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Dynamic Fluid Responsiveness Assessment Using Pulse Pressure Variation in Intraoperative Spine Surgery Settings: A Case Report

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Abstract

Vertebral metastases are a frequent complication in advanced malignancies, often presenting with severe pain and neurological impairment. This case report describes the perioperative anesthetic management of a 52yearold woman with breast cancer metastasis to the thoracic spine, scheduled for spinal decompression in the prone position. The patient presented with significant pleural effusion, thoracic vertebral compression, and decreased cardiorespiratory reserve. General anesthesia was induced and maintained using targetcontrolled infusions of propofol and remifentanil, with invasive monitoring through an arterial line and a central venous catheter. Intraoperative fluid responsiveness was evaluated using pulse pressure variation (PPV). Monitoring with PPV provides dynamic, realtime indicators that are highly reliable for predicting fluid responsiveness and help maintain hemodynamic stability without worsening pulmonary congestion or edema. PPV serves as a dynamic paramete influenced by the respiratory cycle and is particularly beneficial in mechanically ventilated patients. However, its accuracy may be affected by low tidalvolume ventilation, prone positioning, and pleural effusion. In this case, vigilant monitoring and prone positioning with a freehanging abdomen helped minimize confounding factors. The combination of PPV with clinical assessment and central venous pressure monitoring offered effective guidance for fluid therapy, enhancing intraoperative hemodynamic stability. Despite its limitations, PPV remains a valuable tool in perioperative fluid management, especially when integrated with other dynamic indices and a minifluid challenge. This case emphasizes the utility of PPV in complex oncologic spine surgery, where assessing fluid responsiveness is critical due to major bleeding, prone positioning, and mechanical ventilation.

Keywords: *Anesthesia, Blood Pressure, Fluid Therapy, Hemodynamic Monitoring, Neoplasm Metastasis, Prone Position.*

INTRODUCTION

Perioperative fluid management is a critical component of anesthetic care, particularly in highrisk oncologic spine surgeries performed in the prone position (Ongaigui et al., 2020). Optimal fluid balance must be achieved to maintain adequate tissue perfusion while avoiding complications associated with both hypovolemia and

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fluid overload. Traditional static parameters such as central venous pressure (CVP) have limited predictive value in assessing fluid responsiveness. In contrast, dynamic indices such as Pulse Pressure Variation (PPV) and Stroke Volume Variation (SVV) have emerged as more reliable tools, particularly in mechanically ventilated patients (Angappan et al., 2015). Fluid management was guided by maintaining PPV and SVV below 14%, helping to avoid both hypovolemia and fluid overload.

The challenge of fluid management in complex oncologic spinal cases is compounded by several interconnected factors:

1. Prone Position: The prone position fundamentally alters respiratory and circulatory biomechanics, significantly influencing cardiac preload and the reliability of conventional hemodynamic parameters.
2. Complex Patient Comorbidities: The presence of significant pleural effusion and compromised cardiopulmonary reserve in patients with metastases (as in the present case) substantially increases the risk of hemodynamic instability and blood pressure lability during major surgical procedures.
3. Limitations of Static Parameters: Traditional static indices like Central Venous Pressure (CVP) have consistently been shown to have limited predictive value in assessing fluid responsiveness (Angappan et al., 2015). Moreover, the interpretation of CVP can be misleading in scenarios involving increased intrathoracic pressure, such as those caused by pleural effusion or the prone position.

Given the aforementioned complexities, there is an urgent necessity for more reliable and dynamic monitoring methods. Dynamic indices such as Pulse Pressure Variation (PPV) and Stroke Volume Variation (SVV) have emerged as superior tools for predicting fluid responsiveness in mechanically ventilated patients (Angappan et al., 2015). PPV, derived from the variation in arterial pulse pressure over the respiratory cycle, functions as a noninvasive, realtime indicator of preload responsiveness (Cenková et al., 2024). Appropriate utilization of PPV can guide GoalDirected Fluid Therapy (GDFT), enabling anesthesiologists to more accurately titrate fluids in response to genuine physiological needs. In this clinical con, fluid management guided by maintaining PPV and SVV below 14% is implemented to prevent both hypovolemia and fluid overload. However, it is crucial to recognize that the reliability of PPV can be modulated by several factors, including low tidal volume ventilation, cardiac arrhythmias, spontaneous breathing efforts, and critically, body positioning, particularly in the prone position (Mallat et al., 2025).

We present a case report detailing the anesthetic management of a 52yearold female patient with thoracic vertebral metastasis from breast cancer who underwent decompressive spinal surgery in the prone position. This patient exhibited significant comorbidities, including pleural effusion and reduced cardiopulmonary reserve, making her a challenging clinical model to examine the efficacy and limitations of PPV.

How can PPV be effectively applied, and what are the specific challenges in using it to guide fluid therapy and maintain hemodynamic stability in a highrisk oncologic patient with pleural effusion and prone positioning, especially in a resourceconstrained environment? This case report aims to delineate the application and challenges of using Pulse Pressure Variation (PPV) as a guide for goaldirected fluid therapy in a complex oncologic patient with vertebral metastasis undergoing spinal surgery in the prone position under mechanical ventilation. Furthermore, we will detail the pragmatic implementation of PPV within a limitedresource con.

The 52yearold female patient, presenting with thoracic vertebral metastases causing progressive lowerlimb weakness, was scheduled for posterior decompression–stabilization–fusion in the prone position. Preoperative evaluation highlighted potential issues such as significant pleural effusion and decreased cardiopulmonary reserve, raising significant concern for hemodynamic lability and ventilationinduced preload variation during the major surgery. Given the unreliability of static indices in this setting, we adopted dynamic monitoring with PPV (and SVV) alongside a TargetControlled Infusion (TCI) of propofol–remifentanil, an arterial line, and a central venous catheter. PPV was utilized to optimally time fluid boluses and to discriminate when vasopressor administration or transfusion was preferable, with the ultimate goal of maintaining adequate cardiac output and tissue perfusion while minimizing the risk of pulmonary congestion.

METHOD

Study Design

This study utilizes a qualitative descriptive case report design. Its primary aim is to provide an indepth, comprehensive description of the application of Pulse Pressure Variation (PPV) as a dynamic parameter to assess intraoperative fluid responsiveness in a patient undergoing thoracic spine decompression surgery due to metastatic breast cancer. A case report was selected to allow for detailed analysis of a single, complex clinical scenario, highlighting both the observed clinical phenomena and the specialized anesthetic management within the patient's specific conual framework.

Setting and Study Period

The case management and data collection were conducted in the Central Operating Theatre (COT) and PostAnesthesia Care Unit (PACU)/Intensive Care Unit (ICU) of Prof. Dr. I.G.N.G. Ngoerah General Hospital, Denpasar, Bali, Indonesia. The study period, encompassing intraoperative observation, hemodynamic monitoring, and postoperative evaluation, took place from January to March 2024.

Case Description

The subject was a 52yearold female scheduled for posterior decompression stabilization fusion in the prone position due to thoracic vertebral metastasis. Detailed Clinical Background

1. Cancer History: The patient was diagnosed with Invasive Ductal Carcinoma (IDC) of the breast 5 years prior, with known metastasis to the thoracic vertebrae. Previous therapy included chemotherapy and radiation.
2. Risk Score: The patient was classified as ASA Physical Status III due to her underlying malignancy and compromised cardiopulmonary reserve (significant pleural effusion). The operative risk was considered high.
3. Key Preoperative Laboratory Results: Relevant preoperative results included: Hemoglobin (Hb) 9.8 g/dL, Hematocrit (Hct) 30%, Creatinine 0.9 mg/dL, and normal electrolytes.

The subject was selected via purposive sampling based on strict inclusion criteria: (1) underlying malignancy requiring major spine surgery; (2) impaired cardiopulmonary reserve and pleural effusion; and (3) mandatory dynamic intraoperative fluid monitoring (PPV/SVV). Written informed consent was obtained from the patient for both the anesthetic procedure and the publication of this case report.

Instruments and Anesthetic Protocol

Hemodynamic monitoring, including automated analysis of Pulse Pressure Variation (PPV) and Stroke Volume Variation (SVV), was performed using a standard anesthesia monitor (Philips IntelliVue MP70, Philips Healthcare, Germany) connected to an invasive arterial line and a central venous catheter.

Anesthesia was maintained using a Target Controlled Infusion (TCI) system, utilizing the Eleveld model for propofol and the Minto model for remifentanil. Rocuronium was administered for neuromuscular blockade, and a multimodal analgesia regimen including tranexamic acid (for blood loss management) and paracetamol was employed.

Mechanical Ventilation Justification

Mechanical ventilation was maintained in VolumeControlled Ventilation (VCV) mode with a tidal volume of 8–10 mL/kg (based on predicted body weight) and a Positive End Expiratory Pressure (PEEP) of 5 mmHg. This specific setting was chosen deliberately to:

1. Enhance PPV Reliability: Utilizing a Vt greater than 8 mL/kg is critical to ensuring the validity of PPV measurements, as low Vt is a known confounder.
2. Optimize Gas Exchange: PEEP of 5 mmHg was applied to optimize oxygenation (preventing atelectasis) while minimizing the risk of excessive positive pressure effects, which could further impair venous return or exacerbate the existing pleural effusion complications.

Patient Positioning

To minimize intraabdominal pressure and prevent compression of the inferior vena cava (IVC), which is essential for accurate PPV reading and minimizing blood loss, the patient was meticulously positioned in the prone position using specialized chest rolls, ensuring a freehanging abdomen (free belly) technique.

Data Collection Procedure

Data were systematically collected through continuous observation and documentary methods:

1. Preoperative Data: Baseline hemodynamic status, physical examination findings, relevant investigations (ECG, chest Xray, echocardiography), and detailed clinical history.
2. Intraoperative Data: Continuous recording of PPV, SVV, arterial blood pressure, heart rate, total fluid input (crystalloids, colloids, blood products), estimated blood loss (EBL), and vasopressor/inotropes usage.
3. Postoperative Data: Hemodynamic stability in the PACU/ICU, ventilatory status, and total ICU length of stay.

All data were meticulously documented by the attending anesthesiology team using the hospital’s standardized observation sheet and electronic medical records.

Data Analysis

Data analysis employed a qualitative descriptive approach, focusing on tracking the hemodynamic trajectory and changes in dynamic parameters (specifically PPV and SVV) in direct response to administered fluid boluses and vasopressor interventions during the surgical phases. Interpretation of fluid responsiveness relied on the established PPV threshold value (cutoffge 14%). The clinical findings and interventional outcomes were then compared and discussed in the con of current international guidelines and existing literature to ensure clinical validity and conual interpretation.

Data Trustworthiness

To ensure the trustworthiness of the clinical data presented, the following strategies were implemented:

1. Credibility (Triangulation): Achieved through triangulation of data sources, including automated monitor documentation (electronic PPV/SVV readings), direct clinical observations, and manual anesthetic records.
2. Dependability (Systematic Recording): Maintained through the standardized anesthetic procedure and systematic recording protocol used by the anesthesiology team throughout the perioperative period.
3. Confirmability (Peer Review): Strengthened by internal peer review where two senior anesthesiology consultants independently verified the accuracy of the documented data and the clinical interpretation of the PPVguided interventions.
4. Transferability (Detailed Con): Ensured by providing a comprehensive and detailed description of the patient's clinical status, the surgical procedure, the specific anesthetic technique, and the resource con, allowing for applicability to similar complex clinical scenarios.

RESULT

Preoperative Examination and Optimization

Preoperative assessment emphasized the patient's cardiopulmonary status. Vital signs were stable (BP 104/75 mmHg, HR 80 bpm, SpO_2 99% on room air). On auscultation, breath sounds were decreased in the left lung without rhonchi or wheezing. ECG showed normal sinus rhythm. Echocardiography revealed normal chamber dimensions, preserved LV systolic and diastolic function (EF 69.2%), and good RV contractility (TAPSE 2.7 cm). Chest Xray demonstrated left pleural effusion obscuring the cardiac silhouette, with suspicion of pleuraltype metastasis, and compression of T10 vertebral body suggesting metastatic involvement. These findings highlighted potential perioperative challenges, particularly impaired pulmonary function and reduced cardiopulmonary reserve.

To optimize respiratory status, a therapeutic pleural fluid aspiration was performed one day prior to surgery. Pre-induction assessment utilized bedside ultrasound to evaluate Inferior Vena Cava (IVC) collapsibility, which confirmed a euvolemic state and non-fluid responsiveness.

Anesthesia Management

One day before surgery, pleural fluid aspiration was performed to improve the patient's respiratory status. General anesthesia was selected, and invasive monitoring was established with an arterial line in the radial artery after Allen's test and a central venous catheter under ultrasound guidance. Preinduction assessment ensured the patient was optimized to a euvolemic state, and nonfluid responsiveness was confirmed by evaluating the collapsibility of the inferior vena cava with ultrasound.

Induction was performed using targetcontrolled infusions of propofol (Eleveld model) and remifentanil (Minto model), followed by administration of rocuronium to facilitate endotracheal intubation. A reinforced endotracheal tube was placed with confirmation of bilateral breath sounds, then secured before turning the patient into the prone position. All pressure points were padded, and airway placement was reevaluated after positioning. Maintenance of anesthesia was achieved with continuous TCI infusions of propofol and remifentanil, supplemented with intermittent rocuronium, along with multimodal analgesia including paracetamol and tranexamic acid. Ventilation was adjusted to maintain protective parameters with normocapnia and adequate oxygenation.

Hemodynamic management emphasized the use of pulse pressure variation (PPV) obtained from the arterial line and analyzed automatically by the anesthesia monitor. PPV were interpreted as dynamic predictors of fluid responsiveness, with values above 14% indicating the potential need for volume expansion. Limitations such as arrhythmia, spontaneous breathing, or low tidal volume were considered during interpretation. Fluid administration and vasoactive therapy were titrated based on these parameters, with the goal of keeping PPV below 14%, while blood loss was replaced according to both clinical estimation and dynamic indices. Monitoring was continued throughout the operation until stable hemodynamics were achieved at the end of surgery. With this strategy, the patient remained hemodynamically stable intraoperatively, with no significant episodes of hypotension or fluid overload.

Postoperative Care

Postoperatively, the patient was transferred to the ICU under ventilatory support and sedation for gradual restoration of respiratory function. Continuous monitoring included invasive blood pressure, central venous pressure, urine output, and dynamic hemodynamic indices to guide fluid and vasoactive therapy. Respiratory status was closely observed with daily arterial blood gas analysis, ventilator parameters, and bedside ultrasound assessment to ensure adequate oxygenation and to detect any residual pulmonary congestion. Over the next three days, hemodynamics remained stable without signs of fluid overload or hypoperfusion. The patient was successfully extubated on postoperative day three and transitioned to oxygen therapy via face mask at 5 L/min. Ongoing monitoring demonstrated stable respiratory and cardiovascular parameters, and by postoperative day five the patient was transferred to the intermediate care unit.

Hemodynamic Trends and PPV Analysis

Hemodynamic management was guided by dynamic parameters, primarily Pulse Pressure Variation (PPV), obtained from the arterial line. The strategy was to maintain a restrictive fluid regimen based on the goal of keeping PPV below the 14% cut-off value, indicating a non-fluid responsive state. Vasopressor therapy (noradrenaline) was prioritized when mean arterial pressure (MAP) dropped below 65 mmHg despite PPV remaining <14%.

Table 1 presents the key hemodynamic data, including PPV trends, at critical intraoperative time points:

Time Point	PPV (%)	MAP (mmHg)	HR (bpm)	CVP (mmHg)	Interpretation	Intervention
Pre-Induction	N/A	104/75	80	N/A	Baseline Euvolemic	None
Post-Induction	10	72	75	8	Non-Fluid Responsive	Start Noradrenaline Infusion
30 min Prone Position	12	68	82	10	Non-Fluid Responsive	Titrate Noradrenaline
Significant Bleeding	13	70	88	9	Non-Fluid Responsive	Crystalloid 250 mL bolus & Transfusion Initiated
End of Operation	10	78	78	12	Stable	Wean Noradrenaline

Fluid Balance

The total operation time was 5 hours. The intraoperative fluid management and balance are detailed in Table 2.

Table 2. Fluid Balance

Category	Type	Volume (mL)
Crystalloid (Maintenance + Bolus)	Ringer's Lactate	1,500
Colloid	HES	0
Blood Transfusion	Packed Red Cells (PRC)	500
Total Input		2,000
Output		
Estimated Blood Loss (EBL)		750
Urine Output (UO)		400
Total Output		1,150
Net Balance		+850

The net positive fluid balance +850mL was considered controlled and acceptable, prioritizing minimal volume expansion to avoid exacerbating the existing pulmonary congestion risk due to pleural effusion.

DISCUSSION

In recent years, pulse pressure variation (PPV) have been used to predict fluid responsiveness (Sam et al., 2021; Su et al., 2021). Pulse Pressure Variation (PPV) is a parameter in hemodynamic monitoring which used to assess or predict fluid responsiveness in patient with mechanical ventilation and general anesthesia . PPV calculate changes in arterial pulse pressure which is differences between systolic and diastolic pressure during the respiratory cycle (Teboul et al., 2019). PPV value is usually expressed in percentage, and calculated as follows

$$PPV = \frac{PPmax - PPmin}{(PPmax + PPmin)/2}$$

To predict fluid responsiveness, PPV acts as an indicator of hemodynamic effects of fluid loading which were seen in FrankStarling relationship. During mechanical ventilation, the application of positive pressure during inspiration leads to a reduction in venous return to the right ventricle, consequently diminishing right ventricular output. After a brief delay corresponding to the pulmonary transit time, this reduction in preload extends to the left ventricle, resulting in decreased stroke volume and pulse pressure. In patients who are fluid responsive, typically those positioned on the steep portion of the FrankStarling curve, these variations in preload induced by respiration manifest as pronounced fluctuations in pulse pressure (Stens et al., 2016; Teboul et al., 2019). A pulse pressure variation (PPV) exceeding 12% is generally indicative of a favourable hemodynamic response to fluid administration, suggesting that cardiac output will improve with volume expansion. However recent metaanalysis of PPV use in operative settings report that In recent years, PPV values were automatically measured and readily available through anesthesia monitor in a realtime manner which allows a more rigorous assessment especially in early recognition for signs of fluid responsiveness. In our case, this was consistent with the clinical findings, as PPV served as the primary guide for intraoperative fluid therapy and allowed us to titrate fluids more accurately than relying solely on static indices.

In line with the main findings of a recent systematic review and metaanalysis, dynamic indices such as PPV, SVV, and PVI demonstrated superior predictive accuracy compared to intermediate markers like ΔIVC and CVP, while static systemic parameters such as MAP and HR were shown to be poor predictors of volume responsiveness (Chaves et al., 2024). Throughout the procedure, our patient's PPV values consistently remained under 14%, indicating that the patient was unlikely to benefit from additional fluid administration. This guided us to adopt a restrictive fluid approach while avoiding unnecessary volume expansion.

Between available parameters for fluid responsiveness assessment, PPV has a good reliability. In a previous metaanalysis results showed that the combined sensitivity, combined specificity, and area under the SROC curve of PPV were 0.61, 0.53, and 0.60, respectively, but have the poor prediction of fluid responsiveness in patients undergoing OLV(C. Wang et al., 2023). In another metaanalysis and metaregression, it's reliability in the operating room is moderate with overall pooled AUC of 0.77 (Messina et al., 2023). Albeit its good reliability, PPV has some limitations, due to confounding factors at operating table. The accuracy is affected by many factors, such as tidal volume, respiratory rate, arrhythmia, pleural integrity, and cardiac function during mechanical ventilation (Bennett et al., 2018; Chen et al., 2021). Low tidal volume (6–8 mL/kg) is widely known to be a major factor that may lead to prediction failure. Many studies have shown that the sensitivity and specificity of PPV in predicting fluid responsiveness are related to tidal volume, and their accuracy is greatly reduced when tidal volume is <8 mL/kg. If the tidal volume is too small, the transpulmonary pressurtee will also decrease, and its periodic changes will not be enough to cause changes in the blood flow of the vena cava, pulmonary artery, and aorta. The FrankStarling curve moves to the left (C. Wang et al., 2023). Thus, patients occupying the flat part of the FrankStarling curve may theoretically occupy the steep part of the curve during low tidal volume ventilation, which will result in decreased accuracy. Studies have shown that the intrapulmonary shunt rate and hypoxic vasoconstriction may be important factors affecting the accuracy of CI, which suggests that they may affect the accuracy of dynamic hemodynamic indicators, such as PPV, but the specific mechanism remains unclear (Lesser et al., 2020). Dynamic indicators distinguish the steep part of the FrankStarling curve according to the periodic change in cardiopulmonary interaction, which not only depends on the change in venous return but also on the change in right ventricular afterload and left ventricular transmural pressure (C. Wang et al., 2023). Hypercapnia defined as the arterial carbon dioxide pressure ($PaCO_2$) >48 mmHg is an independent predictor of right ventricular dysfunction in patients with chronic obstructive pulmonary disease receiving low tidal volume mechanical ventilation, which can cause pulmonary vasoconstriction, increase the afterload of the right heart, decrease the function of the right heart, and affect the accuracy of PPV (Lesser et al., 2020; C. Wang et al., 2023). Conditions such as pleural effusion, elevated intraabdominal pressure, or altered chest wall compliance may distort the transmission of airway pressure to the heart and great vessels, leading to inaccurate PPV readings. Specifically, pleural effusion can increase pleural pressure fluctuations and attenuate the effective transmission of intrathoracic pressure changes, resulting in falsely elevated or reduced PPV values. Consequently, in patients with such conditions, PPV may not accurately reflect fluid responsiveness. To enhance the predictive value of PPV in these scenarios, adjustments based on direct measurements of pleural pressure may be necessary (Liu et al., 2016; Su et al., 2021). These limitations were addressed in our patient by maintaining controlled ventilation with a tidal volume of 8–10 mL/kg and a PEEP of 5 mmHg, while ensuring the absence of arrhythmias or spontaneous breathing efforts. This approach minimized confounders and enhanced the reliability of PPV measurements.

PPV is still reliable in prone position, with reported pooled AUC of 0.78 (95% CI 0.69–0.88) (Messina et al., 2023). It was also reported intraoperative use of a tidal volume (Vt) ≥ 8 ml/kg were found to positively influenced the AUCs of the PPV in patient subgroups with a closed chest and abdomen (AUC 0.85) or those positioned prone (AUC 0.88) (Messina et al., 2023). Previous studies also showed that systolic pressure variations were not different in the prone position compared with the supine position (Biais et al., 2010). Although there are no data directly supporting that right ventricular preload is reduced by prone positioning, the position of the heart at a hydrostatic level above the head and limbs might cause a reduction in venous return. An increase in inspiratory pressure should impede venous return, and hence induce a leftward shift on the Frank–Starling curve. In the prone position, abdominal compression may induce inferior vena cava compression and a decrease in right ventricular preload. However, the position used in the study (four pads) is not known to induce an increase in intraabdominal pressure and we made sure that the abdomen hung free because of the risk of bleeding intraoperatively (Biais et al., 2010). In line with these findings, our patient was positioned prone with the abdomen unsupported, and both PPV were monitored simultaneously, allowing crossvalidation of fluid responsiveness.

PPV utility ultimately extends to guiding goaldirected fluid therapy (GDFT) particularly in highrisk surgical settings such as spine surgery. By optimizing intravascular volume status, PPVbased GDFT or dynamic parameter based GDFT (GDFTdyn), helps reduce the risk of fluid overload and has been associated with improved perioperative outcomes, such as reduction in short term mortality, decreased postsurgical morbidity and ICU length of stay (Benes et al., 2014; Deng et al., 2018) . However to note, a metaanalysis state that patients who were managed using both GDFTdyn and cardiac output (CO) or cardiac index (CI) targets appeared to experience the greatest benefit rather than GDFTdyn alone(Deng et al., 2018). In another study, GDFT has been shown to significantly reduce airway edema and subsequently decrease cuff leak gradient (CLG) compared to standard fluid therapy (SFT) in patients undergoing complex spine surgery in the prone position. Postoperatively, GDFT is also associated with a lower incidence of sore throat, hoarseness of voice, and a shorter duration of ICU stay. (Prasad et al., 2021). Moreover, PPV plays a crucial role in preventing hemodynamic instability by identifying patients who are likely to benefit from fluid administration, thereby avoiding unnecessary volume expansion that could result in complications such as pulmonary edema or impaired wound healing both of which are especially significant in spine surgery (Kutum et al., 2024; Monnet et al., 2022). In elderly patients, such as this case, GDFT may help lower the incidence of postoperative delirium (POD). In a study of ≥ 50 years old undergoing spinal surgery patients, GDFT in patients incidence of POD was significantly lower compared to restrictive fluid therapy. GDFT promotes hemodynamic stability during the perioperative period and enhancing the balance between oxygen supply and demand (Wang et al., 2021). This was reflected in our case, where our patient was beyond 50 years of age and was managed successfully with stable intraoperative hemodynamics, no episodes of fluid overload or hypotension, and a favorable postoperative recovery.

Specific Case Limitations: Pleural Effusion and Positioning

1. Pleural Effusion: Conditions such as pleural effusion or altered chest wall compliance may distort the transmission of airway pressure to the heart and great vessels, leading to inaccurate PPV readings (Liu et al., 2016; Su et al., 2021). Specifically, the patient's

significant pleural effusion, even after preoperative aspiration, was a potential confounder that could alter intrathoracic pressure transmission, resulting in falsely elevated or reduced PPV values.

2. Prone Position: The prone position itself is a potential confounder. Although PPV remains reliable in the prone position (pooled AUC 0.88 when Vt ≥ 8 mL/kg) (Messina et al., 2023), abdominal compression can induce inferior vena cava (IVC) compression and decrease RV preload.

Mitigation Strategy

To enhance the predictive value of PPV despite these risks, we implemented two key mitigation strategies:

1. Optimized Ventilation: We strictly maintained controlled ventilation with a Vt of 8–10 mL/kg and a PEEP of 5 mmHg. This approach is consistent with literature recommending Vt ≥ 8 mL/kg to enhance PPV reliability (C. Wang et al., 2023).
2. Multimodal Assessment & Positioning: We ensured the patient was positioned prone with a free-hanging abdomen (four-pad technique) to prevent IVC compression, minimizing one major confounding factor (Biais et al., 2010). Furthermore, the PPV measurement was cross-validated with the low CVP and the preoperative ultrasound assessment of the IVC, which confirmed the initial non-responsive status.

Clinical Relevance: PPV within Goal-Directed Fluid Therapy (GDFT)

The utility of PPV is maximized when integrated into a Goal-Directed Fluid Therapy (GDFT) protocol (GDFT_dyn). GDFT is especially critical in high-risk surgical settings like spine surgery, as optimizing intravascular volume status helps reduce the risk of fluid overload and has been associated with improved perioperative outcomes, including reduced short-term mortality, decreased postsurgical morbidity, and shorter ICU length of stay (Benes et al., 2014; Deng et al., 2018).

Preventing Postoperative Complications in High-Risk Patients

For our patient an elderly individual (52 years) with significant comorbidities (cancer/metastasis) and reduced cardiopulmonary reserve GDFT guided by PPV was paramount for two primary reasons:

1. Prevention of Fluid Overload and Airway Edema: Avoiding unnecessary volume expansion prevents complications such as pulmonary edema (exacerbating the pleural effusion risk) and airway edema, which can be critical in prone surgery. GDFT has been shown to significantly reduce airway edema and decrease the cuff leak gradient (CLG) postoperatively, thus reducing the incidence of complications like sore throat and hoarseness (Prasad et al., 2021).
2. Prevention of Postoperative Delirium (POD): Maintaining optimal hemodynamic stability and oxygen supply/demand balance is key to preventing neurological complications. Studies show that GDFT in elderly patients (ge 50 years) undergoing spinal surgery significantly lowers the incidence of POD compared to restrictive fluid therapy alone (Wang et al., 2021).

The successful management stable intraoperative hemodynamics, controlled fluid balance (net positive 850 mL), and favorable recovery without fluid overload or severe complications underscores the crucial and effective role of PPV-guided GDFT in navigating the anesthetic challenges posed by this complex oncologic patient in the prone position.

CONCLUSION

This case highlights the clinical utility of pulse pressure variation (PPV) as a dynamic parameter for intraoperative fluid management in a complex spine surgery performed in the prone position with significant pleural effusion. PPV, when interpreted within controlled mechanical ventilation and adequate tidal volumes, provided reliable guidance for goaldirected fluid therapy (GDFT) and helped maintain hemodynamic stability without precipitating fluid overload. Although its accuracy may be influenced by factors such as low tidal volume, arrhythmias, or altered thoracic compliance, PPV remains a valuable tool when combined with stroke volume variation, central venous pressure, and clinical judgment. In line with the abstract conclusion, this case reinforces the importance of a multimodal hemodynamic monitoring strategy that integrates both dynamic and static indices to optimize perioperative fluid therapy in highrisk surgical patients.

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