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HEMODYNAMIC MONITORING AND GOAL-DIRECTED THERAPY IN MAJOR ABDOMINAL SURGERY: CURRENT CONCEPTS AND FUTURE DIRECTIONS

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Abstract

Objective: Major abdominal surgery is frequently associated with substantial physiological stress, fluid shifts, inflammatory activation, and perioperative hemodynamic instability, all of which may contribute to postoperative organ dysfunction and increased morbidity.

Over recent decades, perioperative hemodynamic management has evolved from reliance on static physiological variables toward individualized, physiology-driven optimization strategies.

Materials and Methods: This narrative review summarizes current concepts in perioperative hemodynamic monitoring and GDT in major abdominal surgery. The physiological basis of tissue perfusion, preload responsiveness, and cardiovascular optimization is discussed together with the clinical role of static and dynamic monitoring variables, including mean arterial pressure, central venous pressure, lactate, pulse pressure variation, stroke volume variation, and passive leg raising. Contemporary monitoring technologies such as arterial waveform analysis, minimally invasive cardiac output monitoring, and perioperative echocardiography are also reviewed.

Discussion: Contemporary perioperative medicine increasingly integrates dynamic hemodynamic monitoring, minimally invasive cardiac output assessment, arterial waveform analysis, ultrasound-based evaluation, and goal-directed therapy (GDT) protocols to optimize tissue perfusion while avoiding both hypovolemia and fluid overload. Current evidence suggests that individualized GDT strategies integrating fluids, vasopressors, and inotropic therapy may reduce postoperative complications, shorten hospital stay, and optimize perioperative outcomes in selected abdominal surgery populations. Emerging technologies including artificial intelligence, predictive analytics, and machine learning-assisted monitoring systems may further transform future perioperative management through precision-based physiological optimization.

Conclusion: Current evidence suggests that individualized GDT strategies integrating fluids, vasopressors, and inotropic therapy may reduce postoperative complications, shorten hospital stay, and optimize perioperative outcomes in selected abdominal surgery populations.

Keywords: *Dynamic hemodynamic monitoring; fluid responsiveness; goal-directed therapy; hemodynamic monitoring; major abdominal surgery; perioperative medicine.*

Introduction

Major abdominal surgery remains associated with significant perioperative morbidity and mortality despite major advances in surgical techniques, anesthetic management, and perioperative care pathways. Procedures involving the gastrointestinal, hepatobiliary, colorectal, and upper abdominal systems are characterized by substantial physiological stress, intravascular fluid redistribution, inflammatory activation, vasodilation, blood loss, and perioperative cardiovascular instability. These alterations may impair tissue perfusion and oxygen delivery, thereby contributing to postoperative complications such as acute kidney injury, pulmonary dysfunction, postoperative ileus, prolonged hospitalization, sepsis, and increased mortality (1).

Over the last several decades, perioperative medicine has undergone a major transition from traditional empiric fluid administration toward physiology-driven hemodynamic optimization. Historically, perioperative management relied predominantly on static physiological variables such as mean arterial pressure (MAP), heart rate, central venous pressure (CVP), urine output, and serum lactate. Although these variables remain clinically important, accumulating evidence has demonstrated that static indices often fail to accurately predict intravascular volume status, tissue perfusion, or fluid responsiveness (2).

This limitation has contributed to the emergence of dynamic hemodynamic monitoring and goal-directed therapy (GDT).

Goal-directed therapy refers to the use of predefined physiological targets to optimize tissue oxygen delivery and organ perfusion through individualized administration of fluids, vasopressors, and inotropic agents. Multiple randomized controlled trials and meta-analyses have evaluated the role of GDT in major abdominal surgery, demonstrating variable but generally favorable effects on postoperative morbidity, gastrointestinal recovery, and length of hospital length (3–5).

Modern perioperative management increasingly emphasizes individualized physiology-based optimization rather than generalized hemodynamic thresholds. Dynamic monitoring variables such as pulse pressure variation (PPV), stroke volume variation (SVV), cardiac output (CO), cardiac index (CI), and tissue oxygenation assessment are progressively replacing traditional static variables in high-risk surgical populations (6). In parallel, substantial technological advances have expanded perioperative monitoring capabilities through minimally invasive cardiac output systems, arterial waveform analysis, esophageal Doppler monitoring, microcirculatory assessment, and artificial intelligence-assisted predictive analytics.

Recent developments involving predictive monitoring systems such as the Hypotension Prediction Index (HPI) reflect a broader transition from reactive hemodynamic correction toward anticipatory hemodynamic optimization (7). Furthermore, enhanced recovery after surgery (ERAS) protocols have integrated perioperative hemodynamic optimization into multimodal recovery pathways aimed at reducing complications and accelerating postoperative rehabilitation (8).

The contemporary framework of perioperative hemodynamic optimization is illustrated in Figure 1, which summarizes the interaction between surgical stress, physiological determinants of tissue perfusion, monitoring strategies, therapeutic interventions, and postoperative outcomes.

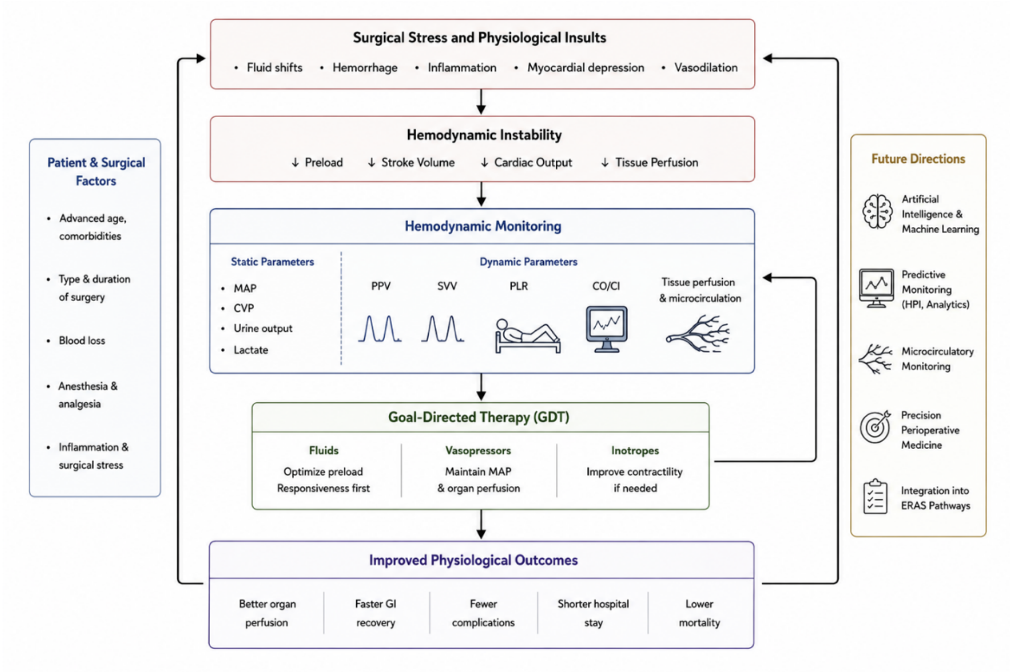

Figure 1. Conceptual framework of perioperative hemodynamic monitoring and goal-directed therapy in major abdominal surgery.

Major abdominal surgery causes physiological stress responses that may lead to hemodynamic instability and impaired tissue perfusion. Contemporary perioperative management combines static and dynamic hemodynamic monitoring to guide individualized goal-directed therapy with fluids, vasopressors, and inotropes. Emerging technologies, including artificial intelligence and predictive analytics, may further improve perioperative hemodynamic optimization and postoperative outcomes.

The objective of this review is to summarize current concepts in perioperative hemodynamic monitoring and goal-directed therapy in major abdominal surgery, with particular emphasis on physiological principles, dynamic monitoring modalities, monitoring technologies, clinical evidence, ERAS integration, and future directions involving artificial intelligence and precision perioperative medicine.

Discussion

Physiological Basis of Hemodynamic Monitoring

-Oxygen Delivery and Tissue Perfusion

The primary objective of perioperative hemodynamic management is preservation of adequate tissue oxygenation and organ perfusion. During major abdominal surgery, physiological homeostasis may be substantially disrupted through sympathetic activation, inflammatory cytokine release, vasodilation, blood loss, endothelial dysfunction, and intravascular fluid shifts. These alterations directly influence oxygen delivery and tissue metabolism. Oxygen delivery (DO2) represents the amount of oxygen transported to tissues per minute and depends primarily on cardiac output and arterial oxygen content. Oxygen delivery may be expressed mathematically as: When oxygen delivery becomes insufficient relative to tissue metabolic demand, anaerobic metabolism ensues, leading to lactate accumulation, mitochondrial dysfunction, cellular injury, and, ultimately, organ failure. Consequently, modern perioperative hemodynamic management focuses not only on maintaining blood pressure but also on ensuring sufficient global and regional tissue perfusion. Major abdominal surgery is associated with considerable hemodynamic instability due to anesthesia-induced vasodilation, fluid redistribution into the interstitial space, blood loss, and inflammatory activation (9).

Excessive perioperative hypotension may compromise renal, intestinal, hepatic, and myocardial perfusion, thereby increasing postoperative morbidity.

Goal-directed therapy attempts to maintain physiological equilibrium by optimizing preload, stroke volume, cardiac output, and oxygen delivery while simultaneously minimizing unnecessary fluid administration and tissue edema. Meta-analyses have demonstrated improved postoperative recovery and reduced complications when hemodynamic optimization is guided by dynamic physiological assessment rather than empiric fluid administration alone (3,4,10).

The relationship between surgical stress, oxygen delivery, hemodynamic monitoring, and postoperative outcomes is illustrated in Figure 1.

-Preload, Afterload, Cardiac Output

Cardiac output is determined by preload, afterload, contractility, and heart rate, all of which are essential components of perioperative hemodynamic management. Preload reflects ventricular filling and intravascular volume status, while excessive preload may contribute to pulmonary and bowel edema. Afterload represents ventricular resistance during systole and is primarily influenced by systemic vascular resistance and arterial pressure. Contractility reflects myocardial performance independent of loading conditions and may be impaired during anesthesia, inflammation, ischemia, or sepsis. Importantly, hypotension does not necessarily indicate hypovolemia, nor does normal blood pressure guarantee adequate tissue perfusion, which explains the limitations of static hemodynamic variables alone (1,2). Consequently, contemporary perioperative management increasingly utilizes dynamic monitoring techniques to assess preload responsiveness and guide individualized hemodynamic optimization.

- Microcirculation and Organ Perfusion

Recently, there has been growing attention focused on the role of microcirculation in perioperative physiology. Even when macrohemodynamic parameters such as MAP and cardiac output appear preserved, impaired microvascular flow may compromise oxygen delivery and tissue utilization. Microcirculatory dysfunction may result from endothelial injury, inflammatory activation, capillary leakage, vasoconstriction, or impaired autoregulation, potentially contributing to organ dysfunction despite apparently adequate systemic hemodynamics. Flick et al. (11) found significant alterations in sublingual microcirculation during major abdominal surgery, highlighting the potential disconnect between systemic hemodynamics and tissue-level perfusion. Similarly, Coeckelenbergh et al. (12) observed improved microvascular flow during assisted fluid management in high-risk abdominal surgery.

These findings suggest that future perioperative management may increasingly incorporate microcirculatory endpoints in addition to traditional macrohemodynamic variables.

Static Hemodynamic Parameters

- Central Venous Pressure

Central venous pressure (CVP) has historically been one of the most commonly used perioperative hemodynamic variables and was traditionally considered a surrogate marker of preload and intravascular volume status. Consequently, perioperative fluid administration strategies frequently relied on predefined CVP targets, particularly in critically ill and high-risk surgical patients.

However, accumulating physiological and clinical evidence has challenged the reliability of CVP as an indicator of fluid responsiveness.

Numerous investigations have demonstrated poor correlation between CVP values and actual intravascular volume status or cardiac preload responsiveness (2). Static filling pressures are strongly influenced by ventricular compliance, venous tone, intrathoracic pressure, mechanical ventilation, right ventricular function, and pulmonary vascular resistance. As a result, patients with similar CVP values may exhibit markedly different responses to fluid administration.

The limited ability of CVP to predict fluid responsiveness contributed to the transition toward dynamic hemodynamic monitoring.

Elevated CVP does not necessarily indicate adequate preload, while low values do not always imply hypovolemia. Moreover, excessive fluid administration targeting arbitrary CVP thresholds may increase postoperative morbidity through pulmonary and bowel edema. Despite these limitations, CVP monitoring may still provide useful contextual physiological information in selected high-risk surgical populations. In patients with severe cardiovascular disease, pulmonary hypertension, major fluid shifts, or right ventricular dysfunction, CVP trends may contribute to overall hemodynamic assessment when interpreted alongside additional physiological variables. Nevertheless, contemporary perioperative guidelines emphasize that CVP should not be used in isolation to guide fluid therapy decisions (1). The decline in routine CVP-guided therapy reflects a broader shift from static physiological assessment to dynamic, individualized hemodynamic optimization. Modern perioperative medicine increasingly prioritizes direct assessment of fluid responsiveness and tissue perfusion rather than reliance on isolated static preload variables.

- Mean Arterial Pressure

Mean arterial pressure (MAP) remains one of the most important perioperative hemodynamic parameters because adequate arterial pressure is essential for maintaining organ perfusion during major surgery. Sustained intraoperative hypotension has been associated with postoperative myocardial injury, acute kidney injury, stroke, and increased mortality. However, universal blood pressure thresholds may not be appropriate for all patients, as individuals with chronic hypertension, diabetes, or vascular disease may require higher perfusion pressures to maintain adequate organ blood flow (13).

Therefore, recent perioperative investigations have increasingly explored individualized blood pressure management strategies. The IMPROVE-multi randomized clinical trial evaluated individualized perioperative blood pressure targets in major abdominal surgery, reflecting growing interest in patient-specific hemodynamic optimization (11). Although individualized strategies remain an evolving area of research, these investigations emphasize the limitations of rigid universal MAP thresholds.

Intraoperative hypotension may result from vasodilation, hypovolemia, blood loss, myocardial depression, or inflammatory vasoplegia. Importantly, treatment requires identifying the underlying physiological disturbance rather than indiscriminate fluid administration, as excessive crystalloids may worsen tissue edema and postoperative recovery. Contemporary perioperative management, therefore, increasingly combines arterial pressure monitoring with dynamic assessment of stroke volume, cardiac output, and tissue perfusion to guide individualized use of fluids, vasopressors, and inotropes.

The emergence of predictive technologies such as the Hypotension Prediction Index further illustrates the growing importance of arterial pressure monitoring in modern perioperative medicine.

These systems aim to identify impending hypotension before clinically significant hemodynamic deterioration develops, thereby enabling proactive intervention (7).

- Urine Output

Urine output remains a widely used indicator of organ perfusion and intravascular status in perioperative medicine. Although oliguria during major abdominal surgery traditionally prompted aggressive fluid administration, contemporary understanding recognizes that urine output is influenced by multiple physiological factors beyond hypovolemia, including sympathetic activation, hormonal responses, inflammation, and reduced renal perfusion pressure. Consequently, oliguria may occur without true volume depletion, while preserved urine output does not necessarily guarantee adequate tissue perfusion.

Excessive fluid administration solely in response to transient oliguria may contribute to positive fluid balance, pulmonary edema, bowel edema, impaired wound healing, and delayed gastrointestinal recovery. Egger et al. (14) found an association between intraoperative fluid balance and perioperative complications in major oncologic surgery, further emphasizing the importance of balanced fluid management.

Current perioperative management therefore evaluates urine output within the broader context of overall hemodynamic assessment, including dynamic monitoring variables and tissue perfusion indicators. Although urine output remains clinically useful as a marker of renal perfusion and function, contemporary perioperative medicine discourages isolated interpretation of oliguria as an indication for indiscriminate fluid administration.

- Lactate

Serum lactate is an important marker of tissue perfusion and metabolic stress in perioperative medicine. Although elevated lactate traditionally indicates anaerobic metabolism from inadequate oxygen delivery, it may also result from adrenergic stimulation, impaired clearance, or inflammatory activation. During major abdominal surgery, persistent hyperlactatemia has been associated with postoperative complications, organ dysfunction, prolonged hospitalization, and mortality. Contemporary perioperative management therefore evaluates serial lactate trends within integrated hemodynamic assessment, as elevated lactate may occur despite apparently preserved systemic hemodynamics due to occult tissue hypoperfusion or microcirculatory dysfunction (11,12).

Dynamic Hemodynamic Monitoring

- Pulse Pressure Variation

Pulse pressure variation (PPV) is one of the most extensively studied dynamic predictors of fluid responsiveness in perioperative medicine. It reflects respiratory-induced changes in arterial pulse pressure during positive pressure ventilation caused by heart-lung interactions. During inspiration, increased intrathoracic pressure transiently reduces venous return and ventricular preload, leading to fluctuations in stroke volume and arterial pulse pressure. These variations are more pronounced in preload-responsive patients and attenuated in patients operating on the flat portion of the Frank-Starling curve.

PPV has consistently demonstrated superior predictive accuracy compared with static preload variables such as CVP. Salzwedel et al. (6) conducted a multicenter prospective randomized study that showed a reduction in postoperative complications with PPV-guided goal-directed therapy during major abdominal surgery. Similarly, Cesur et al. (15) reported improved intraoperative fluid optimization with pleth variability index-guided therapy in colorectal surgery. Ochiai et al. (16) additionally demonstrated variability between pulse wave transit time-derived stroke volume variation and arterial waveform-derived measurements, emphasizing the importance of cautious interpretation when integrating advanced arterial waveform technologies into perioperative decision-making.

The advantages of PPV include continuous real-time assessment of fluid responsiveness and integration into arterial waveform monitoring systems commonly used during high-risk surgery. PPV-guided fluid optimization may help avoid both hypovolemia and unnecessary fluid administration. However, accurate interpretation requires controlled mechanical ventilation, sinus rhythm, adequate tidal volume, and preserved chest wall compliance, while arrhythmias, spontaneous breathing activity, and elevated intra-abdominal pressure may reduce reliability. Despite these limitations, PPV remains a key component of contemporary goal-directed therapy protocols.

- Stroke Volume Variation

Stroke volume variation (SVV) is another major dynamic parameter used to predict fluid responsiveness during major surgery. SVV measures cyclic respiratory-induced fluctuations in stroke volume occurring during positive pressure ventilation. Similar to PPV, SVV exploits cardiopulmonary interactions to identify preload-responsive patients.

The physiological rationale underlying SVV monitoring is based on the observation that mechanically ventilated patients with preload dependency exhibit substantial respiratory changes in ventricular filling and stroke volume.

High SVV values generally suggest that cardiac output may increase following fluid administration, whereas low SVV values imply limited preload responsiveness. Li et al. (17) demonstrated the predictive value of SVV during gastrointestinal surgery, while Sun et al. (18) reported shorter hospital stays and improved postoperative gastrointestinal recovery with SVV-guided fluid optimization in major abdominal surgery. These findings support the growing role of SVV-guided therapy within contemporary perioperative hemodynamic management.

SVV-guided strategies may improve perioperative care by promoting individualized fluid optimization and reducing unnecessary crystalloid administration, which has been associated with bowel edema, pulmonary complications, delayed gastrointestinal recovery, and prolonged hospital stays. Modern minimally invasive monitoring systems increasingly integrate continuous SVV analysis with cardiac output estimation and arterial waveform interpretation to enable real-time hemodynamic assessment. However, SVV reliability may be reduced by arrhythmias, spontaneous respiratory effort, low-tidal-volume ventilation, or altered thoracic compliance (16,17).

- Passive Leg Raising

Passive leg raising (PLR) is a reversible endogenous fluid challenge that transiently increases venous return without intravenous fluid administration. A positive hemodynamic response suggests preload responsiveness, whereas the absence of significant cardiac output augmentation indicates limited benefit from additional fluids. PLR is especially useful when PPV or SVV become unreliable, including spontaneous breathing activity, arrhythmias, or low tidal volume ventilation (1).

- Fluid Responsiveness

Fluid responsiveness is a central concept of modern goal-directed therapy and refers to the ability of cardiac output or stroke volume to increase following fluid administration. Importantly, not all hypotensive patients are preload responsive, and unnecessary fluid administration may contribute to pulmonary dysfunction, bowel edema, impaired oxygen diffusion, and delayed recovery. Therefore, contemporary perioperative medicine increasingly prioritizes identification of patients likely to benefit from fluid administration using dynamic monitoring variables such as PPV, SVV, PLR response, together with cardiac output assessment, rather than empiric fluid loading (3,6).

Static hemodynamic variables remain useful for general cardiovascular assessment; however, contemporary perioperative medicine increasingly prioritizes dynamic monitoring parameters because of their superior ability to predict fluid responsiveness and guide individualized hemodynamic optimization. A comparative overview of static and dynamic hemodynamic monitoring modalities is presented in Figure 2.

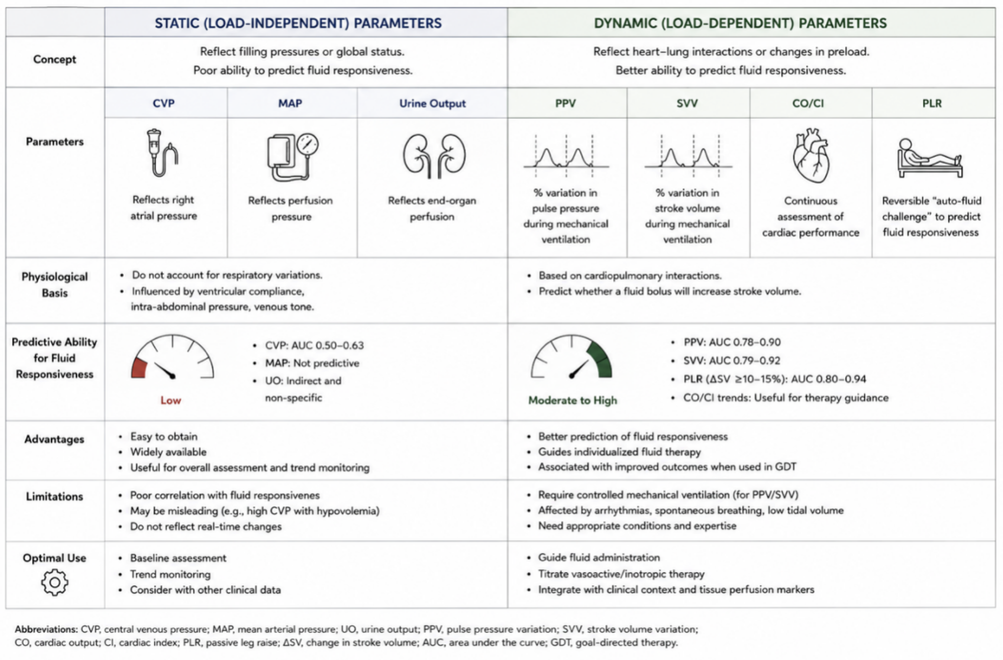

Figure 2. Comparison of static and dynamic hemodynamic monitoring parameters in perioperative goal-directed therapy.

Static hemodynamic parameters such as central venous pressure (CVP), mean arterial pressure (MAP), and urine output provide general physiological information but have limited ability to predict fluid responsiveness. Dynamic parameters, including pulse pressure variation (PPV), stroke volume variation (SVV), passive leg raising (PLR), and cardiac output/cardiac index (CO/CI) assessment, are based on cardiopulmonary interactions and provide superior prediction of preload responsiveness and individualized fluid optimization. Contemporary perioperative goal-directed therapy increasingly integrates dynamic monitoring strategies to improve tissue perfusion and postoperative outcomes (1,3,4).

Goal-Directed Therapy (GDT)

Principles of GDT

Goal-directed therapy (GDT) is a structured perioperative hemodynamic strategy that optimizes tissue perfusion and oxygen delivery by setting individualized physiological targets. Unlike traditional empirical fluid administration, GDT integrates continuous hemodynamic monitoring with protocolized fluid, vasopressor, and inotrope administration. The concept emerged from the recognition that perioperative hypoperfusion contributes substantially to postoperative organ dysfunction, including acute kidney injury, pulmonary complications, myocardial injury, bowel dysfunction, and prolonged hospital stay. Therefore, cContemporary perioperative medicine increasingly emphasizes individualized hemodynamic optimization guided by dynamic monitoring variables such as pulse pressure variation, stroke volume variation, cardiac output, and cardiac index assessment (3,4,19).

Several landmark trials have evaluated perioperative GDT during major abdominal surgery. Pearse et al. (19) investigated cardiac output-guided hemodynamic therapy during major gastrointestinal surgery, whereas the OPTIMISE II Trial Group (20) evaluated contemporary cardiac output-guided protocols in elective gastrointestinal surgery. Although results have varied, meta-analyses generally indicate improved postoperative recovery and reduced morbidity when appropriately implemented GDT strategies are implemented (3,4).

Importantly, GDT should not be interpreted as a single universal protocol but rather as a broader physiological framework emphasizing individualized optimization based on continuous hemodynamic assessment. Variability in study results likely reflects differences in patient populations, monitoring technologies, fluid strategies, vasopressor use, surgical complexity, ERAS implementation, and definitions of perioperative optimization.

The contemporary framework of perioperative goal-directed therapy integrates dynamic monitoring, individualized fluid optimization, vasopressor support, and continuous reassessment of tissue perfusion. A proposed perioperative hemodynamic optimization algorithm based on current GDT and ERAS principles is presented in Figure 3.

Major clinical studies evaluating perioperative GDT in abdominal surgery are summarized in Table 1.

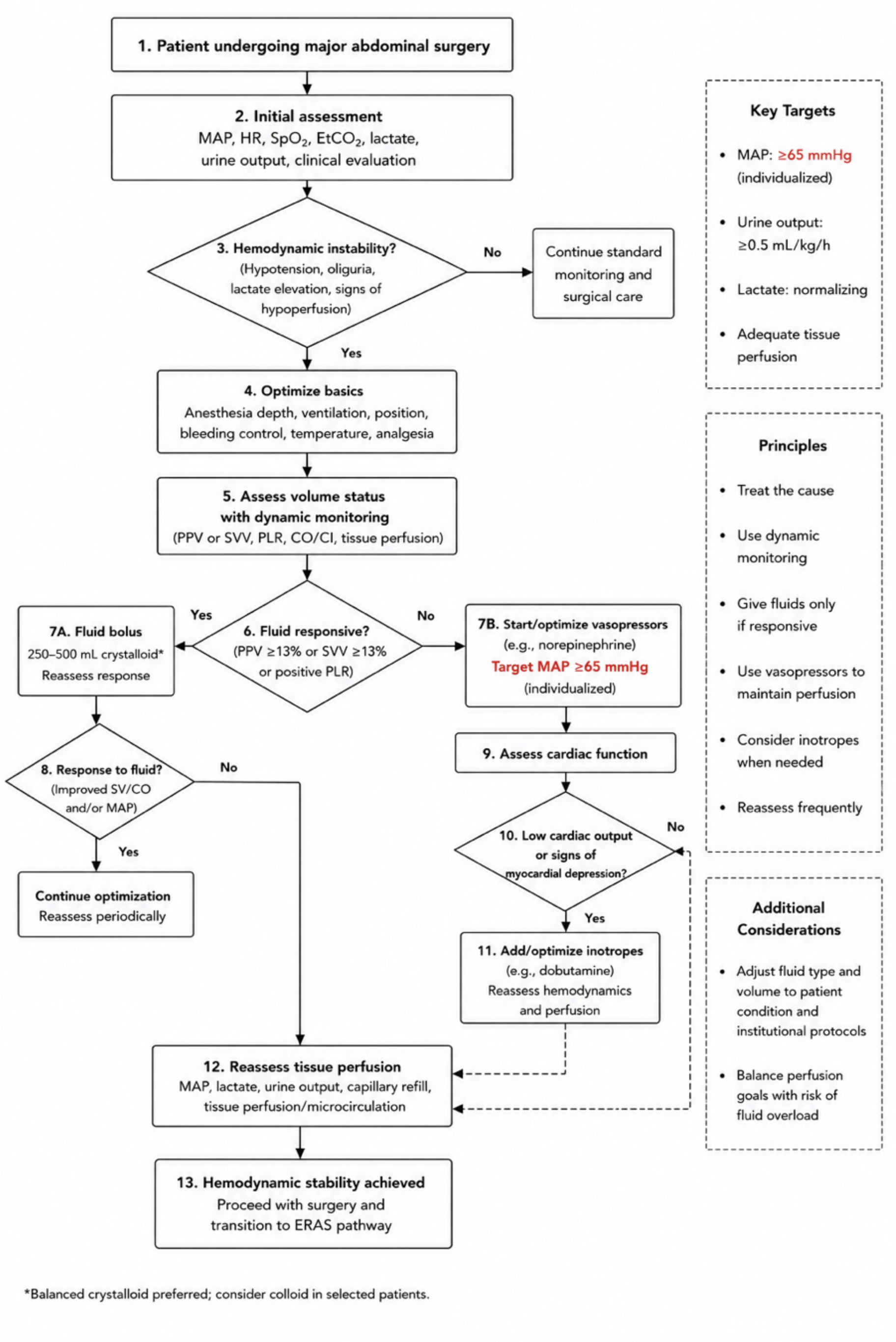

Figure 3. Suggested perioperative hemodynamic optimization algorithm in major abdominal surgery.

Major abdominal surgery causes physiological stress responses that may lead to hemodynamic instability and impaired tissue perfusion. Contemporary perioperative management combines static and dynamic hemodynamic monitoring to guide individualized goal-directed therapy with fluids, vasopressors, and inotropes.

Emerging technologies, including artificial intelligence and predictive analytics, may further improve perioperative hemodynamic optimization and postoperative outcomes. *Algorithm synthesized from contemporary perioperative hemodynamic optimization and goal-directed therapy literature* (1,3,4,8).

Table 1. Key clinical evidence on goal-directed hemodynamic therapy and perioperative hemodynamic optimization in major abdominal and gastrointestinal surgery

Study	**Design/population**	**Monitoring or intervention**	**Comparator**	**Main finding**	**Relevance to the review**
Pearse et al., 2014 (19)	Multicenter RCT; high-risk major gastrointestinal surgery	Cardiac output-guided hemodynamic therapy algorithm based on fluid administration and inotrope support	Usual care	Did not significantly reduce composite complications and 30-day mortality, although updated meta-analysis suggested fewer	Landmark trial showing both the promise and limitations of cardiac output-guided GDT

				complications	
Salzwedel et al., 2013 (6)	Multicenter prospective randomized study; major abdominal surgery	PPV, cardiac index trending, and MAP-guided GDT	Standard perioperative management	Reduced postoperative complications	Supports dynamic, protocolized hemodynamic optimization in major abdominal surgery
OPTIMISE II Trial Group, 2024 (20)	Large multicenter RCT; major elective gastrointestinal surgery	Cardiac output-guided hemodynamic therapy	Usual care	No reduction in the primary composite outcome compared with usual care	Important modern negative trial; suggests GDT benefit is context-dependent
Sun et al., 2017 (3)	Systematic review and meta-analysis of RCTs; major abdominal surgery	Perioperative goal-directed hemodynamic therapy	Conventional therapy	Suggested improved postoperative recovery	Provides pooled evidence supporting GDHT, while highlighting heterogeneity

Chong et al., 2018 (4)	Systematic review and meta-analysis; perioperative surgery	Goal-directed hemodynamic and fluid therapy	Standard care	Evaluated whether GDHT improves perioperative outcomes	Useful for summarizing broader perioperative evidence
Gómez-Izquierdo et al., 2017 (21)	RCT; elective laparoscopic colorectal surgery	Goal-directed fluid therapy	Standard perioperative fluid therapy	Did not reduce primary postoperative ileus	Demonstrates that GDT may not benefit all patients, especially within optimized ERAS settings
Cesur et al., 2019 (15)	Elective colorectal surgery	PVI-guided goal-directed fluid management	Conventional fluid management	Compared crystalloid administration, lactate levels, and creatinine concentrations during surgery	Supports discussion of non-invasive dynamic monitoring in colorectal surgery
Sun et al., 2023 (18)	RCT; major abdominal oncologic surgery	SVV- and cardiac index-guided GDFT using	Conventional management	Shorter hospital stay and faster gastrointestinal recovery	Strong recent evidence for SVV-guided fluid optimization

		FloTrac/Vigileo			
Coeckelenbergh et al., 2025 (12)	RCT; high-risk abdominal surgery	Assisted fluid management-guided GDFT	Standard GDFT	Higher sublingual microvascular flow during surgery	Introduces microcirculatory endpoints beyond macrohemodynamic targets
Ripollés-Melchor et al., 2025 (22)	Multicenter RCT; moderate- to high-risk elective abdominal surgery	HPI-guided hemodynamic therapy	Standard care	Did not reduce postoperative AKI or overall complications	Important cautionary evidence for predictive monitoring technologies
Yoshikawa et al., 2024 (7)	RCT; major non-cardiac surgery	Hypotension Prediction Index-guided management	Conventional goal-directed hemodynamic management	Reduced cumulative intraoperative hypotension	Supports HPI as a tool for reducing hypotensive burden
Saugel et al., 2024 (1)	Guideline; adult non-cardiac surgery	Intraoperative hemodynamic monitoring and	Not applicable	Provides structured recommendations for	Authoritative basis for clinical recommendations

		management recommendations		perioperative monitoring	
Saugel et al., 2025 (13)	European Society statement; adult non-cardiac surgery	Intraoperative hemodynamic monitoring and management	Not applicable	Consensus guidance on contemporary hemodynamic management	Strengthens the review's guideline-based framework
Saugel et al., 2025 / IMPROVE-multi (23)	RCT; major abdominal surgery	Individualized perioperative blood pressure management	Routine blood pressure management	Did not support individualized targets based on preoperative nighttime MAP	Important recent evidence questioning simplified individualized BP strategies
Pasta et al., 2025 (24)	Major oncologic surgery	Progressive implementation of AI-based hemodynamic monitoring and decision-support tools	Earlier-stage monitoring strategies	Suggested decreasing intraoperative hypotension with increasing AI-assisted support	Supports future-perspective discussion on AI-guided perioperative care

Fluid Optimization

Fluid therapy remains a critical component of perioperative management in major abdominal surgery, as appropriate intravascular volume optimization is essential for maintaining cardiac output and tissue perfusion. However, both hypovolemia and fluid overload may contribute to postoperative complications. While hypovolemia may impair organ perfusion and oxygen delivery, excessive fluid administration may promote pulmonary and bowel edema, delayed gastrointestinal recovery, and prolonged hospital stay. Contemporary perioperative medicine, therefore, increasingly favors individualized fluid optimization over liberal empiric fluid administration (14,25).

Egger et al. (14) demonstrated significant associations between intraoperative fluid balance and perioperative complications during major oncologic surgery. Similarly, Sun et al. (18) reported improved gastrointestinal recovery and shorter hospital stay with stroke volume variation-guided fluid optimization strategies.

Dynamic hemodynamic monitoring plays a central role in modern fluid optimization because it allows identification of patients likely to benefit from fluid administration. Rather than administering empiric fluid boluses based solely on hypotension or oliguria, contemporary protocols increasingly assess preload responsiveness using PPV, SVV, or cardiac output response assessment.

The concept of "fluid responsiveness" is fundamental to GDT. Fluid administration should ideally produce meaningful augmentation of stroke volume or cardiac output. If no significant hemodynamic improvement occurs following volume expansion, additional fluids may simply accumulate within the interstitial space without improving tissue perfusion. The type of administered fluid also remains clinically important. Crystalloids remain the primary perioperative fluid choice due to their widespread availability, favorable safety profile, and lower cost. However, excessive crystalloid administration may promote tissue edema through redistribution into the extracellular compartment. Colloid solutions may provide more efficient plasma volume expansion but remain controversial because of potential renal and coagulation effects.

Huisman et al. (25) additionally highlighted the importance of balancing fluid administration and vasopressor therapy during colorectal surgery to avoid both hypoperfusion and fluid overload. Yates et al. (26) compared crystalloid- and colloid-based fluid strategies during colorectal surgery within goal-directed protocols, emphasizing ongoing debate over the optimal perioperative fluid composition.

Contemporary perioperative management increasingly favors balanced, individualized fluid administration guided by physiological monitoring rather than fixed liberal or restrictive strategies.

Vasopressors and Inotropes

Vasopressors and inotropes are essential components of modern perioperative hemodynamic management, as anesthesia-induced vasodilation, inflammatory vasoplegia, and blood loss frequently contribute to hypotension during major abdominal surgery. While hypotension was historically treated primarily with aggressive fluid administration, recognition of the harmful effects of fluid overload has shifted practice toward earlier and more individualized vasopressor use.

Norepinephrine has emerged as the preferred vasopressor because it increases vascular tone and perfusion pressure while generally preserving cardiac output and limiting excessive fluid administration (13,27).

Vokuhl et al. (27) showed improved arterial pressure stability when applying continuous norepinephrine administration during induction of general anesthesia in high-risk surgical patients. These findings support the growing interest in implementing proactive vasopressor strategies during perioperative hemodynamic optimization.

Importantly, vasopressor therapy should not replace appropriate volume assessment. Hypotension secondary to severe hypovolemia may worsen if treated exclusively with vasoconstrictive agents. Consequently, integrated physiological assessment remains essential for distinguishing preload deficiency from vasodilatory hypotension or myocardial dysfunction.

Inotropic agents may become necessary when cardiac output remains inadequate despite optimization of preload and perfusion pressure. Reduced myocardial contractility may occur during major surgery due to anesthesia, ischemia, sepsis, or inflammatory myocardial depression. In such situations, augmentation of cardiac contractility may improve oxygen delivery and organ perfusion.

Modern perioperative medicine increasingly emphasizes balanced hemodynamic optimization integrating fluids, vasopressors, and inotropic agents according to individualized physiological requirements rather than rigid universal protocols.

Individualized Hemodynamic Targets

One of the most important developments in contemporary perioperative medicine is the transition from generalized hemodynamic thresholds toward individualized physiological targets. Traditional perioperative management often relied on fixed MAP values or standardized fluid administration algorithms regardless of baseline patient physiology.

However, autoregulatory capacity and cardiovascular reserve vary substantially among surgical patients. Individuals with chronic hypertension, diabetes mellitus, advanced age, vascular disease, or impaired cardiac function may require different perfusion pressures to maintain adequate organ blood flow.

Recent studies have therefore increasingly explored personalized hemodynamic optimization strategies. The IMPROVE-multi randomized clinical trial evaluated individualized perioperative blood pressure management during major abdominal surgery, reflecting growing recognition that "one-size-fits-all" hemodynamic targets may be physiologically inadequate (13).

Materials and Methods

Similarly, modern GDT protocols increasingly incorporate patient-specific variables including baseline cardiovascular physiology, comorbidities, surgical complexity, and predicted postoperative risk. The emergence of predictive monitoring technologies further supports this individualized approach. Hypotension Prediction Index-guided management permits anticipatory intervention before clinically significant hemodynamic deterioration develops. Yoshikawa et al. (7) demonstrated reduced cumulative hypotension with HPI-guided therapy during non-cardiac surgery. Precision perioperative medicine aims to further expand individualized management through integration of physiological monitoring, predictive analytics, artificial intelligence, and potentially genomic or biomarker-based risk stratification. The movement toward individualized hemodynamic optimization represents a major paradigm shift within modern anesthesiology and perioperative medicine.

Monitoring Technologies

Arterial Waveform Analysis

Arterial waveform analysis has become a major tool for perioperative hemodynamic assessment by deriving dynamic variables such as pulse pressure and stroke volume variation from invasive arterial pressure monitoring. Based on cardiopulmonary interactions during positive-pressure ventilation, these systems provide continuous real-time assessment of preload responsiveness, cardiovascular reserve, cardiac output, and systemic vascular resistance, facilitating individualized hemodynamic intervention during surgery.

Salzwedel et al. (6) showed reduced postoperative complications with PPV-based goal-directed therapy during major abdominal surgery. Similarly, Sun et al. (18) reported improved gastrointestinal recovery and a shorter hospital stay with stroke volume variation-guided fluid optimization.

Arterial waveform systems offer several advantages, including continuous monitoring capability, relatively low invasiveness, and integration with modern perioperative workstations. However, interpretation requires awareness of important physiological limitations, including arrhythmias, spontaneous respiratory effort, low-tidal-volume ventilation, impaired chest wall compliance, and altered right ventricular physiology.

Despite these limitations, arterial waveform analysis remains central to contemporary goal-directed therapy protocols and modern perioperative hemodynamic optimization strategies.

Esophageal Doppler

Esophageal Doppler monitoring provides a minimally invasive assessment of descending thoracic aortic blood flow velocity and stroke volume. A specialized Doppler probe placed within the esophagus enables real-time evaluation of cardiovascular function during surgery.

The principal advantage of esophageal Doppler technology is its ability to continuously estimate stroke volume and cardiac output without requiring a pulmonary artery catheter. This allows individualized fluid optimization and direct assessment of hemodynamic response to therapeutic intervention.

Esophageal Doppler monitoring played a major role in the early development of perioperative goal-directed therapy protocols and has been extensively studied in abdominal surgery. De Pascale et al. (28) compared esophageal Doppler monitoring with non-invasive bioreactance technologies during major abdominal-pelvic surgery and showed important methodological differences between the monitoring systems.

Advantages of esophageal Doppler monitoring include relatively rapid setup, minimally invasive application, and real-time cardiac output assessment. However, important limitations include operator dependency, probe positioning challenges, motion artifacts, and variable signal acquisition.

Although newer arterial waveform and minimally invasive monitoring technologies have become increasingly widespread, esophageal Doppler monitoring remains an important and physiologically valuable tool in perioperative hemodynamic management.

Minimally Invasive Cardiac Output Monitoring

Over the past two decades, technological advances have driven the development of minimally invasive cardiac output monitoring systems that provide continuous hemodynamic assessment with lower procedural risk than traditional pulmonary artery catheterization. Contemporary technologies include pulse contour analysis, bioreactance devices, pulse wave transit time analysis, and noncalibrated arterial waveform systems, which estimate cardiac output using arterial waveform or thoracic bioimpedance analysis.

Bioreactance monitoring is among the most widely studied noninvasive cardiac output technologies. This method analyzes phase shifts in thoracic electrical currents generated by pulsatile blood flow. De Pascale et al. (28) compared noninvasive bioreactance monitoring with esophageal Doppler assessment during major abdominal-pelvic surgery and reported important differences between the methodologies.

The principal advantages of minimally invasive cardiac output monitoring include reduced procedural complications, continuous real-time physiological assessment, simplified perioperative integration, and broader applicability outside specialized intensive care settings. These technologies facilitate dynamic evaluation of stroke volume response, cardiac output trends, preload responsiveness, and therapeutic intervention effects during surgery.

Minimally invasive monitoring also has important limitations, as accuracy may be affected by arrhythmias, vasoplegia, arterial waveform distortion, mechanical ventilation settings, obesity, and severe hemodynamic instability. Nevertheless, these systems have become central to modern goal-directed therapy because contemporary perioperative management increasingly prioritizes continuous physiological assessment and individualized optimization over intermittent static measurements. Recent integration of predictive analytics and machine learning may further expand their clinical utility.

Ultrasound and Echocardiography

Point-of-care ultrasound (POCUS) and perioperative echocardiography have assumed an increasingly important role in modern hemodynamic assessment because they enable rapid bedside evaluation of ventricular function, intravascular volume status, and structural abnormalities. Unlike isolated numerical variables, echocardiography provides direct visualization of cardiac physiology and may identify causes of hemodynamic instability, including ventricular dysfunction, hypovolemia, vasoplegia, or obstructive pathology. Ultrasound assessment of the inferior vena cava has also emerged as a potential tool for estimating preload responsiveness, although its interpretation remains affected by ventilation and intrathoracic pressure changes. Contemporary perioperative medicine increasingly integrates ultrasound alongside conventional monitoring technologies to improve individualized hemodynamic management (13).

Hemodynamic Optimization in Major Abdominal Surgery

Colorectal Surgery

Colorectal surgery is one of the most extensively investigated areas of perioperative hemodynamic optimization and goal-directed therapy because these procedures are associated with significant fluid shifts, inflammatory activation, and postoperative gastrointestinal dysfunction. Although colorectal surgery historically favored liberal fluid administration, excessive crystalloids are now recognized to contribute to bowel edema, delayed gastrointestinal recovery, pulmonary complications, and prolonged hospital stay. Consequently, contemporary perioperative management increasingly emphasizes individualized fluid optimization guided by dynamic hemodynamic monitoring (15,29,30).

Cesur et al. (15) compared conventional fluid management with pleth variability index-guided goal-directed therapy during elective colorectal surgery and reported improved intraoperative fluid optimization. Similarly, Resalt-Pereira et al. (29) evaluated goal-directed fluid therapy during laparoscopic colorectal surgery within ERAS pathways.

Gómez-Izquierdo et al. (21) examined goal-directed fluid therapy during elective laparoscopic colorectal surgery and reported no reduction in postoperative ileus despite protocolized optimization. These findings highlight ongoing controversy regarding the magnitude of the benefit associated with perioperative GDT within already optimized ERAS programs.

Zorrilla-Vaca et al. (30) conducted a propensity score-matched multicenter study, demonstrating improved postoperative outcomes when goal-directed fluid therapy was incorporated into enhanced recovery protocols for colorectal surgery.

Dynamic monitoring variables such as PPV and SVV remain particularly valuable during colorectal surgery because these procedures frequently involve significant fluid redistribution and prolonged operative duration. Individualized optimization strategies may therefore improve tissue perfusion while minimizing bowel edema and postoperative dysfunction.

The integration of perioperative hemodynamic optimization into ERAS pathways has become increasingly important in colorectal surgery, driven by the growing emphasis on accelerated recovery, reduced complications, and shorter hospitalization.

Hepatobiliary Surgery

Hepatobiliary surgery presents unique hemodynamic challenges due to complex hepatic vascular physiology and substantial blood loss risk. Excessive fluid administration may increase hepatic venous congestion and intraoperative bleeding, whereas excessive restriction may compromise organ perfusion. Consequently, contemporary hepatobiliary anesthesia emphasizes balanced hemodynamic optimization through dynamic monitoring, controlled fluid therapy, and individualized physiological targets (31).

Saito et al. (31) concluded that stroke volume variation-guided monitoring may reduce blood loss during hepatocellular carcinoma resection. These findings support the use of dynamic preload assessment during complex hepatic surgery.

Low central venous pressure anesthesia has historically been administered to minimize hepatic venous bleeding during liver resection. However, excessive preload reduction may impair renal perfusion and tissue oxygen delivery. Consequently, contemporary hepatobiliary management integrates individualized hemodynamic optimization to a greater extent rather than rigid CVP reduction alone.

Major hepatobiliary procedures are also frequently associated with prolonged operative duration, major fluid shifts, ischemia-reperfusion injury, inflammatory activation, and vasodilatory physiology. Advanced hemodynamic monitoring, therefore, plays a key role in maintaining physiological stability during these operations.

Dynamic monitoring strategies enable individualized balancing of adequate organ perfusion against avoidance of excessive venous congestion and tissue edema.

Emergency Abdominal Surgery

Emergency abdominal surgery patients represent a particularly high-risk perioperative population due to sepsis, hypovolemia, hemorrhage, intestinal ischemia, and inflammatory activation. Unlike elective surgical patients, many present with hemodynamic instability, metabolic acidosis, and organ dysfunction before anesthesia induction, substantially increasing perioperative morbidity and mortality. Consequently, contemporary perioperative management prioritizes rapid hemodynamic assessment and individualized optimization through dynamic monitoring, lactate assessment, vasopressor support, and goal-directed therapy, while avoiding indiscriminate crystalloid administration that may worsen bowel edema and pulmonary dysfunction (1,3).

ERAS Protocols

Enhanced Recovery After Surgery (ERAS) protocols (8) are one of the most significant contemporary developments in perioperative medicine. ERAS pathways integrate multimodal perioperative strategies designed to reduce surgical stress, minimize complications, and accelerate postoperative recovery.

Perioperative fluid and hemodynamic optimization constitute the central components of modern ERAS programs. Excessive crystalloid administration has been consistently associated with bowel edema, impaired gastrointestinal motility, pulmonary complications, delayed mobilization, and prolonged hospitalization. Consequently, ERAS pathways promote balanced individualized fluid therapy rather than liberal fluid administration.

McLain et al. (32) highlighted that goal-directed fluid therapy has become a major component of contemporary ERAS implementation due to its ability to individualize fluid administration according to dynamic physiological assessment.

Colorectal surgery remains one of the most extensively researched ERAS populations, with multiple studies demonstrating improved postoperative recovery through integration of individualized fluid optimization and minimally invasive perioperative strategies (29,30).

Ripollés-Melchor et al. (8) described the growing integration of perioperative hemodynamic optimization within ERAS protocols in surgical oncology.

Dynamic monitoring strategies allow for a more physiologically targeted fluid administration and may improve postoperative recovery within enhanced recovery pathways.

Goal-directed therapy has therefore become incorporated into ERAS frameworks because individualized physiological optimization aligns closely with broader ERAS objectives, including reduced complications, earlier feeding, accelerated mobilization, and shorter hospital stay.

Importantly, implementation of ERAS pathways may influence the observed effects of perioperative GDT in contemporary studies. Because modern ERAS care already reduces postoperative morbidity through multimodal optimization, additional incremental benefits from hemodynamic protocols may become more difficult to demonstrate.

Nevertheless, contemporary perioperative medicine recognizes perioperative hemodynamic optimization as a fundamental component of successful enhanced recovery strategies.

Future Directions

Artificial Intelligence

Artificial intelligence (AI) has emerged as one of the most rapidly expanding fields within perioperative medicine and hemodynamic monitoring. Advances in machine learning, predictive analytics, automated physiological interpretation, and real-time computational modeling have accelerated the development of AI-assisted perioperative management.

Traditional perioperative hemodynamic management has largely relied on clinician interpretation of physiological variables after hemodynamic deterioration has occurred. In contrast, AI-assisted monitoring systems aim to predict impending instability before clinically significant deterioration becomes apparent.

This anticipatory approach represents a major conceptual shift from reactive correction toward proactive prevention of hemodynamic compromise.

The Hypotension Prediction Index (HPI) is among the most widely studied AI-assisted perioperative monitoring technologies. HPI utilizes machine learning algorithms, analyzing subtle arterial waveform characteristics to predict impending intraoperative hypotension before significant blood pressure decline occurs. These systems continuously process large quantities of physiological data beyond what is typically recognizable through conventional visual waveform interpretation.

Yoshikawa et al. (7) reported reduced cumulative intraoperative hypotension with HPI-guided management during non-cardiac surgery. Similarly, Ripollés-Melchor et al. (22) evaluated HPI-guided hemodynamic management during abdominal surgery, reflecting the growing interest in predictive perioperative monitoring strategies.

Artificial intelligence technologies may offer several major advantages in perioperative care. Early identification of impending instability may allow timely intervention before prolonged tissue hypoperfusion develops. Potentially, this may reduce postoperative complications including acute kidney injury, myocardial injury, neurological dysfunction, and gastrointestinal impairment.

Pasta et al. (24) investigated the progressive implementation of AI-assisted predictive hemodynamic management during major oncologic surgery and reported improvements in perioperative hemodynamic stability through integration of advanced monitoring systems.

In addition to hypotension prediction, future AI systems may potentially integrate multiple physiological domains, including cardiac output trends, microcirculatory assessment, lactate kinetics, tissue oxygenation, inflammatory biomarkers, ventilatory parameters, and patient-specific risk factors. Such multidimensional integration could substantially improve individualized perioperative decision-making.

Despite these promising developments, several important challenges remain. Artificial intelligence systems require extensive physiological validation across diverse surgical populations and varying hemodynamic conditions. Concerns also remain regarding algorithm transparency, clinician overreliance on automated systems, cost-effectiveness, and integration into routine perioperative workflows.

Importantly, AI-assisted technologies should not replace clinical judgment but rather augment physiological interpretation and support individualized decision-making. Future perioperative medicine will likely involve collaborative interaction between clinician expertise and advanced computational monitoring systems.

Predictive Analytics

Predictive analytics is an emerging field in perioperative hemodynamic optimization that aims to forecast physiological deterioration through continuous data analysis and machine learning algorithms rather than simply displaying current hemodynamic values. By integrating arterial waveform morphology, heart rate variability, cardiac output trends, and additional physiological variables, these systems may identify evolving instability before overt clinical manifestations develop.

This transition toward predictive monitoring reflects the growing emphasis on prevention of intraoperative hypotension and organ hypoperfusion rather than delayed correction of hemodynamic deterioration (7,8).

Ripollés-Melchor et al. (22) evaluated HPI-guided hemodynamic management in abdominal surgery populations, while Yoshikawa et al. (7) demonstrated reduced cumulative hypotension through predictive monitoring-guided intervention. These studies suggest that predictive technologies may improve perioperative hemodynamic stability, although long-term outcome benefits remain under active investigation.

Predictive analytics may also become integrated with perioperative risk stratification systems. Future monitoring platforms may potentially combine baseline patient characteristics, comorbidities, laboratory data, imaging findings, genomic information, and real-time physiological monitoring into individualized predictive models.

Another important area of development involves predictive fluid responsiveness assessment. Dynamic monitoring variables such as PPV and SVV already provide real-time estimation of preload responsiveness, but future systems may potentially forecast evolving fluid requirements before clinically significant instability develops.

Microcirculatory monitoring may similarly become integrated into predictive analytics frameworks. Because tissue hypoperfusion may precede macrohemodynamic deterioration, incorporation of microvascular assessment could potentially improve early identification of organ perfusion abnormalities.

Although predictive technologies remain an evolving field, their integration into perioperative medicine is likely to expand substantially over the coming decade.

Precision Perioperative Medicine

Precision perioperative medicine represents a transition toward individualized physiological management based on patient-specific characteristics rather than generalized treatment protocols. Unlike traditional approaches relying on standardized fluid regimens and fixed blood pressure thresholds, contemporary perioperative care increasingly integrates dynamic monitoring, predictive analytics, artificial intelligence, and individualized cardiovascular assessment.

Recent studies on personalized blood pressure optimization during major abdominal surgery further support this shift toward precision physiology, recognizing that universal hemodynamic targets may not adequately reflect individual patient requirements (13). As perioperative technologies continue to evolve, future anesthesiology practice will likely become personalized, predictive, and physiology-driven.

Conclusion

Hemodynamic monitoring and goal-directed therapy have become central components of modern perioperative medicine in major abdominal surgery. Contemporary perioperative management prioritizes dynamic assessment of fluid responsiveness and tissue perfusion through pulse pressure variation, stroke volume variation, cardiac output monitoring, and individualized hemodynamic optimization. Goal-directed therapy protocols including fluids, vasopressors, and inotropes have yield important benefits including reduced postoperative morbidity, improved gastrointestinal recovery, and shorter hospitalization. In addition, ERAS pathways, predictive analytics, artificial intelligence, and precision perioperative medicine are further advancing individualized physiology-driven care aimed at preserving tissue perfusion, oxygen delivery, and organ function.

Declarations

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