

Pleth Variability Index: A Dynamic Measurement to Help Assess Physiology and Fluid Responsiveness

SUMMARY

PVI[®], an index available with Masimo SET[®] pulse oximetry, is the first and only noninvasive, continuous, easy-to-use method to help clinicians manage fluid responsiveness in sedated patients under positive pressure ventilation. Other clinical uses have also been developed for PVI, including helping clinicians to assess the effects of positive end expiratory pressure on cardiac index and to identify patients at risk for hypotension during anaesthesia induction. PVI, along with the other innovative noninvasive monitoring technologies available with the Masimo rainbow SET[®] platform (SpHb[®], SpCO[®], SpMet[®], RRa[™]), has helped clinicians to realise improved patient outcomes while lowering the cost of care.

INTRODUCTION

Many pulse oximetry technologies display a processed and filtered representation of the photoplethysmographic waveform. Each manufacturer uses unique proprietary algorithms to calculate the waveform displayed on the pulse oximeter. Masimo has extracted and processed information from the waveform to create two physiologic indices, perfusion index (PI) and pleth variability index (PVI). PI is calculated by indexing the infrared (IR) pulsatile signal against the nonpulsatile signal and expressing this number as a percentage. Masimo SET[®] PI has been shown to be useful to gauge the severity of illness in newborns^{1,2} to assess the effectiveness of epidural blocks^{3,4} to indicate successful interscalene nerve block placement in awake patients⁵ and to quantify peripheral perfusion for diagnosis of congenital heart disease in newborns.⁶ PVI is the first and only commercially available measurement that automatically and continuously calculates the respiratory variations in the photoplethysmographic waveform. This paper will review why the photoplethysmographic waveform reflects changes that occur during the respiratory cycle and how monitoring those changes can be used to help clinicians assess the physiological status of patients, including fluid responsiveness. We also will review the limitations of PVI.

THE PULSE OXIMETER PLETHYSMOGRAPHIC WAVEFORM REFLECTS CHANGES THAT OCCUR DURING THE RESPIRATORY CYCLE

Standard pulse oximetry utilises two wavelengths of light in the red and infrared spectrum. Unlike the red wavelength, the absorbance of the infrared (IR) signal is relatively unaffected by changes in arterial oxygen saturation. Instead, the absorbance of the IR signal changes with the pulsations associated with blood volume in the peripheral vascular bed at the sensor site. With each heartbeat, the ventricle pumps blood into the periphery, increasing the pulse pressure in the arteries and arterioles and thus increasing the volume of blood under the sensor during systole. The reverse, decreases in pulse pressure and blood volume in the periphery, occurs during diastole.

The photoplethysmographic waveform displayed on some pulse oximeters represents the highly processed and filtered, pulsatile component of the IR signal over time, and, therefore, provides an indirect measure of blood volume or pulsatile strength under the sensor. Initially the photoplethysmographic waveform was found to be useful as a simple indicator of the pulse oximeter signal integrity and changes in perfusion. Since then, clinicians have used the waveform display in a number of unique ways to obtain information on the physiological status of their patients. Clinicians observed, for example, that respiratory induced variations in the waveform amplitude (referred to as Δ POP) resemble the cyclical changes in pulse pressure and pulse volume that occur during the respiratory cycle, as measured with an arterial catheter (Figure 1). This is because the pumping action of the heart is directly influenced by relative changes in airway (intrapleural) pressure and blood pressure/blood volume.⁷ During normal spontaneous inspiration, the increase in negative intrathoracic pressure causes an increase in venous return and a subsequent decrease in left ventricle stroke volume resulting in a fall in the systolic blood pressure. To accommodate the increased venous return, the ventricles stretch, known as cardiac preload. Since preload is related to cardiac output, increased negative intrathoracic pressure ultimately increases cardiac output. Conversely, during normal expiration, there is an increase in positive intrathoracic pressure resulting in a decrease in venous return, an increase in arterial blood pressure, and a decrease in cardiac output. During normal, quiet respiration, the effect of respiratory variations on blood pressure/blood volume is small and this is reflected in small changes in the PPG waveform amplitude. Several disease states or physiological conditions, however, emphasise the effect of respiratory variations on blood pressure/blood volume.⁸ Asthma is one condition when airway pressures are greatly elevated, resulting in pronounced blood pressure/blood volume changes. The magnitude of these changes correlates with the severity of the airway obstruction.⁹ During positive pressure mechanical ventilation, the changes in blood pressure also become greatly enhanced, especially in volume depleted patients.

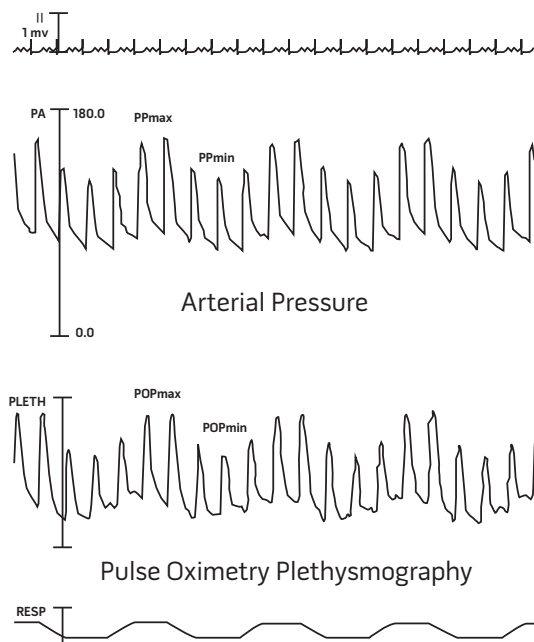


Figure 1. Relation between respiratory variations in pulse oximetry plethysmographic waveform amplitude and arterial pulse pressure in ventilated patients. Adapted from Cannesson et al., 2005.¹⁰

THE PHOTOPLETHYSMOSGRAPHIC WAVEFORM IN FUNCTIONAL HAEMODYNAMIC MONITORING DURING MECHANICAL VENTILATION

Volume expansion is frequently used during and after surgery to correct fluid deficits created by preoperative fasting, surgical blood loss, and urinary excretion and in septic and other critically ill patients to improve oxygen delivery and overall haemodynamic function. However, studies have found that up to 72% of critically ill patients do not respond to volume expansion with an increase in stroke volume or cardiac output.¹¹ In these patients, volume expansion is either ineffective or deleterious, worsening oxygen delivery, inducing systemic and pulmonary edema and, possibly, cardiac failure. It is necessary, therefore, to determine which patients will respond to volume expansion prior to fluid administration. Static and dynamic cardiopulmonary indices have been used to predict fluid responsiveness. Static measures such as central venous pressure (CVP) systolic pressure, diastolic pressure, pulse pressure, pulmonary artery pressure, and pulmonary artery occlusion pressures (wedge pressure), have been shown to have low predictive value¹²⁻¹⁴ (Table 1).

Table 1. Predictive ability of static and dynamic measures of fluid responsiveness.

Measures used for predicting fluid responsiveness	
Static Measures	Dynamic Measures
Central venous pressure (CVP) Poor predictor ¹³	Pulse pressure variation (PPV) Good predictor ¹⁵
Pulmonary artery occlusion pressure (PAOP) Poor predictor ¹¹	Systolic pressure variation (SPV) Good predictor ¹⁵
Left ventricular end diastolic area (LVEDA) Poor predictor ¹⁶	Stroke volume variation (SVV) Good predictor ¹⁵
Systolic arterial pressure (SAP) Poor predictor ¹⁷	Respiratory variations in plethysmographic waveform amplitude (Δ POP) Good predictor ¹⁸
Cardiac Index (CI) Poor predictor ¹⁹	Pleth variability index (PVI) Good predictor ¹⁹

This is because in the normal heart, the change in preload to the change in stroke volume (Frank-Starling curve) has a curvilinear relationship; preload has a nearly linear relationship to stroke volume (preload dependent) in the ascending portion of the curve, and then preload independence occurs as the curve plateaus (Figure 2).

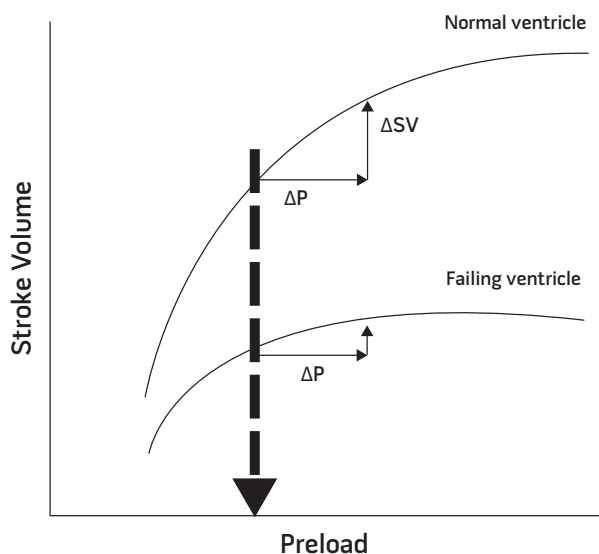


Figure 2. Frank-Starling curve showing relationship between stroke volume and preload in the normal and failing heart.

Static measures such as CVP and pulmonary wedge pressures do not account for whether the patient is in the steep part (preload dependent and therefore fluid responsive) or the plateau part (preload independent and therefore fluid unresponsive) part of the Frank-Starling curve.^{20,21}

Dynamic measures such as pulse pressure variation (Δ PP), SVP, and SVV have been shown to be more accurate for predicting fluid responsiveness, especially in mechanically ventilated patients.¹⁵ Anaesthesiologists and others have long recognised that in mechanically ventilated patients, blood pressure will fluctuate in response to the ventilator cycles and this effect on blood pressure variation is more pronounced in patients who are hypovolemic. Further, fluid administration will diminish the ventilator effect on blood pressure variation. This is because mechanical ventilation exerts a positive pressure on the thorax to assist in ventricular emptying. This causes an increase in systolic pressure during inspiration, impedes venous return to the heart, and decreases cardiac output. In volume depleted patients, venous pressure is lower, resulting in even greater variability in the systolic blood pressure during the respiratory cycle. Rick and Burke were the first to suggest that SPV could be used to assess volume status in ventilated patients,²² but SVP measurement can be technically challenging and time consuming so few clinicians use it to assist in fluid management.²³ Arterial pulse pressure (the difference between the systolic and diastolic pressure) is more closely related to stroke volume than SVP, so PPV during the respiratory cycle is a better predictor of fluid responsiveness. This has been demonstrated in studies that compared the ability of the two parameters to predict responders from nonresponders in septic²⁴ and postoperative cardiac patients^{25,26} among others. Although PPV was useful for predicting fluid responsiveness in a research setting, Rinehart

et al.²⁷ showed that visual estimation of pulse pressure variation from the arterial pressure waveform was not a reliable indicator in clinical practice. Although visual estimation is the most frequent method used to gauge PPV,²⁸ the agreement between the true PPV and estimated PPV was less than 5%. Since PPV is highly correlated with respiratory variations in the Δ POP waveform amplitude and both have also been shown to be closely related to the degree of hypovolemia in ventilated patients, it is not surprising that Δ POP has been used to predict fluid responsiveness with high accuracy.²⁹⁻³³ Δ POP is advantageous over other static and dynamic methods of predicting fluid responsiveness because it is noninvasive and available wherever pulse oximetry is used. Δ POP is impractical to use in a clinical environment, however, because it is not easily calculated from the pulse oximetry display. As with PPV, visual estimation of respiratory variations in the waveform is unreliable because of the post processing of the waveform by commercial pulse oximeters. The unprocessed, unfiltered waveform, which is necessary to obtain sufficient reliable information regarding the respiratory variations, is not easily extractable from commercial pulse oximeters, requiring specific tools and software that are not widely available. Briefly, to calculate Δ POP, the pulse oximeter plethysmographic waveforms are recorded into a personal computer using specialised software, with the plethysmographic gain factor held constant. Then, the vertical distance between the peak and the proceeding trough of the waveform during a respiratory cycle is calculated and measurements from multiple consecutive respiratory cycles are averaged¹⁹ (Equation 1).

$$\Delta\text{POP} = (\text{POPmax} - \text{POPmin}) / [(\text{POPmax} + \text{POPmin}) / 2] \quad \text{Equation 1}$$

PLETH VARIABILITY INDEX

PVI, a measurement only available with Masimo SET[®] pulse oximetry, is the first commercially available index that automatically and continuously calculates the respiratory variations in the photoplethysmogram from data collected noninvasively via a pulse oximetry sensor. PVI visually correlates with Δ POP³⁴ but uses a different algorithm to calculate the PVI value. PVI is a measure of the dynamic changes in the Perfusion Index (PI) that occur during one or more complete respiratory cycles. PI reflects the amplitude of the pulse oximeter waveform and is calculated as the pulsatile infrared signal (AC or variable component), indexed against the non-pulsatile infrared signal (DC or constant component) (Figure 3 and Equation 2). The infrared signal is used because it is less affected by changes in arterial saturation than the red signal.

$$\text{PI} = \frac{\text{AC}}{\text{DC}} \times 100\% \quad \text{Equation 2}$$

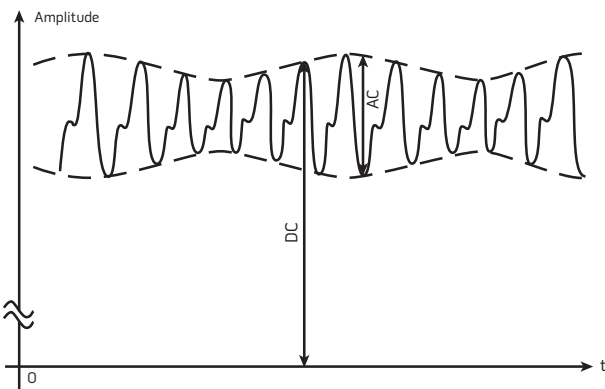


Figure 3. Graphic representation of raw infrared signal processed internally by the pulse oximeters, where AC represents the variable absorption of infrared light due to pulsating arterial inflow and DC represents the constant absorption of infrared light due to skin and other tissues. Using PI, PVI is calculated according to Equation 3.

$$\text{PVI} = \frac{\text{PI}_{\text{Max}} - \text{PI}_{\text{Min}}}{\text{PI}_{\text{Max}}} \times 100\% \quad \text{Equation 3}$$

PVI is displayed as a percentage (numerical value) and a trend graph (Figure 4). The lower the PVI number, the less variability there is in PI over a respiratory cycle. The higher the variability, the more likely the patient will respond to fluid infusion with an increase in cardiac output (Figure 5).

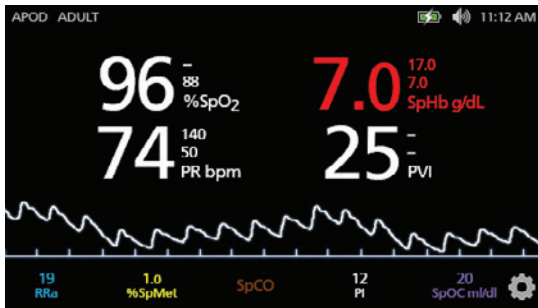


Figure 4. Screenshot of pulse oximeter display showing PVI numerical value and trend graph.

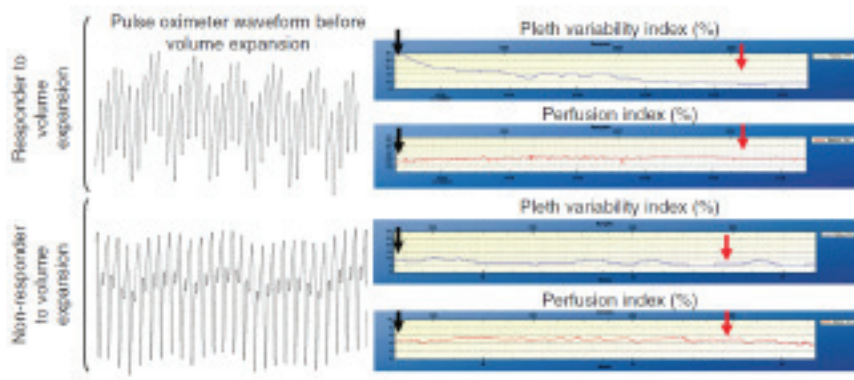


Figure 5. PVI and PI during volume expansion in fluid responder and non-responder.¹⁹

PVI HELPS CLINICIANS PREDICT FLUID RESPONSIVENESS IN MECHANICALLY VENTILATED PATIENTS

Cannesson and coworkers from Louis Pradel Hospital were the first to investigate the relationship between PVI and Δ POP in a clinical setting.³⁴ To test if PVI correlated to Δ POP in anaesthetised mechanically ventilated patients, they recorded haemodynamic parameters, including PP, Δ POP, and PVI during changes in body position in 27 coronary artery bypass patients. Patients were studied while supine, in anti-Trendelenberg position and in Trendelenberg position, after induction of anaesthesia and before surgery. The effects of Trendelenberg position (head down 30°) mimics some aspects of volume loading in that it causes an increase in filling of the heart, which increases blood pressure, venous pressure, and stroke volume. Similarly, anti-Trendelenberg position (head up 30°) mimics some aspects of hypovolemia in that systolic arterial pressure and mean arterial pressure are decreased along with stroke volume. The study demonstrated a strong correlation between PVI and Δ POP in each body position. When patients were moved from supine to anti-Trendelenberg position, there were significant increases in PPV, Δ POP, and PVI with no significant change in PI. When patients were moved from anti-Trendelenberg to Trendelenberg position, there were significant decreases in PPV and Δ POP. This study demonstrated that changes in PVI respond to changes in body position and closely correlate with respiratory induced variations in the plethysmographic waveform.

As a follow-up to their earlier work, Cannesson et al. tested the ability of PVI to predict fluid responsiveness in the operating room. In this study, PPV, Δ POP, and PVI, along with other invasive haemodynamic parameters were recorded before and after volume expansion in 25 anaesthetised and mechanically ventilated coronary artery bypass patients. Following volume expansion, there were increases in mean arterial pressure and central venous pressure as expected. Volume expansion also induced significant decreases in PPV, Δ POP, and PVI, with no significant change in PI. There was a strong correlation between Δ POP and PVI before and after volume expansion ($r = 0.65$; $P < 0.01$). A PVI value of $>14\%$ before volume expansion discriminated between responders and nonresponders with 81% sensitivity and 100% specificity. This was the first study to directly demonstrate the ability of PVI to predict fluid responsiveness in mechanically ventilated patients during general anaesthesia. The study is also important because it demonstrated the poor predictive ability of static measures such as CVP and cardiac index (CI) during the same clinical conditions (same patients) where dynamic measures such as PVI were successful (Figure 6a).

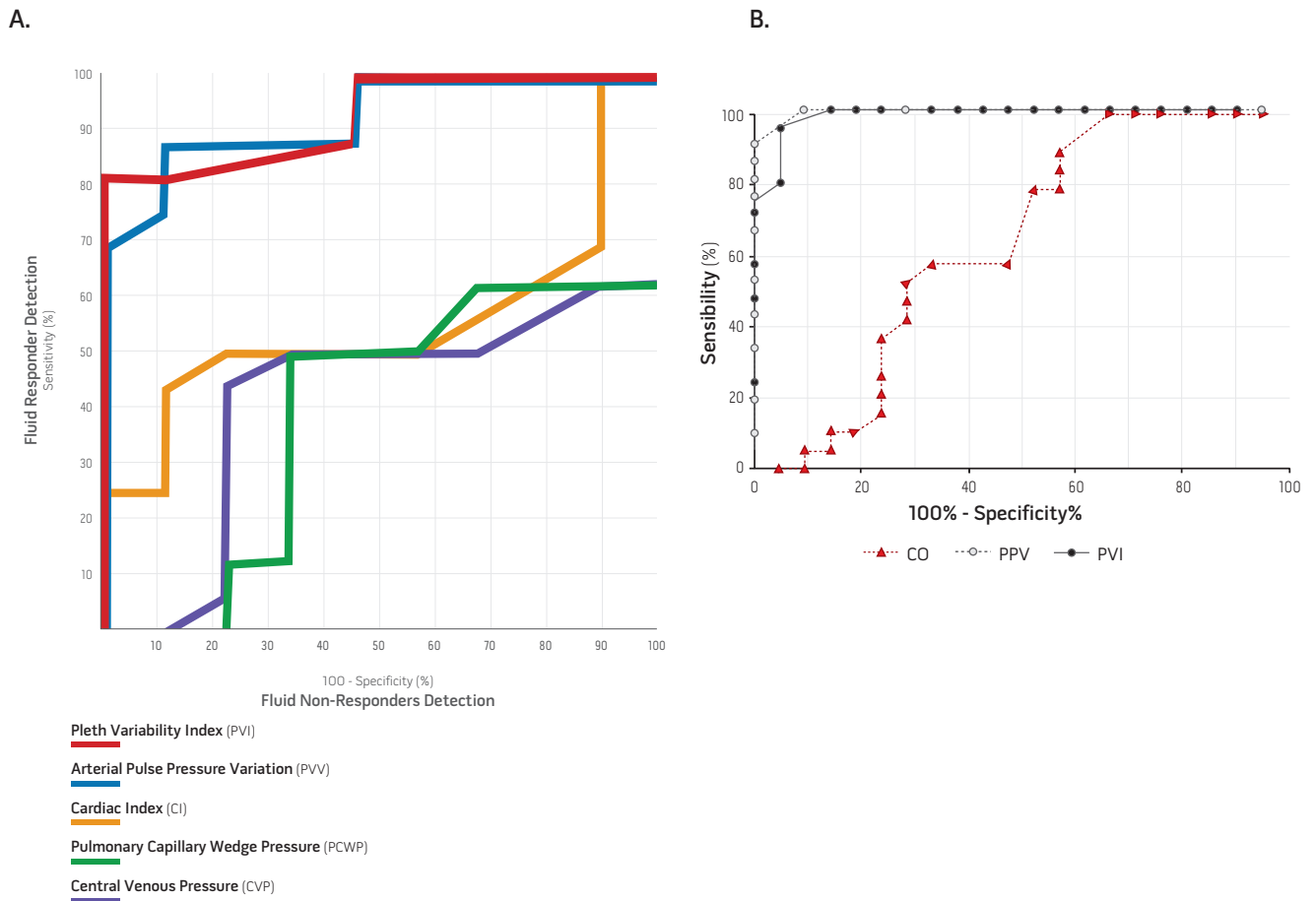


Figure 6. Receiver operator curves showing dynamic indices have high sensitivity and specificity for predicting fluid responsiveness compared to static measures; A) PVI and PPV compared to CVP, PCWP, and CI. (Adapted from Cannesson et al., 2008) and B) PVI and PPV compared to cardiac output (CO).^{35,19}

Since the publication of these initial studies, numerous other independent clinical studies have confirmed the utility of PVI to assess fluid responsiveness in adult surgical and intensive care patients under mechanical ventilation. PVI has been shown to perform similarly to more invasive and costly dynamic fluid assessment technologies during cardiac surgery,³⁶ tumour resection,³⁷ colorectal surgery,³⁸ abdominal surgery^{39,40} in critically ill patients in the intensive care unit (ICU),³⁵ and in severely injured combat casualties.⁴¹ For example, Loupec et al.³⁵ investigated 40 mechanically ventilated intensive care patients with circulatory insufficiency and found that a PVI threshold value of 17% allowed discrimination between responders and nonresponders to fluid challenge with a sensitivity of 95% (95% confidence interval [CI], 74% to 100%) and a specificity of 91% (95%CI, 70% to 99%). Static measures of systolic arterial pressure, mean arterial pressure, diastolic arterial pressure, heart rate, and cardiac output did not discriminate between responders and nonresponders whereas the dynamic measure PP discriminated between responders and nonresponders with a sensitivity of 100% (95% CI, 82% to 100%) and a specificity of 95% (95% CI, 76% to 100%) when a threshold value of 10% was used (Figure 6b). In a similar study, Zimmermann and colleagues³⁹ assessed the ability of PVI, CVP, and SVV to predict fluid responsiveness in 20 abdominal surgery patients. The optimum threshold for prediction of fluid responsiveness was 9.5% for PVI, which resulted in an area under the receiver operating curve (AUC) of 0.973, and 11% for SVV, which resulted an AUC of 0.993. The AUC for CVP was 0.553, indicating poor predictive value. A meta-analysis of 6 studies assessing the accuracy of PVI to predict fluid responsiveness in mechanically ventilated adult patients receiving colloid infusions reported a pooled sensitivity and specificity of 84% and 81% respectively⁴² with one study showing sensitivity and specificity as high as 93% and 100%³⁹ (TABLE 2).

Table 2.

Studies assessing ability of PVI to predict fluid responsiveness in mechanically ventilated adults and children					
Study	Patients (n)	AUC (95%CI)	Cutoff (%)	Sensitivity (%)	Specificity (%)
Haas et al., 2012 ³⁶	Cardiac surgery (18)	0.95 (nr)	≥16	100	89
Fu et al., 2012 ³⁷	Tumour surgery (51)	0.79 (0.65-0.92)	≥13.5	77	80
Monnet et al., 2012 ^{#43}	ICU (42)	0.68 (nr)	16	47	90
Hoiseth et al., 2012 ⁴⁴	Laparoscopic surgery (20)	0.71 (0.48-0.88)	CI≥15	nr	nr
Hood et al., 2011 ³⁸	Colorectal surgery (25)	0.96 (0.88-1.00)	≥10	86	100
Broch et al., 2011 ^{*45}	CABG (81)	0.60 (0.47-0.72)	≥14	41	72
Loupec et al., 2011 ³⁵	ICU (45)	0.88 (0.74-0.96)	≥17	95	91
Biais et al., 2011 ⁴⁶	ICU (67)	0.80±0.06	≥11	70	71
Desgranges et al., 2011 ⁴⁷	Cardiac surgery (28)	0.84 (0.69 – 0.99)	≥12	74	67
Cai et al., 2010 ⁴⁸	General surgery (25)	0.93 (0.83-1.04)	≥15.5	88	88
Zimmermann et al., 2010 ³⁹	General surgery (20)	0.97 (0.91 -1.00)	SVI≥9.5	93	100
Cannesson et al., 2008 ¹⁹	CABG (25)	0.93 (0.83 – 1.03)	≥14	81	100
Neonates and Children					
Bagci et al., 2012 ⁴⁹	Newborns	nr	≥18	86	nr
Renner et al., 2011 ⁵⁰	Infants, congenital heart surgery (27)	0.78 (0.61-0.88)	13	84	61
Byon et al., 2012 ⁵¹	Neurosurgery (33)	0.77 (0.60–0.94)	>11%	73	87
Pereira de Souza Neto et al., 2011 ⁵²	Children 6-14 y (11) neurosurgery	0.63 (0.38-0.84)	10	na	na
	Children 6-14 y (11) neurosurgery	0.54 (-0.24 -0.82)	15	na	na

nr = not reported; *No fluids given. Patients were tested by passive leg raises; #Study tested patients receiving norepinephrine.

PVI TO HELP GUIDE THERAPEUTIC DECISIONS

There are numerous studies that document improved outcomes when patients are managed with goal directed fluid therapy guided by dynamic parameters during surgery and in the ICU. In an early study, Gan et al. showed that goal-directed intraoperative fluid administration guided by systolic flow time measurements obtained from esophageal Doppler monitoring results in earlier return to bowel function, lower incidence of postoperative nausea and vomiting, and decrease in length of postoperative hospital stay.⁵³ Lopes and colleagues showed that monitoring with PP to optimise volume loading during high-risk surgery improves postoperative outcomes and decreases the length of hospital stay.⁵⁴ Other studies have shown that patient outcomes improved when fluid management was directed by dynamic parameters of haemodynamic function (such as PPV and SVV) during gastrointestinal surgery,⁵⁵ hip fracture repair,⁵⁶ and other types of major surgery.⁵⁷ The data showing PVI can help clinicians predict fluid responsiveness similarly to invasive dynamic parameters, lead one to believe it may be helpful in therapeutic management as has been shown for PPV and SVV. Forget and colleagues⁴⁰ were the first to demonstrate improved outcomes with PVI directed fluid therapy. A randomised controlled trial in 82 patients scheduled for major abdominal surgery showed that PVI directed fluid management reduced the volume of intraoperative fluids infused and reduced intraoperative and postoperative lactate levels (a surrogate for tissue hypoperfusion and microcirculatory tissue hypoxia) compared to the standard of care group (Figure 7). Other studies have shown that PVI has been successfully integrated into hospital protocols to improve fluid management and patient outcomes.^{58, 59}

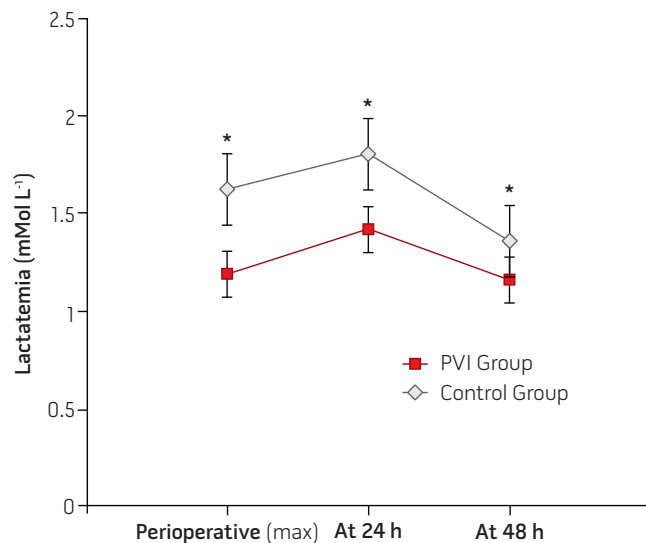


Figure 7. Lactate levels during and after surgery in PVI managed group and control group.⁴⁰

In 2012, the National Health Service Technology Adoption Centre (NTAC) in the United Kingdom recommended hospitals use intraoperative fluid management technologies, including PVI, to facilitate improved patient outcomes and lower the cost of care. No other pulse oximetry technologies were included other than Masimo PVI. The NTAC identifies and supports the implementation of new and innovative technologies that demonstrate benefits to patients and hospitals. Increasing the adoption of intraoperative fluid management has been designated a priority for the NTAC for 2012-2013; the major benefits of adoption being fewer patient complications, reduced number of patients or shorter patients stays in the ICU, shorter hospital length of stay, and improved clinical outcomes. Hospitals with Masimo SET[®] pulse oximetry can use PVI on any patient in whom an invasive arterial line or more complex or costly monitoring technologies may not be justified.

Optimising Ventilator Settings

Besides its use as a fluid responsiveness prediction tool, clinicians have found numerous other ways to use PVI to monitor disease states or physiological conditions that affect the airway pressure/blood volume relationship. For example, Desebbe and colleagues⁶⁰ tested if PVI could predict the effects of end expiratory pressure (PEEP) on cardiac index in 21 mechanically ventilated, sedated patients in the ICU following coronary artery bypass grafting. PEEP, a ventilator setting that can alter cardiac output, can be beneficial if it improves arterial oxygenation and oxygen delivery, but harmful if it decreases blood flow to the tissues, so it would be highly advantageous if clinicians could predict whether the addition of PEEP would have positive or negative haemodynamic effects on patients. The researchers found that sequential increases in tidal volumes from 8 to 10 ml/kg induced significantly higher increases in PVI in the haemodynamically unstable patients compared to stable patients. Therefore, PVI was able to predict the effects of PEEP on cardiac index, which, in turn, could help clinicians optimise the respiratory uptake of oxygen and its delivery to tissues in critically ill patients.

Risk of Hypotension

In another study, Tsuchiya and coworkers⁶¹ investigated if PVI could identify patients at risk for hypotension during anaesthesia induction for surgery. Hypotension can deprive tissues of adequate oxygen and, if severe, can result in brain, heart, and organ damage. Hypotension during anaesthesia induction is common, however, so the ability to properly identify patients at risk could prompt caregivers to be prepared to engage in preventive measures, such as providing inspired oxygen, to reduce patient risk. The researchers found that pre-anaesthesia PVI correlated significantly ($r = -0.73$) with a decrease in mean arterial pressure and a pre-anaesthesia PVI value of $>15\%$ successfully predicted a decrease in mean arterial pressure of >25 mmHg with 79% sensitivity, 71% specificity. The study concluded that PVI is an "easy to perform, noninvasive, and inexpensive method for predicting patients who may develop severe hypotension." In a similar study, Yoshioka et al.⁶² showed that PVI could predict hypotension induced by spinal anaesthesia for cesarean delivery in 19 patients.

Other Studies

Other preliminary investigations in neonates have demonstrated the utility of PVI to detect changes in intrathoracic pressure in a newborn with left congenital diaphragmatic hernia,⁶³ and to monitor early postnatal respiratory changes in newborns as a method to screen for cardiorespiratory abnormalities.⁶⁴

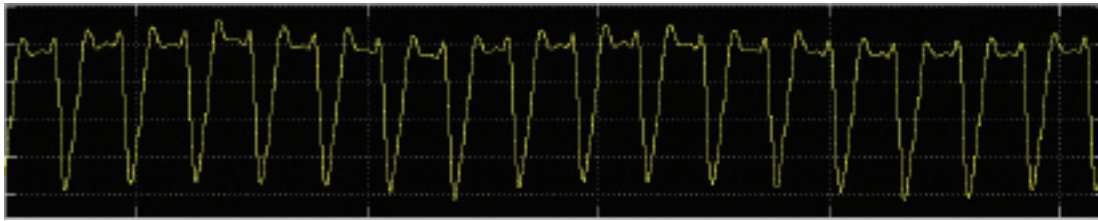
It is expected that more clinical uses for PVI will be developed as clinicians investigate the many potential ways PVI can be used to provide information concerning changes in the balance between intrathoracic airway pressure and intravascular fluid volume.

LIMITATIONS OF PVI

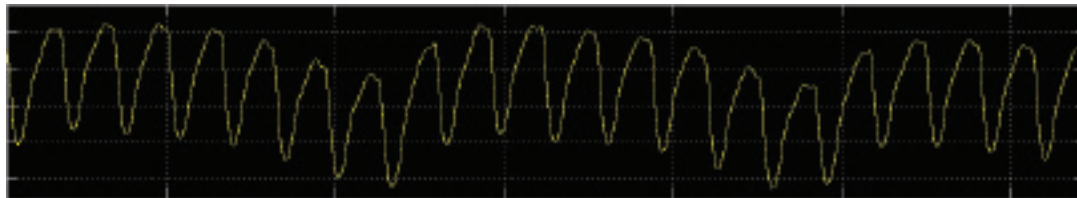
All clinical measurement modalities have limitations to their use, including PVI. PVI is subject to the same limitations as other functional haemodynamic parameters such as SVV and PPV, including reduced reliability during arrhythmias, right heart failure, spontaneous breathing activity, and low tidal volume (<8ml/kg). Although PVI is appropriate to use to predict fluid responsiveness in most ICU and surgical patients, there are certain clinical scenarios where it is not recommended or not possible to use PVI. In general, PVI provides an accurate prediction of fluid responsiveness in mechanically ventilated adults under general anaesthesia with a normal sinus rhythm. PVI is less accurate and therefore not recommended for spontaneously breathing patients^{65,66} because the heart lung interactions and vasomotor tone are no longer consistent, for patients with cardiac arrhythmia^{36,67} for the same reasons, and for patients with extremely low PI, such as some ICU patients treated with vasopressors.^{43,45,46} PVI is also not recommended for patients undergoing open chest⁶⁷ or laproscopic surgery.⁴⁴ Lastly, it may be unnecessary to use PVI for patients who require an arterial line for other reasons because a SVV or a PVV monitor can be used.

PVI also has some limitations specific to its technology. The PVI calculation is based on a photoplethysmogram that has passed strict tests to filter out unrelated signals such as movement artifacts. Some of the tests in the algorithm include, but are not limited to, heart rate constraints and waveform shape. A fast heart rate (>70 beats per minute), abnormally large dichrotic notches (Figure 8a), an abnormally shaped waveform (Figure 8b), or a photoplethysmogram that is corrupted by patient movement (Figure 8c) may cause rejection of the beat-to-beat photoplethysmogram and prevent the calculation of PI and, thus, the estimation of PVI. In these cases, PVI will “drop out” and not be displayed on the monitor.

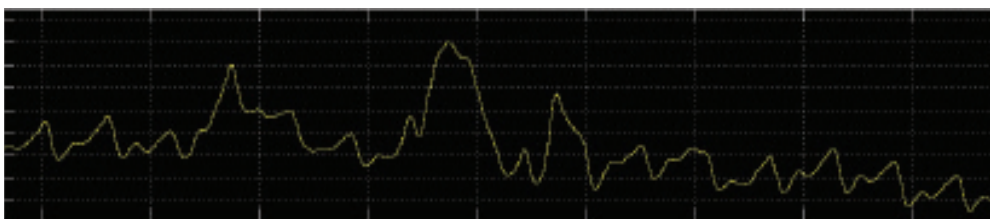
Studies have been inconsistent in results of accuracy of PVI for the prediction of fluid responsiveness in children. Renner et al. showed that a PVI $\geq 13\%$ could predict fluid responsiveness with a sensitivity of 84% and a specificity of 64% whereas CVP could not in 27 infants with a mean age of 17 months. Consistent with these findings, Chandler et al. showed that PVI was strongly correlated with pulse pressure variation ($r = 0.7049$) and plethysmographic variation ($r = 0.715$) in 29 mechanically ventilated children with a mean age of 18 months. This study did not directly test for prediction of fluid responsiveness, however. Byon and colleagues found that a PVI value of 11% predicted fluid responsiveness with a sensitivity of 73% and a specificity of 87% in 33 children (average age of 74 months) undergoing neurosurgery.⁵¹ In contrast, Pereira de Souza Neto et al.⁵² studied prediction of fluid responsiveness in two age groups undergoing neurosurgery: 0 to 6 years ($n = 19$) and 6 to 14 years ($n = 11$). They found no significant differences in PVI, arterial pulse pressure, pulse pressure variation, and plethysmographic waveform amplitude between responders and nonresponders to volume expansion. Stroke volume variation assessed using echocardiography, however, was able to distinguish between responders and nonresponders in both age groups. The sum of these findings has led some to hypothesise that while stroke volume variation may predict fluid responsiveness in children, PVI, pulse pressure variation, and plethysmographic waveform amplitude cannot, perhaps due to higher chest–lung compliance or vascular compliance compared to adults.⁶⁸ Further studies are needed to definitively determine if and how PVI can be successfully used for prediction of fluid responsiveness in children.



A. Photoplethysmogram with abnormally large dichrotic notches.



B. Abnormally shaped photoplethysmogram.



C. Photoplethysmogram corrupted by movement.

Figure 8. Limitations of PVI: Sample of photoplethysmogram with A) abnormally large dichrotic notches, B) abnormal shape, and C) corrupted by patient movement – all of which can prevent the calculation of PI and the estimation of PVI.

CONCLUSION

PVI, a haemodynamic index available with Masimo SET[®] pulse oximetry, allows for the continuous, noninvasive, automatic estimation of respiratory variations in monitored patients. Numerous studies demonstrate that PVI is able to predict fluid responsiveness following volume infusion in sedated adult patients under positive pressure ventilation. PVI represents the first noninvasive, continuous, widely available, easy-to-use index that can be used to predict fluid responsiveness in these patients. Since PVI provides useful information concerning changes in the balance between intrathoracic airway pressure and intravascular volume, other clinical uses have also been developed, including to assess the effects of PEEP on cardiac index and to identify patients at risk for hypotension during anaesthesia induction.

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