Comparison of pulse contour analysis by Pulsioflex and Vigileo to measure and track changes of cardiac output in critically ill patients

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Editor’s key points

- Several commercially available devices use pulse waveform analysis to estimate cardiac output and other variables.
- This study compared the responses of two devices to fluids or an increase in norepinephrine infusion in critically ill patients.
- Although able to track changes after fluid administration, both the Pulsioflex and Vigileo devices were unreliable for determining the absolute values of cardiac index.

Background. We compared the new Pulsioflex and the Vigileo devices to measure cardiac index (CI) in critically ill patients. Both devices measure CI by pulse-contour analysis. The Pulsioflex device also allows an auto-calibration (not based on thermodilution).

Methods. Patients were included if we administered fluids (20 patients), reduced (20 patients), or increased (20 patients) the dose of norepinephrine. Before and after interventions, we measured CI provided by the Vigileo (CI Vig) and Pulsioflex (CI Pfx) devices before and after its auto-calibration. CI measured by transpulmonary thermodilution (CI thermo) was used as the reference.

Results. Considering absolute values of CI (n=120), the percentage error was 59% for CI Vig vs CI thermo and 40% for CI Pfx vs CI thermo. Auto-calibrating CI Pfx after interventions did not improve the percentage error between CI Pfx and CI thermo (39%). Considering the fluid-induced changes in CI, the coefficient of correlation with changes in CI thermo was 0.50 for CI Vig and 0.73 for CI Pfx (P=0.27). It was not significantly improved if CI Pfx was auto-calibrated (r=0.64). Considering the norepinephrine-induced changes in CI, the coefficient of correlation with changes in CI thermo was 0.41 for CI Vig. It tended to be better for CI Pfx (r=0.71, P=0.07). It was not significantly improved by auto-calibration (r=0.53).

Conclusions. The Pulsioflex did not reliably estimate the absolute values of CI. For tracking fluid-induced changes in CI, the Pulsioflex was reliable, and also the Vigileo. For tracking norepinephrine-induced changes in CI, it was also reliable and tended to be better than the Vigileo. Auto-calibration allowed by the system did not improve its reliability.

Keywords: cardiac output, measurement; equipment, monitors; measurement techniques, cardiac output; norepinephrine; shock

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By assimilating the cardiovascular system to a three-component electrical circuit, it is possible to compute stroke volume and cardiac output from the waveform of the systemic arterial pressure. For this purpose, the arterial compliance, resistance, and impedance must be estimated. In addition, if the arterial pressure curve is recorded at the peripheral level, the pulse wave amplification phenomenon must be taken into account. Among the devices that are currently commercialized for estimating cardiac output from such an arterial waveform analysis, the FloTrac/Vigileo (Edwards Life Sciences, Irvine, CA, USA, which will be called ‘Vigileo’ hereafter) has been developed first. With this device, the physiological properties of the arterial system are estimated from a geometric analysis of the arterial curve and from its comparison with a database of arterial curves recorded in numerous patients. The reliability of this device to estimate cardiac output has been reported by several studies. However, it has been shown to be inaccurate in cases when the arterial tone changes to a large extent, during hyperdynamic states and when vasopressors are administered. The same limitations were found with the most recent version of the system, even if the trending ability of this last version is improved compared with the previous one.

The ProAQT/Pulsioflex (Pulsion Medical Systems, Munich, Germany, which will be called ‘Pulsioflex’ hereafter) is a new pulse contour analysis device. Like the Vigileo system, the Pulsioflex does not need any external calibration of pressure waveform analysis. Nevertheless and according to constructor’s indications, it differs from the Vigileo in two main aspects. First, the pressure waveform analysis software is different. Secondly, the initial value of cardiac output from which the pulse contour analysis is started is not estimated...
by pulse contour analysis itself but by an innovative proprietary algorithm that provides an ‘auto-calibration’. Moreover, it is possible to reset cardiac output measurement with this auto-calibration at any time. As far as we know, the validity of this device was investigated in one single study, in the particular context of off-pump coronary artery bypass grafting.21

The goal of this study was to test the validity of the recent Pulsioflex device. We also wanted to compare it with the well-established Vigileo device for estimating cardiac index (CI) and its changes. We specifically investigated critically ill patients. In addition, we specifically compared the ability of the two systems to detect the changes in CI induced by two different interventions: volume expansion, which is supposed not to modify the physiological properties of the arterial tree, and a change in the dose of norepinephrine, which, in contrast, may affect those properties.

**Methods**

**Patients**

Patients were enrolled if they were hospitalized in an intensive care unit, if they received norepinephrine at baseline, if they were monitored by a PICCO2 device (Pulsion Medical Systems) and if a volume expansion (20 patients), an increase (20 different patients), or a decrease (20 different patients) in the dose of norepinephrine were planned by the attending physician. The study was approved by the institutional review board of our institution. Informed patient (or next-of-kin) consent was obtained from all patients.

**Measurements**

All patients had a catheter inserted into the internal jugular vein and a catheter inserted into the femoral artery (PV8215 monitoring kit, Pulsion Medical Systems). The arterial line was divided into three branches through a stopcock, one connected to the PICCO2 device, another one connected to a FloTrac sensor plugged to a third-generation Vigileo device through a FloTrac sensor, and the last connected to a ProAQT sensor, plugged to a Pulsioflex device.

The Vigileo device estimates CI (CI Vig) by analysing the arterial curve obtained from the arterial line to which it is connected. With this system, stroke volume is estimated as the product of the standard deviation (SD) of arterial pressure and an adjusting factor. This factor takes into account the biometric properties of the patient (age and gender) and some geometric properties of the arterial waveform. It was developed and validated from a large database of arterial pressure curves recorded in various kinds of patients.2 This estimation of CI Vig is updated every 20 s.2

The Pulsioflex device estimates CI (CI Pfx) in a different way. It provides a punctual estimation of CI that is not inferred from pulse contour analysis but from software developed by the constructor. This ‘auto-calibration’ is automatically performed when the system is plugged to the arterial line. It can be repeated on demand by clicking on a button. After this auto-calibration, trends in CI are assessed by pulse contour analysis, with an algorithm that is different from the Vigileo monitor. The auto-calibration is based on the analysis of the characteristics and details of the arterial curve. For this purpose and as stated by the manufacturer, the Pulsioflex system uses biometric values (height and weight) and age. Additionally, mean arterial pressure and heart rate are used and an abstract value is calculated from the arterial pressure curve. The statistical approach for auto-calibration is not based on a classical physiological Windkessel model but is the result of analysis of a comprehensive database. Thus, at any time, the value of CI results from both the previous auto-calibration and the pulse contour analysis that has run afterwards. To note, the Pulsioflex device also allows to calibrate CI by manually entering a value of CI obtained from another technique (echocardiography, for instance). This external calibration was not used in the present study.

The PICCO2 device estimates CI (CI thermo) from transpulmonary thermodilution.24 For this purpose, 15 ml of iced saline (<10°C) was injected through the central venous line. The injection was performed in triplicate and the values of CI thermo were averaged. With this three-bolus technique, the least significant change of CI measurements is 12.25 In addition to transpulmonary thermodilution, the PICCO2 also estimates CI from a pulse contour analysis26 27 (CI PiCCO pulse) that is similar to the one of the Pulsioflex. However, the initial value from which pulse contour analysis starts is provided by a measurement of transpulmonary thermodilution. Thus, conversely to the Vigileo and Pulsioflex devices, the pulse contour analysis performed by the PICCO2 is calibrated with a technique that is considered as reliable.

**Study design**

Study design is represented in Figure 1. Before all therapeutic interventions, we auto-calibrated the Pulsioflex device. We performed a first set of haemodynamic measurements, including heart rate, systemic arterial pressure, CI thermo, CI PiCCO pulse, CI Vig, CI Pfx, and systemic vascular resistance. The systemic vascular resistance was calculated as systemic vascular resistance (index) = mean arterial pressure × 80/(CI thermo). The CI PiCCO pulse, CI Vig, and CI Pfx were recorded before transpulmonary thermodilution for avoiding interference between the temperature drift and the accuracy of pulse contour analyses. After the first set of haemodynamic measurements was completed, volume expansion was performed (500 ml of saline over 10 min) or the dose of norepinephrine was either increased or decreased, according to the decision of the clinician in charge of the patient. All other treatments were kept unchanged during the therapeutic interventions (Fig. 1).

After each therapeutic intervention (i.e. at the end of fluid administration and 5 min after stabilization of mean arterial pressure when the dose of norepinephrine was changed),16 18 CI Pfx was measured. The Pulsioflex was then auto-calibrated and transpulmonary thermodilution measurements were performed. A last set of haemodynamic measurements was carried out. It included heart rate, systemic arterial pressure, CI PiCCO pulse, CI Vig, CI thermo, the auto-calibrated CI Pfx, and systemic vascular resistance. As before the therapeutic interventions, CI PiCCO pulse, CI Vig, and CI Pfx were recorded before transpulmonary thermodilution.
Splitting the arterial line into two branches may introduce differing harmonic influences into the system that might influence the monitors. For this purpose, before and after the therapeutic interventions, the CI_{PICCO}pulse, CI_{Vig}, and CI_{Pfx} were recorded after turning on the tap sharing the femoral arterial line, such that the lines directed to both devices were alternatively closed.

**Statistical analysis**

The normality of data distribution was tested with the Kolmogorov–Smirnov test. Data are expressed as mean (SD) or median (inter-quartile range), as appropriate. Comparisons between values recorded before vs after therapeutic interventions were performed within groups of patients by a paired Student t-test or a paired Wilcoxon test, as appropriate. Comparisons between groups of patients were performed by a two-tailed Student t-test or a Mann–Whitney U-test, as appropriate. Correlations were assessed by the Pearson coefficient and correlation coefficients were compared by using the Fisher transformation.

In the group of patients receiving volume expansion (n=20) on the one side and in the groups of patients in whom norepinephrine was either increased or decreased (n=40) on the other side, we tested the ability of CI_{PICCO}pulse, CI_{Vig}, and CI_{Pfx} (non-calibrated and auto-calibrated) to track the changes in CI_{thermo} induced by therapeutic interventions. For this purpose, we performed a linear regression analysis (for per cent changes from baseline) between the treatment-induced changes of CI_{thermo} and those of CI_{PICCO}pulse, CI_{Vig}, and CI_{Pfx}. For the latter variable, the changes were measured between the value of auto-calibrated CI_{Pfx} measured before therapeutic interventions and the value of non-calibrated CI_{Pfx} measured after therapeutic interventions before auto-calibrating the system again (Fig. 1). For CI_{PICCO}pulse, the changes were measured between the value of CI_{PICCO}pulse before interventions, which is similar to CI_{thermo} because of calibration, and the value of CI_{PICCO}pulse measured after therapeutic interventions before transpulmonary thermodilution. Correlation coefficients were compared between Group 1 and Group 2 using the Fisher transformation.

Expecting a coefficient of correlation between norepinephrine-induced changes in CI_{Vig} and CI_{thermo} of 0.30 \pm 0.18 and between norepinephrine-induced changes in CI_{Pfx} and CI_{thermo} of 0.70, setting α-risk at 5% and β-risk at 20%, 40 patients must be included in the norepinephrine group. The statistical analysis was performed by using MedCalc 8.1.0.0 (Mariakerke, Belgium) and SigmaPlot 12.0 (Systat Software Inc., San Jose, CA, USA).

**Results**

**Patients' characteristics**

Patients’ characteristics are summarized in Table 1. A diagram describing the number of patients who were approached,
excluded, and included in the study is provided in the Supplementary material. All patients were admitted for septic shock. On average, patients were investigated at the initial phase of shock (Table 1). The second set of measurements was recorded 13 (1) min after the first set in patients receiving volume expansion and 25 (7) min after the first set in patients in whom the dose of norepinephrine was changed. Each set of measurements was performed in 5 min.

**Ability of Cl\textsubscript{Vig} and Cl\textsubscript{Pfx} to estimate absolute values of Cl\textsubscript{thermo}**

When considering the 120 pairs of measurements performed before and after all therapeutic interventions, the bias (lower to upper limits of agreement) between the absolute values of Cl\textsubscript{thermo} and Cl\textsubscript{Vig} was 0.5 (–1.4 to 2.4) litre min\(^{-1}\) m\(^{-2}\) and the percentage error was 59% (Fig. 2).

When considering the 60 pairs of measurements of Cl\textsubscript{thermo} and Cl\textsubscript{Pfx} after interventions but before auto-calibration of Pulsioflex, the bias (lower to upper limits of agreement) between the absolute values of Cl\textsubscript{thermo} and non-calibrated Cl\textsubscript{Pfx} was −0.1 (−1.5 to 1.4) litre min\(^{-1}\) m\(^{-2}\) and the percentage error was 40%.

When considering the 60 pairs of measurements of Cl\textsubscript{thermo} and Cl\textsubscript{Pfx} before interventions and the 60 pairs of measurements of Cl\textsubscript{thermo} and Cl\textsubscript{Pfx} after interventions and after auto-calibration of Pulsioflex, the bias (lower to upper limits of agreement) between the absolute values of Cl\textsubscript{thermo} and auto-calibrated Cl\textsubscript{Pfx} was −0.1 (−1.5 to 1.3) litre min\(^{-1}\) m\(^{-2}\) and the percentage error was 39% (Fig. 2).

**Ability of Cl\textsubscript{Vig} and Cl\textsubscript{Pfx} to track changes in Cl\textsubscript{thermo} induced by volume expansion**

Table 2 presents changes in haemodynamic values before and after volume expansion.

The bias (lower to upper limits of agreement) between the changes in Cl\textsubscript{thermo} and in Cl\textsubscript{Vig} was 0.2 (−1.0 to 1.3) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation of the fluid-induced per cent changes in Cl\textsubscript{thermo} and in Cl\textsubscript{Vig} was 0.50 (P=0.03) (Fig. 3). The concordance rate between the fluid-induced changes in Cl\textsubscript{thermo} and in Cl\textsubscript{Vig} was 73% (Fig. 3).

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age [mean (range), yr]</td>
<td>28–82</td>
</tr>
<tr>
<td>Gender [M/F]</td>
<td>38/22</td>
</tr>
<tr>
<td>SAPS II [mean (SD)]</td>
<td>38 (12)</td>
</tr>
<tr>
<td>Origin of septic shock</td>
<td>55 (92)</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>55 (92)</td>
</tr>
<tr>
<td>Peritonitis</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Pancreatitis</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Angiocholitis</td>
<td>1 (2)</td>
</tr>
<tr>
<td>Time from admission [mean (SD), days]</td>
<td>3 (2)</td>
</tr>
<tr>
<td>ARDS (n, %)</td>
<td>42 (70)</td>
</tr>
<tr>
<td>Mechanical ventilation (n, %)</td>
<td>60 (100)</td>
</tr>
<tr>
<td>Respiratory variables</td>
<td></td>
</tr>
<tr>
<td>Tidal volume [mean (SD), ml kg(^{-1}) of predicted body weight]</td>
<td>7 (2)</td>
</tr>
<tr>
<td>Respiratory rate [mean (SD), bpm]</td>
<td>20 (3)</td>
</tr>
<tr>
<td>Total PEEP [mean (SD), cm H(_2)O]</td>
<td>9 (2)</td>
</tr>
<tr>
<td>P(_{a}\text{O}<em>2)/F(</em>{I}\text{O}_2), [mean (SD), mm Hg]</td>
<td>190 (30)</td>
</tr>
</tbody>
</table>

Fig 2 Bland–Altman plot for the absolute values of Cl obtained by transpulmonary thermodilution (Cl\textsubscript{thermo}), by the Vigileo device (Cl\textsubscript{Vig}) and by the Pulsioflex after auto-calibration (auto-calibrated Cl\textsubscript{Pfx}) considering all pairs of measurements performed during the study. n=120; lines: bias and +2SD/2SD limits of agreement.
When considering CI\textsubscript{Pfx}, measured before Pulsiflow autocalibration, the bias (lower to upper limits of agreement) between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Pfx} was 0.0 (−0.7 to 0.6) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation between the fluid-induced per cent changes in CI\textsubscript{thermo} and in non-calibrated CI\textsubscript{Pfx} was 0.73 (P<0.01) (Fig. 3). The concordance rate between the changes in CI\textsubscript{thermo} and in CI Pfx induced by volume expansion was 91% (Fig. 3).

When considering CI\textsubscript{Pfx}, measured after Pulsiflow autocalibration, the bias (lower–upper limits of agreement) between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Pfx} was 0.3 (−1.1 to 1.8) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation between the fluid-induced per cent changes in CI\textsubscript{thermo} and in auto-calibrated CI\textsubscript{Pfx} was 0.64 (P<0.01) (Fig. 3). The concordance rate between the changes in CI\textsubscript{thermo} and in auto-calibrated CI\textsubscript{Pfx} induced by volume expansion was 79% (Fig. 3).

There was no statistical difference between the coefficient of correlations of changes in CI\textsubscript{thermo} vs changes in CI\textsubscript{Vig} and the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in non-calibrated CI\textsubscript{Pfx} (P=0.27).

There was no statistical difference between the coefficient of correlations of changes in CI\textsubscript{thermo} vs changes in CI\textsubscript{Vig} and the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in auto-calibrated CI\textsubscript{Pfx} (P=0.54). There was also no statistical difference between the coefficient of correlations of changes in CI\textsubscript{thermo} vs changes in non-calibrated CI\textsubscript{Pfx} and the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in auto-calibrated CI\textsubscript{Pfx} (P=0.50).

**Ability of CI\textsubscript{Vig} and CI\textsubscript{Pfx} to track changes in CI\textsubscript{thermo} induced by norepinephrine**

Table 2 presents changes in haemodynamic values before and after the increase and decrease in norepinephrine. Considering the 40 patients in whom norepinephrine was increased or decreased, the bias (lower to upper limits of agreement) between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Vig} was 0.2 (−1.6 to 1.2) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation between the per cent changes in CI\textsubscript{thermo} and in CI\textsubscript{Vig} was 0.44 (P<0.01). The concordance rate between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Vig} was 79% (Fig. 4).

In the same 40 patients, when considering CI\textsubscript{Pfx} measured before Pulsiflow autocalibration, the bias (lower to upper limits of agreement) between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Pfx} was −0.1 (−1.4 to 1.3) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation between the per cent changes in CI\textsubscript{thermo} and in non-calibrated CI\textsubscript{Pfx} was 0.71 (P<0.01) (Fig. 4). The concordance rate between the changes in CI\textsubscript{thermo} and in non-calibrated CI\textsubscript{Pfx} was 83% (Fig. 4).

In the same 40 patients, when considering CI\textsubscript{Pfx} measured after Pulsiflow autocalibration, the bias (lower–upper limits of agreement) between the changes in CI\textsubscript{thermo} and in CI\textsubscript{Pfx} was −0.2 (−1.4 to 1.0) litre min\(^{-1}\) m\(^{-2}\). The coefficient of correlation between the per cent changes in CI\textsubscript{thermo} and in auto-calibrated CI\textsubscript{Pfx} was 0.53 (P<0.01) (Fig. 4). The concordance rate between the changes in CI\textsubscript{thermo} and in auto-calibrated CI\textsubscript{Pfx} was 74% (Fig. 4).

There was no significant difference between the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in CI\textsubscript{Vig} and the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in non-calibrated CI\textsubscript{Pfx} (P=0.61). There was also no significant difference between the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in CI\textsubscript{Vig} and the coefficient of correlation of changes in CI\textsubscript{thermo} vs changes in auto-calibrated CI\textsubscript{Pfx} (P=0.20).

**Influence of the changes in systemic vascular resistance on the concordance between CI\textsubscript{thermo} and CI\textsubscript{Vig}, between CI\textsubscript{thermo} and auto-calibrated CI\textsubscript{Pfx}, and between CI\textsubscript{thermo} and non-calibrated CI\textsubscript{Pfx}-non-cal**

Considering all therapeutic interventions as a whole, the changes in systemic vascular resistance ranged from −35% to +51%. The changes in systemic vascular resistance were...
significantly correlated with the bias between the changes in CI thermo and in CI Vig (\(r=0.55, P<0.001\)) and with the bias between the changes in CI thermo and in auto-calibrated CI Pfx (\(r=0.30, P=0.03\)). There was no correlation between the changes in systemic vascular resistance and the bias between the changes in CI thermo and in non-calibrated CI Pfx (\(r=0.19, P=0.17\)).

**Fig 3** Trending ability of the FlotTrac/Vigileo device (CI Vig), of the Pulsioflex device when it was auto-calibrated or not (CI Pfx) after the therapeutic intervention against CI measured by transpulmonary thermodilution (CI thermo) during volume expansion based on a polar plot analysis. \(n=20\).

**Fig 4** Trending ability of the FlotTrac/Vigileo device (CI Vig), of the Pulsioflex device when it was auto-calibrated or not (CI Pfx) after the therapeutic intervention against CI measured by transpulmonary thermodilution (CI thermo) during increase \((n=20)\) or decrease \((n=20)\) in norepinephrine, based on a polar plot analysis. Correlation: \(n=40\).
Ability of CI\textsubscript{PiCCOpulse} to estimate absolute values of CI\textsubscript{thermo} and to track changes in CI\textsubscript{thermo} induced by therapeutic interventions

These results are summarized in Supplementary Figures S2–S4.

Discussion

The main conclusion of this study conducted in a series of critically ill patients receiving norepinephrine is that the Pulsioflex device was unreliable to estimate the absolute value of cardiac output. This was also the case for the Vigileo device. The Pulsioflex device correctly tracked changes in cardiac output when they were induced by volume expansion and by norepinephrine. For the changes induced by norepinephrine, the tracking ability of the Pulsioflex device tended to be better than that of the Vigileo device. Finally, the auto-calibration option did not improve the accuracy of the Pulsioflex monitor.

Study background: pulse contour analysis

Devices that estimate cardiac output from the arterial pressure curve proceed in two steps. The first is to estimate a starting value of cardiac output and the second is to continuously track changes in cardiac output from that starting value. For determining the starting cardiac output value, the devices that are currently available differ fundamentally. Some ‘calibrated’ devices do not estimate the initial value of cardiac output from the arterial pressure waveform but infer it from an independent reliable method. For instance, the PICCO\textsubscript{2} uses transpulmonary thermodilution, a method known to provide a reliable estimation of cardiac output.\textsuperscript{26 32 33}

In contrast, the ‘uncalibrated’ devices, such as the Vigileo and the Pulsioflex, do not need independent calibration to estimate the starting cardiac output value. For this purpose, the Vigileo analyses the arterial pressure waveform by using the geometric properties of the curve, by comparing it with a database of several patients' waveforms and taking into account patient's biometric characteristics.\textsuperscript{2} The Pulsioflex device determines the starting cardiac output value in a different way, using new constructor software that analyses the arterial pressure waveform characteristics and details. During the second step, after the initial estimation of cardiac output, all these devices provide a continuous estimation of cardiac output that is based upon arterial pressure waveform analysis, but the algorithms used for this purpose differ between the devices.

The originality of our study was to test the very recent Pulsioflex device and to compare it with the widely established Vigileo device. Also, we conducted the study in the intensive care unit, while many validation studies for such devices are performed in the operating theatre. This allowed us to perform the original comparison of devices’ behaviour during volume expansion and changes in norepinephrine dose, two conditions that fundamentally alter the cardiovascular system in a very different way. It was previously reported that estimation of cardiac output by the Vigileo device poorly tracked the changes in cardiac output when induced by vasoactive agents, which change to a large extent the mechanical properties of the arterial tree on which pulse contour analysis is based. As far as we know, whether the new Pulsioflex device has the same limitation has not been investigated yet.

Ability of Vigileo and Pulsioflex to measure absolute values of CI

As a first result, we found that, as the Vigileo, the Pulsioflex device was not reliable enough for estimating absolute values of CI\textsubscript{thermo}. The percentage error was higher than 30%, that is, the limit that is considered acceptable when the precision of the reference technique is around 10%,\textsuperscript{10} as it is the case for transpulmonary thermodilution.\textsuperscript{25} Results obtained from the Vigileo device were as poor as we previously reported in a previous superimposable study in another series of critically ill patients.\textsuperscript{18} Even though the percentage error of the Pulsioflex device was lower than that of Vigileo, it was still higher than 30%. This strongly suggests that neither the Pulsioflex nor the Vigileo reliably estimate absolute values of cardiac output in critically ill patients under norepinephrine.

The ProAQT/Flotrac device has the ability to perform an internal auto-calibration of cardiac output. This auto-calibration estimates cardiac output from an analysis of the arterial pressure curve different from the classical pulse contour analysis, according to the manufacturer’s information. Auto-calibration is supposed to improve the estimation of cardiac output at each time it is ordered by the physician. Nevertheless, we found that the percentage error for absolute values of cardiac output was not better after auto-calibrating the system than before. One limitation of this study is that we were not able to investigate what could explain failure of auto-calibration, since we could not access the details of the proprietary algorithm.

Ability of Vigileo and Pulsioflex to track changes in CI

Validation of devices measuring cardiac output should be based not only on their ability to measure absolute values, but also on their ability to track trends. As a second result of our study, the Pulsioflex reliably followed the changes in cardiac output induced by volume expansion or norepinephrine, as shown by the relatively high correlation coefficients between the changes in CI\textsubscript{thermo} and in non-calibrated CI\textsubscript{Pfx} and by their high concordance rates.

As for absolute values, auto-calibration did not improve the tracking reliability of the device since it did not improve the correlation with changes in CI\textsubscript{thermo} the reference technique and even tended to worsen it when changes were induced by norepinephrine. In such cases, the tracking ability of the Vigileo tended to be poorer than that of non-calibrated CI\textsubscript{Pfx}. This could be explained by a lower influence of changes in systemic vascular resistance on the bias between changes in CI\textsubscript{thermo} and non-calibrated CI\textsubscript{Pfx} than between changes in CI\textsubscript{thermo} and CI\textsubscript{Vig}. Indeed, several studies suggested that the changes in systemic vascular resistance, modifying the coupling between cardiac output and peripheral arterial pressure, accounted for the unreliability of the trending ability of the Vigileo.\textsuperscript{16 18 34} Again, we could not investigate which differences between the proprietary algorithms could account for this difference between devices.
Limitations
First and importantly, we compared the Vigileo and the Pulsioflex devices with transpulmonary thermodilution used as a reference. Even though the latter technique has been repeatedly demonstrated to be as reliable as classical thermodilution, it cannot be perfect. One must thus keep in mind that differences between $C_{I\text{Vig}}$ or $C_{I\text{Pfx}}$ and $C_{I\text{thermo}}$ could also be partly related to transpulmonary thermodilution inaccuracy, even though the Bland–Altman analysis tends to reduce this.

Secondly, we connected the Vigileo and Pulsioflex devices to the femoral artery while they are supposed to be used at the radial site. Although the pulse contour analysis algorithms of the Vigileo and Pulsioflex monitors are proprietary, there is no reason why it should work differently between both arteries. In particular, there is even less blood turbulences around the catheter in a larger than a smaller artery. Also, some studies consistently showed that pulse wave analysis by the Vigileo system is not influenced by the site where arterial pressure is measured. However, this was not tested with the Pulsioflex device. Another potential limitation is that the arterial line was divided into two branches, each being connected to one device. This could theoretically induce diverging distribution of the original signal into the three branches and some cross-talk phenomena. Nevertheless, in order to avoid such phenomena, we took cautiously turned off the tap of the Vigileo line when performing the Pulsioflex measurements and vice versa.

Thirdly, we only studied norepinephrine as a vasopressor, while differences in the pharmacological properties of vaso-active agents might differently affect the trending ability of the arterial pressure waveform analysis to different extents, as shown for phenylephrine and ephedrine.

Finally, we did not explore one possible advantage of the Pulsioflex over the Vigileo device, which is to allow an external calibration of pulse contour analysis by entering into the device a value of CI obtained from another technique. Obviously, doing so would have definitely precluded to investigate the intrinsic reliability of the Pulsioflex device.

Conclusion
In critically ill patients receiving norepinephrine, the Pulsioflex did not reliably estimate absolute values of CI. For tracking fluid-induced changes in CI, the Pulsioflex device was reliable, and also the Vigileo device. For tracking norepinephrine-induced changes in CI, it was also reliable and tended to be better than the Vigileo. Auto-calibration allowed by the system did not improve its reliability.

Supplementary material
Supplementary material is available at British Journal of Anaesthesia online.

Authors’ contributions
X.M.: conceived the study, performed analysis and interpretation of the data, and drafted the manuscript. S.V., N.A., M.J., and F.C.: performed the collection of data, contributed to analysis and interpretation of the data, and to drafting of the manuscript. C.R.: participated in the study conception. J.-L.T.: conceived the study, contributed to analysis and interpretation of the data, and to drafting of the manuscript. All authors read and approved the final manuscript.

Declaration of interest
J.-L.T. and X.M. are members of the Medical Advisory Board of Pulsion Medical Systems.

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