Systematic review of uncalibrated arterial pressure waveform analysis to determine cardiac output and stroke volume variation

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Editor’s key points

- Analysis of uncalibrated arterial pressure waveform is often used to derive cardiac output and stroke volume (SV).
- The performances of different models of FloTrac/Vigileo™ during different haemodynamic conditions were reviewed.
- The third generation FloTrac/Vigileo™ performed adequately in normo- and hypodynamic conditions but not during hyperdynamic conditions.
- SV variability was found to be a reasonable indicator of fluid responsiveness.

Summary. The FloTrac/Vigileo™, introduced in 2005, uses arterial pressure waveform analysis to calculate cardiac output (CO) and stroke volume variation (SVV) without external calibration. The aim of this systematic review is to evaluate the performance of the system. Sixty-five full manuscripts on validation of CO measurements in humans, published in English, were retrieved; these included 2234 patients and 44 592 observations. Results have been analysed according to underlying patient conditions, that is, general critical illness and surgery as normodynamic conditions, cardiac and (post)cardiac surgery as hypodynamic conditions, and liver surgery and sepsis as hyperdynamic conditions, and subsequently released software versions. Eight studies compared SVV with other dynamic indices. CO, bias, precision, %error, correlation, and concordance differed among underlying conditions, subsequent software versions, and their interactions, suggesting increasing accuracy and precision, particularly in hypo- and normodynamic conditions. The bias and the trending capacity remain dependent on (changes in) vascular tone with most recent software. The SVV only moderately agreed with other dynamic indices, although it was helpful in predicting fluid responsiveness in 85% of studies addressing this. Since its introduction, the performance of uncalibrated FloTrac/Vigileo™ has improved particularly in hypo- and normodynamic conditions. A %error at or below 30% with most recent software allows sufficiently accurate and precise CO measurements and trending for routine clinical use in normo- and hypodynamic conditions, in the absence of large changes in vascular tone. The SVV may usefully supplement these measurements.

Keywords: comparing cardiac output; haemodynamic optimization; stroke volume variations; uncalibrated arterial pressure waveform analysis

The use of the peripheral arterial waveform to calculate stroke volume (SV) was first described in 1904.1 Although pulse pressure (PP) directly relates to SV, arterial compliance and tone shape the arterial waveform and thus affect the SV calculation from PP. The majority of cardiac output (CO) measurement devices utilizing the arterial pressure waveform need external calibration to establish the relation between PP and SV by taking arterial compliance and tone into account in individual patients. In 2005, the FloTrac/Vigileo™ system (Edwards Lifesciences, Irvine, CA, USA) has been introduced.2 3 This technique allegedly does not require external calibration and uses the arterial pressure signal obtained by a standard peripheral arterial catheter to calculate SV (and thus SV variations, SVVs) and thereby CO. An undisclosed algorithm uses the mean, standard deviation, skewness and kurtosis of arterial pressure, and arterial compliance derived using sex, age, weight, and height.4 The use of the arterial waveform to calculate SV (variations) places high demands on the quality of the signal.5 The presence of sinus rhythm and the absence of rhythm disturbances reduce the chances of error in the measurements.3 6–10 Moreover, the relation between PP and SV becomes less fixed in pathophysiological conditions like liver disease, liver surgery, or septic shock associated with hyperdynamic and vasodilated states. Normally, PP increases down the arterial tree, but in the latter conditions, the PP decreases down the arterial tree leading to an underestimation of SV. This may thus affect FloTrac/Vigileo™ readings.

Software versions subsequently released in order to allegedly, yet unproven, improve performance and applicability include first generation (1.01, 1.03), second generation (1.07, 1.10, 1.14), and the most recent third generation version 3.02. In the 1.03 software version, the internal calibration
window was 10 min. In the 1.07 software version, the window
was changed to 1 min. In the 1.10 version, the algorithm was
improved to better account for hypertension, tachycardia,
and volume loading. The 1.14 version was only an update of
the display. The third generation version includes two models
for arterial tone: (i) a model that was developed predominantly
from patients in normo- and hypodynamic conditions (as in
the previous version 1.10) and (ii) a model that was developed pre-
dominantly from patients in hyperdynamic conditions. The
switching between the two models is based on an algorithm
that uses 14 parameters of the arterial pressure waveform to
detect the occurrence of hyperdynamic conditions.

We hypothesized that the performance of the FloTrac/Vigileo™
to measure CO depends on underlying condition and haemodynamic profile, and on the software version applied.
This systematic review summarizes data from clinical studies,
analysed to define the current performance of the system in
clinical practice and to explore future areas for improvement,
as attempted before using 16 early studies.12 We will systematically
review the performance according to commonly used criteria
for CO and SVV measurements but will only summarize the
findings on the use of the system in therapeutic settings
in a narrative way.

**Methods**

A PubMed literature search on the FloTrac/Vigileo™ system
using the headings FloTrac and uncalibrated waveform anal-
ysis was performed on the use of the system until May 1,
2013. In total, 139 full manuscripts were found. We excluded
animal experimental studies (n=20), non-English publications
(n=16), non-original manuscripts (n=8), and the papers from
the German group which have been retracted (n=3). All references of these articles were searched for additional FloTrac
articles which yielded an extra 23 manuscripts. One hundred
and fifteen manuscripts were included in this review. In 65
papers, CO was compared with a reference standard. The fol-
lowing values were documented: type of patients, underlying
clinical condition, software version involved, the mean CO,
bias, precision (standard deviation of the bias), percentage
(%) error (95% limits of agreement or 2 × standard deviation,
divided by the mean, according to the Bland–Altman plots),
correlation, and concordance with the reference technique if
available. The latter is defined by the similarity of direction (in
%) or correlation of changes in FloTrac/Vigileo™ and reference
method-derived CO. The correlation coefficients are given as
coefficients of determination $r^2$. The CO was calculated using
a body surface area of 1.73 m² when only cardiac index was
given. Bias and precision are expressed in litre min$^{-1}$ in order
to facilitate comparison among studies. We have also recalcu-
lated other variables, when appropriate and possible from the
available data, to standardize the format of reporting. In many
studies, horizontal lines in the Bland–Altman plots were drawn
for reporting bias, precision, and %error (95% limits of agree-
ment) and we extrapolated numbers from these plots if un-
available in the text. Bias was always expressed (or converted
if necessary) as the difference between the FloTrac/Vigileo™
and the reference method, so that a negative number indicates
underestimation. A 30% error is generally considered accept-
able, depending on the error of the reference technique,
taken from its reproducibility if solely available.13 The age
and number of patients and paired data were recorded. We
did a similar analysis for SVV as far as data were available
(n=8 studies). The quality of the validation studies was rated
according to Ceconi and colleagues14 using the following cri-
ria: the reference technique should be as accurate and
precise as possible, for instance, by pulmonary or transpulmon-
ary thermodilution; the precision of the reference technique
should be measured within the study; the desired precision of
the FloTrac/Vigileo™ technique should be described a priori
or thoroughly analysed in the discussion; the bias and limits
of agreement between the two techniques should be quoted;
and the precision of the new tested technique should be calcu-
lated. We evaluated comparisons of radial and other artery
pressure-derived CO and evaluated therapeutic studies utilizing the system.

**Statistical analysis**

We evaluated the factors that may affect system performance
of measuring CO. The range of observations and lumping of
haemodynamic conditions may confound bias, precision, and
%error.12 15–18 We therefore evaluated conditions separately
and divided patients into three groups accordingly: a group
of general critically ill patients including general critically ill or
(post)surgical patients with presumably normodynamic condi-
tions, a group of cardiac and (post)cardiac surgery patients
with presumably hypodynamic conditions, and a group of
patients with liver disease (surgery) or sepsis with hyperdy-
namic conditions in order to evaluate differences among
patient categories and associated haemodynamic states. If
data had been obtained in general critically ill patients and
the number of patients with sepsis exceeded 50%, we included
the respective study in the sepsis category. We constructed
tables with relevant variables from the studies and summar-
ized key variables, weighted for patients or data number, by
the mean and 95% confidence intervals for the three software
generations involved. For concordance, only $r^2$ was sum-
marized and evaluated. The Kolmogorov–Smirnov test showed
that variables were normally distributed ($P$>0.05). Generalized
estimating equations19 were used to estimate the effect of
underlying condition and software version and their first-order
interaction on study variables taking repeated measurements
into account and adjusted for patient and data numbers. A
$P$-value of $<0.05$ was considered statistically significant and
exact numbers are given if $>0.001$.

**Results**

A total of 65 CO validation studies involved 2234 patients
and 44 592 data points. Results are shown in Tables 1–3. For hypo-
and normodynamic conditions, only few data for concordance
with third-generation software are available. Adjusted for repeated measurements, patient, and data
number, the CO, bias, precision, %error, correlation, and
concordance with the reference standard differed among underlying conditions, software versions, and their interactions, except for %error which did not differ among underlying conditions (Table 4). CO was thus low in cardiac (surgery) patients, intermediate in general critically ill and surgical patients, and relatively high in patients with sepsis or liver disease as expected. The system performed better, considering bias, precision, %error, correlation, and concordance in

Table 1  Summary statistics of validation studies for FloTrac/Vigileo™ cardiac output performed in general critically ill and (post)surgical patients (n = 16); details of individual studies are available in Supplementary material. CO, cardiac output, mean values for FloTrac/Vigileo™ if available, otherwise for combination with reference method; bias, mean difference between CO FloTrac/Vigileo™ and reference CO; precision, standard deviation of the bias; percentage (%) error = 95% limits of agreement or 2 × standard deviation, divided by the mean CO; r², coefficient of determination; concordance is defined by the similarity of direction (in %) or correlation of changes in FloTrac/Vigileo™ and reference method-derived CO; CS, Cecconi score (see text)

<table>
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<tr>
<th></th>
<th>Mean CO (litre min⁻¹)</th>
<th>Bias (litre min⁻¹)</th>
<th>Precision (litre min⁻¹)</th>
<th>%error</th>
<th>r²</th>
<th>Concordance (r² or %)</th>
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Table 2  Summary statistics of validation studies for FloTrac/Vigileo™ cardiac output performed in cardiac and (post)cardiac surgery patients (n = 30); details of individual studies are available in Supplementary material. CO, cardiac output, mean values for FloTrac/Vigileo™ if available, otherwise for combination with reference method; bias, mean difference between CO FloTrac/Vigileo™ and reference CO; precision, standard deviation of the bias; percentage (%) error = 95% limits of agreement or 2 × standard deviation, divided by the mean CO; r², coefficient of determination; concordance is defined by the similarity of direction (in %) or correlation of changes in FloTrac/Vigileo™ and reference method-derived CO; CS, Cecconi score (see text)

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<td>0.60 (n=1)</td>
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Table 3 Summary statistics of validation studies for FloTrac/Vigileo™ cardiac output in liver disease/surgery or sepsis (n=19); details of individual studies are available in Supplementary material. CO, cardiac output; mean values for FloTrac/Vigileo™ if available, otherwise for combination with reference method; bias, mean difference between CO FloTrac/Vigileo™ and reference CO; precision, standard deviation of the bias; percentage (%) error = 95% limits of agreement or 2× standard deviation, divided by the mean CO; r², coefficient of determination; concordance is defined by the similarity of direction (in %) or correlation of changes in FloTrac/Vigileo™ and reference method-derived CO; CS, Cecconi score (see text).

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Discussion

The last 9 yr have witnessed an exponential increase in clinical research on the application of the FloTrac/Vigileo™ system and this systematic review was intended to identify areas for routine clinical use and for future development. Our analysis is useful, even though older software will not be used anymore, by displaying the capability to improve the performance of this less invasive CO measurement technique. Indeed, the accuracy and precision of the FloTrac/Vigileo™ system can be regarded as sufficient for routine clinical use in hypo- or normodynamic conditions in the absence of large changes in vascular tone. The performance of the system in hyperdynamic conditions, even with the latest software version, is still inadequate as our systemic review suggests. Even though SVV may not perfectly agree with that obtained by other means, it is useful in predicting fluid responsiveness.

We will now illustrate that our systematic review is limited by the heterogeneity of the included studies, so that conclusions should be drawn cautiously. An unconventional reference method was used in one study of general critically ill and surgical patients (Table 1), since SV derived from the FloTrac/Vigileo™ was compared with SV determined with the help of two oesophageal Doppler probes, a technique that is operator-dependent. In comparing FloTrac/Vigileo™ with transthoracic Doppler during induction of anaesthesia and intubation in patients undergoing abdominal aortic reconstruction,35 increases in arterial pressure led to an overestimation of CO by FloTrac/Vigileo™. On the other hand, second- and even third-generation software resulted in underestimation of CO during vasodilation in patients with intracranial haemorrhage.25,36 The second-generation software may not suffice to monitor prone positioning of patients with acute respiratory distress syndrome.37 In cardiac (surgical) patients (Table 2), the accuracy of FloTrac/Vigileo™-derived CO was limited by arrhythmias, alterations in the arterial pressure waveform in aortic stenosis and insufficiency and during intra-aortic balloon pumping.38 However, a good correlation between FloTrac/Vigileo™ and thermodilution CO was documented...
Table 5  Flotrac/Vigileo\textsuperscript{TM} -derived stroke volume variation compared with other dynamic indices (provided by indicated manufacturers), grouped according to year of publication and name of first author. Ref, reference; CABG, coronary artery bypass grafting; ICU, intensive care unit; age expressed as mean (standard deviation) in years or range if unavailable; SVV, stroke volume variation, mean values for Flotrac/Vigileo\textsuperscript{TM} if available, otherwise for combination with reference method (in subscript); SPV, systolic pressure variation; PPV, pulse pressure variation. Financial industry sponsorship; NA, not available

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Version</th>
<th>Patient type</th>
<th>Age (yr)</th>
<th>Ref. method</th>
<th>Mean SVV</th>
<th>Bias (%)</th>
<th>Precision (%)</th>
<th>%error</th>
<th>$r^2$</th>
<th>Concordance ($r^2$ or %)</th>
<th>Patients</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hofer and colleagues\textsuperscript{27}</td>
<td>2008</td>
<td>1.07</td>
<td>CABG</td>
<td>67 (9)</td>
<td>SVV\textsubscript{PiCCO}</td>
<td>Na</td>
<td>2.0</td>
<td>2.4</td>
<td>NA</td>
<td>0.75</td>
<td>40</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Biais and colleagues\textsuperscript{28}</td>
<td>2009</td>
<td>1.07</td>
<td>Liver surgery</td>
<td>53 (9)</td>
<td>SVV\textsubscript{Doppler}</td>
<td>11.4</td>
<td>-0.7</td>
<td>2.5</td>
<td>44</td>
<td>NA</td>
<td>30</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Cannesson and colleagues\textsuperscript{29}</td>
<td>2009</td>
<td>1.10</td>
<td>CABG</td>
<td>NA</td>
<td>PPV\textsubscript{Intellivue}</td>
<td>NA</td>
<td>1.3</td>
<td>2.8</td>
<td>NA</td>
<td>NA</td>
<td>25</td>
<td>50</td>
<td></td>
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<tr>
<td>Derichard and colleagues\textsuperscript{30}</td>
<td>2009</td>
<td>1.10</td>
<td>Abdominal surgery</td>
<td>48–75</td>
<td>PPV\textsubscript{Intellivue}</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.71</td>
<td>11</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Monge García and colleagues\textsuperscript{31}</td>
<td>2009</td>
<td>1.10</td>
<td>ICU</td>
<td>55</td>
<td>Doppler\textsubscript{LVPeak,Vivid 3}</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.47</td>
<td>0.26</td>
<td>38</td>
<td>76</td>
</tr>
<tr>
<td>de Wilde and colleagues\textsuperscript{32}</td>
<td>2009</td>
<td>1.07</td>
<td>CABG</td>
<td>66</td>
<td>SVV\textsubscript{Lidco}</td>
<td>10.2</td>
<td>1.5</td>
<td>2.5</td>
<td>49</td>
<td>NA</td>
<td>15</td>
<td>136</td>
<td></td>
</tr>
<tr>
<td>Qiao and colleagues\textsuperscript{33}</td>
<td>2010</td>
<td>3.02</td>
<td>Neurosurgery</td>
<td>43 (12)</td>
<td>SPV\textsubscript{Datex}</td>
<td>NA</td>
<td>2.31</td>
<td>1.8</td>
<td>NA</td>
<td>0.80</td>
<td>26</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Khwannimit and Bhurayanontachai\textsuperscript{34}</td>
<td>2012</td>
<td>3.02</td>
<td>Sepsis</td>
<td>54 (20)</td>
<td>PPV\textsubscript{Intellivue}</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.77</td>
<td>26</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>291</td>
<td>935</td>
<td></td>
</tr>
</tbody>
</table>

Weighted average for

| Patients | 11 | 1.2 | 2.2 | 46 | 0.71 | 0.32 |
| 95% confidence interval | 11–11 | 1.0–1.3 | 2.1–2.3 | 45–46 | 0.69–0.73 | 0.31–0.34 |

| Data | 11 | 1.1 | 2.0 | 47 | 0.71 | 0.33 |
| 95% confidence interval | 11–11 | 1.0–1.2 | 2.0–2.1 | 46–47 | 0.71–0.73 | 0.31–0.34 |
during atrial pacing. Marqué and colleagues studied 12,099 paired data obtained with the first-generation FloTrac/Vigileo software and continuous thermodilution CO, yielding acceptable performance with small bias and %error, short response time, accurate amplitude response, and ability to detect significant directional changes. In comparing 1.03 and 1.07 versions of the software with intermittent thermodilution CO, the latter version proved better. For measurement around cardiac surgery, utilizing the second-generation software patients with moderately abnormal left ventricular function, good agreement with intermittent thermodilution CO was noted, except in the presence of large changes in vascular tone. Mehta and colleagues used the 1.07 version in 12 patients and compared CO at eight different intervals during cardiac surgery. The %error was 29%, rendering FloTrac/Vigileo-derived CO almost identical to intermittent thermodilution CO. Sampling 136 data points in 30 small children post-cardiac transplantation revealed poor agreement between intermittent thermodilution and FloTrac/Vigileo-derived CO, reflecting the limitations of the Langewouters-derived vascular compliance at young age. In comparing calibrated and uncalibrated (FloTrac/Vigileo version 1.10) arterial pressure-based CO during liver transplantation (Table 3), both methods showed increased error with decreasing resistance when compared with intermittent thermodilution CO. Other authors also noted that the mean difference between FloTrac/Vigileo, using the 1.07 or 1.14 versions, and thermodilution CO increases below a systemic vascular resistance of about 800 dyn s⁻¹ cm⁻⁵. The latest software version 3.02 may not fully prevent this phenomenon. In comparing two FloTrac/Vigileo software versions (1.10 and 3.02) with right-sided thermodilution during liver surgery, the 3.02 version performed even worse. An increased bias was observed with 31% error compared with intermittent thermodilution CO and of 38% compared with continuous CO when exceeding 8 litre min⁻¹, while bias was lower and %error stayed below 30% at lower CO. During septic shock, another condition with a well-known decrease in vascular tone, a similar underestimation of FloTrac/Vigileo compared with thermodilution CO has been observed. During a comparison of FloTrac/Vigileo with transpulmonary thermodilution CO during norepinephrine treatment of patients suffering from septic shock, arrhythmias were accepted and the average systemic vascular resistance was below 800 dyn s⁻¹ cm⁻⁵. The latter was associated with large bias, limits of agreement, and %error as in other studies. We compared software versions 1.07, 1.10, and 3.02 with intermittent thermodilution CO in septic shock and showed improved accuracy and precision with the subsequent versions, although a bias dependent on systemic vascular resistance persisted with the most recent one. A French group compared calibrated and uncalibrated FloTrac/Vigileo measurement of CO (version 1.10) during the treatment of patients with septic shock and favoured the former. Recently, the latest software (3.02) was studied in multiple centres and 58 patients with sepsis were included. Simultaneous data were obtained for CO derived from intermittent and continuous thermodilution and the FloTrac/Vigileo 1.10 and 3.02 software versions. The bias (and its dependence on vascular tone) improved with the latest software version (3.02), but the %error remained unchanged at 30%. However, most measurements were performed at a systemic vascular resistance of >500 dyn s⁻¹ cm⁻⁵ and data analyses were performed offline.

Changes in CO other than absolute values may be of greater clinical use if highly predictive of those in a reference standard, for instance, in evaluating fluid responsiveness and other responses to therapeutic interventions. However, only few studies evaluated the concordance of CO changes with a reference standard and they suggest improving performance with evolving software versions, even though highly variable indicators of concordance and acceptability for clinical use have been described. In hypovolaemic patients with spontaneous breathing, V̇Ṡ as measured by FloTrac/Vigileo increased within 2 min after passive leg raising and adequately predicted fluid responsiveness assessed by echocardiography. Changes in PP with aortic clamping and declamping may alter FloTrac/Vigileo CO but not that measured by echocardiography. Changes in FloTrac/Vigileo CO during large alterations in vascular tone may less well correlate to those measured by a reference technique than during fluid loading or passive leg raising, particularly in hyperdynamic conditions and in spite of most recent software. Indeed, concordance of measurements with the reference standard seemed high during and after cardiac surgery but moderate (60–75% or r² < 0.50) in patients with an impaired left ventricular function or with hyperdynamic conditions, including sepsis. The latter has been denied by other studies. Changing doses of inotropes, vasopressors, or vasodilators, which is commonly done in clinical practice, can thus transiently change FloTrac/Vigileo compared with thermodilution CO, but a slow response of the latter to detect rapid changes in CO cannot always be excluded. An early study reported a concordance of 59% with intermittent thermodilution-derived CO for changes < 15% in a mixed patient population. These changes may be too small to be clinically relevant. However, the FloTrac/Vigileo failed to detect an increase in transpulmonary thermodilution CO of 15% or greater after fluid challenges and use of norepinephrine in septic patients. With the use of the most recent software, the same group reported slightly improved performance, but with better concordance with transpulmonary thermodilution for CO changes during fluid loading than norepinephrine administration in septic patients. We compared software versions 1.07, 1.10, and 3.02 with intermittent thermodilution CO in the treatment of septic shock and showed good tracking ability during the course of treatment of the syndrome. Dobutamine treatment of subarachnoid haemorrhage patients with delayed cerebral ischaemia resulted in an error of only 15% when comparing FloTrac/Vigileo with transpulmonary thermodilution CO, at an unaltered vascular tone. Otherwise, we did not individually assess the interventions for reporting concordance.
The pressure (wave form) differs at different measuring sites within the same patient. Ascending aorta and radial artery pressure have been used to calculate CO by FloTrac/Vigileo during cardiac surgery and indicate that results may vary according to site. Studies compared radial and femoral arterial pressure-derived CO, showing considerable differences. However, studies using more recent software versions have contradicted these findings. In contrast to CO measurements, the sampling site may not affect SVVs.

There were eight comparative studies of SVV measurements (Table 5). The FloTrac/Vigileo-derived SVV moderately agreed with the SVV obtained with other devices and analyses of the arterial pressure waveform, but not in all studies. FloTrac/Vigileo-derived SVV was able to predict fluid responsiveness in 85% of studies addressing this in mechanically ventilated patients. Arterial pressure, prone position, or various ventilation modes did not affect these results. First- to third-generation software has been suggested to yield successfully discriminating SVVs, performing equally well as PP variation or pleth variability index. Observers observed that the FloTrac/Vigileo-derived SVV was a better predictor and monitor of fluid responsiveness than static parameters. In mechanically ventilated cardiac surgery patients, the increase in SVV with removal of blood and the decrease with replacement by colloids were predictive of the course of CO and echocardiography-determined left ventricular end-diastolic volume. The SVV derived from FloTrac/Vigileo predicted, and also PP variation, a decrease in SV (thermodilution and FloTrac/Vigileo) induced by positive end-expiratory pressure. After oesophageal surgery, FloTrac/Vigileo-derived SVV may be a useful parameter to predict hypovolaemia and fluid responsiveness. Only few studies failed to validate the usefulness of FloTrac/Vigileo-derived SVV to predict fluid responsiveness. Echocardiography-derived variations in vena cava inferior diameter predicted fluid responsiveness in fully mechanically ventilated patients. Absence of right ventricular overloading, fluid responsiveness in 85% of studies addressing this in mechanically ventilated patients, but the FloTrac/Vigileo system. Others used the system to monitor patients perioperatively, during induction of anaesthesia in patients with left ventricular dysfunction and during fluid challenges and vasopressor administration around Caesarean sections.

In conclusion, the performance of uncalibrated FloTrac/Vigileo has improved since its introduction, particularly in hypovolemic and fluid responsive patients. Since the average % error is below 30%, the CO measured with help of most recent software may be sufficiently accurate for routine clinical use in these conditions, even though trending capacity remains affected by changes in vascular tone. The SVV may usefully supplement these measurements, particularly in future outcome studies.

**Supplementary material**

Supplementary material (including additional references) is available at British Journal of Anaesthesia online.

**Authors’ contributions**

C.S., I.M., and A.B.J.G. have made substantial contributions to conception and design, literature search, and analysis and interpretation of data. All authors were involved in drafting the manuscript. All authors have read and approved the final manuscript.

**Declaration of interest**

C.S. and A.B.J.G. have received lecture fees from Edwards Life Sciences.
## Table 6

Therapeutic studies utilizing guidance by FloTrac/Vigileo™ ($n=7$) vs standard monitoring in randomized clinical trials grouped according to type, year of publication, and name of the first author. NA, not applicable; CI, cardiac index; SVI, stroke volume index; SVV, stroke volume variation; ScvO₂, central venous oxygen saturation; DO₂I, oxygen delivery index; SVRI, systemic vascular resistance index; MAP, mean arterial pressure; CVP, central venous pressure; UO, urine output; ABG, arterial blood gas analysis; SpO₂, pulse oximetry oxygen saturation; ICU, intensive care unit; HR, heart rate

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Version</th>
<th>Patient type</th>
<th>Treatment guided by FloTrac/Vigileo™-derived variables, number of patients</th>
<th>Control guided by routine variables or other values, number of patients</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapoor and colleagues⁹⁴</td>
<td>2008</td>
<td>NA</td>
<td>Cardiac surgery</td>
<td>CI, SVI, SVV, ScvO₂, DO₂I, SVRI, 13</td>
<td>MAP, CVP, UO, ABG, SpO₂, 14</td>
<td>More fluid volume and frequency of changes of inotropics in the treatment arm. No differences in duration of ventilator support, duration of inotropic drug use, length of ICU and hospital stay</td>
</tr>
<tr>
<td>Benes and colleagues⁹⁵</td>
<td>2010</td>
<td>1.10</td>
<td>High-risk surgery</td>
<td>CI, SVV, CVP, 60</td>
<td>MAP, CVP, HR, UO, 60</td>
<td>Improved intraoperative haemodynamic stability, decreased serum lactate at the end of surgery and less postoperative complications in treatment arm. No differences in mortality, ICU and hospital lengths of stay</td>
</tr>
<tr>
<td>Mayer and colleagues⁹⁶</td>
<td>2010</td>
<td>1.14</td>
<td>High-risk surgery</td>
<td>CI, SVI, SVV, MAP, 30</td>
<td>MAP, CVP, UO, 30</td>
<td>Reduced length of hospital stay by 4 days in treatment arm. Less postoperative complications in treatment arm. No differences in ICU length of stay and mortality</td>
</tr>
<tr>
<td>Cecconi and colleagues⁹⁷</td>
<td>2011</td>
<td>1.07</td>
<td>Hip surgery</td>
<td>SVI, DO₂I, 20</td>
<td>MAP, 20</td>
<td>The treatment group received more intraoperative fluids, dobutamine, and blood transfusion. Less postoperative complications in treatment arm</td>
</tr>
<tr>
<td>Takalo and colleagues⁹⁸</td>
<td>2011</td>
<td>1.07</td>
<td>Intensive care</td>
<td>CI, MAP, 201</td>
<td>MAP, 187</td>
<td>Early, non-invasive continuous cardiac output monitoring did not shorten the time to reach haemodynamic stability, produce any outcome benefit, or reduce the amount of resources used during the ICU stay when compared with standard treatment (with echo or pulmonary artery catheter)</td>
</tr>
<tr>
<td>Wang and colleagues⁹⁹</td>
<td>2012</td>
<td>1.07</td>
<td>Liver surgery</td>
<td>SVV, 25</td>
<td>CVP, 25</td>
<td>Greater diuretic use in the control group, but no differences in blood loss, acute kidney injury, and survival</td>
</tr>
<tr>
<td>Wang and colleagues¹⁰⁰</td>
<td>2012</td>
<td>NA</td>
<td>Gastrointestinal surgery</td>
<td>SVV 5–7%, 20</td>
<td>SVV 11–13%, 20</td>
<td>With high SVV guidance less fluids and urinary output; enhanced gastrointestinal recovery and reduced length of hospital stay</td>
</tr>
</tbody>
</table>
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