Cardiac output monitoring by pressure recording analytical method in cardiac surgery

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Abstract

Objective: A less-invasive method has been developed that may provide an alternative to monitor cardiac output from arterial pressure: beat-to-beat values of cardiac output can be obtained by pressure recording analytical method (PRAM). The purpose of this study was to assess the reliability of cardiac output determination by PRAM in cardiac surgery.

Methods: Cardiac output was measured in 28 patients undergoing coronary artery bypass grafting at 15 min after anaesthesia induction, 30 min after extracorporeal circulation, 1 and 3 h after arrival in the intensive care unit using thermodilution (ThD) method through a pulmonary artery catheter and PRAM. ThD cardiac output was calculated as the mean of five separate measurements. PRAM provided beat-by-beat cardiac output data continuously throughout the study and the cardiac output values displayed on a dedicated personal computer at each time point were recorded. Correlations were calculated and differences were compared by Bland–Altman analysis.

Results: A total of 112 measurements were obtained. Cardiac output ranged from 2.3 to 7.4 l/min, and a good linear correlation (R^2 = 0.78, P < 0.0001) was found between ThD and PRAM. The highest degree of correlation (R^2 = 0.86) was obtained at 3 h after arrival in the intensive care unit. The lower degree of correlation (R^2 = 0.70) was obtained 30 min after extracorporeal circulation. At Bland–Altman analysis, the overall estimates of cardiac output measured by PRAM closely agreed with ThD (mean difference, 0.027; standard deviation, 0.43; limits of agreement, ±0.83 and ±0.89).

Conclusions: Under the studied conditions, our results demonstrate good agreement between PRAM data and ThD measurements, and this new method has shown to be accurate for real-time monitoring of cardiac output in cardiac surgery. Further studies will be required to assess this method in higher-risk patients and in the setting of haemodynamic instability or arrhythmias. This is the first study designed to assess the accuracy of PRAM in cardiac surgery.

Keywords: Cardiac output; Monitoring; Pulse contour; Coronary artery bypass grafting

1. Introduction

Continuous monitoring of cardiac output (CO) during cardiac surgery could allow the detection of sudden hemodynamic changes which may influence patients management and outcome [1]. Usually, CO is monitored with a pulmonary artery catheter (PAC) with thermodilution (ThD), the most widely employed method for the assessment of CO in this type of surgery. Unfortunately, several factors may intervene in negatively affecting the performances of ThD [2]. Furthermore, use of PAC carries significant risks (e.g. arrhythmia, infection), and some authors are of the opinion that PAC may be associated with worse outcome in some critically ill patients, and that low-risk patients do not require perioperative assessment of CO by PAC [3]. Taken together, these factors have prompted efforts to develop alternatives to the PAC. Recently a less-invasive method has been developed: beat-to-beat values of CO can be obtained by pressure recording analytical method (PRAM) [4]. This new method is based on the mathematical analysis of the arterial pressure profile changes. It allows beat-by-beat stroke volume (SV) assessment from the pressure signal recorded in radial artery [4].

In cardiac surgery, patients often experience fluctuations in vascular tone and may require changes in treatment (e.g. fluid infusions, inotropics, vasopressors/vasodilators). In addition, the arterial line is frequently used for blood sampling, which may result in over-damping of the transducer pressure signal [5]. Because PRAM relies completely on the analysis of the arterial pressure waveform
to calculate CO, each of these factors may influence the reliability of PRAM determinations. This is the first study designed to assess the accuracy of CO measurements made by PRAM compared with ThD technique during and after cardiac surgery.

2. Materials and methods

2.1. Patients

Twenty-eight patients (18 male, 10 female; mean age 66 ± 3 years) undergoing elective coronary artery bypass grafting (CABG) with extracorporeal circulation (ECC) were enrolled in a study designed to assess the accuracy and reliability of PRAM in the clinical setting. A Cleveland Clinic Score beyond four points was an exclusion criteria. We also excluded patients with valvular heart disease or contraindications for the use of PAC, and those with known peripheral vascular disease. Written informed consent was obtained from all patients after approval of the study by the Institutional Review Board. Standardized pre- and post-operative management and cardiopulmonary bypass conduction were performed [6].

2.2. Study protocol

2.2.1. Thermodilution data acquisition

After induction of anesthesia, a thermodilution PAC (7F Baxter-Edwards, Irvine, CA) was inserted into the pulmonary artery. Thermodilution cardiac output (ThD-CO) was calculated as the mean of five separate measurements obtained over 5 min by injection of 10 ml of 5% glucose cold solution. In the absence of hemodynamic stability, the series of CO measurements were discarded and repeated until satisfactory measurements were obtained.

2.2.2. PRAM data acquisition

A standard arterial catheter was inserted into the radial artery. A Baxter Truwave PX-600F transducer (Baxter-Edwards, Irvine, CA) was connected to the monitoring system (Hewlett Packard, Andover, MA) for the continuous recording of the systemic arterial pressure waves and the subsequent computation of CO. PRAM cardiac output (PRAM-CO) values displayed on a dedicated personal computer at each time point were recorded. Besides, PRAM provided arterial pressure values and beat-by-beat cardiac output data continuously throughout the study (Fig. 1).

2.2.3. PRAM basic physical principles

Changes in volume which occur in all arterial vessels are mostly due to wall radial expansion in response to blood pressure changes. This depends on various physical factors such as the force of cardiac contraction, the arterial impedance and compliance, and the peripheral vessels’ resistance. These variables are closely interdependent and need to be evaluated at the same time. To this end, a variable called $Z$, aimed at representing the relationship between changes in pressure and changes in volume with time, is taken into account for the evaluation of SV in the various approaches to determine CO by pulse contour methods (PCMs). The conversion of pulse pressure to SV is obtained by calculating the area under the pulsatile portion of the pressure wave, and $Z$ (mmHg s/cm$^3$) is calculated as a dimensional factor retrospectively approximated from the results of in vitro experiments or by calibration with an independent measure of SV (i.e. ThD bolus).

At variance with other PCMs, PRAM is the practical application of a model developed completely a priori and not requiring retrospective adjustments [4]. With PRAM, the whole instead of the pulsatile systolic area under the pressure curve is measured in each cardiac cycle. At the same time, $Z$ is obtained directly from the morphologic analysis of both the pulsatile and continuous components of the pressure waveform without the use of predicted data or calibration factors.

Briefly, according to PRAM [4], $Z$ is equal to $(P/l)K$, and SV is calculated as follows (cm$^3$)

$$SV = \frac{A}{P/l \times K}$$
where:

\[ A = \text{area under the systolic portion of the pressure curve} \]

\[ \frac{P}{t} = \frac{\text{line of systole}}{\text{time}} \]

\[ K = \text{a dimensional factor related to the instantaneous acceleration of the vessel cross sectional area (s²/cm)} \times (1/cm^2) \]

The value of \( K \) is obtained from the ratio between expected and measured mean blood pressure. The numerator of the relationship is constant (theoretical mean value), and the denominator is measured. As a consequence, \( K \) may change from cardiac cycle to cardiac cycle, and the constant value at the numerator is taken as a reference to gauge the deviation from normality of the mean arterial pressure. Because mean arterial pressure is lower at the peripheral level with respect to central arteries [7], PRAM applies two different values of expected mean pressure for the computation of \( K \) at the central (aorta) and peripheral level (e.g. radial), namely the values originally indicated by Burton [7] and Guyton [8] (i.e. 100 mmHg at the central and 90 mmHg at the peripheral level). Since PRAM allows the use of two proper algorithms for central or peripheral artery to obtain SV for each cardiac cycle, we were able to monitor cardiac output by applying the proper formula (i.e. expected mean value = 90 mmHg) for radial artery [4]. The \( A, \frac{P}{t} \) and \( K \) variables are closely interdependent in each cardiac cycle [4].

2.2.4. Study interval

All determinations of CO were carried out at four times: 15 min after anesthesia induction (T1), 30 min after ECC (T2), 1 and 3 h after arrival in the intensive care unit (ICU) (T3 and T4, respectively).

2.3. Statistical analysis

Paired-sample \( t \)-test was used to ascertain differences between ThD-CO and PRAM-CO values at each time point. Differences were considered statistically significant at \( P < 0.05 \). To further compare data acquired by two techniques, concordance correlations were calculated. Finally, the agreement between different measurements of CO was assessed using the Bland–Altman procedure; this one takes into account the fact that neither modality being compared is the de facto gold standard [9].

3. Results

A total of 112 measurements were obtained. All patients remained hemodynamically stable throughout the study interval. CO values (range 2.3–7.4 l/min) were successfully collected by ThD and PRAM methods at any interval of the study for each patient. An average of 4.3 ± 0.9 arterial line blood samples were collected per patient over the study interval.

CO values, correlations between ThD and PRAM and some physiologic data collected at all time points are presented in Table 1.

Differences in CO values were normally distributed and no significant differences were noted between evaluations made with two methods at any interval of the study as assessed by the paired-sample \( t \)-test. Overall, a good linear correlation \((R^2 = 0.78)\) was found between CO-ThD and PRAM-CO (Fig. 2A). Bland–Altman analyses demonstrated good agreement between measurements.

### Table 1

Cardiac output values, correlations and agreement between thermodilution and pressure recording analytical method (PRAM), and some physiologic measurements

<table>
<thead>
<tr>
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<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
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<tbody>
<tr>
<td>ThD-CO (l/min) (mean ± SD; range)</td>
<td>3.9 ± 0.7; 2.8–5.7</td>
<td>4.1 ± 0.9; 2.4–6.7</td>
<td>4.4 ± 0.8; 3.2–7.4</td>
<td>4.1 ± 0.6; 2.7–5.5</td>
</tr>
<tr>
<td>PRAM-CO (l/min) (mean ± SD; range)</td>
<td>4.0 ± 0.6; 3.3–5.5</td>
<td>4.2 ± 0.7; 3.2–6.5</td>
<td>4.5 ± 0.9; 3.5–7.2</td>
<td>4.2 ± 0.8; 3.0–5.1</td>
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**ThD-CO vs PRAM-CO**

- **\( R^2 \) (Pearson), P value**
  - T1: 0.82, <0.0001
  - T2: 0.70, <0.0001
  - T3: 0.75, <0.0001
  - T4: 0.86, <0.0001
- **Bias, SD**
  - T1: 0.02, 0.61
  - T2: 0.01, 0.33
- **Limits of agreement**
  - T1: -1.19 ± 1.23
  - T2: -1.58 ± 0.78
  - T3: -1.68 ± 1.75
  - T4: -0.57 ± 0.75
- **MAP (mmHg) (mean ± SD)**
  - T1: 85.9 ± 12.2
  - T2: 82.1 ± 9.8
  - T3: 86.5 ± 12.0
  - T4: 88.0 ± 7.7
- **HR (b/min) (mean ± SD)**
  - T1: 67.9 ± 12.2
  - T2: 90.8 ± 12.2
  - T3: 90.6 ± 10.6
  - T4: 89.8 ± 7.8
- **Temp. (°C) (mean ± SD)**
  - T1: 36.5 ± 0.4
  - T2: 36.2 ± 0.6
  - T3: 36.8 ± 0.5
  - T4: 37.3 ± 0.4
- **Vasopressors\(^a\)**
  - T1: 0/28 (0%)
  - T2: 3/28 (11%)
  - T3: 3/28 (11%)
  - T4: 2/28 (7%)
- **Vasodilators\(^a\)**
  - T1: 9/28 (32%)
  - T2: 23/28 (80%)
  - T3: 23/28 (80%)
  - T4: 20/28 (70%)

\( T1, 15 \text{ min after induction of anesthesia}; T2, 30 \text{ min after cardiopulmonary bypass}; T3, 1 \text{ h after ICU admission}; T4, 3 \text{ h after ICU admission. HR, heart rate; MAP, mean arterial pressure; PRAM-CO, cardiac output by pressure recording analytical method (PRAM); SD, standard deviation; Temp., temperature; ThD-CO, cardiac output by thermodilution.} \)

\( ^a \) Absolute numbers are given with % of total in parentheses.
obtained by PRAM and ThD at each time point (data shown in Table 1) and for all data collected (Fig. 2B). The highest degree of correlation \(R^2 = 0.86\) between ThD-CO and PRAM-CO was obtained at T4 (3 h after arrival in ICU). Conversely, the lower degree of correlation \(R^2 = 0.70\) was observed at T2 (Table 1). At this phase (30 min after ECC), a tendency toward loss of agreement was noted at extreme values of ThD-CO: PRAM seemed to overestimate cardiac output when it was very low, and underestimate CO when it was high.

All patients were extubated within 9 h of arriving in the ICU (6.6 ± 1.4 h). The length of ICU was 22.7 ± 0.4 h. No post-operative major complications occurred in each patient up to the discharge from hospital and no patients had adverse events complications related to the use of PAC.

4. Discussion

The commonly employed reference techniques for assessment of CO are represented by the direct Fick method in physiology and by ThD with the PAC in clinical practice. However, the former is not feasible in cardiac surgery, and the latter, although widely used for more than 30 years, was never intended to be used as a bedside monitor. As a consequence, surgeons and anaesthesiologists have developed increased interest in identifying a less-invasive means of monitoring cardiac performance in patients.

Recently, it has been shown that beat-to-beat absolute values of CO, which compare favourably with those obtained by direct oxygen Fick and ThD methods, can be obtained by PRAM [4].

According to the authors [4], PRAM is based on the principle that in any given vessel volume changes occur mainly because of radial expansion in response to variations in pressure. The morphologic analysis of the pressure profile allows the determination of the SV which, multiplied by the cardiac frequency, provides the CO value.

The concept behind the measurement and monitoring of CO based on the analysis of arterial blood pressure waveform is not new. Similar approaches have been studied by several authors in the course of the last three decades and have led to the development of important clinical applications (e.g. PiCCO system, LiDCO system, Modelflow method) [10–12]. However, the PiCCO system does not start without a ThD-CO; moreover, even if both the LiDCO system and the Modelflow methods start pulse contour CO computations directly after connection to a radial artery pressure signal with a trending of CO, these two methods have a higher accuracy only after considering age-and-sex and external calibration data. As such, the evaluation of CO is more bound up either with age-and-sex predicted values not directly pertaining to the subject under study or with a previously measured calibrating factor, rather than depending on the actual pressure wave morphology at the time of SV determination. On the contrary, PRAM can measure absolute values of SV, independently from calibration, by determining parameters able to characterize the elastic properties of the arteries, such as the time to peak of the systolic curve, the presence of sudden slope changes, and the length of the diastolic phase from the objective analysis of the pressure wave profile [4].

Intermittent ThD is the most widely employed clinical method to assess CO clinically. However, several factors may intervene in negatively affecting the performance of ThD after cardiopulmonary bypass [2,13].

Despite the limitation of ThD in cardiac surgery, if PRAM is to be considered an alternative technique for CO monitoring, it must at least demonstrate good agreement with this method. In stable cardiac patients, estimates of CO by PRAM agreed with CO measurements obtained with both the direct oxygen Fick method and ThD [4]. Although these results do represent an indirect indication about the intrinsic accuracy of PRAM, they do not give a direct answer to the questions arising about the accuracy of the methods to measure CO during cardiac surgery.

Some interesting findings emerged from the present study. CO estimates obtained by PRAM during cardiac surgery show good agreement with those simultaneously obtained by conventional bolus ThD. Over the studied intervals, no significant differences between these two
techniques emerged. This likeness persisted despite changes in volume infusions and losses; vascular resistance and arterial compliance; the use of vasoactive drugs; and the use of arterial line for blood sampling.

Of note, PRAM seemed to overestimate lower values and underestimate higher values of ThD-CO at T2 phase (30 min after ECC). Besides to represent a possible inaccuracy of PRAM, we also considered the hypothesis that this result may be accounted for by the feasible loss of reliability of ThD after the end of ECC [2,13]. In fact, patients subjected to ECC may show a transient increase in the magnitude of respiratory variations in pulmonary artery blood temperature after ECC, and this increased 'thermal noise' have been cited as a potential source of significant error in ThD measurements within the first 30–45 min after ECC [2,13]. When systemic cooling and rewarming are performed during ECC, the pulmonary artery temperature typically decreases after ECC causing the thermal noise, so that ThD-CO values at this phase might not represent the true CO [2,13]. Bottiger and co-workers studied this temperature drift after hypothermic ECC and compared continuous versus intermittent CO thermodilution measurements in patients undergoing hypothermic ECC [14], and in intensive care cardiac surgery patients [15]. They found that the major bias between methods was in the first 45 min after ECC. In contrast, in ICU cardiac surgery patients, in whom temperature equilibration was completed, a strong correlation and excellent agreement were obtained [14,15]. Similar results were later observed by the same study group comparing a PCM with ThD [16], and our results agree with those findings. Finally, during haemodynamic instability and in critical conditions, the requirements for the application of ThD are often not fulfilled [17–21]. Since the early phases after the end of ECC might represent a condition of haemodynamic instability, this fact may intervene in negatively affecting the performance of both ThD and other methods. Unfortunately, this interpretation cannot be demonstrated in the absence of a third method or a gold standard preferable to ThD, and we cannot offer a definitive explanation for the disagreement between PRAM and ThD after the end of ECC. However, we believed that the most important problem is the possibility that neither ThD methods nor other temperature-dependent devices reflect the true CO in the early phase after hypothermic ECC, which may result in wrong therapeutic decision being made.

Generally, PCM may have advantages over PAC-derived ThD measurements. (1) Measurement of CO by PRAM does not depend on specific assumptions about hemodynamic and/or thermal conditions, but on the objective analytical measurement of numerical parameters, reflecting the relationship between arterial pressure and flow, derived from the pressure curve profile. (2) PRAM does not require external calibration by ThD, and no other additional invasive procedures (a central line can be avoided completely), avoiding both time-consuming and potential complications [4]. (3) Finally, because PCM provide a beat-to-beat readout, abrupt changes in CO resulting from blood loss, tamponade, or changes in arterial resistance may be detected more quickly [5] (Fig. 1 is an example of a beat-to-beat hemodynamic changes recording started before the induction of anaesthesia).

The limitations of this study are the use of patients at low-risk, and the very homogeneous population of patients. Heterogeneous and high-risk patients dictates significant variability in the surgical and anaesthesiological management, and careful haemodynamic control due to sudden haemodynamic changes. Another issue is that, severe hypothermia during ECC is responsible for profound vasoconstriction and uneven distribution of flow through various tissues. Under this condition, PRAM, such as the other PCMs, might mislead the true peripheral arterial flow. In our CABG patients, a moderate hypothermia (32–34 °C) was maintained during ECC; moreover, the whole cardiac output measurements were done when body temperature was over 36 °C. Lastly, other questions remain to be solved: (1) several factors could affect the accuracy of cardiac output measurements based on the analysis of arterial waveform, such as stenosis of the arterial tree, partial catheter dislodgement, arterial pathology in the proximal segments, etc. which need to be well investigated; (2) the additional data regarding the loading condition of the patients (e.g. wedge pressure) represent an important information that allows accurate interpretation (and therapy) of aetiology of low cardiac output states. The absence of preload measures may represent a disadvantage of many of PCMs, but sometime this is the ‘penalty we have to accept’ for being less invasive. In our opinion, all these important issues should be considered whenever such devices are used to optimize treatment of the patients. For this reason, no clinical decision was taken based on these first PRAM results in our cardiac surgical patients. In addition, we obtained data during stable haemodynamic situations and in absence of cardiac arrhythmias, and selected this kind of patients with those specific clinical patterns to gain familiarity with this new method. Further studies will be required to assess this method in heterogeneous and higher-risk patients and in the setting of haemodynamic instability or arrhythmias.

In conclusion, in this small series of homogeneous CABG patients and under the studied conditions, our results demonstrate good agreement between PRAM data and ThD measurements. This new method has shown to be accurate for real-time monitoring of CO during cardiac surgery and the immediate post-operative period, despite variations of arterial pressure profile caused by temperature changes, inotropics or vasodilators/vasopressors administration or the use of arterial line for blood sampling. This method seems a practical alternative to the traditional ThD method when the indwelling of a PAC is deemed harmful or not essential for clinical management. This is the first study designed to
assess the accuracy of CO measurements made by PRAM compared with ThD technique during cardiac surgery.

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References