

Original Article

Cardiac output and blood volume parameters using femoral arterial thermodilution

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Abstract *Background:* The pulse-induced continuous cardiac output (PiCCO) system is a less invasive method than pulmonary thermodilution for the measurement of cardiac output and estimating blood volume parameters. The normal values in children have not been defined. The purpose of the present paper was therefore to evaluate cardiac output and parameters of blood volume using femoral arterial thermodilution in critically ill children.

Methods: A prospective study was performed in 17 critically ill children aged between 2 months and 14 years. Two measurements were taken for each determination of cardiac output, global end diastolic volume (GEDVI), intrathoracic blood volume index (ITBI), extravascular lung water index (ELWI), systolic volume index (SVI), stroke volume variation (SVV), cardiac function index (CFI), left ventricular contractility (dp/dt max), and the systemic vascular resistance index (SVRI).

Results: One hundred and seventeen measurements were performed. The mean cardiac index (CI) was 3.5 ± 1.3 L/min per m^2 . The GEDVI (399.7 ± 349.1 mL/ m^2), ITBI (574.5 ± 212.2 mL/ m^2) and dp/dt max (804.6 ± 372.1 mmHg/s) were lower than reported in adults, whereas ELWI (18.9 ± 9.3 mL/ m^2) and CFI (8 ± 2.5 L/min) were higher. The GEDVI, SVI, dp/dt max and CI increased with the weight of the patients whereas the ELWI values decreased.

Conclusions: Femoral arterial thermodilution is a suitable technique for the measurement of cardiac output in critically ill children. The intrathoracic and intracardiac volumes are lower than in adults, whereas extrapulmonary water is higher; these values are related to the weight of the patient.

Key words cardiac index, cardiac output, children, extravascular lung water, femoral arterial thermodilution technique, intrathoracic blood volume.

The hemodynamic monitoring of cardiac function and the estimation of blood volume are fundamental to the control of critically ill children. The measurement of cardiac output is one of the principal elements for estimating a patient's hemodynamic situation and tissue perfusion, and can help to direct treatment and monitor the clinical course of patients with septic and/or cardiogenic shock. Although several methods exist for measuring cardiac output, the most widely used in adults is pulmonary thermodilution using a Swan–Ganz catheter. But this technique is not widely used in children due to the difficulty and risk of complications of inserting a Swan–Ganz catheter into the pulmonary artery, particularly in infants.^{1,2} The blood volume is estimated from indirect clinical parameters (state of hydration, peripheral perfusion, diuresis) and pressure measurements (central venous pressure [CVP], left atrial pressure, pulmonary capillary pressure), assuming a linear relationship between blood volume and the pressure within the cardiac cavities. But there are

many situations in the critically ill child (valvular insufficiency, heart failure, pulmonary hypertension, increased intrathoracic pressure etc.) in which there is no satisfactory relationship between the pressures and the blood volume, and hypovolemia may coexist with normal or even elevated venous or pulmonary capillary pressures.

The pulse-induced continuous cardiac output (PiCCO) system is a method for the continuous measurement of cardiac output by thermodilution in the femoral artery and analysis of the pulse contour curve. It is less invasive than pulmonary thermodilution because it does not require the insertion of a catheter in the pulmonary artery but only a central venous catheter and an arterial catheter. Experimental and clinical studies have found a good correlation between cardiac output measured by arterial thermodilution and by pulmonary thermodilution.^{3,4} Apart from the measurement of hemodynamic parameters, arterial thermodilution enables the parameters of intracardiac and intrathoracic blood volume and the extravascular lung water to be calculated. Some experimental studies and studies in adults have indicated that the calculation of the intracardiac volumes by arterial thermodilution is a more reliable method for estimating blood volume, and that it correlates better with cardiac filling measured by transesophageal echocardiography than pressure measures such

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Table 1 Patient characteristics

No.	Diagnosis	Age (months)	Weight (kg)	Vasoactive drugs
1	Scoliosis. Postoperative period. Hemorrhagic shock	168	30	No
2	Complete atrioventricular canal. Postoperative period	120	31	Dopamine 20 µg/kg/min; dobutamine 5 µg/kg/min; milrinone 0.8 µg/kg/min; nitroprusside 3 µg/kg/min
3	Cardiomyopathy	11	11	Dopamine 10 µg/kg/min; dobutamine 10 µg/kg/min; nitroprusside 2.4 µg/kg/min
4	Fallot's tetralogy. Postoperative period	3	6	Epinephrine 0.15 µg/kg/min; dopamine 15 µg/kg/min; milrinone 0.8 µg/kg/min
5	Anomaly of the coronary arteries. Postoperative period	72	22	Dopamine 7.5 µg/kg/min; milrinone 0.5 µg/kg/min; nitroglycerine 1 µg/kg/min;
6	Complete atrioventricular canal. Postoperative period	84	22	Epinephrine 0.38 µg/kg/min; dopamine 3 µg/kg/min; milrinone 0.8 µg/kg/min; nitroprusside 1.5 µg/kg/min
7	TGA + ASD + PS. Postoperative period	72	21	Epinephrine 0.5 µg/kg/min; dopamine 10 µg/kg/min; milrinone 0.5 µg/kg/min
8	Meningococcal sepsis	48	18	Epinephrine 0.3 µg/kg/min; dopamine 20 µg/kg/min
9	Fallot's tetralogy. Postoperative period	6	7.5	Epinephrine 0.1 µg/kg/min; dopamine 15 µg/kg/min; milrinone 0.7 µg/kg/min
10	Bone marrow transplant	168	70	Epinephrine 0.2 µg/kg/min; dopamine 6 µg/kg/min
11	Fallot's tetralogy. Postoperative period	2.5	5.8	Epinephrine 0.3 µg/kg/min; dopamine 5 µg/kg/min; milrinone 0.7 µg/kg/min
12	VSD + ASD. Postoperative period	14	7	Dopamine 5 µg/kg/min; adrenaline 0.8 µg/kg/min; nitroprusside 1.5 µg/kg/min; milrinone 0.7 µg/kg/min
13	Cardiomyopathy. Complete atrioventricular block	7	5.1	Dopamine 10 µg/kg/min; dobutamine 10 µg/kg/min; nitroprusside 5 µg/kg/min; milrinone 0.7 µg/kg/min
14	Pneumonia	96	33	Dopamine 12.5 µg/kg/min
15	Cardiomyopathy	156	52.4	Epinephrine 0.7 µg/kg/min; dopamine 5 µg/kg/min; dobutamine 5 µg/kg/min; milrinone 0.25 µg/kg/min; isoproterenol 0.02 µg/kg/min
16	Septic shock	2	5	Norepinephrine 1 µg/kg/min; epinephrine 0.5 µg/kg/min; dopamine 5 µg/kg/min; terlipressin 20 µg/kg/h
17	Cardiomyopathy	24	9	Dopamine 5 µg/kg/min; dobutamine 10 µg/kg/min; nitroprusside 3 µg/kg/min; milrinone 0.7 µg/kg/min

ASD, atrial septal defect; PS, pulmonary stenosis; TGA, transposition of the great arteries; VSD, ventricular septal defect.

as CVP or pulmonary capillary wedge pressure.⁵ But there are few studies that have investigated the reliability of arterial thermodilution in children^{2,6} or in small animals.^{5,7-9} Furthermore, although it has been suggested that the normal blood volume values obtained by arterial thermodilution will show the same relationship to body surface area in children and in adults, there are no studies that have confirmed this. A previous study in small

animals showed that intrathoracic and intracardiac volume values obtained by arterial thermodilution are lower than those considered normal in the adult, whereas the extravascular lung water is higher.¹⁰ The objective of the present study was to analyze cardiac output, cardiac function and blood volume in critically ill children and to compare these with the normal values reported for adults.

Table 2 Hemodynamic parameters of cardiac function and blood volume

Parameter	Mean $\pm$ SD (17 children)	Normal adult values	Schiffmann <i>et al.</i> ²³ (10 children)	Cecchetti <i>et al.</i> ²⁴ (17 children)
HR (beats/min)	131.1 $\pm$ 23.6	60–80	130 $\pm$ 26	115.2 $\pm$ 24.7
MBP (mmHg)	68.8 $\pm$ 11.5	80–95	70 $\pm$ 19	83.5 $\pm$ 18.1
CVP (mmHg)	8.7 $\pm$ 3.5	2–6	6.9 $\pm$ 3.2	
CI (L/min/m ²)	3.5 $\pm$ 1.3	2.5–4.5	3.2 $\pm$ 0.5	4.1 $\pm$ 1
SVV (%)	12.1 $\pm$ 5.3	<10%	—	7.8 $\pm$ 4.2
GEDVI (mL/m ²)	399.7 $\pm$ 349.1	490 $\pm$ 100	405 $\pm$ 129	
ITBI (mL/m ²)	574.5 $\pm$ 212.2	850–1000	598 $\pm$ 198	524.4 $\pm$ 179.2
ELWI (mL/kg)	18.9 $\pm$ 9.3	3–7	27.7 $\pm$ 16.8	8.4 $\pm$ 3.2
SVRI (dyn $\times$ cm ⁵ /m ²)	1500 $\pm$ 515.9	1200–2000	—	—
dp/dt max (mmHg/s)	804.6 $\pm$ 372.1	1200–2000	—	946 $\pm$ 285.2
CFI (L/min)	8.0 $\pm$ 2.5	4.5–6.5	—	—
SVI (mL/beat/m ²)	28 $\pm$ 11.2	40–60	27.8 $\pm$ 7.4	36.9 $\pm$ 10.6

CFI, cardiac function index; CI, cardiac index; CO, cardiac output; CVP, central venous pressure; dp/dt max, left ventricular contractility; ELWI, extravascular lung water; GEDVI, global end diastolic volume; HR, heart rate; ITBI, intrathoracic blood volume index; MBP, mean blood pressure; SVRI, systemic vascular resistance index; SVI, systolic volume index; SVV, stroke volume variation.

Methods

A prospective study was performed in 17 critically ill children who needed cardiac output monitoring and were admitted during a period of 18 months to the Pediatric Intensive Care Unit at Gregorio Marañón General University Hospital. Patients were aged between 2 months and 14 years and weighed between 4 and 70 kg. The protocol of the study was approved by the Institution Review Board and informed consent was obtained from parents. The diagnoses and patient treatments are summarized in Table 1. The femoral artery was catheterized using a 4 or 5 Fr PiCCO arterial thermodilution catheter (FT-Pulsioncath, Pulsion Medizintechnik, Munich, Germany) to monitor the arterial blood pressure and measure cardiac output. We did not use a 3 Fr catheter because this catheter was not available in Spain at the time of the study. In patients with cardiopathy, echocardiography was performed to discard residual shunts.

A total of 117 cardiac output measurements were performed using thermodilution. For these measurements, a volume of 5 mL of cold normal saline, at a temperature below 8°C, was injected

rapidly through the central venous catheter, recording the thermodilution curve with measurement of the cardiac output at the arterial catheter. Each measurement was performed twice, calculating the mean of the two measurements for the record. A third measure was performed in the case of large discrepancy between the two initial measures. The following parameters of cardiac function were recorded: systolic, diastolic and mean blood pressures, heart rate, cardiac output (CO) and cardiac index (CI), cardiac function index (CFI), systolic volume index (SVI), left ventricular contractility (dp/dt max), systemic vascular resistance index (SVRI); and parameters of blood volume: global end diastolic volume index (GEDVI), intrathoracic blood volume index (ITBI), stroke volume variation (SVV), and the extravascular lung water index (ELWI). The cardiac output catheter was maintained for a period of 6.3 $\pm$ 4.2 days (range: 2–15 days).

A statistical analysis of the results was performed using SPSS 11.5 (SPSS, Chicago, IL, USA). Student's *t*-test was used for the comparison of the different parameters in children with different

Table 3 Cardiac function and blood volume in children over and under 20 kg

AParameter	>20 kg	<20 kg	P
Measurements	52	65	
No. patients	8	9	
HR (beats/min)	115.2 $\pm$ 24.1	142.7 $\pm$ 15.1	0.000
MBP (mmHg)	75.2 $\pm$ 11.1	64.1 $\pm$ 9.3	0.000
CVP (mmHg)	10.6 $\pm$ 2.9	7.6 $\pm$ 3.2	0.000
CI (L/min/m ²)	3.4 $\pm$ 1.5	3.5 $\pm$ 1.3	0.719
SVV (%)	11.1 $\pm$ 4.5	12.9 $\pm$ 5.8	0.090
GEDVI (mL/m ²)	442.5 $\pm$ 323.3	556 $\pm$ 428	0.001
ITBI (mL/m ²)	585.6 $\pm$ 231.3	586 $\pm$ 221.4	0.992
ELWI (mL/m ²)	12 $\pm$ 3.7	26.9 $\pm$ 9	0.000
SVRI (dyn $\times$ cm ⁵ /m ²)	1623.2 $\pm$ 543.1	1418.5 $\pm$ 484	0.049
dp/dt max (mmHg/s)	958.5 $\pm$ 477.2	685.7 $\pm$ 198.6	0.001
CFI (L/min)	7.7 $\pm$ 1.3	8.2 $\pm$ 3.1	0.270
SVI (mL/beat/m ²)	31.5 $\pm$ 12	25.5 $\pm$ 9.2	0.007

CFI, cardiac function index; CI, cardiac index; CO, cardiac output; CVP, central venous pressure; dp/dt max, left ventricular contractility; ELWI, extr avascular lung water; GEDVI, global end diastolic volume; HR, heart rate; ITBI, intrathoracic blood volume index; MBP, mean blood pressure; SVRI, systemic vascular resistance index; SVI, systolic volume index; SVV, stroke volume variation.

Table 4 Cardiac function and blood volume in children over and under 30 kg

Parameter	>30 kg	<30 kg	<i>P</i>
Measurement	29	88	
No. patients	5	12	
HR (beats/min)	102.2 ± 24.2	139.9 ± 14.8	0.001
MBP (mmHg)	79 ± 12.2	65.7 ± 9.3	0.001
CVP (mmHg)	9.5 ± 3	8.5 ± 3.6	0.107
CI (L/min/m ²)	3.9 ± 1.8	3.3 ± 1.1	0.597
SVV (%)	12.4 ± 5	12.1 ± 5.4	0.403
GEDV (mL/m ²)	505.4 ± 435.5	482.6 ± 310	0.03
ITBI (mL/m ²)	721 ± 254.5	549 ± 202	0.019
ELWI (mL/m ²)	10.4 ± 4	22.8 ± 9.8	0.001
SVRI (dyn × cm ⁵ /m ²)	1524.3 ± 638.3	1494.1 ± 484.6	0.739
dp/dt max (mmHg/s)	1117.8 ± 605.6	712.2 ± 192.7	0.153
CFI (L/min)	7.4 ± 1.7	8.1 ± 2.7	0.477
SVI (mL/beat/m ²)	39.6 ± 11.8	24.5 ± 8.2	0.001

CFI, cardiac function index; CI, cardiac index; CO, cardiac output; CVP, central venous pressure; dp/dt max, left ventricular contractility; ELWI, extravascular lung water; GEVD, global end diastolic volume; HR, heart rate; ITBI, intrathoracic blood volume index; MBP, mean blood pressure; SVRI, systemic vascular resistance index; SVI, systolic volume index; SVV, stroke volume variation.

weights and diagnoses. The Pearson test was used to study the correlation between the different parameters. Statistical significance was taken as $P < 0.05$.

Results

Table 2 shows the mean values of the hemodynamic, blood volume and cardiac function parameters for all the measurements taken. When the values obtained were compared with the values reported as normal in adults, lower values were found for the SVI and dp/dt max, whereas the CFI was higher. With respect to the blood volume parameters, the GEDVI and the ITBI were clearly lower than the normal values reported for adults, whereas the ELWI and the SVV were significantly higher (Table 2).

On comparison of the values between children <20 kg and those over this weight, it was found that the lower bodyweight children had lower dp/dt max, SVI and GEDVI and higher ELWI. These differences were more marked on comparing children

over and under 30 kg, despite finding a similar CI in the two groups (Tables 3,4). On analysis of the correlation between the blood volume variables and weight, a correlation was found for GEDVI (Fig. 1), ITBI and SVI, and an inverse correlation for ELWI (Fig. 2). A correlation was also observed between weight and dp/dt max and CI ($r = 0.421$, $P < 0.001$).

Patients with cardiopathies had significantly lower weight, CO, CI, GEDVI, SVI and dp/dt max, and significantly higher CFI, SVRI and ELWI than the patients with other pathologies (Table 5).

A good correlation was found between CI and SVI (Fig. 3), ITBI (Fig. 4), GEDVI ($r = 0.626$, $P = 0.001$), and dp/dt max ($r = 0.607$; $P = 0.01$). There was also an inversely proportional correlation between CI and SVRI (Fig. 5). No correlation was found between CI and mean blood pressure (MBP) or CVP. When the blood volume parameters were analyzed, a high correlation was found between SVI and ITBI and GEDVI (Fig. 6).

Table 5 Cardiac function and blood volume in children according to disease

Parameter	Cardiopathies	Other patients	<i>P</i>
Measurement	85	32	
No. patients	12	5	
Weight (kg)	16 ± 11.3	27.4 ± 23	0.001
HR (beats/min)	135 ± 21.6	120.4 ± 26	0.003
MBP (mmHg)	69.2 ± 10.6	67 ± 13.8	0.443
CVP (mmHg)	8.9 ± 3.6	8.1 ± 3.1	0.256
CI (L/min/m ²)	3.3 ± 1.2	4.1 ± 1.6	0.016
SVV (%)	12.2 ± 5.4	12.1 ± 5.1	0.935
GEVD (mL)	427 ± 177.1	575.5 ± 477.7	0.000
ITBI (mL/m ²)	561.9 ± 217	645.7 ± 235.1	0.074
ELWI (mL/m ²)	21.6 ± 10.9	16.5 ± 7.8	0.019
SVRI (dyn × cm ⁵ /m ²)	1559.8 ± 525.6	1303 ± 449.8	0.033
dp/dt max (mmHg/s)	687.8 ± 190.6	1141.3 ± 536.3	0.000
CFI (L/min)	8 ± 2.7	7.9 ± 1.9	0.956
SVI (mL/beat/m ²)	25.3 ± 8.5	35.7 ± 14.1	0.001

Bold. Statistically significant parameters. CFI, cardiac function index; CI, cardiac index; CO, cardiac output; CVP, central venous pressure; dp/dt max, left ventricular contractility; ELWI, extravascular lung water; GEVD, global end diastolic volume; HR, heart rate; ITBI, intrathoracic blood volume index; MBP, mean blood pressure; SVRI, systemic vascular resistance index; SVI, systolic volume index; SVV, stroke volume variation.

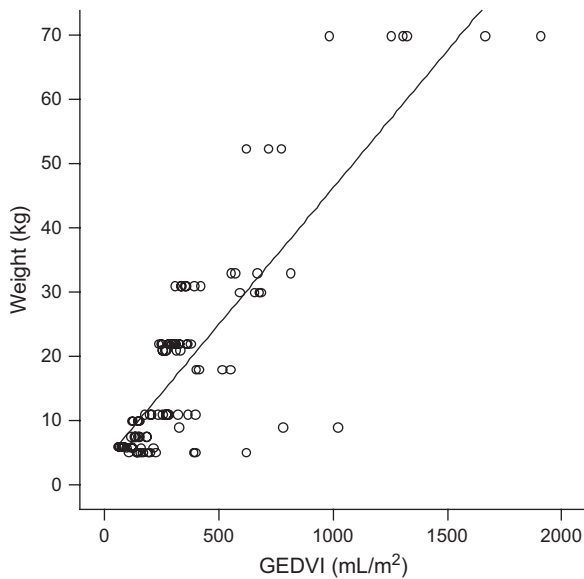


Fig. 1 Correlation between global end diastolic volume (GEDVI) and weight ($r = 0.842$, $P = 0.001$).

No correlation was found between the parameters measuring blood volume (GEDVI, ITBI, SVI) and the pressure parameters (MBP and CVP). A correlation was found between left ventricular contractility (dp/dt max) and GEDVI ($r = 0.745$, $P = 0.01$), SVI ($r = 0.650$, $P = 0.01$), and ITBI ($r = 0.399$, $P = 0.01$), and an inverse correlation with SVRI ($r = -0.356$, $P = 0.01$) and ELWI ($r = -0.400$, $P = 0.01$).

No side-effects secondary to the technique were observed although ischemia, hemorrhage or air embolus may occur during catheterization or permanence of the arterial catheter.

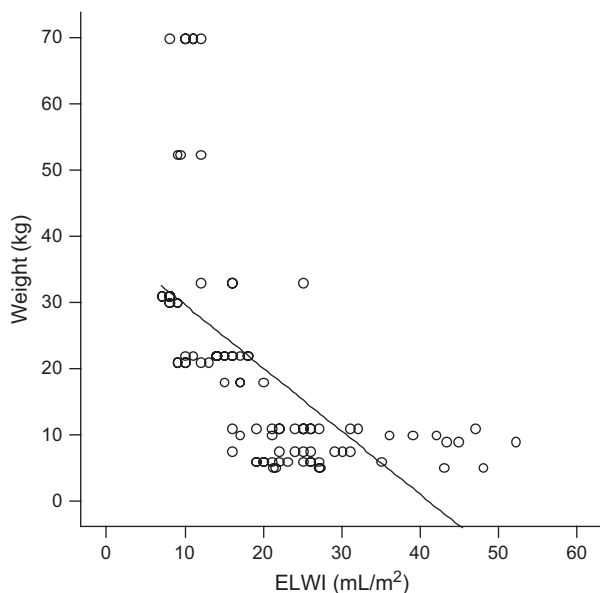


Fig. 2 Correlation between the extravascular lung water index (ELWI) and the weight ($r = 0.590$, $P = 0.001$).

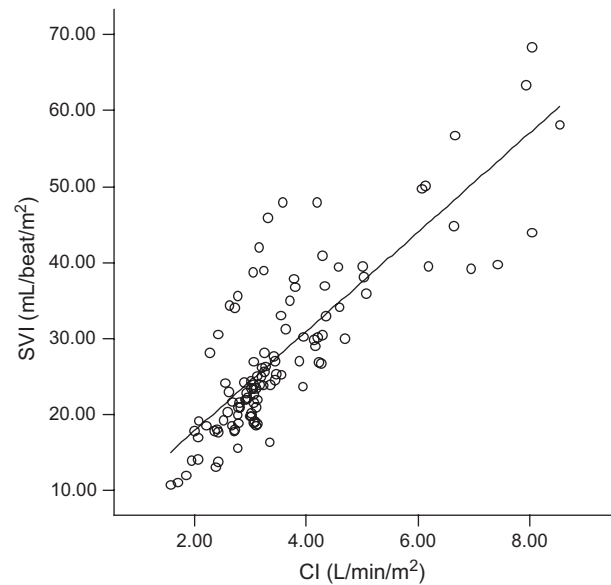


Fig. 3 Correlation between the cardiac index (CI) and the systolic volume index (SVI; $r = 0.825$, $P = 0.001$).

Discussion

Femoral arterial thermodilution has been shown to be a useful method for the measurement of cardiac output both in adults^{3,4} and in children.^{6,8,11–13} There is a good correlation between pulmonary thermodilution,^{3,4,8,11,13} the direct Fick method,^{6,12} lithium dilution¹⁴ and dye dilution.¹⁵ Nevertheless, there is still very little clinical experience in children. The CI found in the present study are within the normal limits for children, but the present patients had hemodynamic disturbances and these values may not therefore be taken as reference values for healthy children. The present

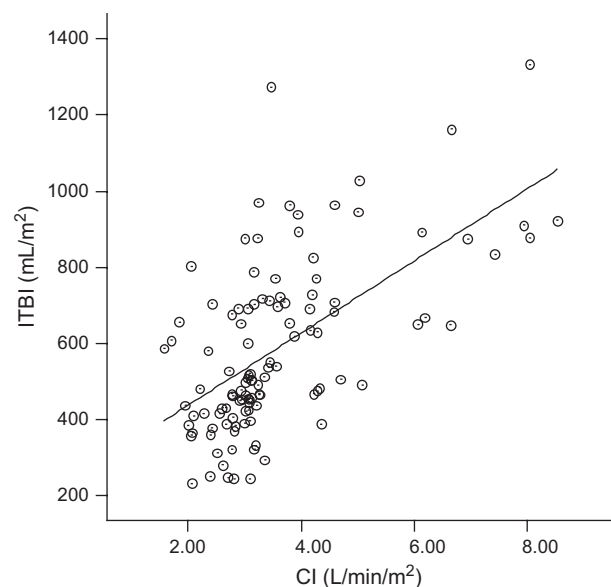


Fig. 4 Correlation between the cardiac index and the intrathoracic blood volume index (ITBI; $r = 0.597$, $P = 0.001$).

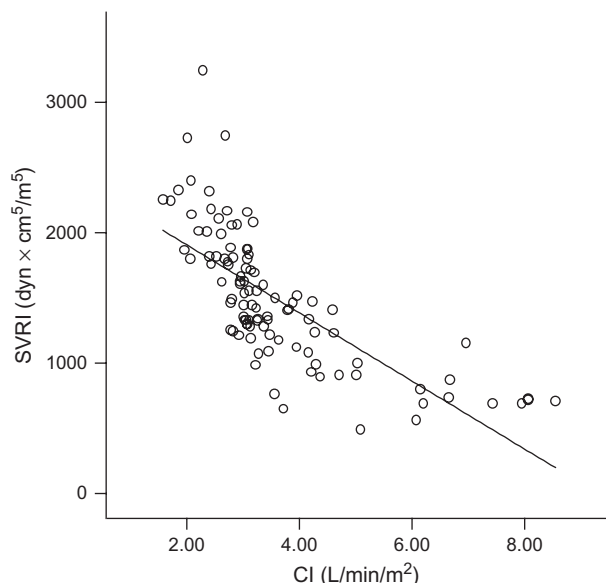


Fig. 5 Correlation between the cardiac index (CI) and the systemic vascular resistance index (SVRI; $r = -0.732$, $P = 0.001$).

study found a good correlation between blood volume parameters (ITBI and GEDVI) and CI and SVI, with no correlation being found with CVP. These findings coincide with observations in other studies in adults and children that suggest that these parameters provide a better evaluation of blood volume than the pressure measurements.^{13,16–19} In adults, the ITBI appears to be the best indicator of the state of cardiac preload, particularly in patients on assisted ventilation.^{16–18} In contrast, the SVV has been found to be a good parameter for evaluating the response to volume expansion and the ELWI correlates with pulmonary edema. These measurements could help to provide a better evaluation of the blood volume, the need for expansion, and the response to

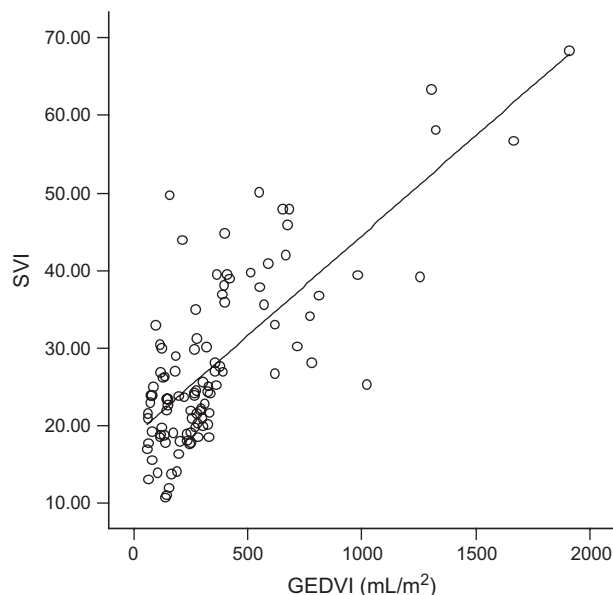


Fig. 6 Correlation between the systolic volume index (SVI) and the global end diastolic volume (GEDVI; $r = 0.751$, $P = 0.001$).

this, as well as the determination of pulmonary edema and the response to the different therapeutic measures. But there are still no studies that have evaluated the utility of these parameters in children.

There are few studies in children. In 10 critically ill neonates and infants, Schiffmann *et al.* found a correlation between SVI and GEDVI of 0.76 and ITBI of 0.56 ($P < 0.05$), with no correlation between SVI and CVP.¹⁹ After volume expansion, the SVI, the GEDVI and the ITBI increased significantly while no change was observed in CVP, CFI, MBP or ELWI.¹⁹ Mahajan *et al.* studied 16 children with a mean age of 10 years in the postoperative period after cardiac surgery, finding a much higher correlation of CI with ITBI than with CVP, and no correlation between ITBI and CVP.¹³ In contrast, Egan *et al.* did not find a good correlation between the blood volume parameters determined using PiCCO and on clinical evaluation.²⁰

Some parameters of cardiac function (dp/dt max and CFI) and, particularly, the blood volume parameters (ITBI, GEDVI) obtained in the present study are outside the range considered normal in adults. There are no studies that define the normal values for intracardiac and intrathoracic blood volumes and the extravascular lung water in children. In a previous study in small animals we have observed a good correlation between the blood volume parameters (ITBI and GEDVI) and the CI and systolic volume index.¹⁰ But intrathoracic and intracardiac volumes obtained on arterial thermodilution were lower whereas the extravascular lung water was higher than those considered normal in the adult.¹⁰ The present values are similar to those found in three previous studies in children.^{19–21} It may be that small children have proportionally lower intracardiac and intrathoracic volumes than adults and a higher percentage of extravascular lung water. In contrast, most of the present patients were in a situation of cardiogenic or septic shock, which could lead to changes in the intrathoracic blood volume and extravascular water, but none of these patients presented clinical or radiological signs of pulmonary edema, despite the very high ELWI. On analyzing the variables with respect to bodyweight, however, we found that the GEDVI and the ITBI increased in relation to the weight of the patient while the ELWI decreased. These data suggest that the algorithms used by the PiCCO system for calculating the blood volume parameters (GEDVI, ITBI and ELWI) might not be appropriate for use in small children. The differences in the blood volume parameters found between patients with cardiopathy and the other patients are probably due to the differences in bodyweight between the two groups.

The present study had some limitations. Values were obtained in critically ill children with different pathology and hemodynamic situations. Several patients had congenital cardiac defects. Although echocardiography discards residual shunts, it is possible that occult defects could alter the results. A recent article showed that there are differences in GEDVI measured using transpulmonary thermodilution between jugular and femoral catheters.²² In the present study we did not analyze influence of catheter site and this could have influenced the GEDVI results.

Moreover, although PiCCO is a less invasive method than Swan-Ganz catheter, hemorrhage, air embolus or ischemia may occur during catheterization or prolonged permanence of relatively large arterial lines.

We conclude that femoral arterial thermodilution is a less invasive method that could substitute for pulmonary arterial thermodilution in critically ill children. The blood volume results, however, must be interpreted with caution in small children, and more prospective studies need to be performed in children to define the normal values in pediatric patients.

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