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ORIGINAL ARTICLE

Carotid Doppler Ultrasonography for Hemodynamic Assessment in Critically Ill Children

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Abstract

An accurate assessment of cardiovascular performance is essential to predict and evaluate hemodynamic response to interventions. The objective of this prospective study was to assess whether point-of-care ultrasonography of the common carotid artery (CCA) can estimate the stroke volume (SV) and cardiac index (Ci) of critically ill children. Participants underwent Doppler ultrasonography of the left CCA and transthoracic echocardiography (TTE). Variables measured by TTE were SV and Ci. Carotid blood flow (CBF) was calculated based on both systolic velocity–time integral ($\text{CBF}_{(s)}$) and total velocity–time integral ($\text{CBF}_{(t)}$). Carotid corrected flow time(CFT)was also determined. A total of 50 children were enrolled. The median age and weight of participants were 36.0 months and 14.2 kg, respectively. Both $\text{CBF}_{(s)}$ and $\text{CBF}_{(t)}$ correlated very strongly with SV ($\rho = 0.98$ and 0.97, respectively) and Ci ($\rho = 0.96$ and 0.92, respectively). Agreement analysis showed low biases and clinically acceptable percentage errors between variables measured by TTE (SV and Ci) and those estimated by Doppler ultrasonography. Linear regression analysis revealed that the Ci of mechanically ventilated children can be estimated by the following equation: $\text{Ci} = 0.703 + \frac{6.479 \times \text{CBF}_{(s)} \times \text{heart rate}}{\text{body surface area}}$. CFT did not significantly correlate with SV or Ci ($\rho = 0.27$ and 0.05, respectively). Doppler ultrasonography of the left CCA is able to estimate the SV and Ci of critically ill children. Therefore, the CDU may be considered as an alternative for estimating Ci in critically ill children when TTE is not feasible or available.

Keywords Hemodynamic monitoring · Doppler ultrasonography · Cardiac output · Common carotid artery · Child, infant

Abbreviations

CDU	Carotid Doppler ultrasonography
CCA	Common carotid artery
CI	Cardiac index
CI	Confidence interval
$\text{CBF}_{(s)}$	Systolic carotid blood flow
$\text{CBF}_{(t)}$	Total carotid blood flow
$\text{CBFi}_{(s)}$	Systolic carotid blood flow index
$\text{CBFi}_{(t)}$	Total carotid blood flow index
CFT	Carotid-corrected flow time
CO	Cardiac output
CoV	Coefficient of variation
Da	Aortic diameter
Dc	Carotid diameter
eCi	Estimated cardiac index
eSV	Estimated stroke volume
IQR	Interquartile range
PICU	Pediatric intensive care unit
POCUS	Point-of-care ultrasonography
SD	Standard deviation
SV	Stroke volume
SVRI	Systemic vascular resistance index
TTE	Transthoracic Echocardiography
VTIa	Aortic velocity–time integral
$\text{VTI}_{(s)}$	Systolic velocity–time integral
$\text{VTI}_{(t)}$	Total velocity–time integral

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Introduction

Intravenous fluids and vasoactive agents are the most common administered therapies for critically ill children and are the cornerstone of hemodynamic management of patients in pediatric intensive care units (PICUs). However, deciding how, when, and which of these two therapies should be used is a very difficult task faced by pediatric intensivists. Although they can be life-saving, its inappropriate use may increase morbidity and mortality [1]. The main objectives of these therapies are to increase cardiac output (CO) and oxygen delivery to ultimately improve tissue oxygenation. Therefore, an accurate assessment of cardiovascular performance is essential to predict and evaluate hemodynamic response to interventions.

Unfortunately, physicians have a poor agreement with objective measurements of cardiac index (Ci) and systemic vascular resistance index (SVRI) in pediatric patients with shock [2]. Clinical studies have demonstrated that only 40% to 69% of children who were deemed to have low CO responded to intravascular volume expansion increasing their stroke volume (SV) [3]. Thus, objective CO measurements can be valuable to guide proper bedside clinical decisions. Thermodilution techniques requiring pulmonary artery catheterization are regarded as the gold standard for CO monitoring [4, 5]. Nevertheless, due to their reduced anatomical dimensions, this technique is difficult in children and carries the risk of serious complications, such as infections and thromboembolic events. With this, there is an increasing interest in minimally invasive or non-invasive technologies to measure CO, including transpulmonary dilution techniques, lithium dilution, electrical bioimpedance, and Doppler ultrasound techniques [6]. The latter is becoming a standard of care in many PICUs, as point-of-care ultrasonography (POCUS) has gained popularity.

Critical care echocardiography may provide a non-invasive, cost-effective, and accurate tool for CO measurement. However, critically ill patients often have inadequate cardiac windows, which makes transthoracic echocardiography (TTE) examination a challenge even for experienced operators. To overcome the limitations of TTE, we studied an alternative method of CO measurement in children: the common carotid Doppler ultrasonography (CDU). This technique is potentially easier and more attractive for pediatric intensivists, especially for those who are familiar with ultrasound guidance techniques for vascular catheterization [7]. This study aimed to assess whether the CDU can estimate SV and Ci of critically ill children.

Methods

This observational cross-sectional study was conducted at the Clinical Hospital of the State University of Campinas (UNICAMP) (a quaternary care teaching hospital), Sao Paulo, Brazil. The study was approved by the local institutional review board (UNICAMP's Research and Ethics Committee, approval number 31665420.9.0000.5404). Written informed consent was obtained from the participants' legal guardians.

The enrollment period was from July 2020 to December 2020. All patients aged between 28 days and 13 years old admitted to the PICU were assessed for eligibility. Patients were excluded if they presented the following criteria: (1) anatomical anomalies of the neck; (2) contraindication for cervical mobilization (e.g. post-operative care from head and neck surgery, traumatic brain and spinal cord injury); (3) suspected intracranial hypertension; (4) congenital heart disease; (5) cardiac arrhythmias; (6) cervical or thoracic skin lesions; (7) presence of neck bandages, and (8) psychomotor agitation.

Participants underwent CDU, followed by TTE. The following demographic data were abstracted and recorded: age, sex, weight, major diagnosis, positive end-expiratory pressure, tidal volume, and vasoactive agents.

TTE and CDU were performed using Healthcare Vivid Q (CA, USA) equipped with a phased array transducer (3.5–8 MHz) and a linear transducer (5–13 MHz), respectively. Patients were positioned in the elevated supine position at 30º from the horizontal, and for the CDU examination, their heads were rotated away from the ultrasound operator. Although both exams were performed at the same time, the calculation of the variables of interest was performed at a later time. Therefore, the operator was unaware of the value of TTE variables during the performance of the CDU. All examinations were performed by a qualified pediatric ultrasound instructor of the Brazilian Society of Intensive Care, with 7 years of experience in pediatric point-of-care ultrasound.

Carotid Doppler Ultrasonography

Ultrasonographic images of the left common carotid artery (CCA) were obtained at the level of the thyroid gland. The CCA diameter (Dc) was measured in centimeters from intimal to intimal edge in the short-axis view, and the mean of the maximal and the minimal Dc were considered. The transducer was then rotated 90° into the long axis and spectral Doppler tracings were obtained by placing a 0.5 mm sample gate through the center of the vessel with the angle correction parallel to the CCA wall. The insonation angle was limited to a maximum of 60º.

The collected parameters include the following: systolic velocity–time integral ($VTI_{(s)}$), total VTI ($VTI_{(t)}$), systolic time, and cycle time. Parameters were obtained as illustrated in Fig. 1. $VTI_{(s)}$ and $VTI_{(t)}$ were determined through automatically traced envelopes during a single respiratory cycle, and the means of the highest and the lowest values were registered. The means of three registered $VTI_{(s)}$ and $VTI_{(t)}$ were considered for analysis purposes.

The systolic carotid blood flow ($CBF_{(s)}$) was determined using the following equation: $CBF_{(s)}(\text{ml}) = \left(\left(\pi \times Dc^2/4\right) \times VTI_{(s)}\right)$, where Dc and $VTI_{(s)}$ are in cm. Similarly, the total carotid blood flow ($CBF_{(t)}$) was determined as $CBF_{(t)}(\text{ml}) = \left(\pi \times Dc^2/4\right) \times VTI_{(t)}$.

Systolic carotid blood flow index ($CBFi_{(s)}$) was determined as: $CBFi_{(S)} = \frac{CBF_{(s)} \times \text{heart rate}}{\text{body surface area}}$. Similarly, total carotid blood flow index ($CBFi_{(t)}$) was determined as: $CBFi_{(t)} = \frac{CBF_{(t)} \times \text{heart rate}}{\text{body surface area}}$.

Carotid corrected flow time (CFT) was calculated by the following formula: $\text{CFT (ms)} = \frac{\text{Systolic time}}{\sqrt{\text{Cycle time}}}$.

Transthoracic echocardiography

The parasternal long-axis view was used to measure the aortic diameter (Da) at the level of the aortic annulus. The aortic VTI (VTIa) was measured from an apical five-chamber view by pulsed Doppler at the level of the aortic annulus. The VTIa was determined through automatically traced envelopes during a single respiratory cycle, and the mean of the highest and the lowest values was registered. The mean of three registered VTIa were considered for analysis purposes.

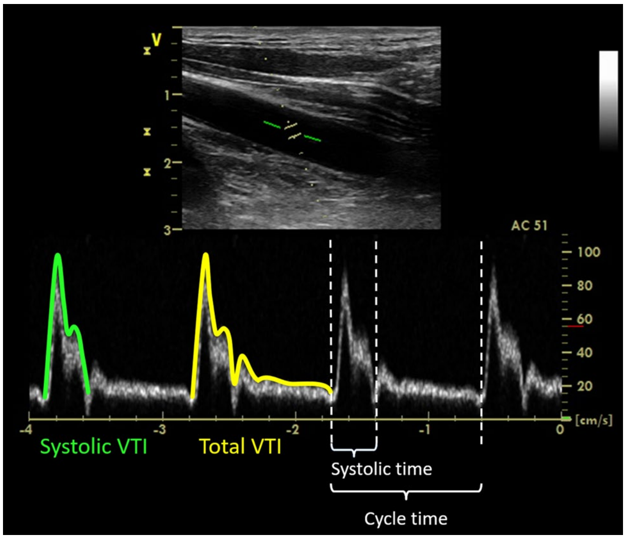


Fig. 1 Doppler ultrasonography of the left common carotid artery. Red line illustrated the automatically traced systolic velocity–time integral ($VTI_{(s)}$), while the yellow line illustrated the total velocity–time integral ($VTI_{(t)}$). The dotted lines determine the systolic and cycle times

The left ventricular stroke volume (SV) was determined using the following standard formula: $\text{SV (ml)} = \left(\pi \times Da^2/4\right) \times \text{VTIa}$, where Da and VTIa are in cm. CO was calculated by multiplying the SV by heart rate. Ci was determined as $\text{Ci} = \frac{\text{SV} \times \text{heart rate}}{\text{body surface area}}$.

Statistical Analysis

Statistical analysis was performed using MedCalc Statistical Software version 14.8.1 (MedCalc Software bvba, Ostend, Belgium). The normality of the data distribution was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Continuous variables were expressed as a mean and standard deviation (SD) if data were normally distributed or as a median and interquartile range (IQR) if they were not. Categorical variables were expressed as absolute values and associated percentages.

Correlations between TTE and CDU variables were analyzed using Pearson's correlation coefficient (ρ) and simple linear regression using the least-squares method. The linear regression models were used to estimate SV (eSV) from the variables measured by CDU ($CBF_{(s)}$ and $CBF_{(t)}$). Similarly, Ci were estimated (eCi) from $CBFi_{(s)}$ and $CBFi_{(t)}$. We assessed the agreement between TTE variables (SV and Ci) and the estimated variables (eSV and eCi) by analysis of Bland–Altman plots [8]. We calculated the percentage error as the 95% limit of agreement (1.96 SD from the bias) divided by the mean TTE variable (SV and Ci) multiplied by 100. The clinically acceptable percentage error is $< 30\%$ [9]. Significance was defined as $p < 0.05$.

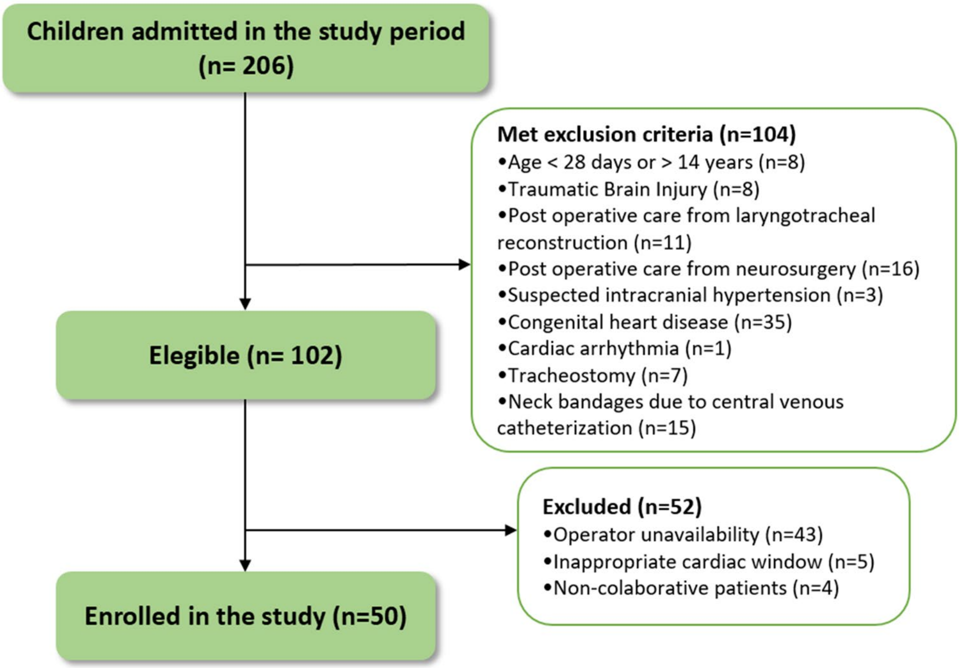
The largest and smallest of the 3 measurements of Ci, $CBFi_{(s)}$, and $CBFi_{(t)}$ were selected for intra-rater variability analysis. Intra-rater reliability was assessed by calculating the intraclass correlation coefficient (ICC) by using a model for 2-way random single measures (consistency), and by calculating the coefficients of variation (CoV) of duplicate measures.

A sample size of 25 participants was calculated to detect a pre-specified correlation coefficient of 0.6 between Ci and eCi, with a statistical power of 90% and a two-tailed type I error of 0.05 [10]. Due to significant differences in cardiorespiratory interactions, we decided to include 25 patients on controlled invasive mechanical ventilation and 25 patients breathing spontaneously.

Results

Of the 206 eligible patients, 50 were included in the final analysis. The eligibility assessment, recruitment, and inclusion are illustrated in Fig. 2. Median age and weight were

Fig. 2 Flow diagram showing the study recruitment process



36.0 months (IQR 6.0–107.0) and 14.2 kg (IQR 8.0–27.0). Demographic characteristics of the study population are shown in Table 1.

The mean Ci was 3.64 ± 1.15 L/min/m^2, while the mean CBFi$_{(s)}$ and CBFi$_{(t)}$ were 0.43 ± 0.16 L/min/m^2 and 0.64 ± 0.24 L/min/m^2, respectively. Except for the CFT, all

Table 1 Distribution of demographic and clinical characteristics of the participants

Variables	All ($n = 50$)	Mechanically ventilated patients ($n = 25$)	Spontaneously breathing patients ($n = 25$)
Age, mo[a]	36.0 (6.0–107.0)	17.0 (4.0–43.75)	81.0 (29.5–143.0)
Weight, kg[a]	14.2 (8.0–27.0)	12.0 (4.77–14.1)	21.0 (14.75–34.25)
Sex, *n* (%)			
Female	34 (68)	18 (72)	16 (64)
Male	16 (32)	7 (28)	9 (36)
Vasoactive drugs use, *n* (%)	7 (14)	7 (28)	0
Diagnosis, *n* (%)			
Clinical	33 (66)	17 68)	16 (64)
Surgical	17 (34)	8 (32)	9 (36)
PIM2	4.85 (1.00–9.70)	8.40 (1.57–17.02)	1.8 (0.87–6.05)
Transthoracic echocardiography[b]			
Stroke volume (ml)	22.37 ± 14.76	14.33 ± 8.88	30.41 ± 15.20
Cardiac index (L/min/m^2)	3.64 ± 1.15	3.51 ± 0.97	3.76 ± 1.32
Carotid Doppler ultrasonography[b]			
Systolic carotid blood flow (ml)	2.58 ± 1.64	1.72 ± 0.99	3.44 ± 1.71
Total carotid blood flow (ml)	3.97 ± 2.78	2.47 ± 1.50	5.48 ± 2.96
Systolic carotid blood flow index (L/min/m^2)	0.43 ± 0.16	0.43 ± 0.14	0.43 ± 0.17
Total carotid blood flow index (L/min/m^2)	0.64 ± 0.24	0.61 ± 0.22	0.66 ± 0.26
Corrected flow time (seg)	10.2 ± 1.2	10.2 ± 1.5	10.3 ± 1.0

[a] Data are presented as median (interquartile range)

[b] Data are presented as mean ± SD

other variables measured by CDU correlated very strongly with the variables measured by TTE (Table 2). Pearson's correlation between the $\text{CBFi}_{(s)}$ and Ci had an $r = 0.96$ (95% CI 0.92 to 0.97, $p < 0.001$). Linear regression analysis revealed a significant relationship between $\text{CBFi}_{(s)}$ and Ci ($r^2 = 0.916$; $p < 0.001$) and the linear relationship between them is described by the following regression equation: $\text{eCi} = 0.586 + 7.719 \times \text{CBFi}_{(s)}$ (Table 2). The bias between eCi (obtained from $\text{CBFi}_{(s)}$) and Ci (measured by TTE) was 0.00 L/min/m^2 (LOA: – 0.66 to 0.66 L/min/m^2) (Fig. 3). The mean percentage error of Ci between eCi and Ci was 19.5%. Analysis of patients with and without invasive mechanical ventilation showed similar results. All correlations and linear regression analysis performed are summarized in Tables 2 and 3.

The coefficient of variation of duplicate measures for $\text{CBFi}_{(s)}$ was 6.96%, for $\text{CBFi}_{(t)}$ was 7.00%, and for Ci was 5.99%. For singles measures, the ICC between the $\text{CBFi}_{(s)}$ measurements was 0.986 (95% CI 0.976 to 0.992), between $\text{CBFi}_{(t)}$ measurements was 0.974 (95% CI 0.955 to 0.985), and between the Ci measurements was 0.982 (95% CI 0.969 to 0.989).

Discussion

The present study provides evidence to support the potential of CDU as a novel method for hemodynamic monitoring in PICU. The results showed almost perfect correlations between some pairs of CDU and TTE variables with low biases and clinically acceptable percentage errors. The lower percentage errors were observed between the reference method and the cardiac index estimated from $\text{CBFi}_{(s)}$ in all patients and both subgroups. In addition, linear regression

Table 2 Linear regression and Pearson's correlation analysis of variables obtained from transthoracic echocardiography (stroke volume and cardiac index) and carotid Doppler ultrasonography

Pair of variables	Linear regression model		Pearson's correlation coefficient	
	Equation	r^2	ρ (95% CI)	p-value
Total ($n = 50$)				
Stroke volume and				
$\text{CBF}_{(s)}$	$\text{eSV} = -0.516 + 8.860 \times \text{CSV}$	0.964	0.98 (0.97–0.99)	$p < 0.001$
$\text{CBF}_{(t)}$	$\text{eSV} = 1.900 + 5.152 \times \text{CTV}$	0.940	0.97 (0.95–0.98)	$p < 0.001$
CFT	–	–	0.27 (– 0.01 to 0.51)	$p = 0.055$
Cardiac index and				
$\text{CBFi}_{(s)}$	$\text{eCi} = 0.586 + 7.719 \times \text{CBFi}_{(s)}$	0.916	0.96 (0.92–0.97)	$p < 0.001$
$\text{CBFi}_{(t)}$	$\text{eCi} = 0.840 + 4.394 \times \text{CBFi}_{(t)}$	0.845	0.92 (0.86–0.95)	$p < 0.001$
CFT	–	–	0.05 (– 0.23 to 0.32)	$p = 0.74$
Mechanically ventilated patients ($n = 25$)				
Stroke volume and				
$\text{CBF}_{(s)}$	$\text{eSV} = -0.686 + 8.720 \times \text{CSV}$	0.947	0.97 (0.94–0.99)	$p < 0.001$
$\text{CBF}_{(t)}$	$\text{eSV} = 0.338 + 5.659 \times \text{CTV}$	0.920	0.96 (0.91–0.98)	$p < 0.001$
CFT	$\text{eSV} = -17.158 + 3.093 \times \text{CFT}$	0.268	0.52 (0.15–0.76)	$p = 0.008$
Cardiac index and				
$\text{CBFi}_{(s)}$	$\text{eCi} = 0.703 + 6.479 \times \text{CBFi}_{(s)}$	0.905	0.95 (0.90–098)	$p < 0.001$
$\text{CBFi}_{(t)}$	$\text{eCi} = 1.111 + 3.947 \times \text{CBFi}_{(t)}$	0.835	0.91 (0.81–0.96)	$p < 0.001$
CFT	–	–	0.00 (– 0.40 to 0.40)	$p = 0.989$
Spontaneously breathing patients ($n = 25$)				
Stroke volume and				
$\text{CBF}_{(s)}$	$\text{eSV} = 0.597 + 8.656 \times \text{CSV}$	0.952	0.98 (0.94–0.99)	$p < 0.001$
$\text{CBF}_{(t)}$	$\text{eSV} = 3.508 + 4.913 \times \text{CTV}$	0.916	0.96 (0.90–0.98)	$p < 0.001$
CFT	–	–	0.16 (– 0.25 to 0.53)	$p = 0.431$
Cardiac index and				
$\text{CBFi}_{(s)}$	$\text{eCi} = 0.546 + 7.379 \times \text{CBFi}_{(s)}$	0.942	0.97 (0.93–0.99)	$p < 0.001$
$\text{CBFi}_{(t)}$	$\text{eCi} = 0.618 + 4.730 \times \text{CBFi}_{(t)}$	0.857	0.93 (0.84–0.97)	$p < 0.001$
CFT	–	–	0.10 (– 0.31 to 0.48)	$p = 0.637$

$\text{CBF}_{(s)}$ systolic carotid volume, *$\text{CBF}_{(t)}$* total carotid volume, *CFT* carotid corrected flow time, *$\text{CBFi}_{(s)}$* systolic carotid blood flow index, *$\text{CBFi}_{(t)}$* total carotid blood flow index, *eSV* estimated stroke volume, *eCi* estimated cardiac index

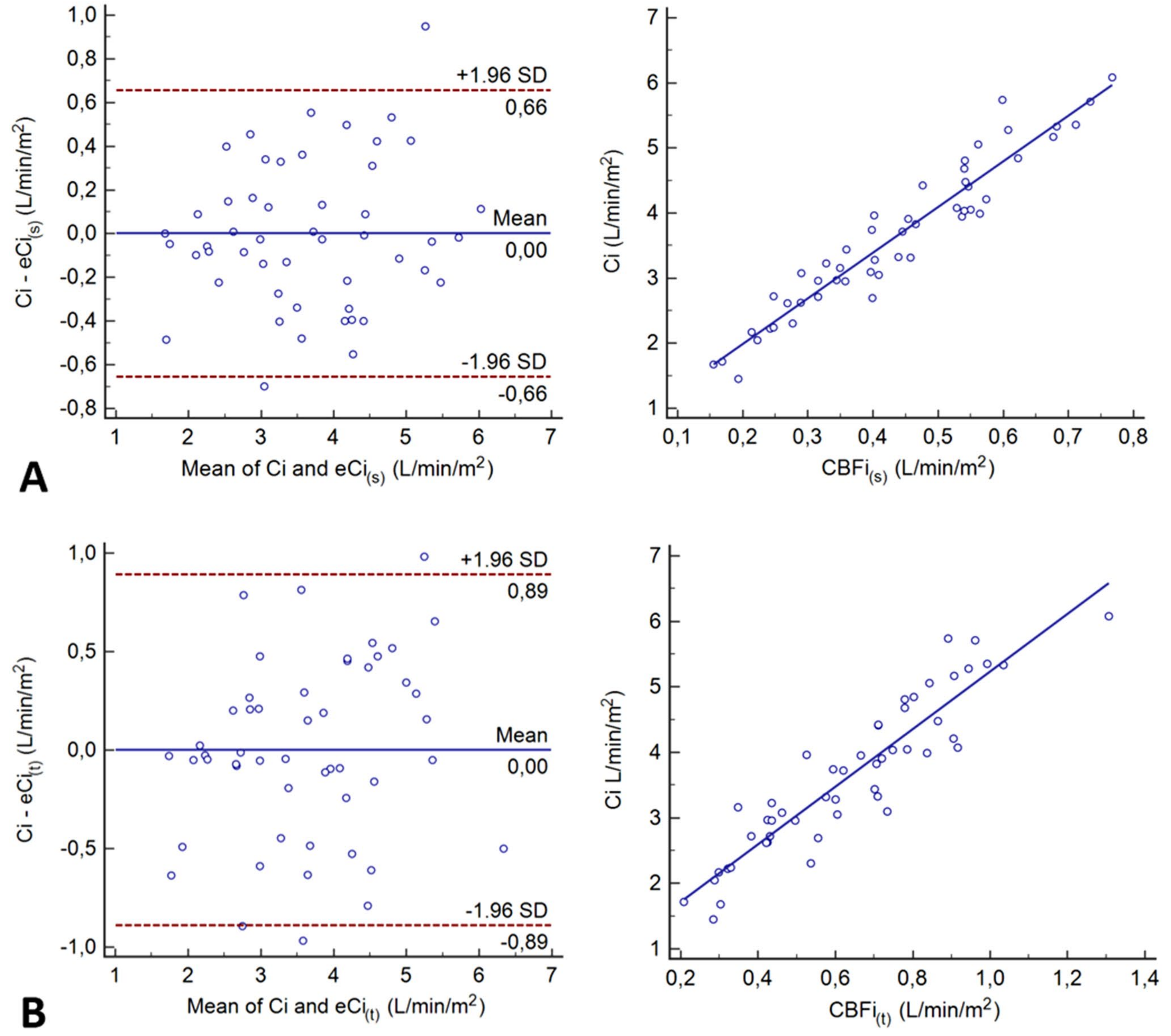


Fig. 3 Bland–Altman and linear regression plots of cardiac index, measured by transthoracic echocardiography, and those estimated from: **A** systolic carotid blood flow index, and **B** total carotid blood flow index

analysis revealed that the cardiac index of mechanically ventilated children can be estimated by the following equation: $\mathrm{eCi} = 0.703 + 6.479 \times \mathrm{CBFi}_{(s)}$. Therefore, the CDU may be considered as an alternative for estimating Ci in critically ill children when TTE is not feasible or available.

The ideal method for hemodynamic monitoring should be accurate, has an acceptable risk–benefit profile, and be easy to use. Although accurate and safe, TTE has some limitations. First, TTE requires significant training and skills and, therefore, may have a low agreement between experienced and novice operators [11]. Second, critically ill children often have suboptimal cardiac windows due to positioning difficulties, mechanical ventilation, interfering incisions, or wound dressings, which makes it difficult to assess blood flow in the left ventricular outflow tract using Doppler ultrasound. With this, some authors suggest that CDU may be an easier alternative for CO monitoring in the intensive care setting [12, 13]. Pediatric intensivists are increasingly familiar with the linear probes used for ultrasound-guided central venous catheterization [7]. Even so, further studies evaluating learning curves and inter-operator agreement are needed to elucidate whether CDU is an easier technique than TTE.

To the best of our knowledge, this is the first study evaluating the use of POCUS of the CCA as a method of hemodynamic assessment in PICU. Studies involving adults have shown moderate to strong correlations between CCA blood

Table 3 Bland–Altman and percentage error analysis

Pair of variables	Bland–Altman analysis			Percentage error (%)
	Bias	Lower LOA	Upper LOA	
Total ($n = 50$)				
Stroke volume and				
eSV (estimated from CBF$_{(s)}$)	0.00	– 5.48	5.48	24.8
eSV (estimated from CBF$_{(t)}$)	0.00	– 7.11	7.11	28.7
Cardiac index and				
eCi (estimated from CBFi$_{(s)}$)	0.00	– 0.66	0.66	19.5
eCi (estimated from CBFi$_{(t)}$)	0.00	– 0.89	0.89	28.0
Mechanically ventilated patients ($n = 25$)				
Stroke volume and				
eSV (estimated from CBF$_{(s)}$)	0.00	– 4.01	4.01	27.2
eSV (estimated from CBF$_{(t)}$)	0.00	– 4.90	4.90	32.0
eSV (estimated from CFT)	0.00	– 14.89	14.89	148.93
Cardiac index and				
eCi (estimated from CBFi$_{(s)}$)	0.00	– 0.59	0.59	16.7
eCi (estimated from CBFi$_{(t)}$)	0.00	– 0.77	0.77	22.8
Spontaneously breathing patients ($n = 25$)				
Stroke volume and				
eSV (estimated from CBF$_{(s)}$)	0.41	– 6.15	6.97	22.4
eSV (estimated from CBF$_{(t)}$)	0.30	– 8.43	9.03	26.6
Cardiac index and				
eCi (estimated from CBFi$_{(s)}$)	0.12	– 0.52	0.75	20.2
eCi (estimated from CBFi$_{(t)}$)	0.00	– 0.99	0.99	32.0

CBF$_{(s)}$ systolic carotid volume, *CBF$_{(t)}$* total carotid volume, *CFT* carotid corrected flow time, *CBFi$_{(s)}$* systolic carotid blood flow index, *CBFi$_{(t)}$* total carotid blood flow index, *eSV* estimated stroke volume, *eCi* estimated cardiac index, *LOA* limits of agreement

flow and Ci measured by invasive methods or TTE [13, 14]. However, these studies have important methodological limitations that do not allow the use of CDU as a surrogate for CO measurement [12–16]. They did not carry out essential statistical approaches for comparing two methods, such as Bland–Altman and percentage error analysis [17]. Also, some of these studies estimated the CO by multiplying the carotid blood flow by 10, when the most appropriate would be to perform linear regression analyzes. Nevertheless, preliminary research suggests that CDU may be useful in determining fluid responsiveness [18]. In a recent systematic review, the areas under the receiver operating characteristic curves varied from 0.75 to 0.88 for CFT, and from 0.81 to 0.91 for respirophasic variation in blood flow peak velocity [18]. Unfortunately, none of these studies involved children.

Interestingly, we observed that the hemodynamic variables estimated from the VTI$_{(s)}$ presented higher correlation coefficients and lower percentage errors when compared to those estimated from the VTI$_{(t)}$. This is consistent with the findings reported by Sidor et al. [13] In their study, the correlation with CO was not significant when carotid blood flow was calculated based on VTI$_{(t)}$ (Spearman's correlation coefficient of only 0.41, $p < 0.06$). However, statistical significance was reached when the VTI$_{(s)}$ was used (Spearman's correlation coefficient of 0.67, $p < 0.05$). The diastolic portion of blood flow in the CCA may be determined by other factors than stroke volume, such as the reflection of the pulse wave from the aortic valve in early diastole, vascular resistance, and compliance. Like Sidor et al. we suggest the use of carotid VTI$_{(s)}$ to estimate the hemodynamic variables of interest (SV or Ci).

In our study, CFT did not significantly correlate with SV or Ci when considering all patients. Only in the subgroup of mechanically ventilated children, the CFT presented a regular correlation with SV [$\rho = 0.52$ (95% CI 0.15–0.76); $p < 0.008$]. Other studies found similar results [13, 16]. Sidor et al. found a positive correlation between CFT and CO in 20 healthy adult volunteers (Spearman's correlation coefficient of 0.57), while Ma et al. found a weak correlation in 51 adults undergoing right cardiac catheterization (Spearman's correlation coefficient of 0.29) [13, 16]. Although CFT does not seem to be useful for estimating CO, some studies highlight its potential as a predictor of fluid responsiveness [19, 20]. CFT measurements have important technical advantages that may be particularly useful for unskilled operators, such as simplicity, minimal time consumption, and the independence of the Doppler insonation angle. Therefore, it is a method that deserves further studies, especially in the pediatric population.

Our study has some limitations. The main one is the use of TTE as a reference method instead of a gold standard technique, such as Fick or thermodilution techniques. However, pediatric Doppler CO measurements have accuracy, precision, and acceptable repeatability [9]. In addition, the results herein reported may justify the risks of further pediatric studies using invasive methods of CO measurement. Second, like any other ultrasound-based method, CDU is a highly operator-dependent technique. The involvement of only one operator in our study limits the extrapolation of our results. Although we found a low intra-observer variability, further studies assessing inter-operator agreement are needed. Third, only the left CCA was evaluated in this study. We decided to evaluate the left one because the right cervical region is often used for catheterization of the internal jugular vein. Fourth, we studied critically ill children with hemodynamic and respiratory stability. Our results may not be true for unstable children, using high doses of vasoactive drugs, or with abnormalities in carbon dioxide levels. Likewise, patients with intracranial hypertension were not contemplated in this study.

Conclusion

Our study found a very high correlation between carotid blood flow and some important hemodynamic variables, such as SV and Ci. Therefore, the CDU may be considered as an alternative technique for hemodynamic assessment in critically ill children. However, further studies using gold standards as a reference method are needed to validate this promising technique.

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Author Contributions AJR and LLdS: responsible for data collection, drafting and critical revision of the manuscript. RJNN and MBB: responsible for critical revision of the manuscript for important intellectual content. THdS: responsible for the study concept and design, acquisition, analysis and interpretation of data.

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Data Availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Code Availability N/A.

Declarations

Conflict of interest The authors have no conflicts of interest relevant to this study to disclose.

Ethical Approval The study was approved by the local institutional review board (UNICAMP's Research and Ethics Committee, Approval Number 31665420.9.0000.5404).

Consent to Participate Written informed consent was obtained from the participants' legal guardian.

Consent for Publication N/A.

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