacy must be read against substantial trial heterogeneity in patient selection, surgical procedures, protocols, targets, and outcome definitions [9, 10, 76]. Two recent large pragmatic trials have challenged the field. OPTIMISE II found no significant effect of a GDHT strategy combining fluid boluses with routine low-dose inodilator infusion on post-operative infections [77]. iPEGASUS showed that haemodynamic therapy targeting fixed or maximal cardiac index values did not reduce post-operative complications in major abdominal surgery [78]. Both trials enrolled lower-risk populations than those in which the meta-analytic benefit was largest, and both used fixed CO targets rather than individualised multiparameter approaches; these limitations probably explain their neutral results.

A persistent uncertainty concerns the overlap between GDHT and ERAS-embedded fluid optimisation. Since fluid administration guided by dynamic indices is a key component of both approaches, several authors have questioned whether GDHT adds anything beyond what standard ERAS already delivers [79–82]. The available evidence suggests that GDHT benefit is attenuated, though not abolished, within ERAS programmes, possibly because ERAS itself raises

Table 3 Summary of meta-analyses and systematic reviews on peri-operative goal-directed haemodynamic therapy (GDHT). GI: gastrointestinal; SSI: surgical site infection; ERAS: enhanced recovery after surgery; OR: odds ratio; NR: not reported; AKI: acute kidney injury

Study (yr)	*N* trials	*N* patients	Population	GDHT intervention	Main outcome	Key result
Giglio [72]	16 RCTs	3410	Peri-operative major surgery	Any GDHT vs standard care	GI complications	OR 0.42 major GI complications; OR 0.29 minor GI complications; benefit greatest when control complication rate was high
Dalfino [73]	26 RCTs	4188	Peri-operative major surgery	Any GDHT vs standard care	Infectious complications	SSI OR 0.58; pneumonia OR 0.71; urinary infection OR 0.44; GDHT reduces post-operative infections across multiple subtypes
Gurgel [6]	32 RCTs	5056	Peri-operative major surgery	Any GDHT vs standard care	Mortality, organ dysfunction	Significant reduction in mortality rate (OR: 0.67) and in post-operative organ dysfunction incidence (OR: 0.62)
Cecconi [8]	32 RCTs	2808	Peri-operative major surgery	Any GDHT vs standard care	Mortality, morbidity	Mortality benefit only in studies with control group mortality >20%; morbidity benefit broader; supports stratified patient selection
Giglio [68]	58 RCTs	8171	Peri-operative major surgery	Any GDHT vs standard care	Mortality	Mortality benefit significant when control group mortality >10%; no benefit in low-risk populations; underlines importance of patient selection
Som [65]	41 RCTs	NR	Major surgery	Any GDHT vs standard care	Morbidity, mortality	Reduced morbidity OR 0.57 (95% confidence interval 043–0.75); no significant mortality benefit; GDHT primarily a morbidity-reduction strategy
Rollins [67]	23 RCTs	2099	Colorectal surgery	GDHT with or without ERAS	Outcomes in ERAS vs non-ERAS	GDHT benefit substantially attenuated within ERAS protocols; benefit more pronounced in non-ERAS studies; questions the additive value of GDHT in modern ERAS
Jessen [69]	76 RCTs	9081	Peri-operative major surgery	Any GDHT vs standard care	Morbidity, mortality, hospital stay	GDHT resulted in reduced mortality and hospital length of stay; however, the estimates were imprecise and the overall certainty in the evidence was low. GDHT reduced the risk of pneumonia, surgical site infection, and anastomotic leakage (moderate certainty of evidence). Point estimates from meta-analyses also favoured GDHT for other post-operative complications but the certainty in the evidence was very low to low
Giglio [66]	65 RCTs	9308	Peri-operative major surgery	Any GDHT vs standard care	AKI, whichever definition was adopted	The pooled OR and 95% CI for the development of AKI were 0.64, 95% confidence interval 0.62–0.87; $p = 0.0003$. No statistical heterogeneity was detected.Results confirmed both in high risk and low risk The subset analysis including studies using CO or DO2 as hemodynamic target showed a significant reduction in AKI (OR 0.64, 95% Confidence Interval 0.62 to 0.89, $p = 0.001$)
Jalalzadeh [70]	75 RCTs	13,010	Peri-operative major surgery	Any GDHT vs standard care	Surgical site infection	GDHT is effective in reducing SSI (pooled relative risk of SSI was 0.71 (95% confidence interval 0.62–0.81). This result was substantiated by a subgroup analysis for the low risk of bias studies. No strong evidence for individual subgroup effects. Trial sequential analysis indicated that additional RCTs are unlikely to change the effect

Table 3 (continued)

Study (yr)	*N* trials	*N* patients	Population	GDHT intervention	Main outcome	Key result
Benes [61]	14 RCTs	961	Peri-operative major surgery	GDFT based on dynamic parameters vs standard care	Morbidity, mortality, hospital stay	Post-operative morbidity was reduced by GDHT guided by dynamic indices (OR 0.51; Confidence Interval 0.34 to 0.75; $p < 0.001$). This effect was related to a significant reduction in infectious (OR 0.45; confidence interval 0.27 to 0.74; $p = 0.002$), cardiovascular (OR 0.55; confidence interval 0.36 to 0.82; $p = 0.004$) and abdominal (OR 0.56; confidence interval 0.37 to 0.86; $p = 0.008$) complications. It was associated with a significant decrease in ICU length of stay

the standard of baseline fluid management [76, 81]. GDHT and ERAS are not equivalent; however, ERAS promotes goal-directed fluid administration as one element among many, whereas GDHT is a comprehensive haemodynamic strategy that additionally targets CO, contractility, afterload, and oxygen delivery. The incremental value of this broader approach over ERAS fluid optimisation alone has not been quantified in adequately powered trials.

Figure 2 is a chronological overview of key milestone studies in peri-operative GDHT, from Shoemaker's supranormal targets in the late 1980 s to the most recent large pragmatic trials, showing how the field's interpretation of this evidence has shifted over time.

Where does this leave GDHT in 2026? The evidence supports the following conclusions. First, GDHT retains clinical value most consistently in patients at the highest peri-operative risk [18, 19, 48]: it is in this stratum that mortality and morbidity reductions are most reliably demonstrated across meta-analyses. Second, the optimal GDHT strategy is multiparameter, combining dynamic preload assessment, CO or SV monitoring, and metabolic endpoints (ScvO2, lactate) rather than targeting any single variable. Third, fixed CO targets applied uniformly regardless of patient physiology are ineffective, as the neutral results of OPTIMISE II and iPEGASUS confirm [77, 78]. Fourth, MAP management is necessary but not sufficient as a haemodynamic strategy. Fifth, within ERAS programmes, GDHT retains additive value when it extends beyond fluid optimisation to the full haemodynamic picture; in lower-risk patients managed within a well-implemented ERAS pathway, its incremental benefit is less certain.

Trial heterogeneity in GDHT reflects the heterogeneity of the surgical population itself [9]. A protocol appropriate for a frail octogenarian undergoing emergency colonic resection will not be the same as one for a patient with controlled comorbidities having elective hepatic surgery. Individualised GDHT, defined by patient risk, surgical procedure, available monitoring, and intraoperative haemodynamic response, is therefore the logical endpoint of this evidence-based approach, and several authors and consensus statements have called for its adoption to replace fixed-target protocols [9, 10, 32, 76, 82]. Therefore, risk definition should be better investigated, to identify scores and factors that influence post-operative outcome, to improve preoperative rehabilitation, intraoperative monitoring, post-operative assistance, resource allocation and cost-effective interventions [32].

Economic considerations

Economic considerations bear directly on GDHT implementation decisions. A large US economic modelling study (204,680 non-cardiac surgical patients) suggested that each dollar invested in GDHT implementation may generate a net return of 2.5–4 United States Dollars (USD), with per-patient savings of 754–1286 USD [83]. The magnitude of saving depends on baseline complication rate (higher morbidity populations benefit most) and local complication costs (higher healthcare costs amplify the saving). A Brazilian simulation and a French cost-effectiveness analysis reached similar conclusions irrespective of the monitoring technology used [84, 85]. The only Italian report found potential savings of approximately 400 euros per patient per day through optimised post-operative setting allocation after endovascular repair [86]. These estimates warrant caution: they assume a treatment effect consistent with the positive trial literature, and the neutral results of recent large trials suggest real-world savings may be more modest.

The role of AI

Artificial intelligence (AI) encompasses a range of computational techniques, including machine learning (ML) algorithms that enable pattern recognition and prediction from large datasets without explicit programming [87]. In the peri-operative setting, several ML applications are under active investigation, including preoperative risk stratification, intraoperative haemodynamic monitoring, and, most relevantly to GDHT, automated therapeutic management (Fig. 3).

For preoperative risk stratification, ML models integrating high-dimensional clinical and physiological data can identify risk patterns that traditional scoring systems miss. An interpretable ML cardiovascular risk predictor derived from the NSQIP dataset achieved an AUC of 0.90 in predicting major adverse cardiovascular events, outperforming conventional scores [88].

ML algorithms trained on photoplethysmographic waveforms can reconstruct continuous arterial pressure traces and derive dynamic parameters such as PPV and SVV from non-invasive signals, potentially extending advanced haemodynamic monitoring to settings where arterial cannulation is not routine [89]. Separate algorithms can detect transducer malpositioning and abnormal arterial waveform damping in real time [90, 91].

The Hypotension Prediction Index (HPI) is the first commercially available ML model for predicting intraoperative hypotension, using arterial waveform features to forecast MAP < 65 mmHg at least 1 min in advance [92–95]. Diagnostic performance is reasonable (sensitivity and specificity approximately 83%, AUC 0.90) [93], but

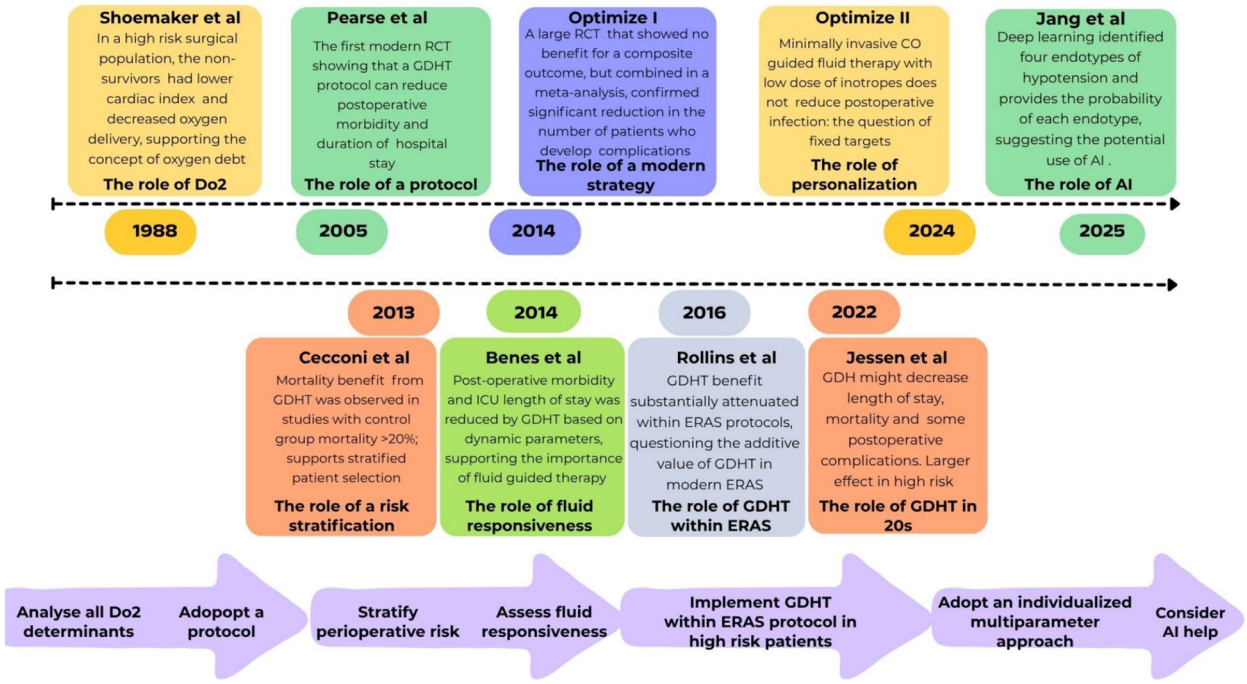


Fig. 2 The timeline of GDHT evolution. The figure depicts key milestone studies with their main findings and implications. Along the upper dotted arrows principal RCTs are shown, while along the lower dotted arrow main meta-analyses are depicted. Violet arrows indicate clinical implications of main literature findings. Goal-directed haemodynamic therapy (GDHT); enhanced recovery after surgery (ERAS); cardiac output (CO), oxygen delivery (DO2)

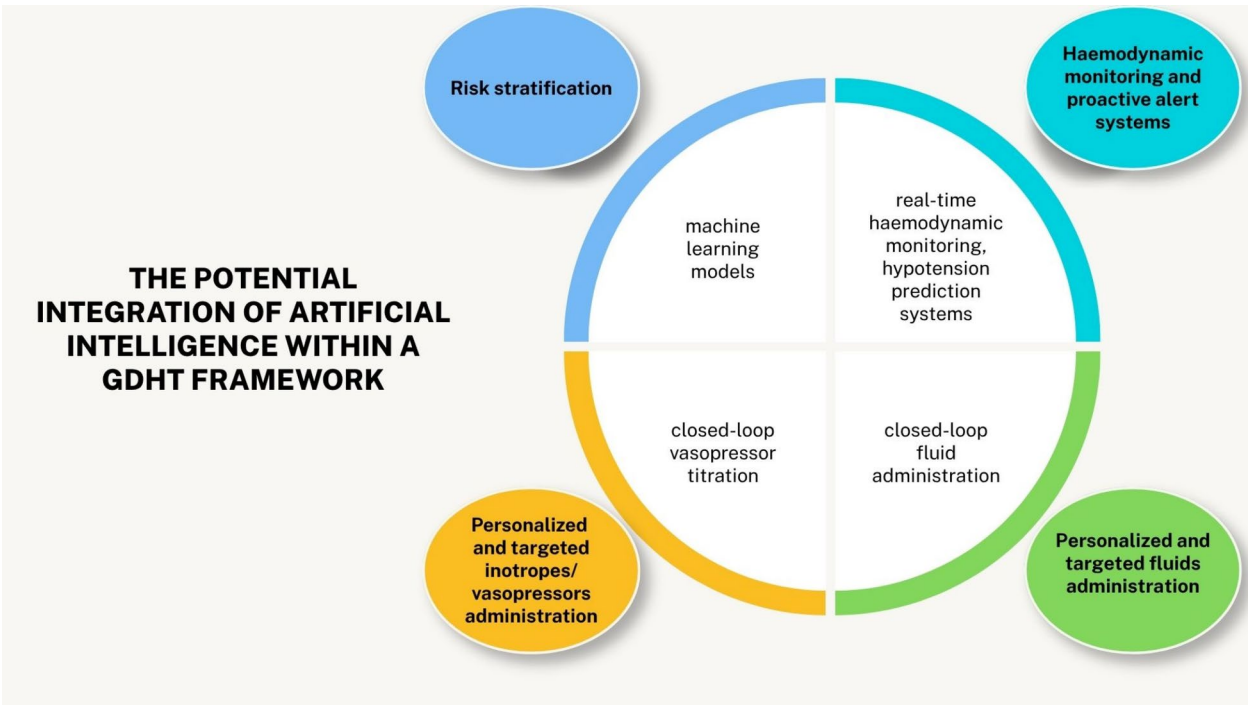


Fig. 3 The potential integration of artificial intelligence within a GDHT framework: the main 4 pillars of GDHT are evidenced, with a proposed role for AI tools for each pillar

HPI has not been evaluated within a GDHT framework, and its clinical relevance to GDHT is therefore limited.

In a large cohort of surgical and critically ill patients, a deep learning method was used to identify four hypotension phenotypes that were labelled vasodilation, bradycardia, hypovolaemia, and cardiac dysfunction, suggesting its utility in interpreting haemodynamic data [96], while others claimed that these algorithms may be unnecessary for managing a relatively limited number of haemodynamic variables [13].

The AI application most directly relevant to GDHT is the closed-loop haemodynamic management system, which uses real-time physiological feedback to automate therapeutic decisions (fluid boluses, vasopressor titration, or inotrope adjustment) towards predefined haemodynamic targets. Three domains of closed-loop control have been investigated. Closed-loop vasopressor titration has the most RCT evidence: three randomised trials ($N=30–53$ each) showed that automated norepinephrine titration reduces the proportion of time spent hypotensive by up to tenfold compared with manual control and improves time within the MAP target range [97–99]. Closed-loop fluid administration, most notably the Acumen Assisted Fluid Management system (Edwards Lifesciences), a CE-marked decision-support tool using SVV-guided fluid challenges, has shown superior fluid responsiveness rates in a post-hoc RCT analysis; a large multicentre stepped-wedge RCT with post-operative outcome endpoints is ongoing [100]. Closed-loop inotrope management has minimal evidence in modern non-cardiac surgical practice. No closed-loop haemodynamic system has yet demonstrated a reduction in hard clinical outcomes such as acute kidney injury, major adverse cardiovascular events, or mortality in an adequately powered trial. The concerns about HPI, the most widely studied component of closed-loop hypotension management, illustrate these limitations: despite reducing surrogate hypotension metrics, HPI is associated with increased hypertensive episodes (overtreatment) [93, 94], and the so-called mirror effect, whereby the HPI alarm triggers when MAP is already 72–76 mmHg with a mean lead time advantage of under one minute over a simple MAP threshold alert, calls into question its clinical added value [94, 95].

AI and closed-loop technologies are a logical evolution of GDHT: rather than requiring clinicians to continuously interpret multiparameter haemodynamic data and manually titrate interventions, automated systems could implement individualised GDHT protocols in real time. The field is advancing rapidly, but the evidence base remains at an early stage. Widespread adoption will require adequately powered RCTs with hard clinical outcome endpoints, validation across diverse surgical populations, and agreed standards for model transparency and clinical accountability.

Conclusions

GDHT has evolved from Shoemaker's supranormal oxygen delivery strategy of the 1980 s [4] into a heterogeneous family of haemodynamic interventions that claim to reduce post-operative complications through monitoring and targeted therapy. Whether that claim holds in 2026, and for whom, is less straightforward than the early meta-analytic literature suggested.

This review supports the following positions. First, GDHT retains clinical relevance in 2026, but primarily in patients at the highest peri-operative risk [18, 48], and reductions in morbidity, including AKI, surgical site infection, and gastrointestinal complications, are consistently demonstrated in high-risk populations across multiple meta-analyses [66, 69, 70]. Second, standardised GDHT protocols do not benefit intermediate-risk populations: the neutral results of OPTIMISE II and iPEGASUS [77, 78] are not simply a failure of targeting, and the residual uncertainty about why they failed warrants caution before applying any single GDHT protocol across unselected surgical patients. Third, GDHT cannot be equated with ERAS fluid optimisation: the two overlap on preload management but diverge in scope; GDHT realises its full potential when it integrates dynamic preload indices, cardiac output monitoring, and metabolic targets (ScvO2, lactate) as a coherent strategy rather than optimising fluid alone [76, 101]. Fourth, pressure management is necessary but not sufficient: MAP monitoring provides a physiological floor, not a complete haemodynamic strategy. Fifth, risk stratification remains a critical bottleneck: the absence of a universally validated tool directly limits both trial comparability and clinical implementation, and its resolution is a prerequisite for meaningful progress in GDHT research.

Three research priorities follow from this analysis. Adequately powered trials comparing multiparameter GDHT with well-implemented ERAS care are needed in clearly defined high-risk surgical populations, rather than the heterogeneous intermediate-risk groups as in recent large RCTs. Validated risk-stratification tools, applicable across diverse healthcare systems, are required to determine which patients should receive GDHT. Finally, closed-loop haemodynamic systems, which are the natural technological evolution of GDHT, require outcomes RCTs demonstrating hard clinical benefit before clinical adoption can be recommended. Until this evidence becomes available, a personalised multiparameter approach, guided by the individual patient's risk profile, the surgical procedure, and the intraoperative haemodynamic response, remains the most defensible clinical strategy.

Abbreviations

GDHT	Goal-Directed Haemodynamic Therapy
ERAS	Enhanced recovery after surgery
DAMPs	Damage-associated molecular patterns
TLRs	Toll-like receptors
CO	Cardiac output
DO_2	Oxygen delivery
RCTs	Randomised controlled trials
AI	Artificial intelligence
SANRA	Scale for the Assessment of Narrative Review Articles
NCBI	National Centre for Biotechnology Information
MeSH	Medical Subject Headings
CI	Cardiac index
ESAIC	European Society of Anaesthesiology and Intensive Care
ESC	European Society of Cardiology
ASA	American Society of Anaesthesiologists
ACS NSQIP	American College of Surgeons National Surgical Quality Improvement Program®
MACE	Major adverse cardiovascular events
NT-pro BNP	N-terminal pro-B-type natriuretic peptide
AUC	Area under the curve
AKI	Acute kidney injury
SV	Stroke volume
$ScvO_2$	Central venous oxygen saturation
O_2ER	Oxygen extraction ratio
MAP	Mean arterial pressure
CVP	Central venous pressure
PPV	Pulse pressure variation
SVV	Stroke volume variation
eaDyn	Dynamic arterial elastance
ICU	Intensive care unit
OR	Odds ratio
US	United States
USD	United States dollars
ML	Machine learning
HPI	Hypotension Prediction Index

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