Cardiology in the Young

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Haemodynamic monitoring after paediatric cardiac surgery using echocardiography and PiCCO

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Abstract

Background: Haemodynamic instability is common after surgical repair of CHDs in infants and children. Monitoring cardiac output in addition to traditional circulation parameters could improve the postoperative care of these patients. Echocardiography and transpulmonary thermodilution are the two most common methods for measuring cardiac output in infants. *Objectives:* To compare the results of cardiac output measurements using echocardiography and a transpulmonary thermodilution setup after paediatric cardiac surgery. *Methods:* Forty children, scheduled for elective repair of a ventricular septal defect or of an atrio-ventricular septal defect using cardiopulmonary bypass, were enrolled in this prospective, observational study. Cardiac output was simultaneously measured using echocardiography and a commercially available transpulmonary thermodilution method (PiCCO™) at 18 h after the end of surgery. *Results:* At 18 h after surgery, PiCCO™ gave a mean of 3.0% higher cardiac output than echocardiography. This difference was not statistically significant. 95% of the observations fell within −50.0 to 82.6%. *Conclusion:* The methods were found to have a good agreement on average, with no statistically significant difference between them. However, the spread of the results was large. It is questionable whether the methods can be used interchangeably in clinical practice.

Introduction

Haemodynamic instability is a common problem in ICUs worldwide, both in patients admitted as emergencies and after elective major surgery. Handling this instability appropriately involves realising that it is present in the patient, diagnosing its causes and choosing the correct treatment options.[1] Unfortunately, clinical examination and traditional laboratory analyses have been shown to struggle to identify patients with deranged haemodynamics, and picking the right remedy based on clinical parameters has proven to be difficult, even for experienced clinicians.[2] A search for a more comprehensive and objective method for evaluating the haemodynamics of critically ill patients has thus been going on for many decades. Initially, the pulmonary artery catheter was used.[3] While it provides much useful data that other methods cannot give, its use has diminished since the advent of less invasive methods. There are also conflicting data regarding its usefulness outside of cardiothoracic surgery and intensive care, and a lively debate over its place in current clinical practice has been ongoing for a while.[4,5]

Measuring cardiac output is one of the most useful variables that a pulmonary artery catheter provides, and the search for a method which can deliver a similar measurement without necessitating a catheter in the pulmonary circulation has provided the ICU with the transpulmonary thermodilution method.[6] Two manufacturers provide similar apparatuses, and in this study, we have used the PiCCO™ equipment.

Transpulmonary thermodilution is thus in many ways similar to the pulmonary artery catheter. As a replacement or complement, echocardiography is often used. This method may be used to estimate the cardiac output, but can also give detailed information on cardiac contractility, valvular lesions, and cardiac volumes, such as the end-diastolic volumes of the ventricles.[8] A major drawback of echocardiography, though, is that it only provides a snapshot of the circulation at one time; another is that its accuracy depends on the personal skill of the clinician. Thus, the possibility of having access to a continuous cardiac output measurement, which is not dependent on which staff is available, is an attractive idea. The question, of course, is how accurate the transpulmonary thermodilution estimate of the cardiac output really is.

Cardiac surgery for CHDs is a procedure which often causes haemodynamic instability during the first 24 postoperative hours, particularly in neonates and young infants.[9,10] These

patients are much too small in size to be monitored using a pulmonary artery catheter, which means that other methods must be considered. We decided to evaluate the use of a transpulmonary thermodilution setup with echocardiography examinations as a comparison. A relatively homogenous patient cohort was chosen, namely children under the age of one year, scheduled for elective repair of a ventricular septal defect, or an atrio-ventricular septal defect, all of which had a non-restrictive blood flow over their septal defects which caused mild to moderate heart failure preoperatively. The aim was thus to compare cardiac output values using simultaneous measurements with a transpulmonary thermodilution method and echocardiography, with the null hypothesis that the methods would yield comparable results.

Materials and methods

Patients

The study was a single-centre study carried out in a university clinic, which is one of two national referral centres in Sweden for congenital heart surgery. Forty children, scheduled for elective repair of a ventricular septal defect or of an atrio-ventricular septal defect, were enrolled in the study. The inclusion criteria were age under one year and a non-restrictive blood flow over the ventricular septal defect, causing clinical signs of mild to moderate heart failure, with a Ross score of at least 3. Exclusion criteria were renal or hepatic failure, defined as creatinine or transaminase levels more than twice the upper values of the age-adjusted normal reference ranges. All parents were given oral and written information about the study before the surgery. Informed written consent was obtained from all parents. The study was carried out according to the Declaration of Helsinki. An approval was also granted from the Regional Ethics Board of Gothenburg (application ID 391-06).

Anaesthetic management

Induction of anaesthesia was conducted using intravenous (IV) midazolam (0.1 mg/kg), fentanyl (2–3 μg/kg), and ketamine (2–5 mg/kg). Maintenance of anaesthesia included inhaled sevoflurane before and during cardiopulmonary bypass, IV fentanyl (10–25 μg/kg), midazolam (0.1–0.3 mg μkg), and atracurium (0.5 mg/kg). All children were anaesthetised by the same anaesthetist, and the anaesthesia procedure remained unchanged during the study period.

Anticoagulation and reversal

An initial IV bolus of unfractionated heparin (Leo Pharma A/S, Ballerup, Denmark), 400 U/kg body weight was administered before cannulation. The level of anticoagulation was repeatedly monitored during bypass using the activated clotting time method (Hemocron Jr. II activated clotting time+; ITC, Edison, NJ) with kaolin as initiator. Reversal of heparinization was achieved using protamine (Leo Pharma A/S), 1 mg per 100 U of the heparin dose (excluding heparin in the prime and additional heparin given during cardiopulmonary bypass). Additional doses of protamine were administered to patients with continuing bleeding and activated clotting time > 130 s.

Bypass technique

Cardiopulmonary bypass was conducted with a hard-shell reservoir and a patient size-adapted membrane oxygenator (Terumo, Tokyo, Japan). For the patients in this study, who weighed <10 kg and required a bypass flow of <1.5 L/min, the RX 05 oxygenator was used. The target rectal temperature (28–36 °C) was decided by the surgeon, depending on the type of surgery. The total pump prime volume was 350–700 mL, depending on the tubing and the oxygenator. The prime consisted of crystalloid fluid and allogenic packed red blood cells, mannitol 5 mL/kg, heparin (one-third to half of the initial IV pre-bypass heparin dose depending on the relationship between the patient's blood volume and the prime volume), and 100 mL of Tribonat (Fresenius Kabi AB, Uppsala, Sweden). Tribonat is a buffer agent; 100 mL binds 50 mmol H^+. During bypass, heparin was administered at an activated clotting time < 480 s. Packed red blood cells were added to the prime aiming at a target haematocrit (Hct) of 27–30% during cardiopulmonary bypass. Myocardial protection was achieved with cold intermittent blood cardioplegia (30 mL/kg), which was prepared during cardiopulmonary bypass by adding buffered Plegisol (Hospira, Inc., Lake Forest, IL, USA) in a 1:4 ratio to whole blood obtained from the arterial line. The cardioplegia solution was kept at 2–4 °C before infusion.

Modified ultrafiltration was performed after weaning from cardiopulmonary bypass with cannulas in place aiming at a Hct of 30–35%. Tranexamic acid was administered before the initiation of cardiopulmonary bypass and after (30 mg/kg). Aprotinin was not used. The cardiopulmonary bypass procedure remained unchanged during the study period.

Study protocol

Transpulmonary thermodilution and echocardiography measurements were made simultaneously 18 h after the end of the surgery. All transpulmonary thermodilution measurements were made by the same anaesthetist, and the same paediatric cardiologist carried out all of the echocardiographic examinations. The clinical staff in charge of the patient care in the ICU did not have access to the cardiac output measurements.

Haemodynamic measurements

For the transpulmonary thermodilution method, cardiac output was measured using the PiCCO™ (Pulsion Medical Systems, Feldkirchen, Germany) equipment. The method has been described in detail previously.[7] Briefly, the method is based on the Stewart–Hamilton principle of measuring dilution. Cold saline is injected into a central venous line, and the drop in the temperature of the blood after it has passed through the pulmonary circulation is measured in a thermistor built into an arterial catheter, placed in the femoral artery. The area under the curve of the measured temperature drop is inversely proportional to the cardiac output. This analysis acts as a calibration for the continuous estimate of cardiac output, which is provided by a mathematically produced pulse contour analysis. A central venous line (Arrow, Teleflex Inc., Wayne, PA, USA) was placed with the tip in the superior vena cava, and a femoral arterial catheter supplied by the manufacturer, containing a thermistor, was inserted. Transpulmonary thermodilution measurements of cardiac output was carried out with injections of iced saline in the central line, and the transient temperature drop in the femoral artery catheter was recorded. At least three injections were given for each measurement point, with an accepted difference of less than 15% between the attempts. The cardiac output was calculated by the integrated software using the decay curve of the temperature drop in the femoral artery.

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Table 1. Patient characteristics

	Study population
Mean age (days)	160 (SD 30)
Mean weight (kg)	5.6 kg (SD 0.97)
Female patients	14 (35%)
Diagnosis	AVSD 19 (48%), VSD 21 (52%)
Mean CPB time (minutes)	103 (SD 30)
Down´s syndrome	30 (75%)

SD = standard deviation, AVSD = atrioventricular septal defect, VSD = ventricular septal defect, CPB = cardiopulmonary bypass.

As comparison, cardiac output was also estimated using echocardiography at the same time points as the transpulmonary thermodilution measurements. Stroke volume was calculated using the measured cross-sectional area of the left ventricular outflow tract and the systolic vertical time integral where SV (cm^3) = $LVOT_{CSA}$ (cm^2) x $LVOT_{VTI}$ (cm).

Statistical analysis

Baseline patient characteristics are shown as mean and standard deviation, with 95% confidence intervals). Any p value<0.05 was considered to be statistically significant. All variables were continuous. The Bland–Altman plot was used to compare the agreement between the two methods for measuring cardiac output. The analysis was carried out using the SPSS statistical package (IBM Corporation, Armonk, NY, USA) and the software application BA-plottR[11].

Results

Study population

All children completed the study, and the data of all the 40 patients were included. There was no in-study mortality. The median age was 160 (range 133) days, and median weight was 5.6 (range 4.3) kg. There were 14 female and 26 male patients, and 24 had Down's syndrome (trisomy 21). Mean preoperative Ross score was 6.1 (standard deviation 2.0). 23 patients had a Ross score between 3 and 6, indicating mild heart failure, and 17 had a score between 6 and 9, indicating moderate heart failure. For a summary of the patient characteristics, see Table 1.

Cardiac output at 18 hours after surgery

There were small differences between the median of the two methods. The median cardiac output for PiCCO™ was 1.16 l/min (range 0.49–1.71 l/min) and the median cardiac index 3.63 (range 2.13 – 5.91) at 18 h after surgery. The median cardiac output for echocardiography was 1.05 l/min (range 0.42–1.66 l/min) and the median cardiac index 3.30 (range 1.20–5.90). A box plot of the cardiac output can be seen in Figure 1. There was no statistically significant difference between the methods neither in cardiac output nor in cardiac index.

Agreement of COcardiac output measurement between PiCCO™ and echocardiography

The agreement of the two methods for measuring cardiac output was analysed 18 h after the end of surgery. The samples were not normally distributed, and calculations were made using log-transformed data. PiCCO™ yielded on average 3.0% (95% CI -10.3–24.1%) higher values than echocardiography. 95% of the observations fell within -50.0 and 82.6% difference. The results are presented as a Bland–Altman plot in Figure 2.

Discussion

In this sample, the analysis showed a small systematic bias when measuring cardiac output with transpulmonary thermodilution and echocardiography, evident by the modest mean difference between the methods. However, the spread of the results was large, with individual sample values exhibiting considerable differences between the two methods. The magnitude of the variation across the range of mean cardiac output in the study, visible in the Bland–Altman plot, shows no tendency to change with increasing or decreasing cardiac output.

There have been previous attempts to evaluate how well different methods of haemodynamic monitoring perform in clinical settings, with conflicting results. Most studies of paediatric haemodynamics focus on the responses to fluid boluses, trying to find methods to identify responders to fluid therapy in haemodynamically unstable patients.[12,13] This study is not designed to evaluate any haemodynamic interventions, however. In this study, the physicians responsible for the care of the patient did not have access to the information gathered by the two methods, to minimise the risk of bias in the treatment of the patients.

Two previous studies relate relatively closely to ours. Gergely et al[14] studied infants after cardiac surgery of the same age as the present study did, albeit with different and varying diagnoses. They could not find any correlation between cardiac output measurement using transpulmonary thermodilution and echocardiography. This study was quite small, however, and no estimate of agreement using a Bland–Altman plot was provided, something that is recommended for method comparisons.[15] Aslan et al[16] compared PiCCO™ and echocardiography in another small study of children with non-cardiac haemodynamic instability (such as septic shock and burns). In this study, the correlation between the methods was excellent, and a Bland–Altman plot revealed a small mean difference, with a relatively high variability of individual measurements. These results are similar to those in our study; however, the variability between the individual patients in our data is even greater. It is possible that this is related to patient age (the patients in the study by Aslan were much older) or clinical situation (our patients being monitored after cardiac surgery).

There are inherent advantages and drawbacks with both transpulmonary thermodilution and echocardiography for haemodynamic monitoring. Echocardiography is non-invasive, and there are no risks for the patient during the procedure. The method only provides a moment frozen in time of the patient´s status, however, which can change rapidly. A competent clinician for performing the examination is also required, something which may not be available at all times (although intensivists who are not cardiologists can be trained in focused echocardiography for the limited purpose of haemodynamic evaluation[8]). In a postoperative setting, limited access to the patient because of bandages, cables, and on occasion an unclosed sternum may also compromise an ideal examination.

Transpulmonary thermodilution methods (in this case the PiCCO™ system) also mandate a skilled clinician for the insertion of the catheters; however, after this, the use of the method

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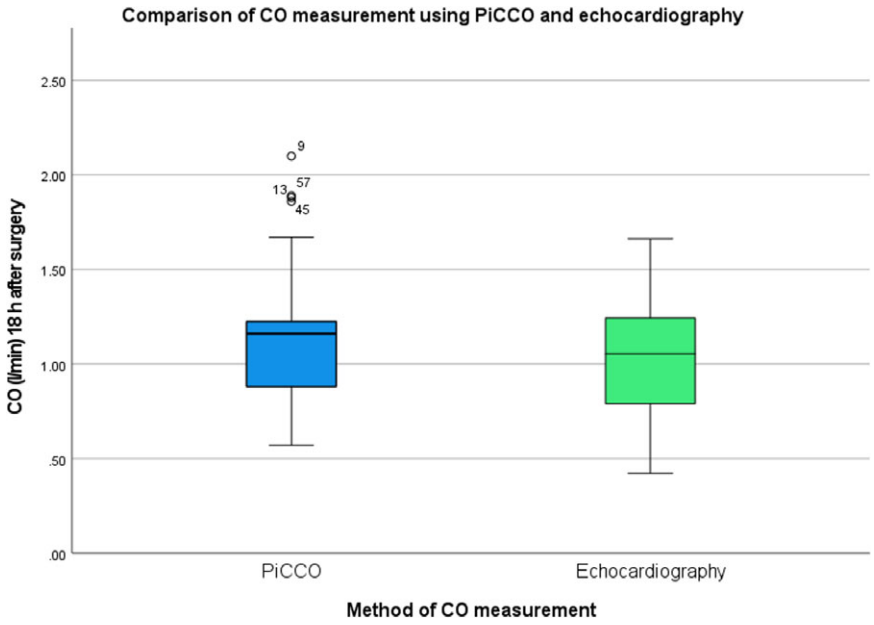

Figure 1. CO = cardiac output.

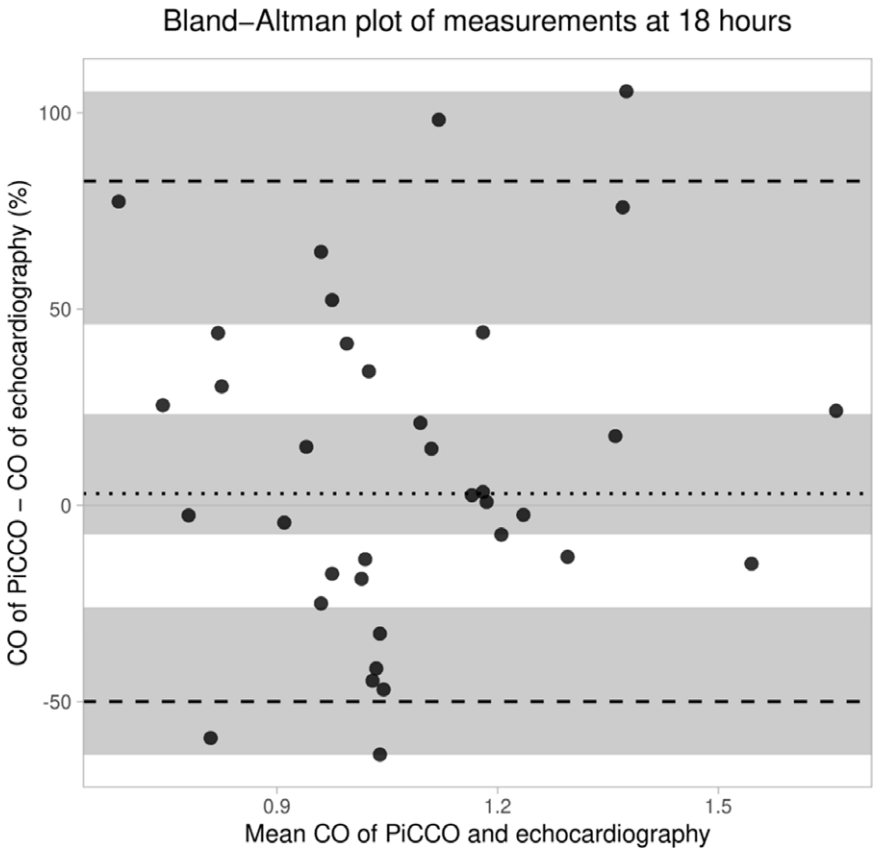

Figure 2. Dotted line: mean difference (%). Dashed lines: interval of 95% of the observations. Shaded areas: 95% CI for mean difference and the upper and lower 95% intervals. CO = cardiac output.

necessitates no particular technical competence. The system also provides the possibility of frequent measurements, with pulse contour analysis available between calibrations for a continuous assessment of the cardiac output. The precision of the transpulmonary thermodilution has been found to be decent, with the ability to discern changes in cardiac output down to 12%.[17] Transpulmonary thermodilution methods are also able to stand up quite well to the gold standard of the pulmonary artery catheter, with cardiac output measurements using the different methods being equally useful.[18] There are pitfalls in this method too, though. In a setting of paediatric cardiac surgery, the most obvious concern is that most infants and children who are scheduled for cardiac surgery have intracardiac shunts of varying degrees, something which makes the transpulmonary thermodilution measurements highly unreliable because of recirculation of the cold saline. In the present study, no transpulmonary thermodilution measurements

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were made before the surgery for this very reason; most of the patients had a pulmonary blood flow of at least 2–3 times that of the systemic circulation. Also, in contrast to echocardiography, transpulmonary thermodilution provides no direct assessment of the cardiac contractility, which is often important information in the first 12–24 h after cardiac surgery using cardiopulmonary bypass. There is also no way of measuring the filling pressures of the right and left ventricle separately, which is possible with a pulmonary artery catheter.

A drawback with the PiCCO™ system in infants which we have observed is the risk of inadequate arterial circulation in the leg into which the catheter has been inserted into the femoral artery. The paediatric catheters provided by the manufacturer are smaller than the adult versions, but still occlude a relatively larger cross-sectional area of the blood vessel than in adults. No serious complications arose in our study, but the risk of ischaemia is still one of the reasons that the PiCCO™ system is not used more frequently in our centre.

The question is, of course: which of these methods, if any, is appropriate to use after paediatric cardiac surgery for estimating cardiac output? On an aggregate level, the methods display excellent agreement, as can be seen by the small mean difference between them. However, the large variation between the methods in individual patients does present a problem for the clinician. It is clear that if trends are to be followed in a patient, the methods are not interchangeable, and cannot be compared directly.

Conclusions

The agreement of cardiac output measurement between echocardiography and the transpulmonary thermodilution method (here, PiCCO™) was strong. However, the variation of the difference between the two methods in individual patients was considerable. The results from this study suggest that even though both methods may be useful for monitoring infants after cardiac surgery, they cannot be used interchangeably for cardiac output measurement in a clinical context.

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Competing interests. None.

Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the Regional Ethics Board of Gothenburg regarding human experimentation, and with the Helsinki Declaration of 1975, as revised in 2008, and has been approved by the Regional Ethics Board of Gothenburg (application number 025-16).

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