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Review Article

Perioperative Fluid Management Guided by Dynamic Hemodynamic Indicators

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ABSTRACT

Static filling pressures correlate poorly with fluid responsiveness, prompting widespread adoption of dynamic hemodynamic indicators such as stroke volume variation (SVV), pulse pressure variation (PPV), and the plethysmographic variability index (PVI) to guide perioperative fluid administration.

This review synthesizes the physiological basis of these indices, their diagnostic accuracy across surgical settings including cardiac, thoracic, laparoscopic, and orthopedic procedures, and the outcome evidence from goal-directed fluid protocols built around them.

Diagnostic accuracy for SVV and PPV is strong under controlled ventilation with adequate tidal volume and sinus rhythm, but degrades meaningfully with low tidal volume protective ventilation, one-lung ventilation, arrhythmia, and pneumoperitoneum, while PVI offers a noninvasive alternative that is itself confounded by low peripheral perfusion states.

Outcome trials, particularly within enhanced recovery colorectal surgery programs, show that dynamic-index-guided therapy reliably outperforms liberal or unstructured fluid administration but shows less consistent benefit when compared against a well-designed restrictive fluid protocol.

We conclude that dynamic indicators are best applied within their validated physiological preconditions and as an adjunct to, rather than a replacement for, a restrictive-leaning baseline fluid strategy and integrated clinical judgment.

Keywords: *goal-directed fluid therapy; stroke volume variation; pulse pressure variation; plethysmographic variability index; perioperative fluid management*

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INTRODUCTION

Intraoperative fluid therapy has always been something of a moving target. Give too little and organs go under-perfused just when surgical stress is at its peak; give too much and the patient leaves the operating room edematous, with a gut that will not

wake up and lungs that struggle to clear the extra volume. For decades the default answer to this dilemma was a static one: central venous pressure, urine output, or simply a generous crystalloid regimen calculated from body weight and estimated blood loss. The trouble, well documented by now, is that static filling pressures correlate poorly with where a given patient sits on the Frank-Starling curve. A central venous pressure of 8 mmHg means one thing in a stiff, hypertrophied ventricle and something else entirely in a dilated, volume-tolerant one.

Dynamic indices emerged from a simple physiological insight: positive-pressure ventilation cyclically loads and unloads the right and left ventricles, and the resulting swing in stroke volume, pulse pressure, or peripheral plethysmographic waveform amplitude is itself a bedside test of preload responsiveness. Stroke volume variation (SVV) and pulse pressure variation (PPV), most often derived from arterial waveform analysis, and the plethysmographic variability index (PVI), derived from pulse oximetry, all exploit this heart-lung interaction to answer the question that matters clinically: will this patient's stroke volume actually increase if I give this fluid bolus, or am I just adding volume they will have to excrete later. This review surveys the evidence behind these dynamic indicators, where they perform well, where they fail, and how they have been incorporated into goal-directed fluid protocols across different surgical settings.

PHYSIOLOGICAL BASIS AND MEASUREMENT

The mechanism underlying SVV and PPV is heart-lung interaction during mechanical ventilation. Inspiration increases intrathoracic pressure, transiently reducing venous return to the right heart and, a few beats later, left ventricular preload and stroke volume. On a steep portion of the Frank-Starling curve, this translates into a large cyclic swing in stroke volume or pulse pressure; on the flat portion, the swing is minimal regardless of tidal volume. PPV is generally calculated from beat-to-beat pulse pressure over a respiratory cycle, while SVV requires either an arterial pulse-contour algorithm or a separate stroke volume monitor (esophageal Doppler, bioreactance, or pulse-contour cardiac output devices). PVI applies the same logic to the photoplethysmographic waveform obtained from a standard pulse oximeter probe, offering a fully noninvasive alternative, though one that is more sensitive to peripheral vasomotor tone and probe site perfusion [1].

Validity depends on a fairly narrow set of preconditions that are frequently violated in real operating rooms: the patient must be fully mechanically ventilated with a tidal volume generally at or above 8 mL/kg predicted body weight, in sinus rhythm, on a closed chest, without significant right ventricular dysfunction, and without spontaneous breathing efforts competing with the ventilator. Low tidal volume ventilation, now standard in most protective ventilation strategies, blunts the cyclic preload swing and pushes both SVV and PPV toward false-negative territory - a limitation increasingly relevant given how widely lung-protective settings have been adopted intraoperatively [2]. Open-chest surgery, arrhythmias, and increased abdominal pressure during laparoscopy each introduce their own distortions, discussed further below.

DIAGNOSTIC PERFORMANCE ACROSS SURGICAL SETTINGS

The pooled diagnostic accuracy of SVV and PPV for predicting fluid responsiveness has been examined in several recent meta-analyses, and the headline finding across them is consistent: these indices work well as a group, but with substantial heterogeneity that tracks surgical and ventilatory context rather than random noise. A metanalysis and metaregression of studies performed specifically in the operating room found reasonable pooled sensitivity and specificity for both PPV and SVV, but identified tidal volume, use of an open versus closed abdomen, and PEEP as significant sources of between-study variability [3]. A companion critical-care commentary made a related point bluntly - that pooling studies performed under wildly different ventilatory and hemodynamic conditions risks "a few rotten apples spoiling the whole barrel," inflating or deflating the apparent accuracy of the index depending on which populations dominate the pooled estimate [2].

In cardiac and thoracic surgery, SVV's performance is further complicated by the specific perturbations these operations impose. A systematic review restricted to cardiac and thoracic surgical patients found SVV retained acceptable predictive value overall but with attenuated accuracy in settings involving cardiopulmonary bypass, arrhythmia, or altered chest wall mechanics [4]. One-lung ventilation, routine during thoracic surgery, represents perhaps the most challenging derangement: a meta-analysis focused specifically on this setting found that both SVV and PPV lost meaningful diagnostic accuracy once the chest was opened and ventilation shifted to a single lung, likely reflecting the altered thoracic pressure transmission and the frequent use of smaller tidal volumes to protect the ventilated lung [5].

Laparoscopic surgery raises a different confound: pneumoperitoneum itself raises intrathoracic pressure and alters venous return independent of intravascular volume status. A systematic review of dynamic indices in laparoscopic procedures found that SVV and PPV values shift with insufflation pressure and patient positioning (steep Trendelenburg for pelvic laparoscopy, reverse Trendelenburg for upper abdominal procedures), meaning that a single static threshold validated in open surgery cannot be applied uncritically once the abdomen is insufflated [6]. In

broader mechanically ventilated cohorts outside the operating room, a comparative meta-analysis of PPV, SVV, PVI, central venous pressure, and inferior vena cava distensibility found the dynamic indices consistently outperformed static measures, reinforcing that the core physiological argument holds even as the numerical thresholds shift by population [7].

GOAL-DIRECTED PROTOCOLS AND POSTOPERATIVE OUTCOMES

Diagnostic accuracy is only useful if incorporating these indices into a treatment algorithm actually changes what matters to the patient. The strongest early evidence for this came from a landmark multicenter trial in high-risk surgical patients, in which fluid boluses were titrated to a stroke-volume-and-SVV-guided algorithm; the trial demonstrated reduced postoperative complications and shorter hospital stay compared to conventional fluid management, establishing the template that many subsequent protocols followed [8]. Similar SVV-guided protocols in major orthopedic surgery improved measures of splanchnic and gastrointestinal perfusion relative to fixed-volume regimens, consistent with the idea that avoiding both hypovolemia and fluid overload protects mesenteric blood flow during large-volume-shift procedures [9]. In head and neck surgery, where flap perfusion and airway edema make fluid balance especially consequential, an SVV-guided protocol reduced total intraoperative fluid administered while maintaining hemodynamic stability compared with a standard weight-based regimen [10]. A comparative study in major abdominal oncologic surgery pitted SVV-guided against PVI-guided algorithms directly and found the noninvasive PVI-based approach achieved comparable fluid optimization to the invasive SVV method, an encouraging signal for centers without routine arterial pulse-contour monitoring [11]. In hepatic resection performed under a low central venous pressure strategy to limit blood loss during parenchymal transection, SVV-guided resuscitation in the post-resection phase restored volume status effectively without reintroducing the venous congestion the low-CVP strategy was designed to avoid [12].

Colorectal surgery within enhanced recovery after surgery (ERAS) pathways has generated the largest and most heterogeneous body of outcome data. A large propensity-matched multicenter study of ERAS colorectal patients found goal-directed fluid therapy was associated with fewer overall and severe postoperative complications relative to conventional management [13], and a systematic review and meta-analysis pooling gastrointestinal surgery trials within ERAS programs similarly found a benefit for goal-directed strategies on complication rates and length of stay [14]. Yet not every outcome moves in the expected direction. A randomized trial of laparoscopic colorectal surgery found that a goal-directed protocol did not reduce the incidence of primary postoperative ileus compared with a more restrictive fixed regimen, despite achieving its intended hemodynamic targets [15], and an earlier randomized comparison of oesophageal Doppler-guided goal-directed therapy against a simple restrictive fluid protocol within an ERAS pathway found no clear advantage for the dynamically guided arm once a genuinely restrictive comparator was used [16]. A further laparoscopic ERAS colorectal study reported improved gastrointestinal recovery metrics with goal-directed dosing relative to liberal fluid administration [17]. Taken as a body of work rather than any single trial, an evidence-based review of goal-directed therapy in colorectal surgery concluded that benefit is most consistent when the comparator is a genuinely liberal or ungoverned fluid strategy, and considerably less clear when the comparator is itself a disciplined restrictive protocol - suggesting that some of the apparent benefit of dynamic-index-guided therapy in earlier literature reflected avoidance of fluid excess rather than any unique property of the monitoring technology itself [18].

THE NONINVASIVE ALTERNATIVE: PLETHYSMOGRAPHIC VARIABILITY INDEX

PVI's appeal is obvious: it requires no arterial line, no specialized cardiac output monitor, just a compatible pulse oximeter probe already on most patients undergoing general anesthesia. Early validation work in critically ill patients demonstrated that PVI tracked fluid responsiveness with accuracy approaching that of invasively derived indices [1], and passive-leg-raise-induced changes in PVI have since been used as a maneuver-based confirmatory test in both spontaneously breathing postsurgical patients and mechanically ventilated critically ill patients, extending the tool's applicability beyond the narrow controlled-ventilation conditions that PPV and SVV strictly require [19] [20]. More recent physiological work in patients supported with nasal high-flow therapy suggests PVI-based preload assessment may extend usefully even to non-intubated, spontaneously breathing patients, a population in which SVV and PPV are essentially inapplicable [21].

The major caveat, established early and repeatedly reconfirmed, is that PVI's accuracy is confounded by peripheral perfusion state. A now-classic study demonstrated that the diagnostic performance of PVI degrades substantially in patients with a low perfusion index, precisely the vasoconstricted state - from hypothermia, norepinephrine infusion, or hypovolemic shock itself - in which clinicians most need a reliable answer [22]. This creates a frustrating circularity: PVI is least trustworthy exactly in the sickest, most vasoconstricted patients where the clinical stakes of a wrong fluid decision are highest. In practice this means PVI is best used as a screening or confirmatory tool in patients with reasonably preserved peripheral

perfusion, with a lower threshold to fall back on invasive monitoring once perfusion index drops or vasopressor requirements escalate.

PRACTICAL INTEGRATION AND LIMITATIONS

Bringing these threads together, a workable approach to dynamic-index-guided fluid management starts with recognizing the preconditions under which any of these tools are valid: controlled ventilation at adequate tidal volume, sinus rhythm, closed chest, and reasonably preserved right ventricular function and peripheral perfusion. Where those preconditions hold - the classic case being open abdominal or major orthopedic surgery under general anesthesia with volume-controlled ventilation - SVV or PPV-guided algorithms have reasonably strong trial support for reducing complications relative to unstructured fluid administration [9] [8]. Where they do not hold - low tidal volume protective ventilation, an open chest, one-lung ventilation, arrhythmia, or a laparoscopically insufflated abdomen - clinicians should expect degraded accuracy and should either adjust interpretation thresholds, add a confirmatory dynamic maneuver such as a passive leg raise or a mini-fluid challenge, or fall back on integrated clinical judgment incorporating lactate trends, urine output, and echocardiographic assessment [5] [6] [3].

The colorectal and ERAS literature carries a further practical lesson that is easy to overlook amid enthusiasm for monitoring technology: the comparator matters as much as the monitor. Trials that pit dynamically guided therapy against genuinely liberal fluid administration tend to show benefit; trials that pit it against a well-designed restrictive protocol tend to show little difference [16] [15] [18]. This does not diminish the physiological rationale for dynamic monitoring, but it does argue against treating SVV, PPV, or PVI monitors as a substitute for basic fluid discipline, and in favor of viewing them as one component - a particularly useful one in hemodynamically unstable or high-risk patients - within a broader restrictive-leaning perioperative fluid strategy.

CONCLUSION

Dynamic hemodynamic indicators have earned their place in modern perioperative fluid management by answering a question static filling pressures never could: whether the heart will actually respond to more volume. The physiological logic is sound and repeatedly validated, but its clinical application is bounded by ventilatory mode, cardiac rhythm, chest and abdominal wall integrity, and peripheral perfusion state - conditions that are violated often enough in contemporary lung-protective, laparoscopic, and hemodynamically unstable patients that blind reliance on a single threshold value is unwise. The most defensible current practice pairs an understanding of these limitations with a restrictive-leaning baseline strategy, using SVV, PPV, or PVI to fine-tune boluses in patients and settings where the underlying physiology permits a trustworthy answer, and falling back on multimodal clinical assessment when it does not.

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Data Availability No new data were generated for this review. All sources discussed are publicly available in the cited literature.

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