https://doi.org/10.15360/1813-9779-2024-5-37-43

Ultrasound-Based Cardiac Output Monitoring During Pediatric Open-Heart Surgery

Nikolay A. Soloviev[1,2]*, Mikhail M. Rybka[1], Jumber Ya. Khinchagov[1], Sofya M. Tsoi[1], Gleb E. Gorbunov[1], Denis A. Dibin[1], Zera A. Kodzokova[1], Madina Yu. Chomaeva[1]

[1] A. N. Bakulev National Medical Research Center for Cardiovascular Surgery, Russian Ministry of Health, 135 Rublevskoe shosse, 121552 Moscow, Russia
[2] G. N. Speransky Children's City Clinical Hospital No. 9, Moscow Health Department, 29 Shmitovsky pr., 123317 Moscow, Russia

For citation: *Nikolay A. Soloviev, Mikhail M. Rybka, Jumber Ya. Khinchagov, Sofya M. Tsoi, Gleb E. Gorbunov, Denis A. Dibin, Zera A. Kodzokova, Madina Yu. Chomaeva.* Ultrasound-Based Cardiac Output Monitoring During Pediatric Open-Heart Surgery. *Obshchaya Reanimatologiya = General Reanimatology.* 2024; 20 (5): 37–43. https://doi.org/10.15360/1813-9779-2024-5-37-43 [In Russ. and Engl.]

*__Correspondence to:__ Nikolay A. Soloviev, nasolovev@bakulev.ru

Summary

Aim of the study. To evaluate the feasibility of using non-invasive hemodynamic monitoring technology based on Doppler ultrasound during open-heart surgery in children.

Material and methods. Prospective, observational, single-center cohort study included 20 patients aged 10 to 34 months undergoing surgery for congenital heart defects. Ten patients underwent atrial septal defect closure (ASD group), other 10 patients had ventricular septal defect closure (VSD group). Cardiac output (CO) was measured in all patients to guide inotropic and infusion therapy adjustments at three control time points: (1) after intubation and before skin incision, (2) during the immediate post-bypass period with the chest open after weaning from cardiopulmonary bypass (CPB), and (3) after sternal closure and before transfer to the intensive care unit (ICU).

Results. At time point 1, the CO values for both the ASD and VSD groups were within the normal reference range: 5.2 L/min [4.7; 5.5] and 5.1 L/min [4.6; 5.6], respectively. At time point 2, CO was measured in 15 of 20 patients, including 8 patients in the ASD group and 7 in the VSD group. Coverage was 75% because of the challenges of measuring 5 patients on the operating table. In the immediate post-bypass period, two patients with VSD (25%) developed hypotension with CO reduced to 3.6 L/min, which is lower than the age-related hemodynamic reference value (5.1 L/min). Inotropic support in these two patients was increased by switching from dopamine, 7 mcg/kg/min, to adrenaline at a dose of 0.05 mcg/kg/min, resulting in improvement of hemodynamic parameters and an increase in CO to 5.2 L/min and 5.0 L/min, respectively, compared to normal age-related reference values (4.1; 6.1 L/min). After sternal closure, CO values in both groups did not differ significantly from age-related reference values.

Conclusion. The USCOM cardiac output monitoring device can be used to manage intraoperative hemodynamics and adjust inotropic therapy even during open chest surgery. However, its routine use in all stages of surgery with median sternotomy is difficult because it requires more time to align the aortic valve projection.

Keywords: pediatric cardiac surgery; open heart surgery in children; hemodynamic monitoring; intensive care; fluid therapy; USCOM device

Conflict of interest. The authors declare no conflict of interest.

Introduction

During cardiac surgery, hemodynamics are directly dependent on fluid and inotropic support [1]. In this case, a reliable method to determine the need for volume loading is required. The use of invasive techniques to determine cardiac output (CO) (prepulmonary and transpulmonary thermodilution) in children with congenital heart disease (CHD) is limited due to the complexity of the circulatory system (the presence of intracardiac shunts). Several researchers confirm that the difference between invasive techniques and echocardiography can be as much as 30% [2].

At the A. N. Bakulev National Medical Research Center for Cardiovascular Surgery, ultrasound examination methods, especially transesophageal echocardiography, are performed by a qualified ultrasound specialist, including during surgery.

An Austrian pharmacologist Adolf Jarisch (1891–1965) once expressed a view that is still relevant today: «It is a source of regret that measurement of flow is much more difficult than measurement of pressure. This has led to an undue interest in blood pressure measurements. Most organs, however, require flow rather than pressure».

Currently, the diagnostic value of central venous pressure (CVP) measurement is declining [3]. It should be noted that CVP depends on intravascular volume, total peripheral vascular resistance (TPVR), right ventricular compliance, total pulmonary vascular resistance (TPulmVR), and intrathoracic pressure. CVP may also be elevated in hypovolemia due to right ventricular failure, pulmonary embolism, cardiac tamponade, tension pneumothorax, and hypervolemia [4]. Therefore, its values depend on multiple factors and cannot serve as a «gold standard» for the assessment of volemia [5]. In cardiothoracic surgery after sternotomy, there is an opportunity to visually assess ventricular filling and contractility.

Currently, many tests and indices have been developed to determine the relationship between cardiac output and preload and to predict response to fluid therapy [6, 7]. All of these tests are reliable only under strict conditions that limit their use in different clinical situations [8]. Non-invasive methods of hemodynamic monitoring are usually more accessible and reduce the number of potentially dangerous invasive procedures [9,10]. However, for monitoring blood pressure in cardiac surgery, it is more appropriate to use an invasive method that does not «mask» hypotension. A left atrial catheter can be used for intraoperative measurement of left heart pressure without the use of a Swan–Ganz catheter. In young children, the use of single-channel 18–22 G catheters placed intraoperatively into the left atrium via an interatrial communication (IAC) is preferred. This is an invasive procedure that in some cases requires creation of a fenestration in the interatrial septum and is therefore used in radical repair of severe congenital heart disease (CHD), such as persistent common atrioventricular canal (PCAC). The use of such a procedure is inappropriate in radical surgery for septal malformations [11,12]. During open-heart surgery, continuous measurement of CVD is performed and direct measurement of left atrial (LA) pressure is used. With the direct method, it is possible to measure pressures in all chambers and major vessels of the heart. This technique can also be used in patients with severe pulmonary hypertension diagnosed by echocardiography without aorto-coronary angiography.

Ultrasound can be used to diagnose left or right ventricular failure. However, we found no studies on the applicability and reliability of USCOM measurements in the right ventricular region. USCOM measures the velocity of blood flow through the aortic and pulmonary valves. Using predetermined internal algorithms based on patient height data, it calculates the diameters of the aortic and pulmonary valves and their cross-sectional areas. Based on the valve cross-sectional area and the measured blood flow velocity, the USCOM device determines the volume of blood pumped by the heart in one minute [13]. N. Patel et al. found that the reliability of USCOM derived values in neonates is quite high [14]. A.U. Lekmanov et al. concluded that the parameters of central hemodynamics in children with severe burn injuries obtained by invasive and non-invasive methods were comparable [15]. Boronina I. V. et al. reported that bedside training under instructor supervision is sufficient to learn practical skills in USCOM monitoring, with an average of 50 independent studies required to master the technique [16]. The statistical significance of data obtained using the USCOM technique in children compared to older age groups may be attributed to the lower incidence or absence of obesity, increased sternal thickness, aortic calcification associated with luminal narrowing and thickening of the arterial wall, and age-related vascular changes that affect signal quality and, consequently, the statistical significance of the results obtained [17].

In 2019, a meta-analysis by Yun Zhang [18] analyzed 26 scientific articles involving 772 patients. This meta-analysis found no significant difference between cardiac output (CO) and cardiac index (CI) measurements using the USCOM device and transpulmonary thermodilution: the mean difference in CO values was –0.06 [95% CI, –0.17 to 0.05; P=0.31], and the mean difference in CI values was –0.04 [95% CI, –0.13 to 0.05; P=0.38].

In 2018, Yu-wei Cheng [19] included 60 children in her study and measured parameters after cardiac surgery for CHD.

The parameters (HR, CVP, stroke volume index, cardiac index, stroke volume change) reflecting left ventricular preload obtained by hemodynamic testing using PiCCO catheter, TE echocardiography, and USCOM were compared. The results showed that volume load sensitivity best reflected stroke volume change, with noninvasive hemodynamic monitoring showing a sensitivity of 84.4% and a specificity of 60.7%. This suggests that the USCOM can reliably predict the response to ongoing fluid therapy in children after correction of CHD, making the device essential for the selection of individualized fluid therapy. There are no studies on the intraoperative use of the USCOM device in cardiac surgery. Intraoperative TE echocardiography is highly informative but requires more time than direct measurements. Intraoperative measurement of basic hemodynamic parameters using the USCOM device is likely to aid in the assessment for the correct choice of cardiac support and fluid therapy.

The aim of the study was to evaluate the feasibility of a non-invasive hemodynamic monitoring technique based on ultrasound Doppler evaluation during open heart surgery in children.

Materials and methods

A single-center, prospective, randomized study was conducted with the approval of the local ethics committee of the Bakulev National Medical Center of Cardiovascular Surgery (protocol No. 002 dated April 28, 2022). The study was not pre-registered on the Clinical Trials platform.

Inclusion criteria:

— children 11 months to 3 years of age;

— informed consent from parents or legal guardians to participate in the study;

— septal heart defect requiring surgical correction under cardiopulmonary bypass via midline access;

— no history of previous open heart surgery.

Exclusion criteria:

— severe genetic abnormality;

— massive blood loss;

— severe comorbidities;

— repeated sternotomy in the early postoperative period.

Of the 41 young children with CHD who underwent surgery between March and April 2022, 20 patients were included in the study. Of these, 10 patients underwent correction of the atrial septal defect (ASD group) and 10 patients underwent correction of the ventricular septal defect (VSD group). No complications were observed in the early postoperative period. All children were extubated on postoperative day 1. All patients were transferred from the ICU to the specialized departments the next day. The structure of all surgical procedures is shown in Table 1 and the study flow chart is shown in Fig. 1.

Patients with septal malformations were selected for the study as the most hemodynamically stable patients requiring the shortest duration of cardiopulmonary bypass (CPB).

All patients were evaluated three times intraoperatively with the USCOM device, and the mean value was used for analysis. Three control time points were selected: when the patient was admitted to the operating room, at the end of cardiopulmonary bypass, and before transfer to the ICU. At the first time point, measurements were taken after tracheal intubation and before skin incision while in deep sedation (RASS, 5 points). At the second time point, measurements were taken with the sternum open, after the end of CPB. At this stage, it was not possible to perform measurements in five patients due to the peculiarities of their positioning on the operating table (Fig. 1). At the third time point, measurements were performed before transfer to the ICU.

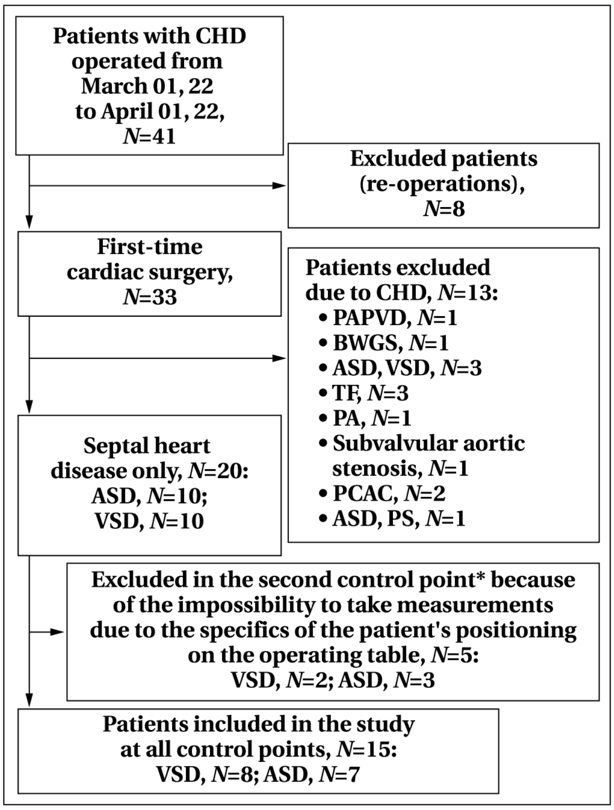

Fig. 1. Flowchart of patient inclusion in the study.
Note. * — control points are detailed in the text.

Patients in both groups were classified as ASA risk group 3 or 4 and NYHA class I–II. The groups were comparable in terms of the duration of CPB, the duration of aortic clamping, the complexity of the surgical procedure, and the time to cardiac recovery in the postperfusion period. A brief description of patient characteristics is presented in Table 2.

SPSS version 11.5 for Windows (SPSS Inc., Chicago, IL) and the analytical add-on for Excel 2016 were used for data analysis. The sample size was not predetermined.

Data distribution was checked using the Shapiro–Wilk test. For normally distributed data, the arithmetic mean *(M)* and the standard error of the mean *(m)* were calculated, and the statistical significance of the differences between the means

Table 1. Surgical interventions in the patient population, *N*=41.

Intervention	Cases, *N*
VSD repair	10
ASD repair	10
Repeated open-heart surgery	8
Simultaneous repair of atrial and ventricular septal defects	3
Radical repair of tetralogy of Fallot (TF)	3
Resection of subvalvular aortic stenosis	2
ASD repair with resection of pulmonary stenosis (PS)	1
Palliative surgery for pulmonary atresia (PA)	1
Radical surgery of persistent common atrioventricular canal (PCAC)	1
Surgical correction of Bland-White-Garland syndrome (BWGS)	1
Radical surgery for partial anomalous pulmonary vein drainage and atrial septal defect repair (PAPVD, ASD)	1

Table 2. Summary of patient characteristics.

Parameter	Values in groups		*P*-value*
	VSD, *N*=8	ASD, *N*=7	
Age, months	20.2±8.6	19.8±8.8	0.9
Height, cm	85.2±7.9	80.5±7	0.9
Body weight, kg	11.17±1.9	10.7±2.1	0.5
Duration of cardiopulmonary bypass, min	48±3	43±10	0.3
Aortic clamping time, min	23±8	21±8	0.4
Volume of blood loss, mL	140±27	150±1	0.2

Note. Results by age are presented as $Me\pm\sigma$, others as $M\pm m$. * — Mann–Whitney test.

was assessed using a one-sample Student's *t*-test. Non-parametric descriptive statistics, such as median *(Me)* calculation and the Mann–Whitney test, were also employed. The critical two-sided significance level was set at *P*=0.05.

The limited number of patients in the study resulted from the number of surgeries performed during the analyzed period.

Results

In 15 of 20 (75%) patients, aortic valve area measurements were possible during the surgical phase with the sternum open (time 2). CO varied within the age-standardized range: 5.2 L/min [4.7; 5.5] in patients with ASD and 5.1 L/min [4.6; 5.6] in patients with VSD. After CPB, hypotension was observed in two patients (17%) with VSD, with CO decreasing to 3.6 L/min, below the age-standardized reference value (5.1 L/min) (*P*=0.032). These patients were switched from dopamine 7 µg/kg/min to adrenaline 0.05 µg/kg/min. During serial measurements, stabilization of hemodynamic parameters was observed with an increase in CO up to 5.2 L/min. After sternal closure, CO parameters were not significantly different from age-related reference values.

The mean CO was 4.9 L/min [4.7; 5.0] in the ASD group (*P*=0.849) and 4.7 L/min [4.6; 5.0] in the VSD group (*P*=0.622).

The clinical presentation was consistent with the values obtained.

Notably, the accuracy of the measurements was influenced by the condition of the patient (calm/crying) and the positioning of the sensor.

For example, in a 2-year-old patient with a body weight of 12.5 kg diagnosed with CHD (atrial septal defect), CI was 5.1 L/min/m² when calm (Fig. 2, *a*), 4.1 L/min/m² while crying (Fig. 2, *b*), and 2.8 L/min/m² with incorrect sensor positioning (Fig. 2, *c*).

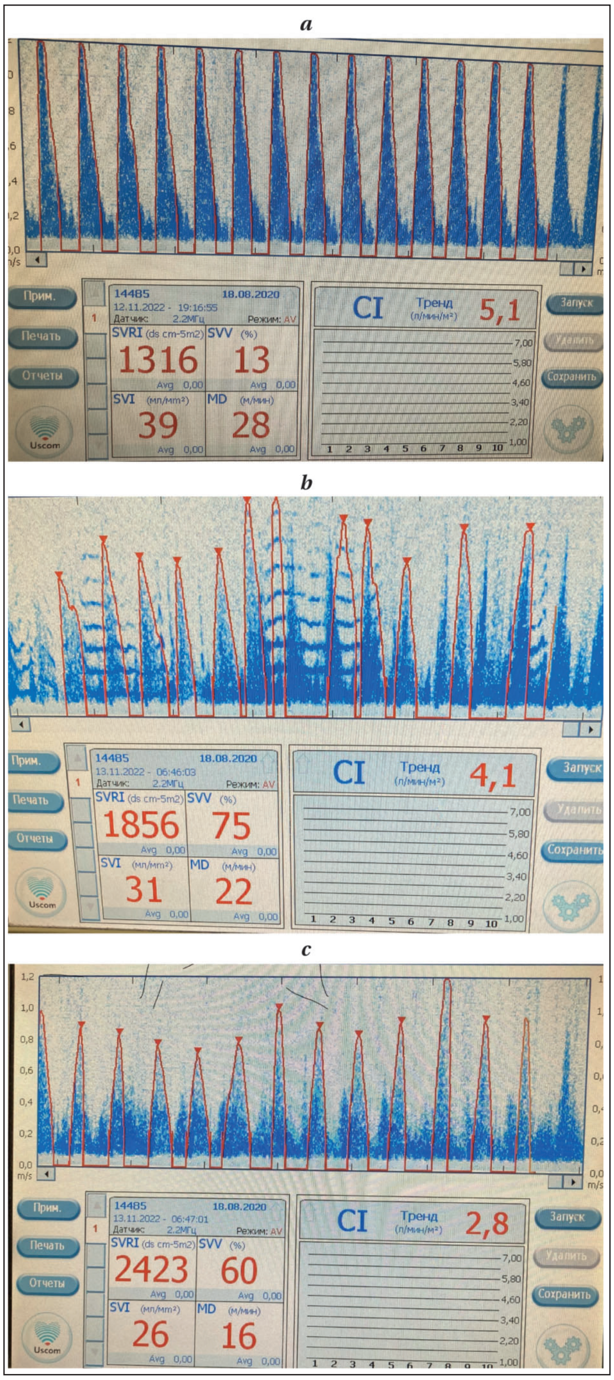

Fig. 2. Example of SI measurement when calm *(a)*, while crying *(b)*, and with incorrect sensor positioning *(c)*.

Discussion

The problem of hypervolemia in pediatric cardiac surgery requires special attention. The study by Sinitsky L. et al. demonstrated a pattern of development of organ dysfunction and prolonged duration of mechanical ventilation with a positive fluid balance exceeding 13% of initial body weight [20, 21].

The use of noninvasive methods for CO monitoring, when properly applied and interpreted, may replace the routine use of invasive CO monitoring [22, 23]. The USCOM device, when used intraoperatively, reliably shows changes in cardiac output but requires time for correct positioning of the sensor. In particular, measurements were performed after stabilization of systemic pressure and CPB, as it was difficult to obtain measurements at earlier stages.

Correct positioning of the transducer, especially during surgery, may not always be feasible in all patients. In addition, the ultrasound method is operator dependent.

Pulmonary valve measurements were not performed in this study because of the difficulty of intraoperative transducer positioning. During sternotomy, the area of the pulmonary artery valve, which is difficult to access for measurements even under normal conditions, is displaced.

During the study, the transducer could not be positioned correctly in 5 patients (25%); however, in 15 patients (75%), the data obtained were consistent with the clinical picture.

The use of the USCOM device may be useful in pediatric cardiac surgery as an adjunct or alternative to the routine use of transpulmonary and prepulmonary thermodilution. The effectiveness of its use in the pediatric intensive care unit has also been confirmed by previous studies [15, 24].

Training in ultrasound techniques takes little time and can be done at the patient's bedside, allowing more staff to master it [16]. The USCOM device is already widely used in pediatrics because the use of noninvasive methods to monitor cardiac output in children reduces the risk of complications [14–16].

Conclusion

The USCOM device can be used for intraoperative hemodynamic assessment and selection of cardiac support therapy even during open heart surgery. However, its routine use in all stages of surgery with median sternotomy is challenging because optimal visualization of the aortic valve requires proper patient positioning.

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Received 06.03.2024
Accepted 05.09.2024