Crit Care & Shock (2015) 18:36-42

Electric velocimetry and transthoracic echocardiography for non-invasive cardiac output monitoring in children after cardiac surgery

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Abstract

***Objective*: Assessment of cardiac output (CO) is essential in the management of children after cardiac surgery. Electric velocimetry (EV) is a newly developed monitoring method for CO and stroke volume (SV). However, applicability in a pediatric population, particularly after cardiac surgery, remains unclear. We sought to assess agreement of CO measured by EV and transthoracic Doppler echocardiography (TTE).**

***Design*: Prospective observational study.**

***Setting*: A cardiac intensive care unit (CICU) at a tertiary children's hospital in Shizuoka, Japan.**

***Patients and participants*: Children <18-year-old admitted to the CICU after cardiac surgery.**

***Intervention*: All patients underwent measurement of SV and CO using EV and TTE between 1 to 3 days after surgery.**

***Measurements and results*: Thirty patients were analyzed. We collected data on patient demographics, body surface area, vital signs, SV, CO, laboratory examination, drugs used, and type or surgery. There were significant correlations between EV and TTE in SV and CO values (r=0.909, p<0.001 and r=0.831, p<0.001, respectively). Bland-Altman analysis showed a good agreement between EV and TTE in SV and CO values (bias 1.33 mL, 0.08 L/min, and 0.02 L/min/m2, respectively, and limits of agreement -8.59 to 9.93 mL and -0.97 to 1.05 L/min, respectively). Mean percentage error for SV and CO values between EV and TTE were 13.76% and 13.19%, respectively.**

***Conclusions*: There is good correlation and clinical agreement between EV and TTE in measuring SV and CO. Electric velocimetry can be used in the hemodynamic monitoring of children after cardiac surgery.**

Key words: Electric velocimetry, transthoracic echocardiography, non-invasive, hemodynamic monitoring, cardiac output, post cardiac surgery children.

Introduction

In the cardiac care unit and pediatric intensive care unit the continuous monitoring of the cardiac output (CO) is important in high-risk patients after cardiac surgery, in patients with heart failure and in the critically ill patients who require titration of cardiovascular drugs and fluid interventions. (1,2)
Recently, minimally invasive and non-invasive methods of estimation of CO were developed to overcome the limitations of the invasive nature of pulmonary artery catheterization (PAC) and the direct Fick method used for the measurement of stroke volume (SV). (2,3) Impedance cardiography is probably the only non-invasive technique in true sense. It provides information about haemodynamic status without the risk, cost and skills associated with the other invasive or minimally invasive techniques. (4)
Electric velocimetry (EV) is a form of thoracic electrical bioimpedance (TEB) that is based on changes of the orientation of erythrocytes in the aorta during the cardiac cycle. Prior to opening of the aortic valve, there is no blood flow in the aorta and the erythrocytes assume a random orientation. Immediately after aortic valve opening, the pulsatile blood flow forces the red blood cells to align parallel with the direction of flow. (5) This parallel alignment in early systole, followed by their return

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to random alignment, causes a change in conductivity that can be used to measure the SV. (6)

Only few studies of CO measurement have been done in infants and children after cardiac surgery for congenital heart disease. These patients require continuous, accurate, portable, easy-to-use, and operator-independent monitoring to enable rapid and appropriate treatment. For this reason, it is very useful to study a tool that can be used in these patients, which is not invasive and can be used continuously to measure CO in order to perform efficient measures in providing therapeutic interventions.

The purpose of this study was to assess the agreement of CO measurement by EV with non-invasive determination of CO by transthoracic Doppler echocardiography (TTE) in post-cardiac surgery children.

Materials and Methods

This was a prospective observational study conducted at Shizuoka Children's Hospital, a tertiary pediatric cardiac center in Japan, from September 1 to October 31, 2013. This study was approved by the local institutional review board, and informed consent was given by the parents of each patient.

Patients

All patients who underwent cardiac surgery and were admitted to the Cardiac Intensive Care Unit (CICU) during the study period were considered for enrollment. Patients were included in the study when they were less than 18-year-old, biventricular, and hemodynamically stable. Single-ventricle patients or patients undergoing valve replacement with a mechanical prosthesis were excluded. All patients underwent both TTE and EV examinations between the first and third day after surgery. Measurements were made only once for each patient. Two pediatric cardiologists performed echocardiography while EV was done.

Electric velocimetry

EV was performed using an Aesculon Mini® (Osypka Medical, Berlin, Germany and La Jolla, California, USA) velocimeter. Body surface area was calculated as (height [cm] x weight [kg] / 3600)$^{1/2}$. Two surface electrocardiography electrodes were attached one to the left side of the neck and one on the lower thorax. Heart rate, SV, CO, and cardiac index were measured continuously.

Transthoracic Doppler echocardiography

TTE was performed using a Philips iE-33 echocardiography machine (Philips, Netherland) equipped with a 12-4 MHz extended-frequency range. We performed simultaneous measurement of left ventricle outflow (LVO). The left ventricle SV was calculated by measuring the left ventricle outflow tract (LVOT) area and the amount of blood going through this area (velocity time integral [VTI]). The diameter of the LVOT (DLVOT) and VTI values were taken from the average of two to three measurements. Left ventricle SV was calculated using the formula SV=(DLVOF/2)^2 x π x VTI. Cardiac output were then calculated using the formula CO (L/min)=SV x heart rate.

Data analysis

We calculated means and standard deviations for quantitative data and also frequencies for qualitative data. The correlation between EV and TTE was determined using Pearson correlation. The Bland-Altman method was used to analyze the limits of agreement (bias±precision) between TTE and EV. We also calculated the mean percentage error. The mean percentage error (MAPE) was calculated using the equation {2xSD mean difference/[(mean from EV + mean from TTE) /2] x 100}. A MAPE of less than 30% was considered clinically acceptable. (7) Data analysis was performed using Microsoft Excel (Microsoft Inc., Redmond, Washington) and SPSS 20.0 (SPSS Inc., Chicago, Illinois).

Results

Fifty-seven pediatric patients underwent cardiac surgery during the study period. Among these, 30 patients met the inclusion criteria and were all enrolled in the study. The clinical characteristics of these 30 patients are shown in **Table 1**. Both TTE and EV were performed in all patients.

More than 50% of the patients were still on hemodynamic support and sedation drugs while examined, although in minimal doses. Each patient used a combination of several hemodynamic support or sedation drugs. Vital signs, laboratory results, haemodynamic support, and sedative medications used are summarized in **Table 2**.

The scatter plot in **Figure 1** shows the simultaneously obtained measurements of CO and SV by EV and TTE. There was a strong and significant correlation between these two techniques ($r=0.909$, $p<0.001$ for SV and $r=0.831$, $p<0.001$ for CO).

Figure 2A and **2B** shows the 95% limits of agreement between TTE and EV in SV measurement using Bland-Altman analysis. The mean difference (bias) between the two methods in SV measurement was 1.33 mL, with 95% limits of agreement of -8.59 to 9.93 mL and a MAPE of 13.76%. For CO measurement, the mean difference was 0.08 l/min, 95% limits of agreement was -0.97 to 1. 05 L/min, and the MAPE was 13.19%. The mean difference for cardiac index was 0.02 L/min, 95% limits of agreement were -2.19 to -2.21 L/min, and the MAPE was 12.79%.

Discussion

The present study demonstrated a good correlation between SV and CO values measured by EV or TTE in pediatric patients after cardiac surgery. Both EV and TTE are non-invasive and reliable, but EV is easier to use and operator-independent. We used echocardiography as a reference, which has a precision of about 30% and a 10% bias compared to PAC. (8) Values obtained by EV tend to be under- or overestimations compared to TTE. SV measured by EV can be up to 8.59 mL below or up to 9.93 mL above the values obtained by TTE. This suggests that there is a wide variation in the agreement between each data pair. While an EV value of CO is not too much different, its value can be up to 0.97 L/min below or up to 1.05 L/min above the TTE value. Our data shows that this study has an excellent accuracy bias in CO with values of only 0.08 L/min, using echocardiography as the reference device. Calculation of SV and CO values from these two methods has a good MAPE of <30% (13.76% and 13.19%, respectively).

Almost all subjects were still using continuous sedation at the time of study, with any combination of midazolam, dexmedethomidhine, and fentanyl infusion. As a result, there was no increase in CO due to manipulation, which was seen in the stable heart rate and blood pressure during the examination process.

Several studies have compared EV with various tools as a reference. Some of these studies support the results of our study. However, we found no previous study assessing the agreement between EV and TTE with similar value limits. A study in newborns with transposition of the great arteries after cardiac surgery showed that the bias (0.71 L/min) and limits of agreement (-0.59 to 2.02 mL) for SV measurement by EV versus Doppler-TTE were acceptable, with an overall average error of 29%. (8)

A comparative study of the use of Doppler-transesophageal echocardiography (TEE) and EV to TTE as the reference for measuring SV and CO in pediatric post-cardiac surgery patients who were hemodynamically stable and still on ventilator showed a good correlation between EV and TTE. The study also found that EV underestimated CO in terms of absolute values in comparison with TTE. The percentage of error was more than 30%. The authors argue that Doppler-TEE and EV are better tools for monitoring cardiac function trends than for determining the absolute values. (9)

A study in 2012, using electrocardiometry (as the test method) and TTE (as the reference) in obese children and adolescents, showed that electrocardiometry is reliable and accurate in measuring CO. (6)

Measurement of CO in 32 infants, children, and adolescents with congenital heart disease using EV and direct Fick-oxygen showed an excellent correlation (r=0.97, p=0.001). This study suggests that the variation of the anatomical position of the great thoracic vessels in congenital heart disease do not affect the accuracy of EV measurements. (10)

However, several other studies do not support our results. Tomaske et al. in 2009 found unacceptable limits of agreement between EV and thermodilution, with a 48.9% error. Although the bias for CO values between the Aesculon monitor and subxyphoidal Doppler flow measurements in the study was 0.31 L/min, CO values obtained by Aesculon monitor and subxyphoidal Doppler flow differed significantly (p=0.04). (11)

The use of EV as a hemodynamic monitoring device remains the subject of controversy. More studies in pediatric patients are needed, since electrode placement may influence the signal quality and reliability of this method, especially in newborns and small children. Because it is easy to use, this tool is worth for additional critical and detailed evaluation, especially in smaller children, before we can use it routinely in the clinical pediatric ICU setting.

Acknowledgements

The authors have disclosed no potential conflict of interest.

We acknowledge the following person for their contributions to our study: Miyakoshi Chisato, MD and Prof. PJ Van den Broek for reviewing this manuscript and making helpful suggestions.

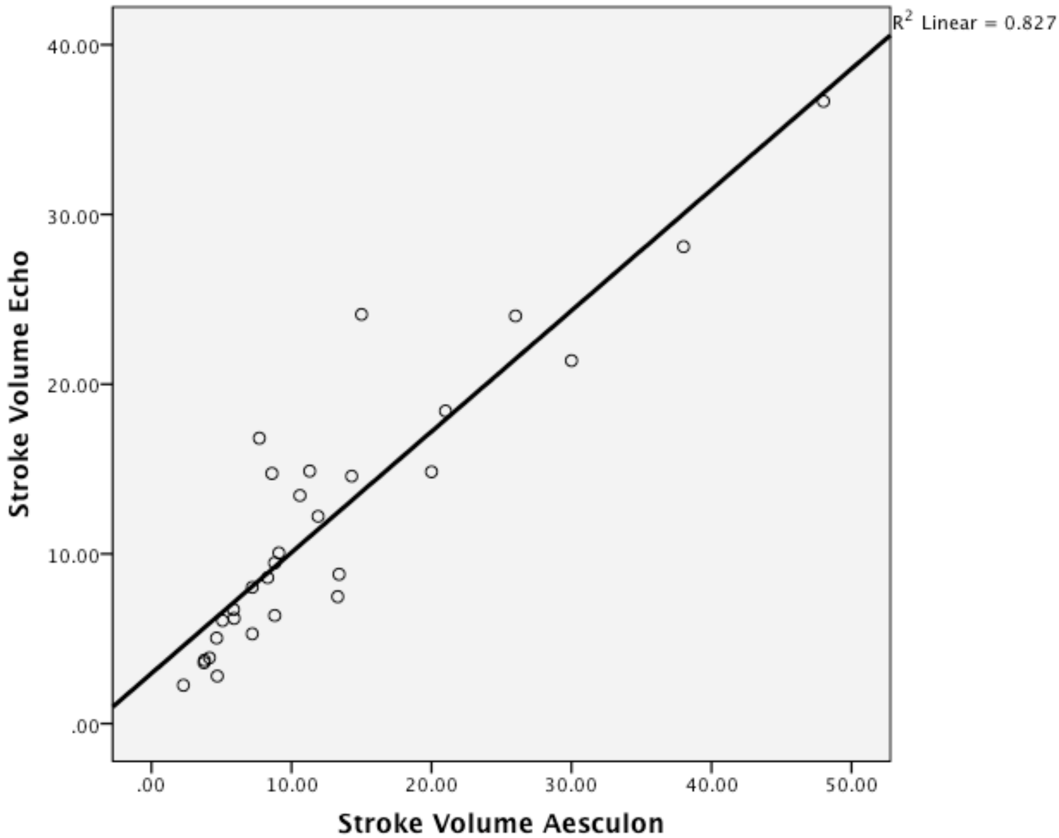
Table 1. Characteristics of study subjects

Characteristic	
• Age (weeks) (median)	39.50
• Sex (n, %): male	19 (63.3)
female	11 (37.7)
• Height/length (cm) (mean, SD)	76.19 (26.18)
• Weight (k) (mean, SD)	10.62 (11.28)
• Body surface area (m2) (mean, SD)	0.46 (0.29)
• Velocity time integral (mean, SD)	11.86 (6.01)
• Diameter of left ventricle outflow (cm) (median)	1.04
Procedure (n)	
• Valve repair/plasty	4
• Ventricle septal defect closure	9
• Jatene	2
• Atrial septal defect closure	3
• Right ventricle outflow track repair	1
• Total correction of tetralogy of Fallot	4
• Pulmonary artery banding	3
• Total anomalous pulmonary venous connection repair	2
• Contegra	2

Table 2. Vital signs, laboratory results, and treatment received

Characteristic	
• Hemoglobin (g/dl) (mean, SD)	14.39 (2.46)
• O2 saturation (%) (mean, SD)	97.67 (3.37)
• Systole (mmHg) (mean, SD)	88.80 (18.86)
• Diastole (mmHg) (mean, SD)	55.37 (12.89)
• Use of hemodynamic support (n, %)	17 (56.67)
o Dopamine/dobutamine	17
o Adrenaline	2
o Sodium nitroprusside	8
o Human atrial natriuretic peptide	3
• Sedation	
o Fentanyl	9
o Midazolam	11
o Dexmedetomidine	17

Figure 1. Scatterplot showing pearson's correlation between TTE and EV in the measurement of SV and CO



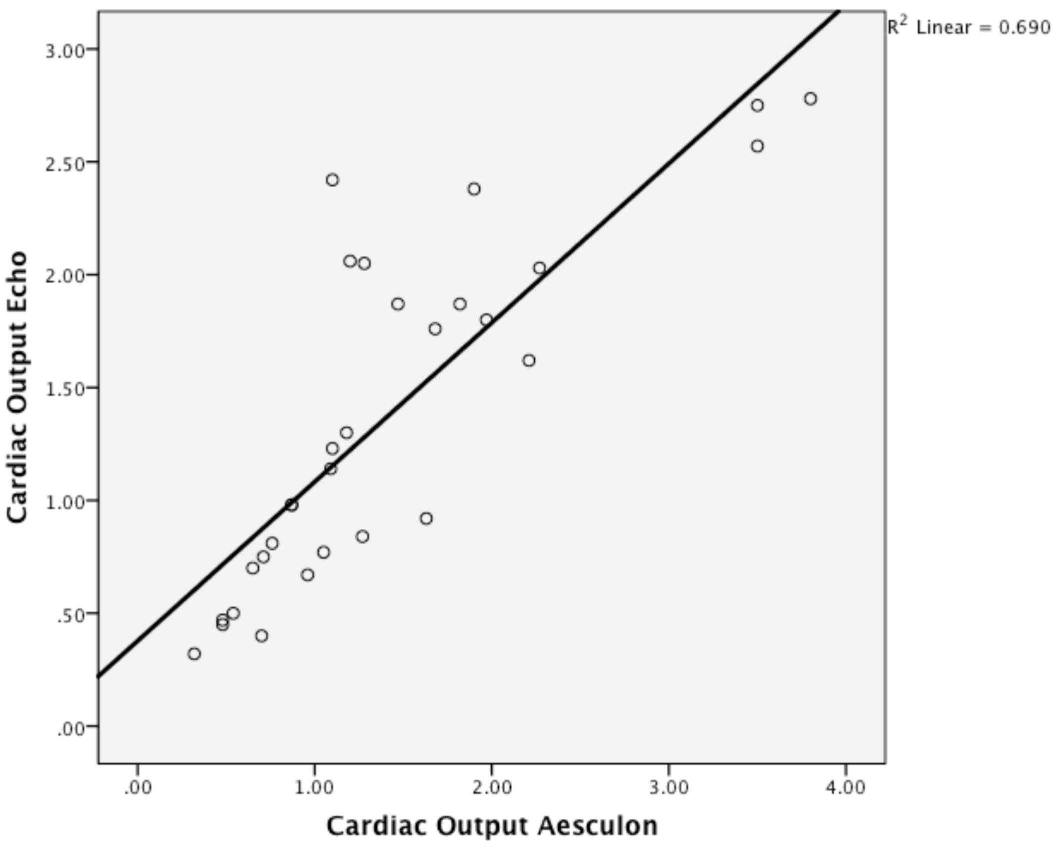


Figure 2A. Bland-Altman plot for SV shows a mean difference between the results of TTE and EV with bias of 1.33 L/min and limit of agreement from -8.59 to 9.93 L/min

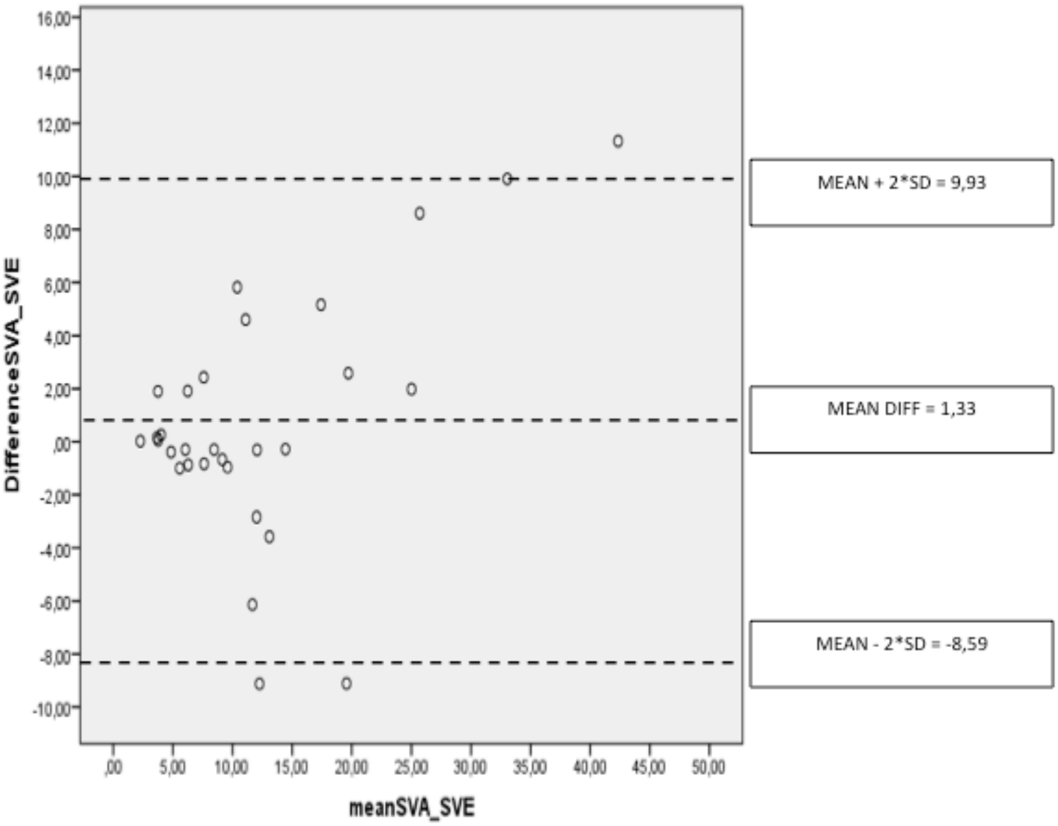
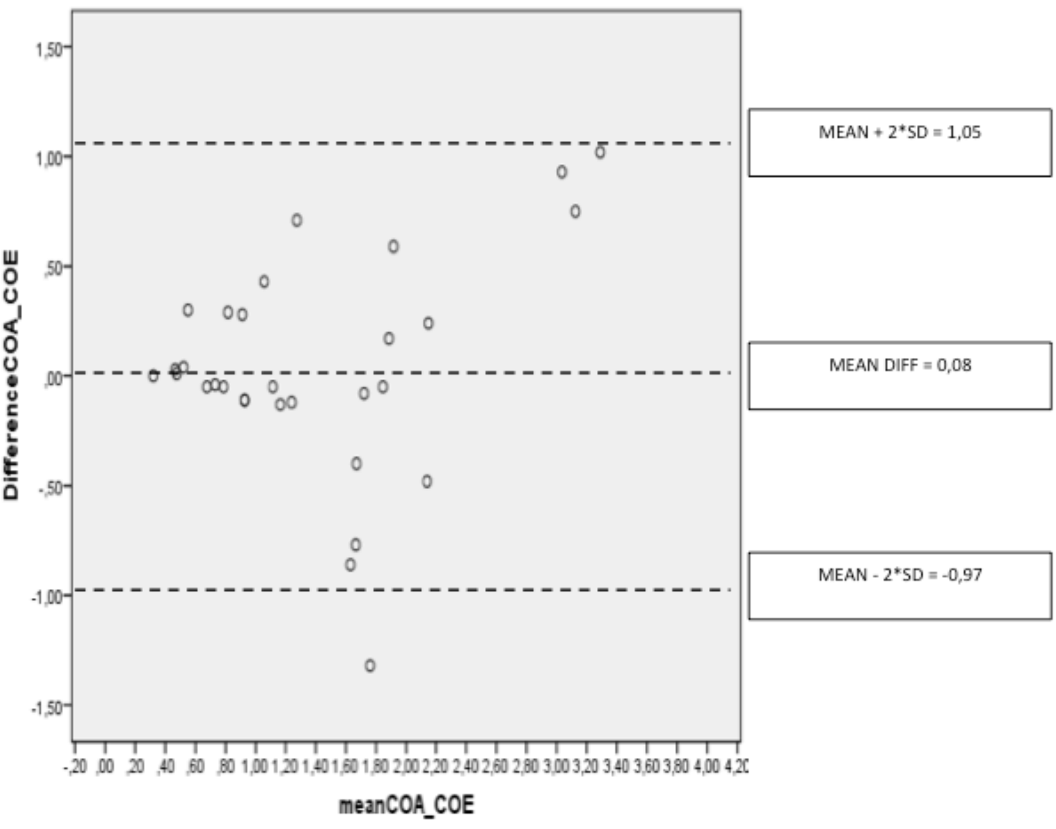


Figure 2B. Bland-Altman plot for CO shows a mean difference between the results of TTE and EV with bias of 0.08 L/min and limit of agreement from -0.97 to 1.05 L/min



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