

Comparison between Respiratory Variations in Pulse Oximetry Plethysmographic Waveform Amplitude and Arterial Pulse Pressure during Major Abdominal Surgery

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ABSTRACT

Background: To assess preload dependence, the variation of the plethysmographic waveform of pulse oximetry (Δ POP) has been proposed as a surrogate of the pulse pressure variation (Δ PP). The aim of the study was to assess the ability of the pulse oximeter-derived plethysmographic analysis to accurately trend Δ PP in patients undergoing major abdominal surgery by using standard monitors.

Methods: A continuous recording of arterial and plethysmographic waveform was performed in 43 patients undergoing abdominal surgery. Δ PP and Δ POP were calculated on validated respiratory cycles.

Results: For analysis, 92,467 respiratory cycles were kept (73.5% of cycles recorded in 40 patients). The mean of intra-patient coefficients of correlation was low ($r^2 = 0.22$). The Bland and Altman analysis showed a systematic bias of 5.21; the Δ POP being greater than the Δ PP, this bias increased with the mean value of the two indices and the limits of agreement were wide (upper 21.7% and lower -11.3%). Considering a Δ PP threshold at 12% to classify respiratory cycles as responders and nonresponders, the corresponding best cutoff value of Δ POP was $13.6 \pm 4.3\%$. Using these threshold values, the observed classification agreement was moderate ($\kappa = 0.50 \pm 0.09$).

Conclusion: The wide limits of agreement between Δ PP and Δ POP and the weak correlation between both values cast doubt regarding the ability of Δ POP to substitute Δ PP to follow trend in preload dependence and classify respiratory cycles as responders or nonresponders using standard monitor during anesthesia for major abdominal surgery.

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What We Already Know about This Topic

- Optimal cardiac outputs during surgery may improve perioperative outcomes but require specific device

What This Article Tells Us That Is New

- Arterial pulse pressure variations were compared to the non-invasive measurement of the plethysmographic waveform of pulse oximetry in 40 patients who underwent abdominal surgeries
- The noninvasive measurement had a poor correlation with the arterial pulse pressure variation

SEVERAL studies have demonstrated that intraoperative optimization of cardiac output improves postoperative outcomes.^{1–4} Preload assessment and continuous monitoring of preload dependence have therefore gained huge interest in the achievement of hemodynamic stability and adequate tissue perfusion. In this respect, dynamic indices have been increasingly proposed to predict fluid responsiveness and guide volume replacement. Such indices have been recently used for intraoperative goal-directed fluid management in some studies.^{5,6}

Although no gold standard has been clearly identified among the dynamic indices, the pulse pressure variations (Δ PP) induced by positive pressure ventilation has been shown to hold the highest sensitivity and specificity.⁷ A value of Δ PP greater than a threshold value from 11 to 13% is predictive of an increase in cardiac output after volume loading.⁸ The Δ PP expresses the cyclic variations of pulse pressure (PP) induced by cardiac preload changes after pleural pressure swings. In accordance with Franck Starling curve, the greater the variations are, the more dependent to preload the ventricle is. However, Δ PP monitoring requires the placement of an arterial line and remains an invasive method limiting its use. A noninvasive dynamic parameter, the variation of the plethysmographic waveform of pulse oximetry (Δ POP) has been proposed as a surrogate of the Δ PP. This

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noninvasive alternative would be attractive to extend a goal-directed fluid management in the operative room to patients not requiring an arterial line. However, results of studies comparing the clinical use of the two dynamic indices are conflicting. Although most of them report a good predictive value of Δ POP for fluid responsiveness in the operating room or in the intensive care unit, its threshold value varies from 9 to 15%.^{9–12} The correlations between Δ PP and Δ POP have been found to be poor^{13,14} or strong,^{11,15,16} and even in this later case, the limits of agreement according to the Bland and Altman method are wide.^{15,17}

Numerous accounts have been provided to explain the discrepancies between both methods: site of measurements, signal processing of the plethysmogram, oscillation of the sympathetic system activity, or thermoregulation. All these factors are not exclusive and could be brought into play during patient monitoring. This could impair the ability of the plethysmographic derived parameters to follow the pulse pressure variations. As plethysmography is gaining wide acceptance in order to estimate the fluid responsiveness during anesthesia, our aim was to assess the ability of the plethysmographic method to trend Δ PP variations in the actual operating room environment by using standard monitors in patients undergoing major abdominal surgery.

Materials and Methods

Patients

This observational study was performed after approval by an ethical committee (Comité de Protection des Patients Sud Est 3, Lyon, France). Written consent was not required for this observational study of current care. Forty-three patients scheduled for major abdominal surgery were included. Patients with cardiac arrhythmias, obvious impaired ventricular function, less than 18 yr old, or undergoing surgery under laparoscopy were excluded.

Protocol

Anesthesia was carried out according to the standard of care of our institution. The induction was performed with propofol, remifentanyl, and cisatracurium, then anesthesia was maintained with desflurane, cisatracurium, and remifentanyl. During all procedures, the depth of anesthesia was monitored by bispectral analysis (BISx Aspect®; Aspect Medical Systems, Inc., Norwood, MA) with an objective of bispectral index between 40 and 50. Epidural anesthesia was used during surgery according to the attending physician decision. Patients were ventilated in a volume- or pressure-controlled mode with a tidal volume (V_T) of 8–10 ml/kg of ideal body weight. The respiratory frequency was set to maintain expiratory carbon dioxide between 30–35 mmHg. The positive end-expiratory pressure was set below 5 cm H₂O according to the attending physician. Fluid management was at the discretion of the physician. During liver transplantations, transesophageal echocardiography was used. To minimize

intraoperative hypothermia, forced-air warming mattresses and fluid warmer were used.

Intraoperative Monitoring and Data Acquisitions

Patients were monitored using a 20-G radial arterial catheter (Seldicath® 3-French; Plastimed, Saint Leu la Forêt, France) and a pulse oximeter probe (Philips Medical Systems MP70®, Suresnes, France). The oximeter probe was placed on the third finger of the hand at the same side as the arterial catheter. At the same time, airway pressure was recorded. These three signals were sampled together at 125 Hz and stored in a laptop computer using a data acquisition software (TrendfaceSolo® 1.1; Ixellence GmbH, Wildau, Germany) for further processing. Acquisitions started after arterial line placement and stopped at the end of abdominal surgery before spontaneous breathing.

Data Analysis

By using signal visualization (AcqKnowledge®, version 3.7.3; Microsoft Corporation, Seattle, WA), we were able to manually delete grossly abnormal signals due to probe movements, arterial line flush, or movements. Then by using the AcqKnowledge® program analysis, the maximum and minimum of each arterial and plethysmographic pulse, the corresponding heart rate and airway pressure were identified and stored on an spreadsheet (Excel®, edition 2007, Microsoft Corporation). A homemade Excel® program allowed automatic deletion of noisy signals and could be briefly described as follows. A waveform analysis applied on the airway pressure values identified the onset of each respiratory cycle. Then each value of systolic arterial pressure, maximum plethysmographic oximetry, and heart rate was compared with their respective average of the six preceding respiratory cycles. If a difference greater than 2.5 SD of this moving average was found, the respiratory cycle was disregarded from the analysis. These values were considered a suitable compromise between the need to delete noisy signals such as premature contractions or instability of the plethysmographic signal and the requirement to keep sharp variations of signal in the analysis. Then Δ PP and Δ POP were automatically calculated for each respiratory cycle kept suitable for analysis as follows: Δ PP = $(PP_{\max} - PP_{\min}) / [(PP_{\max} + PP_{\min}) / 2]$ and Δ POP = $(POP_{\max} - POP_{\min}) / [(POP_{\max} + POP_{\min}) / 2]$. Before final analysis, the same moving average filtering was carried out on the calculated Δ PP and Δ POP values.

Statistical Analysis

Normality of distribution was tested before any statistical evaluation by using the Kolmogorov–Smirnov method. Descriptive statistical data were reported as mean \pm SD. Except for the bias between both methods, all the means were calculated from the 40 individual mean values. The bias between both methods was calculated from all data together from validated cycles. Comparisons between Δ PP and Δ POP were performed with a paired Student *t* test.

Δ PP and Δ POP were compared using Bland and Altman analysis taking into account repeated measurements and the case where the measured value varies.¹⁸ In order to evaluate the ability of Δ POP to reliably detect changes in Δ PP, we used a method based on polar plotting of Δ PP and Δ POP changes over consecutive cycles as described by Critchley *et al.*¹⁹ We excluded from this analysis small changes of mean value of Δ PP and Δ POP less than 3%. In this method, a good trending ability requires an angular bias no greater than $\pm 5^\circ$ and an SD for the polar angle of less than $\pm 15^\circ$. In this method, simultaneous changes of each indices of consecutive validated respiratory cycle are reported on a polar plot.¹⁹ The polar angle is derived from the ratio of the changes of the two indices. Such a ratio close to 1 led to a null angle with the x axis; when the ratio diverged from 1 this angle approached a 90° angle. The radius was the mean of the simultaneous changes of the two indices between two consecutive validated respiratory cycles. In these conditions a mean angle and its SD could be calculated.

The strength of linear dependence between Δ PP and Δ POP for all patients and within each patient was measured by the Pearson coefficient of correlation. The mean of correlation coefficients and comparison between correlation coefficients were performed after a Fisher transformation. In order to analyze the ability of Δ POP to correctly classify the respiratory cycle as responder or nonresponder after a volume loading in respect to a theoretical threshold value of Δ PP of 12%, we measured the area under the curve of a receiver operating characteristic (ROC) curve. Then the selected value of Δ POP for each patient was the one that maximized the Youden index (sensitivity + (specificity - 1)). The agreement between the two classifications was quantified by the κ score for each patient, taking as threshold value of Δ POP the individual value determined by the ROC curve. The reported mean values of areas under ROC curves and κ scores were therefore calculated from the 40 individual values. Taking the inpatients' coefficient of correlation as a dependent variable, we estimated its relationship with potentially explanatory variables by using univariate analysis, including Student *t* test for qualitative data and correlation for quantitative data and multivariate analysis by multiple linear regression. Categorical binary variables have been transformed into dummy variables. Other correlations were evaluated by Pearson coefficient. For all statistical procedures, a *P* value less than 0.05 was considered significant. Statistical calculations were performed by using IBM SPSS Statistics 19 (IBM Corporation, Somers, NY).

Results

Forty-three surgical procedures were recorded. Three patients were excluded, two of them for plethysmographic waveforms unsuitable for analysis, and one due to intraoperative occurrence of arrhythmia. The characteristics of the 40 patients included in the study and the surgical procedures carried out are reported in table 1. Data were collected for

Table 1. Main Characteristics of the Patients

Patients, n	40
Age, yr	60 \pm 15
Sex (male/female)	29/11
Previous hypertensive history (yes/no)	18/22
Surgical procedures	
Liver resection	14
Pancreaticoduodenectomy	8
Liver transplantation	6
Oesophagectomy (abdominal period)	6
Abdominoperineal resection	3
Adrenalectomy	1
Intestinal obstruction	1
Biliary tract repair	1
Mean arterial pressure, mmHg	76.2 \pm 7.3
Heart rate, beats/min	69.7 \pm 18.5
Tidal volume (ml/kg ideal body weight)	8.6 \pm 0.7
Respiratory rate/min	12.3 \pm 5.7
Heart and respiratory rate ratio	5.7 \pm 1.2
Positive expiratory pressure, cm H ₂ O	3.9 \pm 1.6
Plateau airway pressure, cm H ₂ O	13.6 \pm 3.5
Minimal perioperative temperature, degrees	35.8 \pm 0.6
Perioperative epidural analgesia (yes/no)	13/27
Continuous vasoconstrictive agent (yes/no)	10/30

All patients received at least one bolus of vasopressive agent. We separated those who received continuous infusion of nor-epinephrine or neosynephrine during more than 10 min. Data are mean \pm SD.

an average of 4.1 ± 2.0 h for each patient, yielding just more than 125,000 respiratory cycles. Of these, 5.7% of the cycles were manually deleted by investigators due to poor quality of signals (*i.e.*, arterial or plethysmographic signal noise, arrhythmias, spontaneous breathing, arterial lines flush). In addition, 22% were discarded by using the automatic software analysis, leaving 73.5% of the initial respiratory cycles for analysis. As a whole, 23.6% of the analyzed respiratory cycles exhibited a Δ PP higher than 12%. Figure 1 gives an example of pressure and plethysmographic recordings, with the corresponding construction of the intracycle loop of the pressure and the plethysmographic signals.

The mean value and coefficient of variation of Δ PP were lower as compared with Δ POP: $8.9 \pm 5.3\%$ versus $14.2 \pm 7.0\%$, and 56.0 ± 14.7 versus 66.2 ± 20.6 , respectively. The correlation between mean values of Δ PP and Δ POP of all patients was highly significant ($r^2 = 0.62$). Conversely, the mean value of inpatient coefficients of correlation was rather low ($r^2 = 0.22$). The Bland and Altman analysis showed a bias of 5.21, whereas the limits of agreement were wide apart, the upper and lower limits of agreement were 21.7 and -11.3%, respectively (fig. 2). The polar plot analysis further confirmed the bias, the mean angle being 21.5°

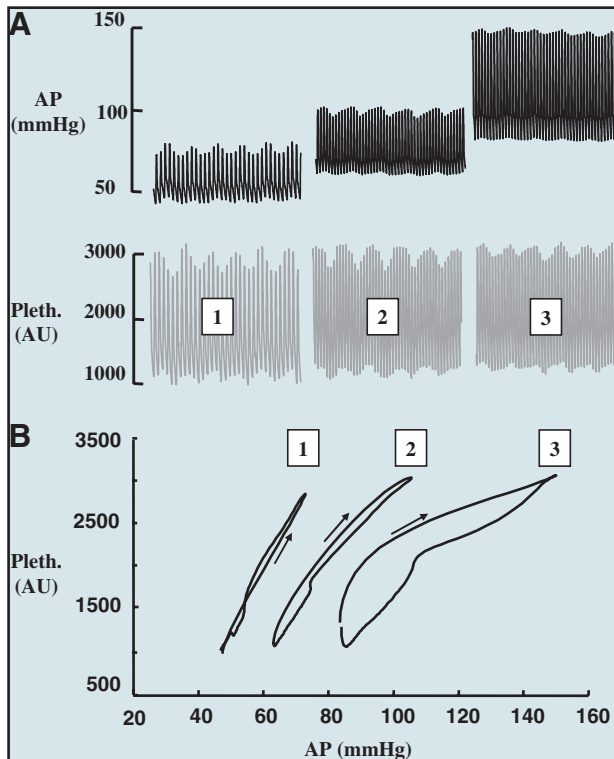


Fig. 1. (A) Example of recordings of arterial pressure (AP) and plethysmographic signals (Pleth.) in a patient at three different levels of AP during an anesthetic procedure. B represents the relationships within a cardiac cycle between arterial and plethysmographic signals at the three different levels of AP. The arrow indicates the increase in AP. It is to be noted that the slope of the loop decreased, whereas its area increased when the AP increased. This is indicative of a change of the recorded compliance and of the phase shift between the two signals, whatever the mechanism (see discussion). AU = arbitrary unit.

$\pm 8.6^\circ$ and the wide variability of the difference between the two indices, the mean of the SD of the angles being $17.7^\circ \pm 4.0^\circ$. Figures 3 and 4 give individual examples of ΔPP and ΔPOP values through an anesthesia with the corresponding Bland and Altman and polar plot analysis.

The analysis of the ability of ΔPOP to correctly predict a preload dependence taking into account a theoretical value of ΔPP of 12% gave a mean area under the ROC curve of 0.76 ± 0.12 with extremes ranging from 0.53 to 0.98. The mean value of the best cutoff value of the ΔPOP was $13.6 \pm 4.3\%$. When using the cutoff value of ΔPOP determined by each patient's individual ROC curve to quantify the agreement between the classification of cycles between responders and nonresponders by the two indices, we observed a κ value of 0.50 ± 0.09 .

We performed a separated analysis for patients who underwent liver transplantation. Indeed, these patients received more vasopressor agents (5/6) than others did. With 40,705 respiratory cycles recorded, 29,054 were analyzed. The mean value of inpatient coefficients of correlation was $r^2 = 0.17$.

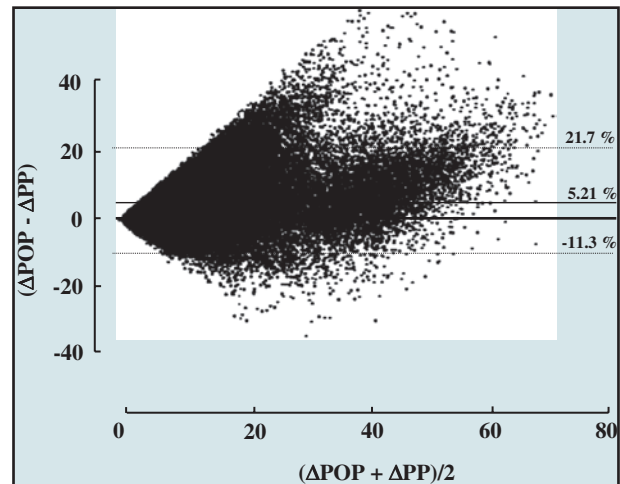


Fig. 2. Bland and Altman representation of all pulse pressure variation (ΔPP) and variation of the plethysmographic waveform of pulse oximetry (ΔPOP) values ($N = 92,467$). Bias was $5.3 \pm 1.6\%$ and limits of agreement were wide apart between 21.7% and -11.3% . The shape of the graph showed that the bias increased with the mean value of ΔPP and ΔPOP according to the following equation: $y = 0.34x + 0.81$ ($r^2 = 0.166$ - P value less than 0.0001). Bias is noted as mean \pm SD.

The mean area under the ROC curve was 0.80 ± 0.15 and the κ score was 0.51 ± 0.09 . These results were not significantly different from those obtained for nontransplanted patients.

For individual patients, the probability to have a ΔPP above 12% was dependent on the ratio of heart rate to respiratory rates ($r^2 = 0.261$), but not on the end-inspiratory plateau pressure or tidal volume.

Finally, using the coefficients of correlation between ΔPP and ΔPOP of each patient as the dependent variable, we searched by univariate analysis a relationship with the hypertensive history, the tidal volume, the peroperative minimal temperature, the mean arterial systolic pressure, the positive end-expiratory pressure, the use of continuous administration of vasoconstrictive agent, the ratio of heart and respiratory rates, the peroperative use of epidural anesthesia, and the percentage of ΔPP greater than 12%. A relationship was observed only with the last variable. Using a multivariate analysis, we found the presence of an epidural anesthesia and the percentage of ΔPP greater than 12% correlated with the inpatient coefficients of correlation. Patients with an epidural anesthesia had a lower coefficient of correlation (table 2).

Discussion

This study showed a poor correlation between ΔPP and ΔPOP in patients undergoing major abdominal surgery. Moreover, we observed a κ value indicating a moderate agreement. The Bland and Altman analysis showed a systematic bias, the ΔPOP being greater than the ΔPP ; this bias increased with the mean value of the two indices and the limits of agreement were found wide. When considering the ability of ΔPOP to follow ΔPP variations with a polar plot

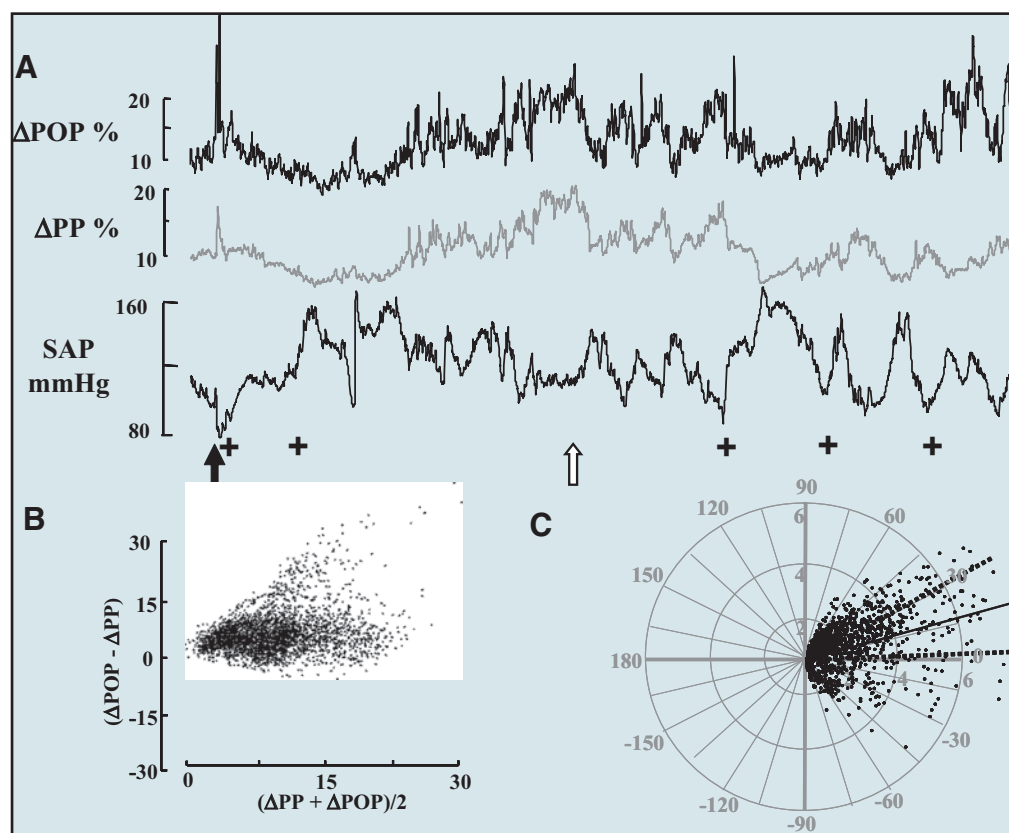


Fig. 3. Example of 6.2-h recordings in a 68-yr-old patient undergoing right hepatectomy in whom pulse pressure variation (ΔPP) and variation of the plethysmographic waveform of pulse oximetry (ΔPOP) were well correlated ($r^2 = 0.52$). (A) Variations in ΔPOP , ΔPP , and systolic arterial pressure (SAP). Salient events are indicated at the bottom: insertion of upper abdominal wall retractor (filled upward arrow), bolus phenylephrine administration (plus sign), and volume loading (open upward arrow). Variations of ΔPP and ΔPOP were roughly parallel. (B) Bland and Altman analysis for ΔPP and ΔPOP showed a bias of 1.2% according to the following equation $y = 0.19x - 1.90$ ($r^2 = 0.03$ – P value less than 0.0001). (C) Polar plot showing relation between variations of ΔPP and ΔPOP . The angle was $16.3 \pm 14.4^\circ$.

analysis, this later confirmed the systematic bias, with a wide variability.

The acquisition of our data involved several steps before being analyzed. The first one is manual deletion after visual examination of the original recordings. This allowed us to disregard grossly abnormal signals. This step left minor instability of signals, or arrhythmias. This is the purpose of homemade software using classical methodology to further eliminate such abnormal data. Our results showed that, being performed in actual operative conditions, more than 70% of the cycles could be simultaneously analyzed. Other circumstances of recording satisfied the usual conditions of measurement of dynamic indices of preload dependence, namely mechanical ventilation on a volume or pressure-controlled mode, a tidal volume greater than 8 ml/kg of ideal body weight, and a ratio between heart and respiratory rates greater than 3.6 (only one patient under 3.6, extreme ranges were 3.4–8.2).^{20,21}

Several studies have already investigated the clinical interest of plethysmographic waveform in comparison to arterial pressure variations. Considering only those taking into account the pulse pressure or plethysmographic variations, they reported a good or a weak predictive value of ΔPOP of

fluid responsiveness after volume loading.^{9,10,12,17} When correlations were evaluated, the r^2 values ranged from 0.38 to 0.83.^{9,11,12,15,16} These values were close to r^2 that we found for the correlation of mean values of ΔPP and ΔPOP for all patients ($r^2 = 0.62$), but well above the mean value of intra-patient correlation ($r^2 = 0.22$). Owing to their study design, all these works reported correlation between data acquired at selected points, most of the time before and after fluid challenge. As a whole, both indices correlated fairly well, as did the mean value we recorded throughout the anesthetic procedure. But the actual question is whether the ΔPOP is able to follow the ΔPP variations on a continuous basis. The Bland and Altman analysis is a former way to answer the question. Regarding the results of the previous mentioned studies, the reported SD of the mean difference between ΔPP and ΔPOP ranged from 3.2 to 7%.^{9,17} These values of SD yielded precision error (SD/mean value) well above the usually accepted threshold of 30% for the interchangeability of two measurement methods. Our own results from 21.7 to –11.3% agree with these large limits of agreement. As a new method has been recently reported aiming at performing trending ability of cardiac output monitors, we applied it

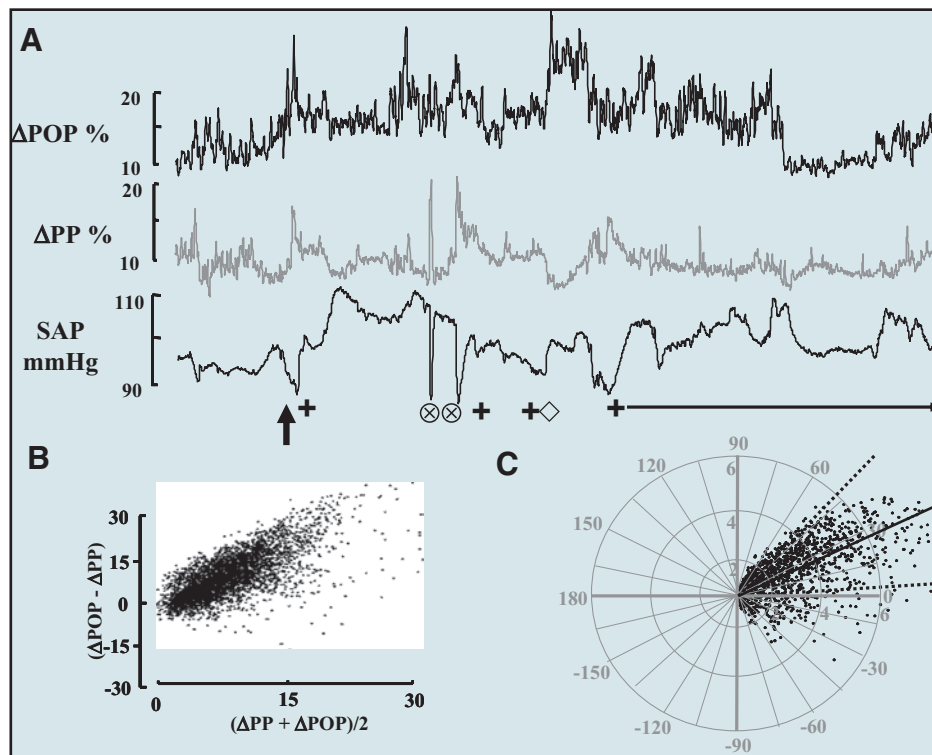


Fig. 4. Example of 6.0-h recordings in a 62-yr-old patient undergoing liver transplantation in whom pulse pressure variation (ΔPP) and variation of the plethysmographic waveform of pulse oximetry (ΔPOP) were poorly correlated ($r^2 = 0.05$). (A) Variations in ΔPOP , in ΔPP , and systolic arterial pressure (SAP). Salient events are indicated at the bottom: insertion of upper abdominal wall retractor (filled upward arrow), bolus phenylephrine administration (plus sign), brief episode of inferior vena cava clamping (stop sign), declamping of portal vein (open diamond) after a phenylephrine administration. This period was associated with an opposite variation of ΔPP and ΔPOP . The last phenylephrine administration was followed by a continuous norepinephrine infusion (right arrow). (B) Bland and Altman analysis for ΔPP and ΔPOP showed a bias (5.6%) which increased with the mean value of ΔPP and ΔPOP according to the following equation $y = 1.19x - 6.64$ ($r^2 = 0.51 - P$ value less than 0.0001). (C) Polar plot showing relation between variations of ΔPP and ΔPOP . The angle was $26.3 \pm 20.2^\circ$.

to our purpose. We found a mean angle greater than 5° indicating a bias and an SD greater than 15° suggesting that the ΔPOP changes were too widely dispersed as compared with ΔPP changes to support trending ability. However, in polar plot analysis a central zone has to be excluded as it represents small changes in indices that included a large random error. We arbitrarily set this exclusion zone at 3% change, corresponding to a value we thought to be clinically significant. Doing so, we captured only the rapid changes, neglecting the more progressive variations. Indeed, in our recordings, 31.3% of the changes satisfied this exclusion threshold. But choosing a lower value for the exclusion zone would have led to a larger SD of the angle. Interestingly, this value of exclusion zone roughly corresponded to the range between 9 and 13%, which was called by Cannesson *et al*²² the “gray zone.”

The poor agreement between ΔPP and ΔPOP observed in our study could have several explanations. It could be related to the patients selected for the study including liver transplantation.²³ However, a separate analysis of patients who underwent liver transplantation did not show any significant difference in the agreement. Two more likely explanations could be involved: the physiological properties of the

arteriolar wall linking the pressure to the volume, that is, the distensibility, and the processing of the plethysmographic signal. Indeed, the oscillation amplitude of the plethysmogram is directly dependent on the volume change and not on the pressure change occurring in the arteriole under the probe. Therefore, plethysmographic amplitude is dependent on the transmural pressure change within this arteriole and its distensibility. The distensibility or compliance could vary over anesthesia, depending on microvascular tone changes induced by anesthetic events such as temperature, sympathetic nervous system activity, or ischemia/reperfusion-induced changes. This could be the likely explanation of the observed opposite changes between ΔPP and ΔPOP in patients undergoing portal vein declamping (fig. 4). This postreperfusion period is usually characterized by a major vasodilatation associated with an increase in cardiac output. This could also explain the low coefficient of correlation between the two indices in patients receiving epidural anesthesia. Although controversial in humans, animal studies have shown an increased sympathetic nerve activity in the unanesthetized segments during thoracic epidural anesthesia.²⁴ Therefore, the presence of an epidural anesthesia was likely to modify the vascular

Table 2. Results of Multiple Linear Regression Analysis between Clinical Data and the Coefficients of Correlation between Δ PP and Δ POP of Each Patient

Variables	Standardized Coefficient	P Value
Continuous vasoconstrictive agent	-0.167	0.395
Peroperative epidural analgesia	-0.502	0.009
Previous hypertensive history	-0.087	0.579
Heart and respiratory rate ratio	-0.117	0.609
Tidal volume	-0.155	0.480
Mean arterial pressure	0.094	0.622
Percentage of Δ PP >12 %	0.487	0.009
Positive end-expiratory pressure	-0.027	0.884
Minimal preoperative temperature	-0.154	0.356

Multiple coefficient of correlation was 0.737. The use of peroperative epidural analgesia and the percentage of the Δ PP >12 % are the only variables significantly correlated with the coefficients of correlation between Δ PP and the Δ POP of each patient. The coefficient of correlation increased with the percentage of Δ PP >12%, whereas it decreased with the use of peroperative epidural analgesia.

Δ POP = variation of the plethysmographic waveform of pulse oximetry; Δ PP = pulse pressure variation.

tone of unblocked upper limb, modifying the arteriolar distensibility. The sympathetic nervous system activity change was advocated by Landsverk *et al.*¹³ to explain the poor correlation between Δ PP and Δ POP observed in intensive care unit patients and more recently during abdominal surgery.²⁵ Although the anesthesia is a classical cause of reduction of the sympathetic nervous system activity, any change in its activity could not be ruled out during abdominal surgery, despite monitoring of the depth of anesthesia.^{26,27} Besides the sympathetic nervous system activity, the distensibility could vary according to the arterial pressure. The loops of arterial pressure *versus* the plethysmogram exhibit a sigmoid-shaped curved, the arterial wall being more compliant at low level of arterial pressure.^{28,29} At this level, a pressure oscillation is likely to induce a higher plethysmogram oscillation than at a higher pressure level. This could explain the dependence of the bias on the mean value of Δ PP and Δ POP we observed, confirming previous report by Landsverk *et al.*¹³ Finally the loop of the arterial pressure *versus* the plethysmogram depends on the dynamic compliance, meaning that the distensibility depends on the rate of the pressure change.²⁸ Therefore, any variation of the heart rate could induce a change in the rate of pressure variation and therefore in the dynamic distensibility. Besides the distensibility, the signal processing itself should be taken into consideration to explain the discrepancy between Δ PP and Δ POP. The original signal of plethysmogram is usually highly processed in standard monitors in order to provide clear display on screens. The difference in filtering process between the pressure and the plethysmographic signals could also explain the dependence on pressure level of the shift and

the hysteresis of loops illustrated by figure 1. However, signal processing could not be the exclusive explanation of the weak correlation between Δ PP and Δ POP because this correlation would have been altered for all patients. In fact, some patients exhibited a good correlation (fig. 3). The observed decrease of the arterial pressure-plethysmogram signal loop illustrated in figure 1 could be the result of a decreased distensibility, of signal processing, or both. A trial with a nonfiltered plethysmogram signal could solve the issue.

As a mean, patients experienced a quarter of time with a Δ PP greater than 12%, but with a great variability among the patients. The value of the percentage greater than 12% could be considered to be mainly dependent on the volemic status of the patient but also on the conditions of recording. This variability was not dependent on the end-inspiratory plateau pressure but on the ratio of heart rate to respiratory rates. This result further confirmed the previous observation indicating that Δ PP decreased when the respiratory rate increased.²¹ The lack of dependence on the plateau pressure and tidal volume is apparently conflicting with previous findings but likely explained by the narrow range of the tidal volume we used.^{30,31} This percentage of Δ PP greater than 12% was correlated with the individual coefficient of correlation. This finding is consistent with previous experimental observations reporting an increased correlation between the two indices with progression of blood withdrawal in animals and therefore with the increasing value of Δ PP.¹⁴ This could also be related to a statistical limitation of interpretation of coefficients of correlation related to their properties to be dependent on the range of the measured values.³²

By using standard monitors to compute Δ PP and Δ POP during 40 surgical procedures, we showed that these two indices were not interchangeable. The nature of both the signals is different, and same hemodynamic conditions did not have same effects. The same analysis should be done with a nonprocessed plethysmographic signal before ruling out Δ POP as a surrogate of Δ PP to follow preload dependence during anesthesia for major abdominal surgery.

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