Validation of noninvasive pulse contour cardiac output using finger arterial pressure in cardiac surgery patients requiring fluid therapy

Charlotte Hofhuizen, MD a,⁎, Benno Lansdorp, Msc b, c, Johannes G. van der Hoeven, PhD, MD b, Gert-Jan Scheffer, MD, PhD a, Joris Lemson, MD, PhD b

a Radboud University Nijmegen Medical Centre, Department of Anesthesiology, PO Box 9101 6500 HB Nijmegen, The Netherlands
b Radboud University Nijmegen Medical Centre, Department of Intensive Care Medicine, 6500 HB Nijmegen, The Netherlands
c University of Twente, MIRA Institute for Biomedical Technology and Technical Medicine, 7500 AE Enschede, The Netherlands

⁎ Corresponding author.
E-mail address: c.hofhuizen@anes.umcn.nl (C. Hofhuizen).

ABSTRACT

Introduction: Nexfin (Edwards Lifesciences, Irvine, CA) allows for noninvasive continuous monitoring of blood pressure (ABPN) and cardiac output (CONI) by measuring finger arterial pressure (FAP). To evaluate the accuracy of FAP in measuring ABPN and CONI as well as the adequacy of detecting changes in ABP and CO, we compared FAP to intra-arterially measured blood pressure (APAI) and transpulmonary thermodilution (COTD) in postcardiac surgery patients during a fluid challenge (FC).

Methods: Twenty sedated patients post cardiac surgery were included, and 28 FCs were performed. Measurements of ABP and CO were simultaneously collected before and after an FC, and we compared CO and blood pressure.

Results: Finger arterial pressure was obtainable in all patients. When comparing ABPN with ABPAI, bias was 2.7 mm Hg (limits of agreement [LOA], ±22.2), 4.9 mm Hg (LOA, ±13.6), and 4.2 mm Hg (LOA, ±13.7) for systolic, diastolic, and mean arterial pressure, respectively. Concordance between changes in ABPN and ABPAI was 100%. Mean bias between CO-TREK and COTD was −0.26 (LOA, ±2.2), with a percentage error of 38.9%. Concordance between changes in CO-TREK vs COTD and was 100%.

Conclusion: Finger arterial pressure reliably measures ABP and adequately tracks changes in ABP. Although COTD is not interchangeable with CO-TREK, it follows changes in CO closely.

A R T I C L E   I N F O

Keywords:
Arterial pressure
Measurement
Equipment
Nexfin
Fluid therapy
Cardiac output
Measurement

1. Introduction

Maintaining adequate tissue perfusion and oxygenation is of paramount importance during anesthesia and in the critical care environment. Establishing an adequate cardiac output (CO) is an essential determinant of this therapeutic goal. Therefore, over the last decade, there has been an increasing interest in the continuous measurement of CO under various clinical conditions. Thermodilution is the clinical criterion standard for CO measurement [1], but this technique requires the placement of a specific intra-arterial or pulmonary artery catheter that might lead to various complications. Therefore, there is a growing need for minimally invasive and continuous CO monitoring. This new technique should meet the desired requirements of accuracy, operator independence, safety, ease of application, and continuous use [2]. Furthermore, a fast continuous method could be beneficial in tracking CO changes as a result of diagnostic maneuvers and interventions. Although a number of methods are available to measure CO noninvasively, none of these techniques answers to all requirements, and therefore, the method of choice will depend on the physician’s experience, the patient, and the clinical situation. The Nexfin device (Edwards Lifesciences, Irvine, CA) measures blood pressure and CO continuously and noninvasively by measuring finger arterial pressure (FAP). The device uses a finger cuff to construct an arterial blood pressure waveform using a technique that is based on the volume clamp method developed by Peñaz and the physical criteria of Wesseling et al [3,4]. Nexfin CO-TREK is a mathematical model incorporated in the software that calculates beat-to-beat stroke volume using the arterial blood pressure waveform [5]. This combination enables the continuous measurement of blood pressure and CO in a noninvasive manner. With the application of the CO-TREK algorithm, it is also possible to determine the CO off-line using the invasive blood pressure signal measured with an intra-arterial catheter. A small number of studies has been undertaken to assess the accuracy of FAP CO in determining absolute CO levels with varying results [6-8]. However, an important part of hemodynamic optimization is the effect of a given treatment such as fluid expansion. Therefore, we assessed the accuracy of FAP in tracking CO changes after a fluid challenge (FC).

In this study, we compared CO-TREK CO derived from the noninvasive finger blood pressure signal (CO-TREK) and CO-TREK CO derived from the intra-arterial blood pressure signal (COAPX) with CO derived from transpulmonary thermodilution (COTD) using PiCCO (Pulsion Medical Systems, Munich, Germany) as the reference method. We also compared FAP blood pressure (APAF) to intra-arterially measured blood pressure (APA).
2. Methods

2.1. Subjects

With the approval of the institutional review board and after obtaining participants' written informed consent, 20 patients admitted to the intensive care unit (ICU) following elective conventional cardiac surgery were studied. Exclusion criteria were cardiac arrhythmias, preoperative inotropic or intra-aortic balloon pump support, and patients requiring emergency or redo cardiac surgery.

2.2. Hemodynamic monitoring

Anaesthesia was according to the institutional protocol at the discretion of the attending anaesthesiologist. A 20GA right radial intra-arterial catheter (Becton Dickinson and Co, Franklin Lakes, NJ) was introduced before anesthesia induction and connected via standard low compliant tubing to a disposable pressure transducer (Edwards Lifesciences). After induction, a 2-lumen central venous catheter was inserted in the right internal jugular vein for the measurement of central venous pressure. Cardiac output was monitored using the PiCCO monitor and a 5F thermostip-perforated arterial PiCCO catheter inserted in the femoral artery (Pulsion Medical Systems). All pressure monitors were zeroed at the midaxillary line. Signals were recorded simultaneously using a sample rate of 200 Hz and stored on a hard disk.

2.3. Finger arterial pressure CO monitoring

Finger arterial pressure is a device for noninvasive and continuous measurement of blood pressure using a finger cuff. A photoplethysmograph mounted inside the finger cuff detects changes in finger arterial diameter. Using a fast pneumatic system, the diameter of the finger artery can be held at a constant level by rapidly varying the pressure in the finger cuff air bladder. This is called the volume clamp method. If the artery is clamped at the correct diameter, the pressure in the air bladder is identical to the pressure inside the artery, and finger arterial pressure is measured. The correct arterial diameter is determined at regular intervals during a blood pressure measurement, by a physiological calibration called physiocal [9]. Nexfin applies a waveform and level correction methodology to reconstruct finger arterial pressure to the arterial pressure waveform at brachial artery level [10].

Finger arterial pressure calculates beat-to-beat stroke volume by dividing the area under the systolic portion of the arterial pressure curve by the aortic input impedance [11]. The value of this aortic input impedance is determined from a 3-element Windkessel model described by Westerhof et al [12]. In this model, the nonlinear effect of mean pressure as well as the influence of the patient’s age, height, weight, and sex on aortic mechanical properties is incorporated. The algorithm that converts finger arterial waveform to CO is called CO-TREK.

The noninvasive arterial signal (ABPNI) and CO (COIN) were obtained using an appropriate size finger cuff applied to the midphalanx of the left middle or index finger according to guidelines provided by the manufacturer. The finger with the cuff was positioned at the midaxillary line, and the finger was checked regularly for signs of tissue hypoxia.

To determine whether inaccuracies in the predictive value of the noninvasive finger signal were caused by the noninvasive character of the measurement or were caused by inaccuracies in the CO-TREK algorithm itself, we also calculated CO using the stored intra-arterial blood pressure signal (COIA). The COIA was calculated off-line using the CO-TREK algorithm, and we compared this with COIN.

2.4. Study design

After surgery, patients were admitted to the intensive care unit (ICU) and sedated with midazolam. Finger arterial pressure recording started immediately after arrival at the ICU. FAP measurement was considered adequate if physical occurred at intervals longer than 30 seconds. The intra-arterial pressure measurement was checked for quality by visually inspecting the waveform and performing fast flash test. If, at the discretion of the attending intensive care physician, an FC was indicated, a transpulmonary thermodilution measurement was performed by 3 injections of 15 mL of ice-cold saline through the central venous catheter before the FC (T1) and 5 minutes after completion of FC (T2). If a difference of more than 20% occurred between the 3 thermodilution measurements, injection was repeated. Criterion for an FC was presence of a mean arterial pressure below 70 mm Hg. To evaluate the clinical effect of the FC, another thermodilution measurement was performed 30 minutes after completion of the FC if the clinical situation permitted, for example, patient still fully sedated, no change in inotropic medication, and others (T3). The FC was performed by infusing 6 mL per kg ideal body weight of a 130/0.4% hydroxyethyl starch solution ( Fresenius Kabi, Bad Homburg, the Netherlands) over a period of 15 minutes. Simultaneous data of COTD, CONI, ABPNI, and ABPIA were collected throughout the postoperative period in the ICU until the patient was extubated according to local standard operating procedures.

2.5. Statistical analysis

To compare COIN and COIA to COTD, we averaged a 20-second time interval of the noninvasive finger measurement and intra-arterial measurement and compared it with the simultaneously performed COTD. This interval was chosen to evade periods of physical, which occurs at regular intervals during a FAP measurement. The same time intervals were used to compare ABPNI to ABPIA. Hemodynamic parameters were reported as mean ± SD. The Kolmogorov-Smirnov test was used to test the normality of the distribution. To assess agreement (bias and limits of agreement [LOA]) between the invasive and noninvasive derived parameters Bland-Altman analysis was used, which was corrected for repeated measurements in 1 subject [13,14]. The mean percentage error was assessed using theCritchley and Critchley method [15]. In addition, we defined an agreement tolerability interval ratio using a tolerability interval of 4 L/min (4-8 L/min)[16].To assess the hemodynamic change that occurred, we compared a time point to the hemodynamic measurement taken earlier, that is, T1 to T2 and T2 to T3. For assessing the trending ability of COTD, we determined concordance using a 4-quadrant plot. Changes in blood pressure and CO smaller than 5% were not considered clinically relevant and therefore excluded. Hereafter, we constructed a polar plot of CO changes among consecutive time points described by Critchley et al [17,18]. Influence of temperature and use of vasoactive drugs on bias were checked using the Student t test. Statistical analyses were carried out using GraphPad Prism version 5.01 (GraphPad software, Inc, La Jolla, CA). Assuming an SD of 1.33 L/min [7], we needed a minimum of 69 simultaneous measurements to achieve a confidence interval of 0.25 L/min. Assuming we would perform 4 measurements in each subject, we included 20 patients.

3. Results

Twenty patients were included in the study. In all patients, a sufficient quality FAP waveform was obtained. There were no signs of tissue hypoxia distal to the finger cuff, and no adverse events were noted. Twenty-eight FCs were performed in 19 patients. One patient did not receive an FC. Because of technical difficulties intra-arterial blood pressure, recording failed in 4 patients, which led to 66 pairs of COIN and COTD and 54 pairs of ABP and COIN, COIA and COTD data.
Patient baseline characteristics and hemodynamic data are shown in Tables 1 and 2, respectively.

### 3.1. ABPNI vs ABPIA

Mean bias (SD) and LOA between ABPNI and ABPIA was 2.7 mm Hg (LOA, ±22.2), 4.9 mm Hg (LOA, ±13.6), and 4.2 mm Hg (LOA, ±13.7) for systolic, diastolic, and mean arterial pressure, respectively. Comparison between ABPNI and ABPIA for mean arterial pressure by a Bland-Altman analysis is depicted in Fig. 1. The ABPNI tracked changes of ABPIA with a mean bias of 0 (LOA, ±13.7), −1 (LOA, ±10.0), and −1 (LOA, ±9.6) mm Hg for systolic, diastolic, and mean arterial pressure, respectively. Concordance between ABPNI and ABPIA was 100% using the 5% exclusion zone. Fig. 2 shows a polar plot depicting the changes in mean arterial pressure for the 2 methods. Mean polar angle was 10.4° with an SD of 10.3°. All data points lie between the 30° radial limits.

### 3.2. CONI and COIA vs COTD

No significant difference was found between mean absolute values of CONI and COTD. The relation between CONI and COTD is depicted in Fig. 3. Mean bias between CONI vs COTD and COIA vs COTD was −0.26 (LOA, ±2.2) L/min and −0.78 (LOA, ±1.9) L/min, respectively. The percentage error between CONI and COTD was 38.9%; the percentage error between COIA and COTD was 35.1%. Agreement interval was 4.4 L/min, which did not meet the criterion of an agreement tolerability interval ratio of 4 L/min, representing marginal agreement. Bias was not influenced by temperature of the hand or the use of vasoactive medication.

### 3.3. Changes in CONI vs COTD

The mean change in CO after an FC measured with thermodilution was 0.59 (range, −1.0 to 2.4) L/min. Concordance rate between CONI and COTD and concordance rate between COIA and COTD were 100% and 91.7%, respectively, using the 5% exclusion zone. The CONI and COIA tracked changes in COTD with a mean bias of −0.31 L/min (LOA, ±1.0) and −0.25 L/min (LOA, ±1.2), respectively. Fig. 4 shows a polar plot depicting the changes in CO for 2 methods. Mean polar

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**Table 1**

<table>
<thead>
<tr>
<th>Patient characteristics</th>
<th>Mean (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>67 (50-81)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>28.3 (21.4-37.1)</td>
</tr>
<tr>
<td>Male/female (n)</td>
<td>17/2</td>
</tr>
<tr>
<td>Type of surgery (n)</td>
<td></td>
</tr>
<tr>
<td>CABG</td>
<td>15</td>
</tr>
<tr>
<td>AVR</td>
<td>2</td>
</tr>
<tr>
<td>CABG + AVR</td>
<td>2</td>
</tr>
<tr>
<td>APACHE II</td>
<td>12.5 (5-20)</td>
</tr>
<tr>
<td>History (n)</td>
<td></td>
</tr>
<tr>
<td>Ischemic heart disease</td>
<td>18 (90%)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>14 (70%)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>7 (35%)</td>
</tr>
<tr>
<td>Obesity</td>
<td>6 (30%)</td>
</tr>
<tr>
<td>Core temperature (°)</td>
<td>37.7 (35.4-38)</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Hemodynamic changes before and after an FC</th>
<th>Before FC, T1 (n = 28)</th>
<th>5 min after completion of FC, T2 (n = 28)</th>
<th>30 min after completion of FC, T3 (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAPNI (mm Hg)</td>
<td>102.3 (12.6)</td>
<td>113.3 (16.7)</td>
<td>125.4 (19.2)</td>
</tr>
<tr>
<td>SAPIA (mm Hg)</td>
<td>101.5 (11.5)</td>
<td>116.7 (17.1)</td>
<td>123.2 (19.4)</td>
</tr>
<tr>
<td>DAPNI (mm Hg)</td>
<td>59.2 (8.9)</td>
<td>63.0 (9.7)</td>
<td>71.0 (14.5)</td>
</tr>
<tr>
<td>DAPIA (mm Hg)</td>
<td>53.5 (7.4)</td>
<td>58.2 (5.9)</td>
<td>62.0 (7.6)</td>
</tr>
<tr>
<td>MAPNI (mm Hg)</td>
<td>71.6 (5.1)</td>
<td>81.8 (12.0)</td>
<td>87.6 (17.2)</td>
</tr>
<tr>
<td>MAPIA (mm Hg)</td>
<td>68.7 (7.7)</td>
<td>77.4 (8.3)</td>
<td>81.0 (10.9)</td>
</tr>
<tr>
<td>COIN (L/min)</td>
<td>5.31 (1.26)</td>
<td>6.29 (0.94)</td>
<td>5.81 (1.36)</td>
</tr>
<tr>
<td>COIA (L/min)</td>
<td>5.32 (1.23)</td>
<td>6.12 (1.03)</td>
<td>5.43 (1.38)</td>
</tr>
<tr>
<td>COOIA (L/min)</td>
<td>4.91 (0.88)</td>
<td>5.50 (1.03)</td>
<td>5.66 (0.99)</td>
</tr>
</tbody>
</table>

Data are expressed as mean and SD; n = 28, 5 pairs missing COIA and MAPIA due to technical difficulties. SAP indicates systolic arterial pressure; DAP, diastolic arterial pressure; MAP, mean arterial pressure.

* Significantly different from reference techniques (P < .05).
angle was 17.8° with an SD of 13.0°. Of all data points, 82% lie within the 30° radial limits.

4. Discussion

The main conclusions from our study are that in a population of patients after cardiac surgery, blood pressure was accurately measured by FAP and also FAP was capable of tracking blood pressure changes. However, both CO\textsubscript{IN} and CO\textsubscript{IA} were not interchangeable with transpulmonary thermodilution for CO measurement, although FAP shows strong tracking capabilities for CO changes after an FC.

Bias and precision of diastolic and mean arterial pressure are within the limits set by the Association for the Advancement of Medical Instrumentation that allow for a maximum bias of 5 mm Hg and a maximal precision of 8 mm Hg [19]. These results are in concordance with previous studies [7,20,21] where FAP was plotted against intra-arterially measured blood pressure. Studies comparing ABP\textsubscript{IA} against a noninvasive blood pressure measurement technique, such as oscillometry, show more diverse results, possibly reflecting the underlying variability of the noninvasive blood pressure measurement technique [22,23].

In this study, FAP was not interchangeable with transpulmonary thermodilution CO. Although bias was low, percentage error did not meet the criterion of a maximum percentage error of 30% proposed by Critchley et al [17]. Accuracy of FAP was, however, similar to the accuracy of CO\textsubscript{IA}, suggesting that inaccuracy of the CO-TREK algorithm is not caused by a less reliable noninvasive arterial signal. However, the technique of intra-arterially measured blood pressure relies on pressure differences where finger pressure measurement relies on arterial diameter changes. This fundamental difference may account for the difference between CO\textsubscript{IN} and CO\textsubscript{IA}. In addition, because of the nature of the measurement, FAP cannot be influenced by several factors that influence the accuracy of intra-arterially measured blood pressure such as kinking, presence of bubbles, and blood clots or underdamping. Several other clinical studies evaluating the accuracy of FAP show diverse results with percentage errors ranging from 25% to 50% [6-8,21,24,25]. However, methodological differences such as reference techniques, use of vasoactive medication, patient characteristics, and clinical situations ranging from critical care to outpatient evaluation preclude direct comparison and may account for this wide range in observed accuracy.

In this study, 82% of all data points fall between the 30° radial LOA reflecting marginal trending. This finding is caused by the angular bias of 17.8°. Although this angular bias is quite large, the spread around this angle was quite small with an SD of 13.0°. This possibly reflects a significant offset in calibration where CO\textsubscript{IN} measured greater changes in CO than did CO\textsubscript{IA}

In this study, we obtained a good quality noninvasive signal in all patients despite the presence of vasoactive medication, hypothermia, or the fact that most subjects had a history of hypertension and vascular disease. Although finger blood pressure and CO measurement are dependent of finger arterial flow, we found no correlation between bias and core temperature or the use of vasoactive medication [26]. However, norepinephrine dosage did not exceed 0.1 μg/kg per minute, and patients were not exposed to core temperatures below 35.4.

Compared with a single CO measurement, tracking of CO changes to evaluate the clinical course or the effect of an instituted treatment may be a more valuable tool in patients with hemodynamic abnormalities. In this study, we found a high concordance between changes in CO\textsubscript{IN} and CO\textsubscript{IA}, which corresponds with previous studies investigating the ability of FAP in tracking CO changes [6,25]. However, this is the first study evaluating the accuracy of FAP in tracking CO changes after fluid expansion, in clinical practice commonly the first intervention to improve CO.

Several limitations of our study should be noted. First, we investigated a group of postoperative cardiac surgery patients under stable hemodynamic conditions. Although 45% of patients required inotropic or vasoactive medication, dosage was low. Our data are, therefore, not automatically transferable to other subgroups such as critically ill patients or trauma care. Second, although, to our knowledge, this is the first study evaluating the accuracy of CO\textsubscript{IN} in tracking CO changes after fluid expansion, CO changes after an FC were modest with a maximum of 2.03 L/min. Further research in tracking CO changes in hemodynamic unstable patients is necessary. Third, this study is not designed to determine the accuracy of FAP in determining fluid responsiveness. In addition to CO measurement, the prediction of fluid responsiveness is an important tool to guide fluid resuscitation during hemodynamic optimization. Considering its desirable characteristics, FAP could provide a valuable monitor to determine fluid responsiveness. However, further research is mandatory to evaluate the accuracy and feasibility of FAP in the guidance of fluid optimization.

In this study, we compared CO\textsubscript{IN} to transpulmonary thermodilution. Although thermodilution is considered the criterion standard for CO measurement, in previous studies, transpulmonary thermodilution using PiCCO has been shown to be less accurate during thoracic surgery or hemodynamic instability [27]. This may, in part, explain the wide percentage error found in the present study. Recently, Peyton
and Chong [27] published a meta-analysis comparing 4 different minimally invasive CO monitors showing that none of the 4 methods tested achieved to meet the 30% LOA with thermodilution. They propose that a percentage error of 45% in agreement with thermodilution after an FC. 

Percentage error of 38.9%, although trending analysis showed a high tracking of blood pressure changes. Our data suggest that FAP CO is a signal. It is reliable in the measurement of blood pressure and the CO. The technique is safe, fast, and easy to use and provides a continuous noninvasive blood pressure and CO measurement device and the esophageal flow from pressure in cardiovascular disease. Anaesthesia 2010;65(11):1119–25.


