



Perioperative Hemodynamic Stability in High-Risk Surgical Patients: Advances in Monitoring, Goal-Directed Therapy and Hypotension Prevention - A Narrative Study

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Abstract

Background: Hemodynamic stability is primary importance in maintaining adequate tissue perfusion and preventing complications during and after surgery. High-risk patients, like the elderly and patients with cardiovascular diseases or major surgeries, are at high risk of developing perioperative hemodynamic disturbances, like hypotension and decreased cardiac output, which are strongly correlated with postoperative organ dysfunction, myocardial injury, acute kidney injury, and increased mortality. **Objective:** The purpose of this narrative review was to discuss the current evidence on recent developments in monitoring techniques, goal-directed therapy, and management of perioperative hypotension in high-risk patients. **Methods:** This narrative review of recent developments was conducted by searching various databases like PubMed, Scopus, Web of Science, and Google Scholar, with eligibility criteria of publications between 1988 and 2026. **Results:** Recent developments in monitoring techniques, like minimally invasive cardiac output monitoring and machine learning algorithms, have greatly improved the detection of perioperative hemodynamic instability. A number of recent randomized trials have shown that goal-directed therapy can improve postoperative outcomes by optimizing tissue perfusion. The recent developments in monitoring techniques and goal-directed therapy are of primary importance for improving perioperative outcomes in high-risk patients.

Keywords: Cardiac Output Monitoring; Fluid Responsiveness; Goal-Directed Therapy; Hemodynamic Monitoring; High-Risk Surgery.

1. Introduction

Hemodynamic stability is one of the key issues in perioperative care. Blood pressure and cardiac output need to be normal to ensure adequate tissue oxygenation during surgical procedures. Hemodynamic instability is one of the most common issues in anaesthesia care. Hemodynamic instability is caused by the combined effects of anaesthetic agents, surgical stress, blood loss, and fluid shifts¹⁸. Patients at risk during surgical procedures have compromised physiological reserve and are at increased risk of developing perioperative complications due to instability in blood pressure. Elderly patients, patients with cardiovascular diseases, and patients undergoing abdominal and

vascular surgery are at increased risk. Even minor episodes of hypotension in these patients can cause serious perioperative complications¹³. Several observational studies have demonstrated that intraoperative hypotension is associated with serious perioperative complications. Walsh et al. demonstrated that patients with a mean arterial pressure of less than 65 mmHg during surgery have an increased risk of myocardial injury in the postoperative period¹³. Similarly, another study by Sun et al., demonstrated that hypotension during surgery increases the risk of acute kidney injury in the perioperative period¹⁴. Earlier studies by Shoemaker et al., demonstrated that optimization of oxygen



delivery to supra-normal values in patients at risk during surgery can improve survival¹. Similarly, several other studies have demonstrated that optimization of perioperative hemodynamics improves patient outcome. Significant advancements in perioperative monitoring techniques have greatly enhanced the ability of clinicians to monitor cardiovascular function in patients during surgery. Goal-directed therapy has also been proposed to optimize fluid and vasoactive drug therapy in patients during surgery⁹. This narrative review aims to discuss the current evidence in the pathophysiology of perioperative instability, advancements in monitoring techniques, and strategies to improve perioperative stability in patients at risk during surgery.

2. Method

2.1. Literature Search Strategy

An exhaustive literature search was undertaken to identify existing literature on the evaluation of perioperative hemodynamic monitoring, goal-directed therapy, and intraoperative hypotension in high-risk surgery patients. The literature search included various databases such as PubMed, Scopus, Web of Science, and Google Scholar. The literature search was done from 1988 to 2026 to cover the period from the beginning of the use and exploration of modern hemodynamic monitoring and goal-directed therapy. The search terms were designed by combining the following key words: hemodynamic monitoring; goal-directed therapy; perioperative hypotension; cardiac output; high-risk surgery; fluid responsiveness. Boolean logic operators AND and OR were used to narrow the search. The reference lists of relevant articles were manually checked for the evaluation of additional literature.

2.2. Study Selection

The literature search results were imported to a reference manager tool. Duplicates were removed from the search results. The title and abstract screening were done to select the articles for further evaluation. The articles were assessed for eligibility according to the inclusion and exclusion criteria. The entire selection process was done according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The selection process for the articles from the literature search to the final

selection is shown in Figure 1.

2.3. Inclusion Criteria

The inclusion criteria for selecting relevant studies were: human clinical studies conducted on adult surgical and critically ill patients; clinical studies evaluating perioperative hemodynamic monitoring techniques; clinical studies evaluating goal-directed therapy and fluid management strategies; clinical studies conducted in the form of randomized controlled trials, observational studies, systematic reviews, and meta-analyses; and clinical studies written in English.

2.4. Exclusion Criteria

The exclusion criteria for selecting relevant studies were: clinical studies conducted on animals and laboratory experiments; clinical studies in the form of case reports, editorials, and abstracts presented in conferences without adequate data; clinical studies not related to perioperative hemodynamic monitoring and management; and clinical studies without adequate clinical outcome data.

2.5. Data Extraction

From each of the selected clinical studies, relevant data were extracted and analyzed to find a pattern in perioperative hemodynamic management strategies.

2.6. Study Selection Results

The database search results yielded 265 clinical studies. Of these results, 43 duplicate records were removed. Thus, 222 clinical studies were selected for title and abstract screening. Of these selected records, 142 clinical study records were excluded due to irrelevance to perioperative hemodynamic monitoring. A total of 80 full-text articles were identified as potentially relevant and suitable for retrieval. Of these, a total of 77 were obtained and assessed. Following this, a further 39 articles were excluded as they were deemed to have little clinical relevance or insufficient outcome information. A total of 82 studies were included within this narrative review. The study selection process is depicted by the following flow diagram Shows Figure 1 The PRISMA 2020 flow diagram showing the study selection and inclusion process within this narrative review of perioperative hemodynamic monitoring and goal-directed therapy³²

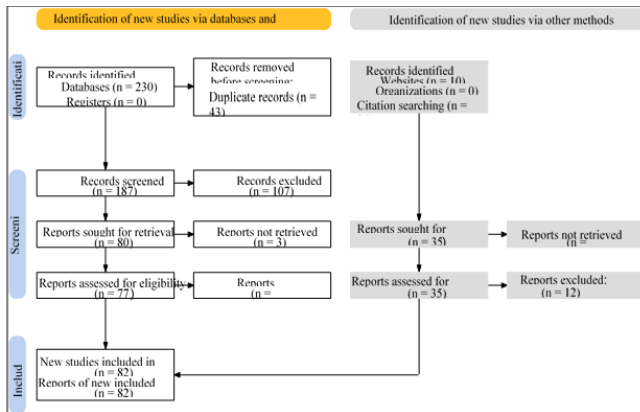


Figure 1 The PRISMA 2020 flow diagram showing the study selection and inclusion process within this narrative review of perioperative hemodynamic monitoring and goal-directed therapy³²

3. Review of Literature

Hemodynamic instability remains one of the major hurdles in the perioperative management of high-risk patients. During the last four decades, various researchers have conducted extensive studies on optimizing the hemodynamic status of high-risk patients with the aim of improving the outcome of the perioperative period. In one of the first studies, Shoemaker et al. demonstrated that supranormal oxygen delivery in high-risk patients can improve survival, thereby promoting the concept of hemodynamic optimization and highlighting the importance of adequate tissue perfusion during the perioperative period. Subsequently, Boyd et al. conducted a randomized clinical trial on the effect of intentional perioperative increases in oxygen delivery, demonstrating that high-risk patients who received hemodynamic therapy had lower mortality compared with conventional therapy. The importance of early hemodynamic optimization was emphasized by Rivers et al., who introduced the concept of early goal-directed therapy in the management of severe sepsis and septic shock, though the focus of the study was on critical care patients. However, the principles of this concept are now applied to perioperative patients. Several meta-analytical studies have also been conducted on the importance of perioperative hemodynamic optimization. Kern and Shoemaker demonstrated that hemodynamic optimization

reduces mortality in high-risk patients, while Hamilton et al. demonstrated that pre-emptive hemodynamic therapy improves outcome and reduces complications. The progress in minimally invasive monitoring techniques has enabled clinicians to improve their ability to optimize intraoperative hemodynamic care. In one study, Wakeling and colleagues demonstrated that fluid management according to oesophageal Doppler monitoring significantly reduced hospital length of stay in patients undergoing major colorectal surgery. Fluid management in surgery is critical and should be tailored to the patient. Subsequent studies have validated the benefits of goal-directed fluid administration. Noblett and colleagues demonstrated that patients undergoing colorectal surgery with fluid administration according to oesophageal Doppler monitoring had enhanced gastrointestinal recovery and fewer complications. Similarly, Pearse and colleagues designed a study, termed the OPTIMISE study, which examined cardiac output-guided perioperative fluid therapy in patients undergoing major gastrointestinal surgery. Although the study had modest findings, it validated the importance of advanced monitoring in perioperative care. Recently, Calvo-Vecino and colleagues designed the FEDORA study, which demonstrated that goal-directed fluid administration in moderate-risk surgical patients had a significant effect in reducing complications. Goal-directed fluid administration in surgery should be tailored to the patient. Several observational studies have investigated the association between intraoperative hypotension and patient outcomes. Walsh and colleagues demonstrated that a mean intraoperative arterial pressure less than 65 mmHg had a strong association with myocardial damage in patients undergoing surgery. Similarly, Sun and colleagues demonstrated that patients with prolonged hypotension had a higher risk of acute kidney injury. Subsequent studies have validated the association between intraoperative hypotension and patient outcome. Salmasi and colleagues demonstrated that intraoperative hypotension independently predicted patient organ damage. Similarly, Wesselink and colleagues demonstrated that intraoperative hypotension had a significant effect in increasing



morbidity and mortality in patients undergoing surgery. The use of dynamic hemodynamic monitoring techniques has improved the capacity to assess fluid responsiveness. Michard and Teboul showed that dynamic parameters, such as pulse pressure variation, have been found to have a higher capacity to predict fluid responsiveness in critically ill patients when compared to static parameters¹⁹. In a similar study, Marik et al. showed that dynamic arterial waveforms can reliably predict fluid responsiveness in mechanically ventilated patients²⁰. Recent breakthroughs in artificial intelligence and predictive monitoring systems have significantly impacted perioperative hemodynamic management. Hatib et al. showed that a machine learning algorithm can predict hypotension in the perioperative period based on arterial pressure waveforms²⁷. In a similar study, Wijnberge et al. and Maheshwari et al. showed that predictive monitoring systems can reduce the

occurrence of hypotension in the perioperative period^{28,29}. In addition, the use of contemporary hemodynamic monitoring techniques, including pulse contour technology and bio-reactance technology, can continuously measure cardiac output. Saugel et al. showed that advanced hemodynamic monitoring plays a critical role in improving perioperative outcomes in critically ill patients⁵. In conclusion, the literature robustly supports the use of advanced hemodynamic monitoring techniques in the perioperative period to improve patient outcomes in high-risk surgical patients. Several randomized trials and observational studies have investigated the role of perioperative hemodynamic and goal directed therapy. The characteristics of key studies included in this review are summarized in Table 1 and Table 2.

Table 1 characteristics of key studies included in the review

Author (Year)	Study Design	Population	Intervention / Monitoring Method	Main Findings	Author (Year)
Shoemaker et al. (1988)	Randomized trial	High-risk surgery patients	Oxygen delivery optimization	Improved survival	Shoemaker et al. (1988)
Boyd et al. (1993)	Randomized trial	High-risk surgery patients	Increased peri-operative oxygen delivery	Reduced mortality	Boyd et al. (1993)
Author (Year)	Study Design	Population	Intervention / Monitoring Method	Main Findings	Author (Year)
Shoemaker et al. (1988)	Randomized trial	High-risk surgery patients	Oxygen delivery optimization	Improved survival	Shoemaker et al. (1988)

Table 2 characteristics of key studies included in the review

Rivers et al. (2001)	Randomized trial	Septic shock patients	Early goal-directed therapy	Reduced mortality
Wakeling et al. (2005)	RCT	Colorectal surgery patients	Doppler-guided fluid therapy	Reduced hospital stay
Noblett et al. (2006)	RCT	Colorectal surgery patients	Goal-directed therapy	Improved recovery
Pearse et al. (2014)	Multicenter RCT	GI surgery patients	CO-guided therapy	Reduced complications
Calvo-Vecino et al. (2018)	RCT	Moderate-risk surgery patients	Hemodynamic GDT	Reduced complications

Table 3 characteristics of key studies included in the review

Author (Year)	Study Design	Population	Intervention / Monitoring Method	Main Findings
Ackland et al. (2020)	Observational study	High-risk Surgical patients	Machine learning prediction models	Improved risk stratification
Salmasi et al. (2017)	Observational study	High-risk Non-cardiac surgery patients	Intraoperative hypotension analysis	Hypotension linked to organ injury
Hatib et al. (2018)	Prospective study	High-risk Surgical patients	Hypotension Prediction Index	Machine learning predicts hypotension

4. Pathophysiology of Hemodynamic Instability

Stability in hemodynamics is determined by the interplay among cardiac output, systemic vascular resistance, and blood volume. The cardiac output is determined by heart rate and stroke volume, while stroke volume is determined by preload, afterload, and contractility²⁵. Preload refers to the end-diastolic

volume, which is determined by blood volume and venous return. Afterload refers to the resistance that the heart must overcome to pump blood out, which is determined by systemic vascular resistance. Contractility refers to the intrinsic ability of the myocardium to contract. Tissue perfusion is dependent on an adequate supply of oxygen, which



can be expressed as follows; $DO_2 = \text{Cardiac Output} \times \text{Arterial Oxygen Content}$ A decrease in any of these values can lead to tissue hypoxia, which can cause organ dysfunction. There are a number of perioperative factors that can lead to instability in hemodynamics. The anaesthetic agents used can cause vasodilation and depression of the heart, leading to decreased systemic vascular resistance and cardiac output. Blood loss can lead to decreased blood volume, leading to decreased preload. Mechanical ventilation can cause an increase in intrathoracic pressure, leading to decreased venous return.

4.1. Hemodynamic monitoring techniques

Table 3 Dynamic indicators of fluid responsiveness

Parameter	Threshold	Clinical Application
Stroke volume variation (SVV)	>13%	Predicts fluid responsiveness
Pulse pressure variation (PPV)	>12%	Used during mechanical ventilation
Pressure leg raising test	Increase in CO	Predicts fluid responsiveness

The basic intraoperative monitoring techniques include electrocardiography, non-invasive blood pressure monitoring, pulse oximetry, and capnography. Although these monitoring techniques are vital for patient monitoring, they might not be effective in monitoring hemodynamic changes in patients at high risk of perioperative complications. Invasive Monitoring. The invasive technique of monitoring arterial blood pressure provides accurate monitoring of arterial pressure. This technique also enables the monitoring of arterial blood gases. This technique of monitoring is particularly beneficial for patients who undergo major surgeries and those suffering from cardiovascular diseases²⁶. The use of central venous pressure monitoring was initially considered to be beneficial for assessing fluid volume status. However, studies have shown that central venous pressure does not accurately predict fluid volume status. Pulmonary artery catheterization provides accurate information regarding cardiac

output, pulmonary artery pressure, and mixed venous saturation. Although this technique of monitoring provides accurate hemodynamic parameters, it has lost favour due to potential complications. Minimally Invasive Monitoring Minimally invasive monitoring of cardiac output has become popular. The monitoring techniques include oesophageal Doppler monitoring and pulse contour analysis monitoring. The technique of using an oesophageal Doppler monitor estimates stroke volume using the descending aorta⁵. Pulse contour analysis monitoring uses arterial pressure waveforms to obtain accurate hemodynamic parameters. This technique of monitoring provides accurate hemodynamic parameters and has become popular for use in goal-directed therapy. Non-Invasive Monitoring Advances in technology have enabled the development of non-invasive hemodynamic monitoring techniques. The non-invasive monitoring techniques include thoracic bioimpedance, bioreactance, and finger cuff monitoring of arterial pressure. The advantages of non-invasive monitoring are the accurate monitoring of hemodynamic parameters and the absence of potential complications.⁶

4.2. Dynamic Parameters for Fluid Responsiveness

Static parameters such as central venous pressure and pulmonary artery occlusive pressure have limited ability in predicting fluid responsiveness. Dynamic parameters based on cardiopulmonary interaction during mechanical ventilation offer more accurate predictions for fluid responsiveness. These include stroke volume variation, pulse pressure variation, and passive leg raising (shown in table 3). These parameters are based on variations in stroke volume or pulse pressure during the respiration cycle due to variations in intrathoracic pressures during mechanical ventilation. Passive Leg Raising Test: This is a reversible maneuver that increases venous return. An increase in cardiac output during passive leg raising is a good indicator of fluid responsiveness.



4.3.Goal-Directed Hemodynamic Therapy

Goal-directed therapy is defined as the use of advanced hemodynamic monitoring for guiding fluid resuscitation and vasopressor therapy in order to optimize tissue oxygen delivery. Several randomized trials have proved the benefits of using goal-directed therapy in high-risk surgical patients. A trial by Wakeling et al. proved that fluid resuscitation using Doppler-guided therapy significantly reduced hospital length of stay in patients undergoing colorectal surgery. Similarly, Noblett et al. proved that fluid resuscitation using Doppler-guided therapy significantly improved patient recovery and

minimized complications in patients undergoing colorectal surgery. Large-scale trials such as the OPTIMISE trial evaluated cardiac output-guided hemodynamic therapy in patients undergoing major gastrointestinal surgery. These trials proved that hemodynamic therapy significantly minimized complications in patients. Meta-analyses have proved that hemodynamic resuscitation in the perioperative period significantly minimizes complications in patients. Several randomized clinical trials have demonstrated the benefits of GDT in improving postoperative outcomes (shown in Table 4).

Table 4 Major clinical trials on Goal-Directed Therapy

Study	Year	Population	Intervention	Outcome
Wakeling et al	2005	Colorectal surgery	Doppler-guided therapy	Reduced LOS
Noblett et al	2006	Colorectal surgery	GDT	Reduced complications
Pearse et al	2014	GI surgery	CO-guided therapy	Reduced complications
Calvo-Vecino et al	2018	Moderate risk surgery	Hemodynamic GDT	Reduced postoperative complications

4.4.Prevention of Perioperative Hypotension

Perioperative hypotension is considered to be a condition in which mean arterial pressure falls to less than 65 mmHg. It is known that intraoperative hypotension is associated with a high risk of postoperative complications such as myocardial injury, acute kidney injury, and stroke. Studies by Walsh et al. have shown that even transient episodes of hypotension are associated with increased morbidity in the postoperative period. Other studies by Sun et al. have shown that prolonged episodes of hypotension have increased the risk of acute kidney

injury in the postoperative period. Preventive measures include optimizing volume status prior to surgery, using anaesthetic agents cautiously, and using vasopressors appropriately.

4.5.Emerging Technologies and Artificial Intelligence

Recent advances in artificial intelligence have enabled the development of predictive algorithms that have the capability to predict early warning signs of impending hypotension. In this regard, Hatib et al. have developed a predictive tool known as the Hypotension Prediction Index, which uses arterial



pressure waveform data to predict impending episodes of hypotension. Studies have shown that predictive monitoring systems have reduced the duration and severity of intraoperative hypotension, which is a significant improvement in monitoring techniques used in the perioperative period.

5. Results and discussion

This narrative review integrates findings from eighty-two studies that examined perioperative hemodynamic monitoring strategies, goal-directed therapy, and the effects of hypotension. Overall, the findings of all the studies, including randomized controlled trials, observational studies, and meta-analyses, show that advanced perioperative hemodynamic monitoring can result in improved outcomes in high-risk surgical patients.

5.1. Impact of Hemodynamic Instability on Surgical Outcomes

Hemodynamic instability in the perioperative period remains a major contributor to postoperative complications. Various observational studies have shown that transient hypotension in the perioperative period can result in significant organ dysfunction. Walsh et al. showed that there was a strong correlation between intraoperative mean arterial pressure (MAP) levels below 65 mmHg and postoperative myocardial injury in non-cardiac surgery patients. In another study, Sun et al. showed that transient hypotension can result in significant postoperative acute kidney injury (AKI). Another study by Salmasi et al. showed that hypotension in the perioperative period can result in postoperative organ injury. In this study, it was also shown that the duration and severity of hypotension can result in organ injury. A systematic review done by Wesselink et al. to assess the relationship between hypotension and postoperative complications also showed that sustained hypotension in the perioperative period can result in postoperative organ injury. The pathophysiology of postoperative organ injury in hypotension involves inadequate tissue oxygen delivery. When the blood pressure drops below the autoregulatory threshold in essential organs, there will be inadequate oxygen delivery to the tissues. This results in tissue hypoxia, leading to organ injury. This effect of hypotension will be more pronounced

in organs that have high oxygen demand, like the kidneys and heart.

5.2. Effectiveness of Goal-Directed Therapy

Goal-directed therapy (GDT) has emerged as one of the most important methods for maintaining perioperative hemodynamic stability. It involves using advanced hemodynamic monitoring for directing fluid and drug therapy based on real-time cardiovascular data. In one of the first studies conducted by Shoemaker et al. on high-risk surgical patients, oxygen delivery in supranormal quantities significantly improved patient survival. This formed the basis for hemodynamic optimization, which is now included in GDT protocols. In a more recent randomized controlled trial by Wakeling et al. on patients undergoing colorectal surgery, GDT significantly decreased hospital length of stay. They concluded that individualized fluid therapy based on optimized stroke volume using Doppler monitoring improved patient recovery. In another similar study conducted by Noblett et al. on patients undergoing colorectal surgery, a randomized clinical trial on Doppler-guided fluid therapy in colorectal surgery revealed improved patient outcomes in terms of gastrointestinal recovery and decreased complications in patients undergoing colorectal surgery using conventional fluid therapy. In yet another randomized controlled trial conducted by Pearse et al. on patients undergoing major gastrointestinal surgery, the OPTIMISE trial assessed cardiac output-guided perioperative hemodynamic therapy. Although complications were not significantly decreased, this trial suggested some benefits for high-risk patients. In a more recent randomized controlled trial conducted by Calvo-Vecino et al. on moderate-risk surgical patients, the FEDORA trial assessed goal-directed hemodynamic therapy. They concluded that moderate-risk surgical patients undergoing goal-directed therapy had significantly fewer complications than those in the standard care group. In a systematic review conducted by Hamilton et al. on perioperative hemodynamic optimization in patients undergoing major abdominal surgery, they concluded that perioperative hemodynamic optimization significantly decreased complications and hospital



length of stay. In another systematic review conducted by Giglio et al. on patients undergoing abdominal surgery, they concluded that goal-directed therapy significantly improved patient outcomes by optimizing tissue perfusion.

5.3. Advancements in Hemodynamic Monitoring Technologies

Advances in monitoring technologies have greatly improved perioperative hemodynamic management. Conventional monitoring techniques, such as non-invasive blood pressure monitoring and central venous pressure monitoring, provide limited information on the cardiovascular system. Modern monitoring techniques allow for continuous monitoring of cardiac output, stroke volume, and fluid responses. Pulse contour analysis monitoring systems interpret arterial pressure waveforms to provide estimates of cardiac output and stroke volume variation. Another monitoring technique used to monitor cardiac output and stroke volume is the oesophageal Doppler monitoring technique. In the study done by Wakeling et al., fluid administration guided by Doppler monitoring was associated with improved outcomes in patients undergoing colorectal surgery⁵. In recent years, non-invasive monitoring techniques such as bioreactance and bioimpedance have become prominent. The techniques use electrical signals to provide estimates of cardiac output. Saugel et al. emphasized the significance of advanced hemodynamic monitoring techniques in improving perioperative patient outcomes⁵. Continuous non-invasive arterial pressure monitoring systems are used to provide continuous non-invasive monitoring of blood pressure. Maheshwari et al. reported that continuous non-invasive blood pressure monitoring improved the detection of hypotensive episodes⁵. These technologies provide clinicians with valuable information to facilitate the timely detection of circulatory instability.

5.4. Dynamic Indicators of Fluid Responsiveness

Static indicators of fluid responsiveness, such as central venous pressure (CVP) and pulmonary artery occlusion pressure (PAOP), have been shown to have poor predictive values in determining fluid

responsiveness. Various studies have shown that CVP and PAOP do not reliably predict fluid responsiveness. Dynamic indicators of fluid responsiveness, which result from cardiopulmonary interactions during mechanical ventilation, have been shown to provide more reliable predictions of fluid responsiveness. Michard and Teboul showed that pulse pressure variation provides a reliable prediction of fluid responsiveness in critically ill patients¹⁹. Marik et al., also showed that dynamic indicators of fluid responsiveness, such as stroke volume variation, have been shown to provide more reliable predictions of fluid responsiveness compared to static indicators. These parameters result from the effects of mechanical ventilation²⁰. The passive leg raising (PLR) test has also been shown to provide reliable predictions of fluid responsiveness. Monnet and Teboul showed that PLR provides a reliable and reversible method of determining fluid responsiveness without the use of intravenous fluids²³. Dynamic indicators of fluid responsiveness provide clinicians with the means to assess whether fluid therapy will result in increased cardiac output, thus preventing fluid overload and its complications.

5.5. Artificial Intelligence and Predictive Monitoring

Recent developments in the field of artificial intelligence and machine learning have enabled new ways of predicting hemodynamic instability before its actual occurrence. Machine learning technology uses physiological data to identify patterns that signal the onset of hypotension. Hatib and his team designed the Hypotension Prediction Index (HPI) to use features of arterial pressure waveforms to forecast hypotension before its actual occurrence. The team showed that the algorithm was capable of predicting hypotension before the actual event of clinically significant hypotension²⁷. Recent clinical trials have been conducted to test the effectiveness of predictive monitoring systems to prevent intraoperative hypotension. Wijnberge and his team showed that using early warning systems based on machine learning technology significantly reduced hypotension during surgeries²⁸. Another study done by Maheshwari and his team aimed to show the effectiveness of the Hypotension Prediction Index to



prevent hypotension during surgeries. The results of the study suggested that predictive monitoring might be effective in preventing hypotension and might allow surgeons to take timely action to prevent further hemodynamic compromise. Artificial intelligence-based monitoring systems might be the future of monitoring hemodynamics during surgeries, as these systems might be capable of providing personalized recommendations for patient care using physiological monitoring.

6. Clinical Implications

The findings of the review underscore the significance of maintaining hemodynamic stability during surgeries, especially in high-risk surgical patients. Current developments in the practice of anaesthesia involve the use of modern monitoring techniques to ensure tissue perfusion and adequate delivery of oxygen to tissues. The clinical implications of the review findings are multifarious. The most important of these is the use of goal-directed therapy (GDT) to ensure improved outcomes for patients. Several studies using an RCT design have shown that GDT improves outcomes for patients. Studies conducted by Wakeling et al., and Noblett et al. showed that the use of fluid administration guided by Doppler improved outcomes for patients who underwent colorectal surgery. The studies support the use of individualized hemodynamic management as an integral component of the management of patients who are at risk of developing complications. Another significant implication of this aspect is in the early detection and prevention of intraoperative hypotension. Previous studies have shown that hypotension is associated with increased risks of postoperative complications such as myocardial injury, acute kidney injury, and increased mortality rates. Walsh et al., in their study, showed that a mean arterial pressure of less than 65 mmHg was associated with increased myocardial injury after surgery. Additionally, Sun et al., in their study, showed that prolonged hypotension increased the risk of acute kidney injury. Technological developments in hemodynamic monitoring have greatly improved clinicians' abilities in the early detection of circulatory instability. Minimally invasive technologies such as pulse contour and

oesophageal Doppler monitoring provide clinicians with information regarding fluid responsiveness, thus improving their abilities in providing appropriate fluid administration. Non-invasive technologies such as bioreactance and finger cuff technologies have greatly improved clinicians' abilities in providing appropriate care to patients in the perioperative period by improving access to continuous hemodynamic monitoring technologies. Saugel et al. emphasized the importance of advanced hemodynamic monitoring systems in improving patient outcomes in the perioperative period. These technologies have improved clinicians' abilities in the early detection of hemodynamic instability and in providing appropriate interventions in a timely manner. Yet another clinical application that is in the process of being utilized is the incorporation of predictive monitoring systems, which use artificial intelligence. Machine learning algorithms can be used to analyze physiological data to predict hypotension before it occurs. A study by Hatib and colleagues presented the concept of the Hypotension Prediction Index, which can be used to analyze arterial pressure waveforms to detect early signs of impending hypotension. Clinical studies that have been done to evaluate the use of predictive monitoring systems have been able to reduce the severity and duration of intraoperative hypotension. If we look at the bigger picture, it is also imperative to realize that the importance of multidisciplinary perioperative care should be emphasized. Anesthesiologists, surgeons, and intensivists should work in harmony to deliver optimal care to patients. Therefore, it can be safely concluded that the use of advanced monitoring technologies, goal-directed therapy, and predictive algorithms represents a major step forward in the development of personalized perioperative medicine.

7. Limitations of the Review

Although considerable progress has been made in perioperative hemodynamic monitoring and management, as described in this review, several limitations need to be acknowledged. First, the studies included in the current review have considerable variability in patient groups, surgical procedures, and monitoring techniques. For instance,



some studies have investigated patients undergoing abdominal surgery, while others have included cardiac or orthopedic surgery patients. Such variability in patient groups and surgical procedures may affect the outcome of perioperative care in terms of patient responses to surgery and surgical procedures. Second, there is no clear definition of intraoperative hypotension. Although several studies have investigated patients with hypotension defined as a blood pressure of less than 65 mmHg or a drop in blood pressure compared to baseline, no clear definition has been agreed upon. Such variability in definition may affect the outcome of studies and may not allow easy comparison of study findings. Third, even though several studies have investigated the effect of goal-directed therapy in patients undergoing surgery, most studies have included small numbers of patients. Large numbers of patients need to be included in future studies to confirm the benefits of individualized perioperative care in patients undergoing surgery. Another limitation of the current review is that several monitoring devices have been introduced in recent years, and their long-term outcomes have not been established. Several monitoring devices have been introduced in recent years, and their cost-effectiveness in patient care needs to be established. Although the current review is not a systematic review, the findings need to be interpreted in the context of a qualitative analysis.

8. Future Directions

Future perioperative hemodynamic management studies are likely to focus on developing personalized monitoring and therapeutic techniques. Advances in artificial intelligence and machine learning are also expected to play a significant role in improving perioperative monitoring systems. For instance, predictive monitoring systems such as the Hypotension Prediction Index represent a major leap in proactive perioperative hemodynamic management. By analyzing vast datasets of physiological signals, machine learning algorithms are able to identify patterns that predict impending hypotension, thereby providing clinicians with timely warnings before significant falls in blood pressure occur. Another important innovation in perioperative hemodynamic management is the use of closed-loop

systems for hemodynamic management. These systems automatically adjust fluids and vasopressor use based on continuous hemodynamic monitoring, thereby freeing clinicians from this burden and providing more accurate patient management. Furthermore, future perioperative hemodynamic management studies could focus on developing personalized anaesthesia techniques based on patient-specific factors such as age, comorbid conditions, and baseline cardiovascular function. Such personalized perioperative hemodynamic management could ensure optimal tissue oxygenation without increasing complications from excessive fluids and vasopressor use. Further studies are required to determine the efficacy of these novel technologies, which are still in the process of development.

Conclusion

Hemodynamic stability is an important predictor of patient outcomes in high-risk surgery patients. Studies have proven that the application of advanced hemodynamic monitoring technologies and goal-directed therapy strategies improves patient outcomes in surgical patients. It is crucial to identify and control intraoperative hypotension to reduce the complications that develop after surgery, such as myocardial injury and acute kidney injury. The application of advanced minimally invasive technology and artificial intelligence-based predictive systems has greatly helped clinicians identify any abnormality in patient hemodynamics. The application of advanced hemodynamic monitoring technology, personalized therapy, and predictive systems represents an important milestone in the development of personalized patient care. Further studies are required to improve patient outcomes using advanced technology.

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