Bruno Riou, M.D., PhD., Editor

Case Scenario: Respiratory Variations in Arterial Pressure for Guiding Fluid Management in Mechanically Ventilated Patients

Matthieu Biais, M.D.,* Alexandre Ouattara, M.D., Ph.D.,† Gérard Janvier, M.D., Ph.D.,‡ François Sztark, M.D., Ph.D.§

MAINTAINING perioperative optimal cardiac preload in surgical patients is paramount for precise hemodynamic management. Hypovolemia may result in tissue hypoperfusion and worsened organ dysfunction, whereas fluid overload appears to impede oxygen delivery and compromise patient outcome. Several clinical and experimental studies have demonstrated the usefulness of dynamic indices based on heart–lung interactions for guiding volume resuscitation.[1,2] Mechanical ventilation induces cyclic changes in intrathoracic and transpulmonary pressures that transiently affect left ventricular preload, resulting in cyclic changes in stroke volume that are more pronounced in preload-dependent, but not in preload-independent, patients. These cyclic changes in left ventricular stroke volume induce cyclic changes in arterial pressure waveform. Schematically, systolic pressure variations, pulse pressure variations, stroke volume variations, and deltadown (ΔDown) are dynamic indicators of preload dependence that can be obtained from arterial pressure waveform. They have been extensively studied in different clinical settings and are robust indicators of fluid responsiveness.

The authors present a patient with hypovolemia and hemodynamic instability during emergency abdominal surgery. Hemodynamic optimization is detailed before, during and after surgery using or not using arterial pressure waveform. In addition, the physiologic basis for these dynamic indices, their use in clinical practice, recent progress, and future perspectives are discussed.

Case Report

Emergency Unit

A 52-yr-old man (height = 175 cm, weight = 72 kg, body mass index = 23.5 kg/m^2 and body-surface area = 1.87 m^2) was admitted to the emergency department because of acute abdominal pain and fever. His main past history revealed arterial hypertension, active smoking, and phlebitis. Chronic medication consisted of nicardipine (60 mg/day). Computed tomography performed as an emergency revealed a pneumoperitoneum and sigmoid diverticulum thickening, so an emergency laparotomy was decided. Preoperative examination revealed normal neurologic status, blood pressure was 92/56 mmHg associated with tachycardia (112 beats/min), skin mottling (knee), and respiratory rate of 15 breaths/min. Biologic examination showed hyperleukocytosis (leukocytes = 24.000/mm^3) due to an excess amount of polymorphonuclear neutrophils, increased C-reactive protein, hemoglobin 14.5 g/dl, and platelet count 225 g/l. Blood electrolytes were normal. Electrocardiogram showed regular sinus rhythm without signs of ischemia. Echocardiography was performed using a standard transthoracic probe (P4–2, Siemens Medical, Malvern, PA) and a dedicated unit (Acuson CV-70, Siemens Medical System). This examination revealed normal left ventricular ejection fraction associated with left ventricular hypertrophy inducing moderate left

* Associate Professor, Université Bordeaux, Adaptation cardiovasculaire à l'ischémie, U1034, Pessac, France, CHU de Bordeaux, Département des urgences, Bordeaux, France, INSERM, Adaptation cardiovasculaire à l'ischémie, U1034, Pessac, France. † Professor and Chairman, Université Bordeaux, Adaptation cardiovasculaire à l'ischémie, U1034, Bordeaux, France, CHU de Bordeaux, Service d'anesthésie réanimation 2, INSERM, Adaptation cardiovasculaire à l'ischémie, U1034. ‡ Professor, Université Bordeaux, CHU de Bordeaux, Département des urgences. § Professor and Chairman, Université Bordeaux, Adaptation cardiovasculaire à l'ischémie, U1034, CHU de Bordeaux, Service d'anesthésie réanimation 1, Bordeaux, France, INSERM, Adaptation cardiovasculaire à l'ischémie, U1034.

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Address correspondence to Dr. Biais: Département des Urgences, Hopital Pellegrin, CHU de Bordeaux, F-33076 Bordeaux Cedex, France. matthieu.biais@chu-bordeaux.fr. This article may be accessed for personal use at no charge through the Journal Web site, www.anesthesiology.org.

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ventricular diastolic dysfunction. Right heart analysis did not reveal any abnormality. A passive leg-raising test was performed during the echocardiography and velocity time integral of aortic blood flow was continuously measured during the maneuver. A passive leg-raising test induced an increase of 24% (from 17.4 cm/s to 21.6 cm/s) in the velocity time integral of aortic blood flow (preload dependence). Consequently, volume expansion using 500 ml saline 0.9% was performed over 15 min through a 16-gauge intravenous catheter. This induced a decrease in heart rate (from 112 beats/min to 92 beats/min) and an increase in velocity time integral of aortic blood flow (27%, from 17.4 cm/s to 22.3 cm/s). Blood pressure did not exhibit any significant change. A second passive leg-raising test was performed and was associated with an increase in the velocity time integral of aortic blood flow from 22.3 cm/s to 23.2 cm/s (4%). No additional fluid was administered before surgery. The patient also received an intravenous injection of antibiotic (piperacilline and tazobactam).

Operating Room

The patient was admitted to the operating room 3 h after entering the emergency department. Monitoring included electrocardiogram, pulse oximetry, noninvasive blood pressure, end-tidal carbon dioxide and oxygen concentration, body temperature and bispectral index monitoring (BIS-XP®, A2000 monitor; Aspect Medical Systems, Natick, MA). A second 16 G intravenous catheter was inserted. After preoxygenation, anesthesia was induced using thiopental (5 mg/kg) and suxamethonium (1 mg/kg). The trachea was intubated and mechanical ventilation was set up using volume-controlled ventilation. Lungs were ventilated using a tidal volume of 8 ml/kg of ideal weight and respiratory rate was adjusted to maintain end-tidal carbon dioxide and oxygen concentrations between 30 and 35 mmHg. Positive expiratory pressure was set at 5 cm H_2O and inspiratory oxygen fraction, F_{IO_2}, was set at 0.5. After the induction of anesthesia, a catheter (Vygon, Ecouen, France) was inserted into the left radial artery and connected to a laptop monitor (Ultraview SL2700, Spacelabs Healthcare, Issaquah, WA) on one side and to a cardiac output monitor (Vigileo/Flotrac™, Edwards Lifesciences, Irvine, CA) on the other to monitor continuously invasive arterial pressure, pulse pressure variations (PPV), stroke volume (SV), and stroke volume variations (SVV). Anesthesia was maintained with sevoflurane (minimum alveolar concentration = 1.2), sufentanil (1 μg/kg/h) and cisatracurium (0.1 mg/kg/h). The patient received a continuous infusion of lactated Ringer's solution (5 ml/kg/h). Hemodynamic variables remained stable during induction of the anesthesia and during the first part of the surgery. Laparotomy was performed and showed a perforated sigmoid diverticulum complicated by peritonitis. Surgery consisted in left colectomy with colostomy. Forty-five min after skin incision, there was a progressive decrease in mean arterial pressure (MAP = 49 mmHg) and SV (50 ml) and an increase in heart rate (88 beats/min), PPV (22%), and SVV (21%). A first-volume expansion was performed (6% hydroxyethyl starch 130/0.4, 250 ml over 10 min) resulting in an increase in SV (61 ml) and MAP (65 mmHg) and a decrease in PPV (17%) and SVV (16%). Because PPV and SVV values remained high, additional volume expansion was performed. Finally, four fluid challenges (total of 1,000 ml 6% hydroxyethyl starch) were performed in the operating room and resulted in hemodynamic stability (heart rate = 75 beats/min, MAP = 72 mmHg, SV = 78 ml, PPV = 8%, and SVV = 6%).

At the end of the surgery during skin closure, the patient progressively presented hypotension (MAP = 60 mmHg) and a decrease in SV (59 ml), whereas SVV and PPV values remained stable (7 and 8%). Oxygen desaturation led to an increase in F_{IO_2} (70%) and to initiate positive end expiratory pressure (8 cm H_2O). Despite a large decrease in SV, fluid was not administered because of low PPV/SVV values and of hypoxemia. Norepinephrine infusion was started (0.5 $\mu g \cdot kg^{-1} \cdot min^{-1}$) and the patient was transferred to the intensive care unit under mechanical ventilation and general anesthesia.

Intensive Care Unit

In the intensive care unit (ICU), mechanical ventilation was done using a tidal volume of 6 ml/kg, respiratory rate of 20/min, positive end-expiratory pressure of 12 cm H_2O, F_{IO_2} = 75%, and inspiratory/expiratory ratio of 1/1.5. Chest x-ray did not show any sign of overload. The patient presented with tachycardia (heart rate = 92 beats/min), hypotension (MAP = 61 mmHg), low SV (62 ml), and high PPV and SVV values (17% and 18%, respectively). A passive leg-raising test was performed and did not show any preload dependence (lack of increase in SV). Interestingly, this maneuver did not induce a decrease in PPV or SVV. Transesophageal echocardiography was performed and revealed normal left ventricular function and a right ventricular dysfunction as manifested by right ventricle dilation, tricuspid insufficiency, and pulmonary hypertension (systolic pulmonary arterial pressure = 51 mmHg). This right heart dysfunction was probably due to high positive end expiratory pressure level and explained the false-positive PPV and SVV values. The patient immediately received an increase dosage of norepinephrine and the positive end expiratory pressure was decreased to 4 cm H_2O. Mechanical ventilation was performed for 5 days. He stayed in the ICU for 9 days and was in the hospital for 21 days.

Discussion

Basic Science

Mechanical ventilation induces cyclic changes in intrathoracic and transpulmonary pressures (alveolar pressure – pleural pressure) resulting in cyclic changes in stroke volume. Four mechanisms participate in these cyclic stroke volume changes.[3] First, the inspiratory increase in pleural pressure

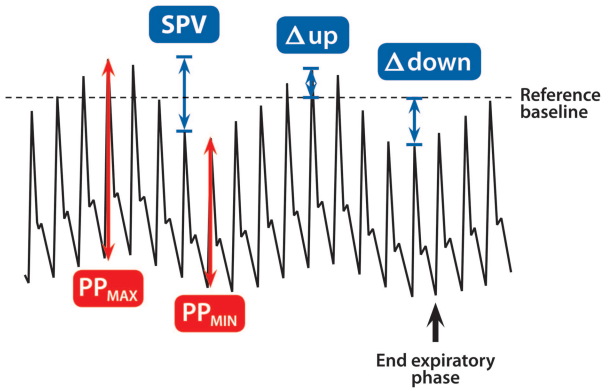

Fig. 1. Mechanical ventilation induced variations in the arterial pressure curve. Four indexes are noted. PP_{MAX} = pulse pressure maximal, PP_{MIN} = pulse pressure minimal, SPV = systolic pressure variations, Δdown = deltadown, Δup = deltaup.

induces a decrease in pressure gradient for venous return and a right ventricular preload reduction. Second, the increase in transpulmonary pressure induces an increase in the right ventricular afterload. Both mechanisms lead to a decrease in right ventricular SV that reaches its nadir during the inspiratory period. After blood pulmonary transit, the decrease in right ventricular SV induces a decrease in left ventricular filling and left ventricular SV that reaches its nadir during the expiratory period. Third, during inspiration, blood is squeezed out of the pulmonary capillaries toward the left side of the heart, thus increasing left ventricular preload. This mechanism is a minor determinant of respiratory-induced changes in left ventricular SV, except in the case of hypervolemia. Fourth, left ventricular afterload decreases during inspiration because positive pleural pressure decreases the intracardiac systolic pressure and the transmural pressure of the intrathoracic part of the aorta. This mechanism is present in the event of left ventricular systolic dysfunction. In summary, mechanical ventilation induces cyclic changes in left ventricular SV that determine the maximal and minimal values of systolic blood pressure. When the heart operates on the steep portion of the Frank-Starling curve, these respiratory variations are large because slight changes in right ventricular preload induced by mechanical ventilation induce significant changes in SV. In contrast, when the heart operates on the plateau of the Frank-Starling curve, these respiratory variations are small. These respiratory variations have been used clinically to assess preload status and predict fluid responsiveness in mechanically ventilated patients under general anesthesia.

Which Is the Best Variable: SPV, ΔDown, PPV, or SVV?

Four dynamic indices are now available for predicting fluid responsiveness (fig. 1). SPV are defined as the difference between maximal and minimal values of systolic blood pressure during one respiratory cycle.[2] Using the systolic pressure at end expiratory as a reference point or baseline, the SPV can

$$PPV\ (\%) = \frac{PP_{MAX} - PP_{MIN}}{(PP_{MAX} + PP_{MIN})/2} \times 100$$

$$SVV\ (\%) = \frac{SV_{MAX} - SV_{MIN}}{(SV_{MAX} + SV_{MIN})/2} \times 100$$

Fig. 2. Pulse pressure variations and stroke volume variations formulae. PP = pulse pressure; PPV = pulse pressure variation, SV = stroke volume; SVV = stroke volume variation

be divided into two components: an increase (Δup) and a decrease (Δdown) in systolic pressure *versus* baseline. The Δdown component is promoted by two different mechanisms: a decrease in systemic venous return and an increase in right ventricular afterload. Thus, a large value of the Δdown component may be due to a preload effect (where volume expansion may be indicated) or an afterload effect (where volume expansion is not indicated and right ventricular afterload has to be decreased). Echocardiography is of major importance in differentiating these two mechanisms. Collapse of the superior vena cava indicates a preload effect, whereas right ventricular output impedance analysis may indicate an afterload effect.[4] The Δup component may be due to an increase in left ventricular preload secondary to a blood shift out of the pulmonary capillaries toward the left side of the heart (present in patient with volume overload) or a decrease in left ventricular afterload, improving left ventricular ejection during tidal ventilation (present in patients with a failed after-load-dependent left ventricle).[5] It has been shown that SPV are related to the fluid status, and that they are able to predict an increase in cardiac output after a volume expansion.[2,6] Likewise, the Δdown component is sensitive to hypovolemia and is able to predict fluid responsiveness.[6]

Pulse pressure is defined as the difference between the systolic and the diastolic pressure and is related to left ventricular SV. Michard *et al.* demonstrated that respiratory changes in pulse pressure (or PPV) were able to predict fluid responsiveness in septic patients under mechanical ventilation[7] (fig. 2.). Many subsequent studies confirmed these results.[1] Finally, SVV is the physiologic variable that needs to be measured when assessing cardiopulmonary interaction (fig. 2). Many studies have demonstrated that SVV measured using pulse contour analysis is able to discriminate *a priori* responders to fluid expansion.[1] Few studies have compared the ability of these indexes to predict fluid responsiveness (table 1). The main interest of systolic pressure variations (SPV) is that it is easier to manually calculate than PPV and that it may consequently be more widely applicable. Michard *et al.* were the first to compare PPV and SPV and found that PPV was superior to SPV for assessing fluid responsiveness.[7] A recent meta-analysis including 29 studies and 685 patients confirmed that SPV, PPV, and SVV were robust indicators of fluid responsiveness. By an analysis of six studies including 136 patients comparing SPV and PPV, the authors concluded that PPV was superior to SPV.[1] However, none of the

Table 1. Advantages and Disadvantages for Systolic Pressure Variations, Pulse Pressure Variations, Stroke Volume Variations, and ΔDown

	Advantage	Disadvantage
Systolic pressure variations	Easy to manually calculate	Depends on diastolic pressure and on changes in pleural pressure
Pulse pressure variations	Directly related to stroke volume variations	Not easy to manually calculate Need specific device for continuous display
Stroke volume variations	Accurate analysis despite multiple extrasystoles	Need specific device
ΔDown	Easy to manually calculate	No continuous display Need an end expiratory pause

studies were designed to specifically compare SPV and PPV and their samples were relatively small.

What Is the Optimal Threshold for PPV, SVV, and SPV?

Some studies evaluating dynamic index used receiver operating curves. An "optimal" threshold is proposed for PPV/SVV/SPV or Δdown with supposed acceptable sensitivity and specificity. These optimal thresholds may vary from 9% to 15% for PPV and SVV for example, depending of the definition of responders to volume expansion and the type and the quantity of fluid administered. Cannesson *et al.* [9] underlined that choosing a single threshold is simplistic because clinical practice is not a "black or white" situation in which patients are either responders or nonresponders. They proposed a new method with a three-zone partition containing two thresholds: a lower limit allowing for an optimal negative likelihood ratio and an upper limit allowing for an optimal positive likelihood ratio. The zone between these two limits is called the gray zone. Values in this gray zone are inconclusive and patients may be responders or not to fluid challenge. Using this method, Cannesson *et al.* demonstrated that the gray zone approach identified a range of PPV values between 9% and 13% for which fluid responsiveness could not be reliably predicted.[8,9] Comparing SPV and PPV using this approach would probably show no difference between these two parameters.

Is an Arterial Catheter Needed to Assess Heart-Lung Interaction?

A major limitation for the clinical use of these indexes is that an arterial catheter is required. However, cardiopulmonary interaction may be assessed noninvasively. SVV may be measured directly at the level of the heart by using echocardiography.[10] This technique is noninvasive and precludes errors in SVV measured peripherally.[11] Although chocardiography is a helpful diagnostic tool, it does not allow continuous monitoring. Thus, SVV may be calculated but cannot be monitored using this device. Another approach consists in analyzing respiratory variations of the plethysmographic waveform. Several studies have shown that respiratory variations of the plethysmographic waveform is strongly correlated with PPV and can predict fluid responsiveness in mechanically ventilated patients in the operating room and the ICU.[12] It is sensitive to vasomotor tone, which strongly affects its waveform. Thus, the results are more encouraging in the operating room (deep general anesthesia) than in intensive care (vasopressor use).[13,14] Furthermore, a noninvasive arterial curve may be obtained using a finger cuff. The technique has been used for many years but its accuracy was insufficient (Finapress™, Ohmeda Monitoring Systems, Englewood, CO).[15] Recently, however, satisfactory precision has been obtained with it.[16] Interestingly, the respiratory variations in PPV obtained using this noninvasive arterial waveform have the ability, like invasive PPV, to predict fluid responsiveness in the operating room.[17] Automated algorithms have been developed and remain to be validated.

Automated Assessment of Respiratory Variations

To be used by the physician at the patient's bedside, dynamic variables have to be displayed continuously and automatically. Besides cardiac output, several monitors display automated and continuous PPV and/or SVV calculation, but require specific equipment.[18] On the other hand, some algorithms for PPV monitoring are proposed alone. Auler *et al.*[19] validated a PPV calculation algorithm using a capnograph and Pestel *et al.*[20] proposed automated calculation of PPV and SPV. Cannesson *et al.*[21] proposed an algorithm for PPV monitoring that has been implemented on Phillips Intellivue MP70 monitors (Philips, Suresnes, France) and validated in the operating room. Finally, respiratory variations of the plethysmographic waveform may be automatically and continuously measured using the Pleth Variability Index algorithm. It has been validated in the operating room and the ICU but depends (as do other variables derived from plethysmographic waveform) on vasomotor tone and norepinephrine use.[13,22,23]

What Are the Limitations of Dynamic Index of Fluid Responsiveness?

Respiratory variations in SV are based on heart-lung interactions. To predict fluid responsiveness, they have to be measured in specific conditions (table 2). "Classic limitations" for dynamic index of fluid responsiveness use are spontaneous breathing activity, arrhythmia, open chest, intraabdominal hypertension, low tidal volume, right ventricular failure, acute respiratory distress syndrome, and heart rate and respi-

Table 2. Limitation of Dynamic Index

	Type of Error
Tidal volume < 8 ml/kg	False negative
Heart rate/respiratory rate ratio < 3.6	False negative
Open chest	False negative
Arrhythmia	False positive and/or false negative
Respiratory effort	False positive and/or false negative
Intraabdominal hypertension	False positive
Right ventricular failure	False positive

ratory rate ratio less than 3.6.[1,3,24–27] Furthermore, vasopressor therapy may interfere with the interpretation of dynamic index and have to be taken into account. Concerning arrhythmia, some companies recently developed a new SVV algorithm (SVVXtra) designed to detect and eliminate extrasystoles and to reconstruct the arterial waveform to calculate SVV. This is a major advance in this setting because extrasystoles are relatively frequent in the ICU and operating room. The algorithm has been validated in an experimental study.[28]

In the operating room setting, Maguire *et al.* studied retrospectively more than 12,000 procedures and demonstrated that heart-lung interactions can be interpreted to predict fluid responsiveness noninvasively in 39% of patients and invasively in 23% of them.[29] The main reasons were spontaneous breathing activity during loco-regional anesthesia and low tidal volume. Limitations for the use of dynamic variables are probably more frequent in the ICU than in the operating room (even if no data are currently available). Patients more frequently present spontaneous breathing (because sedation is stopped as soon as possible), small tidal volumes are recommended to prevent ventilator-induced lung injury, right heart disease may lead to false-positive results, and norepinephrine is frequently used. In such cases and to know which part of the Frank-Starling curve is concerned by the patient's ventricle, other tests may be performed such as the passive leg-raising test, an end-expiratory occlusion test, or a mini-fluid challenge.[30–32]

Passive leg-raising is a simple, reversible maneuver that mimics rapid fluid loading. It transiently and reversibly increases venous return by shifting venous blood from the leg and the splanchnic reservoir to the intrathoracic compartment. If both ventricles are fluid-responsive, the increase in preload induced by passive leg-raising will induce and increase in left ventricular SV. On the contrary, if neither ventricle is fluid-responsive, the increase in preload induced by passive leg-raising will not induce and increase in left ventricular passive leg-raising. Passive leg-raising is effective even in patients with arrhythmia or spontaneous ventilation. The end-expiratory occlusion test consists in a short end-expiratory occlusion that prevents the cyclic impediment in left cardiac preload, thus acting like a fluid challenge.[30] An increase in cardiac output during this maneuver indicates fluid-responsive ventricles. The test may be performed even in the event of arrhythmia. Finally, exploring another physiopathologic concept, Muller *et al.* investigated the original concept of "mini-fluid challenge."[32] The increase in SV induced by rapid infusion of a low volume of fluid is strongly related to the increase in SV induced by a greater quantity of fluid (*e.g.*, 500 ml). Thus, the response to a "mini-fluid challenge" could predict the effect of a larger infusion. Furthermore, by using a low volume for this "mini-fluid challenge," the deleterious effects of fluid among nonresponders would hypothetically be limited.

PPV/SVV and Vasopressors Therapy: What Happens?

Several studies evaluated the effect of vasopressor use on the absolute value of PPV and SVV and on their ability to predict fluid responsiveness. Nouira *et al.* demonstrated in an experimental setting that norepinephrine induces a significant decrease in SPV and PPV in hemorrhagic shock conditions.[33] Even if the study was not designed to answer this question, it may be hypothesized that by constricting the capacitance vessels, norepinephrine shifts blood from unstressed to stressed volumes, thereby increasing venous return. Another mechanism could be a modification in arterial elastance leading to a decrease in PPV. In another experimental study, Renner *et al.* found that in normovolemic conditions, norepinephrine did not induce any variation in SVV or PPV.[34] In any case, norepinephrine use has to be taken into account for PPV interpretation.

Should Fluid Challenge Be Systematically Performed When PPV Values Are High?

A frequently heard comment from residents is: "I performed fluid expansion because SPV/PPV or SVV values were high." A key point in the interpretation and the use of dynamic index is knowing what to do when SPV/PPV or SVV values are high (fig. 3). First, the quality of the waveform has to be taken into account and the arterial line has to be flushed. PPV/SVV/SPV calculation may potentially be affected by reflecting waves and damping. In addition, the perfusion index has to be known when using Pleth Variability Index algorithm. Second, one should ensure that the conditions in which dynamic index are effective have been obtained (see Discussion). Third, if PPV values are in the gray zone and consequently inconclusive, other tests have to be performed, *e.g.*, passive leg raising, end-expiratory occlusion test, or mini-fluid challenge) to determine whether a patient will respond to fluid administration. Fourth, a fundamental point is that fluid responsiveness does not mean that fluid is needed. Patients should not receive fluid only because SPV/SVV or PPV values are high.[35] A clinical approach has to be considered to know whether a patient needs an increase in SV. Clinical or biologic signs of inadequate tissue perfusion (*i.e.*, low systolic blood pressure, tachycardia, presence of skin mottling, oliguria, biologic signs of acute renal failure) have to be taken into account and could trigger fluid administration. Then, dynamic index are useful to discriminate *a priori* patients who will or will not respond to volume expansion.

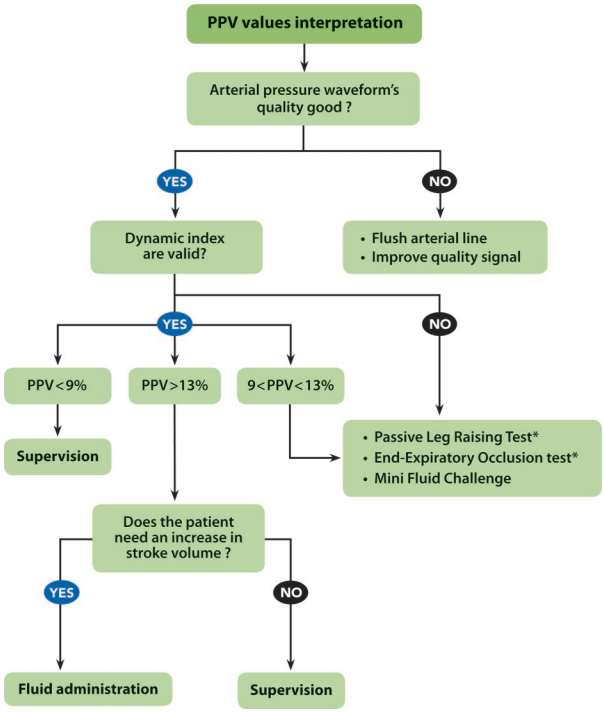

Fig. 3. Algorithm for the analysis of pulse pressure variation (PPV) values. Asterisks denote with respect of specific limitations of their use.

A specific setting in the operating room is the immediate period after induction of anesthesia. Arterial pressure decreases and PPV/SVV or SPV increase because of a vasoplegia induced by the anesthetic drugs. Should we systematically perform fluid expansion after the induction of the anesthesia because of high PPV values or should we use a vasopressor? This is a difficult question that using only dynamic index cannot answer, so it seems that vasopressor use is logical.

Fluid Challenge Did Not Induce a Decrease in PPV: What Could That Mean?

Fluid challenge is performed to increase SV and to bring the ventricle to the flat portion of the Frank-Starling curve Thus, it should induce a decrease in PPV/SVV or SPV. If it does not do this, the first questions have to be: "did I give enough fluid?" and "did my volume expansion induce a significant increase in preload?" If so, there could be a false- positive result in the dynamic index and particularly right heart dysfunction. Right ventricular dysfunction leads to a decrease in right ventricular ejection during the inspiratory increase of right ventricular afterload. Thus, right ventricular dysfunction could involve high Δdown values through an afterload effect, whereas the preload effect is negligible. PPV take the Δup and Δdown components into account. High Δdown values induce high PPV values and false positives. Recently, Mahjoub *et al.* reported a failure to predict fluid responsiveness by PPV in patients who had echocardiographic findings suggestive of right ventricular systolic dysfunction.[27] Furthermore, it has been shown in human and experimental studies that PPV cannot be used to predict fluid responsiveness in the event of increased pulmonary artery pressure.[36,37]

Estimating Arterial Elastance Using Heart-Lung Interaction (PPV/SVV Ratio)

Apart from fluid responsiveness, another possible use of heart-lung interaction is the estimation of arterial tone. Indeed, physiologically, the PPV/SVV ratio defines arterial tone. The latter has already been studied during pharmacologic variations of vascular tone or during volume expansion.[38,39] For example, in a clinical study including 25 patients, Monge-Garcia *et al.* demonstrated that a functional assessment of dynamic arterial elastance evaluated by the PPV/SVV ratio predicted arterial response after volume loading in hypotensive, preload-dependent patients under controlled mechanical ventilation.[39] Other work focusing on its potential clinical applications is required.

Knowledge Gap and Research Perspectives

In the operating room, the concept of supranormal oxygen transport values as a therapeutic goal has been validated in high-risk surgical patients. Several studies have shown that perioperative oxygen delivery maximization (which is proportional to cardiac output, hemoglobin and arterial oxygen saturation) in high-risk surgical patients decreases the length of stay in the ICU and in hospital, while decreasing morbidity and mortality. Moreover, several studies have demonstrated that perioperative cardiac output maximization is able to decrease the length of hospital stay and ICU admissions, and may influence long-term outcome.[40] Most of these studies used colloid titration to increase cardiac output by leading patients to the plateau of the Frank-Starling curve. Cardiac output maximization was performed using cardiac output monitoring (the plateau of the Frank-Starling curve is achieved when cardiac output no longer increases after fluid challenge). However, a recent survey among North American and European anesthesiologists showed a considerable gap between accumulated evidence about the benefits of perioperative hemodynamic optimization and actual clinical practices in both Europe and the United States.[41] One of the explanations may be that semiinvasive cardiac output monitoring is not widely known or used. On the other hand, heart-lung interactions are used by 45–55% of anesthesiologists. Thus, a question that will have to be explored is the following: is PPV-guided fluid management able to improve patient outcome? Should we monitor and maximize cardiac output or should we rely on SPV/SVV/PPV or both? We have seen that heart-lung interactions may now be assessed continuously and noninvasively. Thus, they could theoretically be used to maximize cardiac output in the operating room. Few published clinical studies have evaluated the effect of cardiac output maximization using heart-lung interaction on patient outcome with conflicting results.[40] Even if data available today are not strong enough to support the use of heart-lung interaction-based protocols for fluid management

in the operating room, results based on low sample size are very interesting. Large studies are currently recruiting and the issue should be resolved once results are published. The main challenges of future studies are to define (1) target population that can benefit from perioperative hemodynamic optimization according to their medical history and the type of surgery, (2) algorithms including the specific place of dynamic parameters, and (3) the best threshold values of PPV/SVV/SPV or Δdown that could trigger fluid administration.

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ANESTHESIOLOGY REFLECTIONS FROM THE WOOD LIBRARY-MUSEUM

Casing Cunningham's Apparatus

A future pioneer of hyperbaric medicine from the University of Kansas, Anesthetist-in-Chief Orval J. Cunningham, M.D., was initially hailed by academics in 1908 for designing what he later called his "O. J. Cunningham Nitrous Oxide and Oxygen-Ether Sequence Apparatus." Unfortunately the Kansas City manufacturer that Cunningham chose to produce his namesake apparatus, George Key, used a metallic alloy that oxidized over the years, yielding a brittle device today whose legs and gas-cylinder yokes snap off under incredibly little duress. Perhaps this manufacturing flaw explains why this, the only example extant, has its one yoke cracked (*above, circled in red*) and its other one completely amputated. To curatorially hand-carry this fragile item aboard a jet, I fashioned a foam-padded case inside a suitcase as carry-on luggage. In spite of the Cunningham Apparatus' having hollow chambers, metal pipes, ominous looking dials, etc., airport security never stopped me to examine this suspicious carry-on . . . . (Copyright © the American Society of Anesthesiologists, Inc.)

George S. Bause, M.D., M.P.H., Honorary Curator, ASA's Wood Library-Museum of Anesthesiology, Park Ridge, Illinois, and Clinical Associate Professor, Case Western Reserve University, Cleveland, Ohio. UJYC@aol.com.