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Cardiac output measurement in children: comparison of Aesculon® cardiac output monitor and thermodilution

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Background. We compared cardiac output (CO) measurements by the non-invasive electrical velocimetry (Aesculon®) monitor with the pulmonary artery catheter (PAC) thermodilution method in children.

Methods. CO values using the Aesculon® monitor and PAC thermodilution were simultaneously recorded during cardiac catheterization in children. Measurements were performed under general anaesthesia. To compare, three consecutive measurements for each patient within 3 min were obtained. The means of the three values were compared using simple regression and Bland–Altman analysis. Data were presented as mean (SD). A mean percentage of <30% was defined to indicate clinical useful reliability of the Aesculon® monitor.

Results. A total of 50 patients with a median (range) age of 7.5 (0.5–16.5) yr were enrolled in the study. Mean CO values were 3.7 (1.5) litre min^{-1} (PAC thermodilution) and 3.1 (1.7) litre min^{-1} (Aesculon® monitor). Analysis for CO measurement showed a good correlation between the two methods (r=0.894; P<0.0001). The bias between the two methods was 0.66 litre min^{-1} with a precision of 1.49 litre min^{-1}. The mean percentage error for CO measurements was 48.9% for the Aesculon® monitor when compared with PAC thermodilution.

Conclusions. Electrical velocimetry using the Aesculon® monitor did not provide reliable CO values when compared with PAC thermodilution. Whether the Aesculon® monitor can be used as a CO trend monitor has to be assessed by further investigations in patients with changing haemodynamics.

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A well-established method to assess cardiac output (CO) in adults is the invasive pulmonary artery catheter (PAC) thermodilution method. The PAC bears potential risks with the most deleterious being pulmonary artery perforation.[1] A new technology of continuous CO measurement by pulse contour analysis has been shown to be reliable after paediatric cardiac surgery.[2] However, in children with and without congenital heart disease, there are several circumstances that preclude the routine use of the invasive measurement. A non-invasive measurement of CO in critically ill paediatric patients would be helpful for the cardiovascular assessment and haemodynamic management.

Thoracic electrical bioimpedance (TEB) relates to changes in electrical conductivity of the aortic arch blood flow, and can be obtained from the thoracic skin surface to determine stroke volume and cardiac output (CO).[3] According to the theory of TEB, erythrocytes change their random orientation in the descending aorta during diastole to an alignment at the beginning of the systole. A refined algorithm to calculate CO by TEB, referred to as electrical velocimetry, was introduced recently.[4 5] A new comprehensive and non-invasive cardiovascular monitor implementing the features of electrical velocimetry is the Aesculon® monitor (Osypka Medical GmbH, Berlin,

Germany). Initial studies in adults provided clinically acceptable agreement between CO values measured by electrical velocimetry and transoesophageal Doppler echocardiography[6] and PAC thermodilution.[7]

The aim of this study was to evaluate the agreement of CO values measured by the non-invasive Aesculon® monitor with the PAC thermodilution technique during cardiac catheterization in children.

Methods

We prospectively analysed a total of 50 children with congenital heart disease undergoing interventional or diagnostic cardiac catheterization. Patients with a body weight below 3 kg, an age older than 18 yr, and those with residual intracardiac or extracardiac shunts were excluded from the study. Hospital Ethics Committee approval and written parental consent were obtained.

Pre-medication and induction of the anaesthesia (inhalation or i.v.) depended upon the patient's medical condition and preference. After establishing neuromuscular block, patient's trachea was intubated with cuffed tubes and the lungs mechanically ventilated.

The CO measurements were performed under general anaesthesia at the end of the cardiac catheterization procedure under steady-state haemodynamic conditions. As shown in Figure 1, standard ECG surface electrodes were attached side to side in a vertical direction to the patients left middle and lower neck, and to the lower thorax at the left mid-axillary line, at the level of the heart and xiphoid process. The electrodes were connected to the Aesculon® monitor. A correct signal quality was verified by visualization of the ECG and the impedance waveform. CO was calculated by transformation to the ohmic equivalent of the mean aortic blood flow acceleration and heart rate correction, as described previously.[4 5 8] Electrical velocimetry CO was continuously displayed on the monitor and recorded as an average value over 10 valid cardiac cycles.

A 5 Fr balloon-tipped pulmonary artery thermodilution catheter (Edwards Lifescience, Irvine, CA, USA) was inserted via a 6 French sheath in the femoral vein and directed to the pulmonary artery under fluoroscopic control. CO was obtained by PAC thermodilution with bolus injection of 5 ml iced saline solution (temperature: 4°C). Measurements were performed random to respiratory phases. After a test injection, three consecutive CO values were measured by the PAC thermodilution method and contemporary by the Aesculon® monitor immediately before injection of each of the three fluid boluses. Both operators were blinded for the CO values achieved by either technique.

Data are expressed as either mean (SD) for measured values or median (range) for baseline characteristics, depending on distribution pattern of the data evaluated by the Kolmogorov–Smirnov test. $P<0.05$ was considered significant.

Simultaneous electrical velocimetry and thermodilution CO were obtained using three measurements within 3 min, with the mean CO values per patient calculated for each technique and used for subsequent analysis. CO values obtained by PAC thermodilution technique or Aesculon® monitor were compared using the paired Student's *t*-test. Pearson correlation, linear regression analysis, and Bland–Altman analysis[9] were performed to compare CO values obtained by both methods. Bias was calculated from 50 paired averages as the mean difference, and precision as 2 SD of differences between paired values of the two methods. Moreover, the mean percentage error (2 SD mean $CO^{-1} \times 100$) was calculated. A mean percentage error not exceeding 30% was defined to indicate clinical useful reliability of the Aesculon® monitor.[10]

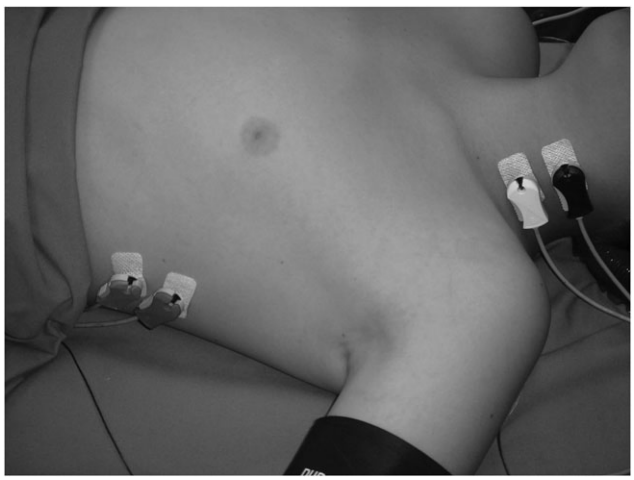

Fig 1 This photograph displays the standard ECG surface electrode position in the paediatric patient of our study cohort recording the electrical velocimetry by the Aesculon® monitor.

Results

A total of 50 patients with a median (range) age of 7.5 (0.5–16.5) yr were enrolled in the study. Clinical characteristics and indications for cardiac catheterization are shown in Table 1. Bedside haemodynamic parameters of the children during CO measurements were within normal limits: arterial haemoglobin was 11.2 (1.3) g dl^{-1}, heart rate was 93 (19) beats min^{-1}, and mean arterial pressure was 62 (9) mm Hg.

A total of 150 paired CO measurements by PAC and Aesculon® monitor were obtained. Within-subject measurement variability of each of the two techniques was low. Median coefficient of variation for the electrical velocimetry CO was 3.7 (0–59)%, and for PAC thermodilution CO it was 3.1 (0–21)% ($P=0.45$). CO values obtained by PAC thermodilution [3.7 (1.5) litre min^{-1}] and by the Aesculon® monitor [3.1 (1.7) litre min^{-1}] differed significantly between both methods ($P<0.05$). A high correlation

Table 1 Baseline characteristics of 50 children undergoing cardiac catheterization. Data are given as medians (range). LVOT, left outflow tract obstruction; RVOT, right outflow tract obstruction. Data are mean (range) for age, mean (sd) for weight and height

	Study group (n=50)
Characteristics	
Gender (male/female) (n)	22/28
Age (yr)	7.8 (0.5–16.5)
Weight (kg)	26.5 (15.4)
Height (cm)	122 (32)
Body surface area (m^2)	0.88 (0.3–1.96)
Indication for cardiac catheterization (n)	
ASD device closure	14
VSD device closure	5
Valvuloplasty of the RVOT	8
Valvuloplasty of the LVOT	2
Diagnostic catheterization	21

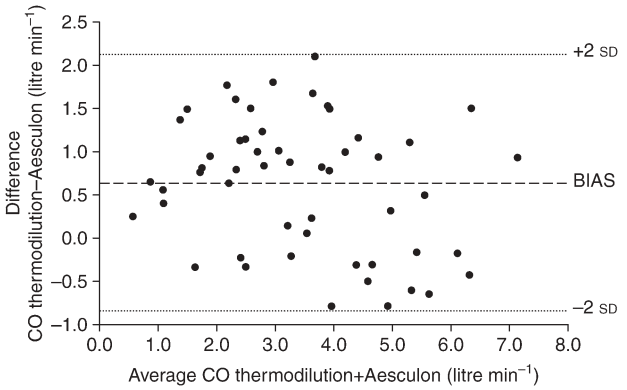

Fig 3 Bland–Altman analysis to compare CO values obtained by the PAC thermodilution technique and the Aesculon® monitor (n=50 patients). The plot shows 2 SD of differences ($\pm$2 SD; precision) and the mean difference (Bias).

was found between CO values measured by the Aesculon® monitor and PAC thermodilution technique (r=0.89; P<0.0001) (Fig. 2).

Bias for CO values between the two methods was 0.66 litre min^{-1} with a precision of $\pm$1.49 litre min^{-1} for all data pairs (Fig. 3). The mean percentage error of CO measurement was 48.9% for Aesculon® monitor compared with PAC thermodilution technique.

Discussion

This study compared CO measurements derived from the new non-invasive Aesculon® monitor with the PAC thermodilution technique in paediatric cardiac patients from infancy to adolescence.

The main findings were that the measurement of CO with the Aesculon® monitor did not reliably present absolute values when compared with PAC thermodilution technique with a mean percentage error far above 30% and therefore clinically not acceptable.[10]

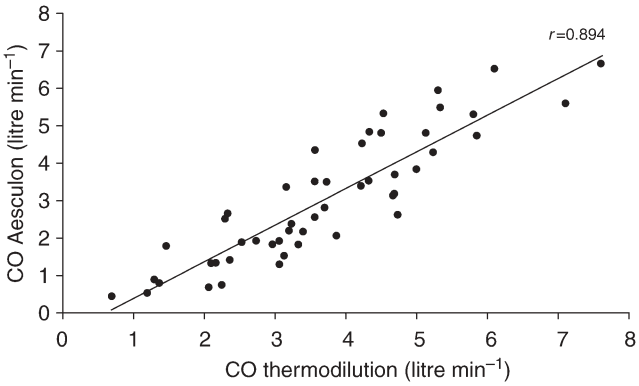

Fig 2 Linear regression analysis of CO measurements using the PAC thermodilution technique and the Aesculon® monitor (n=50 patients).

The development of simple, safe, and non-invasive technique for haemodynamic monitoring in children is highly desirable for critically ill children in the paediatric intensive care unit and in paediatric anaesthesia. TEB is a non-invasive, an easy to perform, and simple technique for CO measurements. However, different meta-analyses performed to provide objective evaluation of the validity of CO measurements achieved by TEB raised concern about the clinical application of TEB measurements.[11–13] Correlation was poor compared with PAC thermodilution and other invasive techniques, especially in patients with cardiopulmonary pathologies.

According to the theory of TEB, erythrocytes change their random orientation in the descending aorta during diastole to an alignment at the beginning of the systole. The original algorithm implemented in the TEB devices interpreted cycle variations in TEB as a result of plethysmographic changes of blood and radial volumetric displacement of blood in the thoracic aorta. A refinement of the algorithm that more closely mimics reality by incorporating the more complex inter-relationships of pulsatile thoracic blood flow was introduced recently.[4 5] It interprets the maximum rate of change of TEB as the ohmic equivalent of mean aortic blood flow acceleration according to the Bernstein–Osypka equation, and is referred to as electrical velocimetry as implemented in the Aesculon® monitor. Preliminary data measuring the electrical velocity by the Aesculon® monitor in adults either before or after cardiac surgery were encouraging. CO measurements derived from the Aesculon® monitor were compared with transoesophageal echocardiography[6] and the PAC thermodilution technique,[7] indicating clinically acceptable agreement with both techniques. Moreover, a longitudinal study in piglets[14] comparing PAC thermodilution technique with the Aesculon® monitor at different settings demonstrated a good agreement for continuous trend monitoring. A recent study in paediatric patients[15] demonstrates good agreement

between CO measured by the Fick principle and the Aesculon® monitor with mainly low CO values. However, patients with intra/extracardiac shunts and cuffed/uncuffed tubes were included bearing potential sources of error. Moreover, it remains unclear whether systemic perfusion values (Qs) have been corrected or low CO values resulted from intra/extracardiac shunts.

In contrast to the studies mentioned above and in accordance with our findings, a recently published study by Heringlake and colleagues[16] demonstrated a disagreement between these two methods before and after elective cardiac surgery, indicating a percentage error of 34–67%. Electrical artifacts in the impedance tracing as was detected by Heringlake and colleagues, and served as explanation for these discrepancies, could be ruled out in our setting.

As several modifications have been investigated to improve the original TEB measurements, new correction factors besides position of the electrode and increased body weight[17] have to be determined to allow a more precise determination of the CO by the Aesculon® monitor. In particular, in paediatric patients with short necks and different body habitus, further modification of correction factor may be needed.

The fact that in our study no patients with normal cardiac anatomy were included may be considered a limitation of this study. However, cardiac catheterization with the possibility of PAC thermodilution CO assessment in non-cardiac patients is very rare and limits this type of investigation to paediatric cardiac patients. Moreover, the thermodilution[18] and electrical velocimetry technique itself may bear some errors in determination of the correct CO. Measurements were performed by a single, experienced paediatric interventionist. Thus, technical errors during the procedure, especially relating to smaller, interference-prone boluses of iced solution in the paediatric population, were limited. Patients with intra- and extracardiac shunt were excluded; no relevant tricuspid regurgitation or low CO states were present as source of under- or overestimation of thermodilution CO. A potential source of error is the measurement performed irrespective of the respiratory phases as it may induce CO variations over the respiratory cycle. However, as a result of high breathing rates in the mechanical ventilated paediatric patients of our study cohort, this was neglected. Potential sources of errors for the electrical velocimetry include left outflow tract obstruction. None of the patients in our study cohort suffered from left outflow tract obstruction when measurements were performed.

On the basis of our findings, electrical velocimetry using the Aesculon® monitor did not provide reliable CO values in children with congenital heart diseases when compared with PAC thermodilution. Whether the Aesculon® monitor can be used as a CO trend monitor has to be assessed by further investigations in patients with changing haemodynamics.

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