

Walter Knirsch
Oliver Kretschmar
Maren Tomaske
Kathrina Stutz
Nicole Nagdyman
Christian Balmer
Achim Schmitz
Dominique Béttex
Felix Berger
Urs Bauersfeld
Markus Weiss

Cardiac output measurement in children: comparison of the Ultrasound Cardiac Output Monitor with thermodilution cardiac output measurement

Received: 11 September 2007
Accepted: 14 January 2008
Published online: 23 February 2008
© Springer-Verlag 2008

All authors are members of the Working Group on Non-invasive Haemodynamic Monitoring in Paediatrics.

W. Knirsch (✉) · O. Kretschmar · M. Tomaske · K. Stutz · C. Balmer · U. Bauersfeld
University Children's Hospital, Division of Pediatric Cardiology, Steinwiesstrasse 75, 8032 Zurich, Switzerland
e-mail: walter.knirsch@kispi.uzh.ch
Tel.: +41-44-2667617
Fax: +41-44-2667981

K. Stutz · A. Schmitz · D. Béttex · M. Weiss
University Children's Hospital, Department of Anesthesia, Steinwiesstrasse 75, 8032 Zurich, Switzerland

N. Nagdyman · F. Berger
German Heart Center, Department of Congenital Heart Disease, Augustenburger Platz 1, 13353 Berlin, Germany

Abstract *Objective:* To compare the assessment of cardiac output (CO) in children using the noninvasive Ultrasound Cardiac Output Monitor (USCOM) with the invasive pulmonary artery catheter (PAC) thermodilution cardiac output measurement. *Design and setting:* Prospective observational study in a tertiary center for pediatric cardiology of a university children's hospital. *Patients:* Twenty-four pediatric patients with congenital heart disease without shunt undergoing cardiac catheterization under general anesthesia. *Measurements and results:* CO was measured by USCOM using a suprasternal CO Doppler probe in children undergoing cardiac catheterization. USCOM data were compared to CO simultaneously measured by PAC thermodilution technique. Measurements were repeated three times within 5 min in each patient. A mean percentage error not exceeding 30% was defined as indicating clinical useful reliability of the USCOM.

CO values measured by PAC ranged from 1.3 to 5.3 l/min (median 3.6 l/min). Bias and precision were -0.13 and 1.34 l/min, respectively. The mean percentage error of CO measurement by the USCOM compared to PAC thermodilution technique was 36.4% for USCOM. *Conclusions:* Our preliminary data demonstrate that cardiac output measurement in children using the USCOM does not reliably represent absolute CO values as compared to PAC thermodilution. Further studies must evaluate the impact of incorporating effective aortic valve diameters on CO measurement using the USCOM.

Keywords Cardiac output · Pulmonary artery catheter · Monitoring · Hemodynamic · Children · Noninvasive

Introduction

In critically ill pediatric patients the measurement of cardiac output (CO) is of considerable interest for the cardiovascular assessment and hemodynamic management [1]. In contrast to adult patients, in whom the thermodilution method by pulmonary artery catheter (PAC) is widely accepted and used for CO measurement, this technique is not routinely used in pediatric critical care due to its increased

risk of complications in children (infections, thrombosis, embolism) and the size of the catheter, which is not convenient for continuous monitoring process in small children [2].

The Ultrasound Cardiac Output Monitor (USCOM, Sydney, Australia) is a noninvasive CO monitor based on continuous-wave Doppler ultrasound (Fig. 1) for adults and children. USCOM has been evaluated for dogs [3] and for adult patients comparing it to CO thermodilution

technique [4–7] and has been used in various clinical settings [8–10]. No data are currently available with regard to reliability of the USCOM for CO measurement in children. The aim of this study was to compare CO measurement by the noninvasive USCOM with the thermodilution technique during cardiac catheterization for CO assessment in pediatric patients.

Materials and methods

Technique

After starting the USCOM device (Fig. 1) patient data, including height, weight, and gender, are typed in as well as the chosen vessel (aorta) is indicated. In children Doppler flow curves by the USCOM are obtained by a 3.3-MHz transducer placed in the suprasternal notch to obtain an optimal aortic flow signal at the aortic valve. With continuous slight movements of the USCOM probe the operator aims to assess a clear systolic beginning and end, full systolic timing, and the highest velocities of the Doppler flow curve. On the monitor display the Doppler curve is presented as a time velocity curve. A representative Doppler curve is saved for further calculations. The CO value is calculated using the flow integral, and the aortic valve diameter as given by the USCOM internal algorithm based on height and gender.

Patients

Hospital ethics committee approval and written parental consent were obtained for all patients. Pediatric patients with congenital heart disease undergoing diagnostic and/or interventional cardiac catheterization under general anesthesia were prospectively enrolled. Patients with residual intracardiac or extracardiac shunt, tricuspid or pulmonary valve regurgitation, body weight below 3 kg, and age older than 18 years were excluded. The analysis included 24 patients aged 0.1–16.7 years (median 7.6) and weighing 3.4–51.0 kg (23.0 kg). Indications for cardiac catheterization were device closure of an atrial septal defect in nine and ventricular septal defect in six, balloon dilatations of the pulmonary valve in two and of branches of the pulmonary arteries in three, stenting of a coarctation of the aortic arch in one, and for other diagnostic reasons in three. Premedication and induction of anesthesia (inhalational or intravenous) depended upon the patient's medical condition and anesthesiologist's preferences. After induction of general anesthesia and after establishing neuromuscular blockade the patient was intubated and ventilated by the anesthesia respirator. Prior to the CO measurements we excluded a residual shunt following device closure or a residual pulmonary valve



Fig. 1 Ultrasonic cardiac output monitor

regurgitation by transesophageal echocardiography and/or angiography.

Cardiac output measurements

CO measurements were performed at the end of the cardiac catheterization procedure under hemodynamic steady-state conditions with the pulmonary artery thermodilution catheter and USCOM device in place. For thermodilution CO assessment a 5-F balloon-tipped pulmonary artery catheter (Edwards Lifescience, Irvine, Calif., USA) was inserted via a 6-F sheath in the femoral vein and directed to the pulmonary artery under fluoroscopic control. CO was measured by PAC with 5-ml bolus injection of NaCl 0.9% at a temperature of 4°C, as described elsewhere [2]. After a test injection three consecutive measurements were performed. CO values for the USCOM measurements were recorded immediately before injection of each of the three repeated thermodilution fluid boli. The USCOM measurement was performed by a single experienced consultant pediatric cardiologist after a learning curve prior the start of the study. The cardiologist performing the USCOM measurement was blinded to the CO measurements by the thermodilution technique. A total of 72 paired CO measurements by thermodilution and USCOM were recorded.

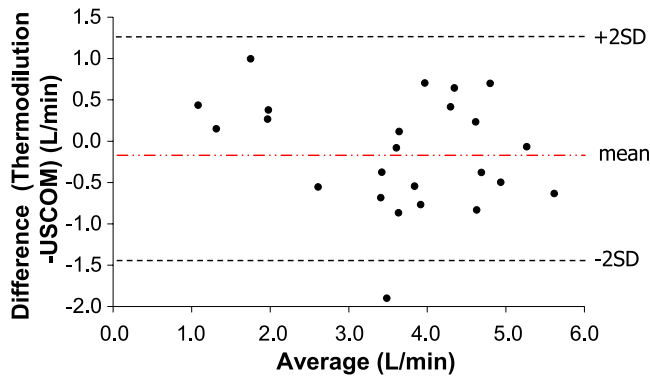


Fig. 2 Bland–Altman analysis to compare cardiac output values obtained by the USCOM and the thermodilution technique in 24 cardiac pediatric patients

Statistics

Mean values of the three measurements for both methods were calculated per patient and used for further statistics. Intraobserver variability was calculated for the two methods. Bland–Altman analysis was performed to compare CO values obtained by the USCOM with those obtained by PAC thermodilution technique [11]. The mean proportional error ($2 \text{ SD}/\text{mean CO} \times 100$) was calculated. Data are presented as median (range). A mean percentage error not exceeding 30% was defined as indicating clinical useful reliability of the USCOM [12, 13].

Results

Mean CO values measured by PAC thermodilution technique ranged from 1.30 to 5.30 l/min (median 3.57) and mean CO values measured by USCOM ranged from 0.86 to 5.93 l/min (4.04). Bias (mean difference) between the two methods was -0.13 l/min and precision ($\pm 2 \text{ SD}$ of differences) was 1.34 l/min (Fig. 2). The signal quality of the USCOM Doppler was comparable and good in all patients independently of age. The intraobserver variability was 3.1% by the PAC thermodilution technique and 5.7% by USCOM measurement. The mean percentage error of CO measurement was 36.4% for USCOM vs. to PAC thermodilution technique.

Discussion

This study compared CO measurements between the new noninvasive continuous-wave Doppler based monitoring system USCOM and the thermodilution technique with pulmonary artery catheter in pediatric patients with congenital heart disease without shunts from infancy to adolescence. The USCOM is a noninvasive cardiac

output monitor based on the transthoracic measurement of Doppler flow velocity of the large intrathoracic vessels. It is easy to operate, and CO is easily displayed by the USCOM device. The technique is reported to be easily learned even by noncardiologists and nursing staff [14]. The usefulness of fast and easy assessment of CO monitoring by USCOM was supported by a previous study by Knobloch et al. [8] in adult patients for hemodynamic assessment in preclinical emergency medicine.

The main findings were that measurement of CO with USCOM does not reliably represent absolute values as compared to pulmonary artery catheter thermodilution technique with a mean percentage error higher than 30%. We believe that user dependency and technical factors may contribute to this disagreement. User-dependent factors must be taken into account such as the insonation angle during measurement. Further technical factors of the Doppler method are well known limitations, such as the circumstance that the Doppler beam is one-dimensional in a typical three-dimensional structure, and its flow is considered laminar and described as plug flow, although it is well known to be skewed.

Other patient-dependent factors such as implication of the type of congenital heart defect in regard to the growth of the aortic valve must be considered. The technique itself may entail certain factors influencing the measurement. One of these is the estimated aortic valve diameter. The algorithm for the calculation of the aortic and pulmonary valve diameter incorporated in the USCOM software is based on the data of Nidorf et al. [15] and may involve a systemic error during growth of the heart. These normal values of cardiac dimensions published by Nidorf et al. were evaluated for healthy children while in our study children with congenital heart disease were examined, which may contribute as a source of error. Further studies could rule out this error by measuring the true aortic valve diameter by transthoracic echocardiography and to “calibrate” and adjust the USCOM measurement. The impact of the direct measurement of the aortic valve diameter to the measurement of the cardiac output by conventional transthoracic Doppler echocardiography has been shown [16].

In addition, the limitations of transthoracic pulsed Doppler cardiac output measurement in comparison to cardiac output measurement by the thermodilution technique has been recognized [17]. On the other hand, transesophageal continuous-wave Doppler cardiac output measurement in comparison to the thermodilution technique seems to be suitable [18]. Therefore the Doppler flow quality remains an important influencing factor. Doppler flow signal quality may have been affected by intrathoracic air, patient position, and operator’s learning curve. In our study, however, the modalities of the USCOM were optimal standardized (anesthesia, pediatric patients with excellent access, and good sonographic window) so that the impact of these factors may be rather low.

Table 1 Summary of literature evaluating reliability of CO measurement by USCOM (*d.n.a.*, data not available; *LOA*, limits of agreement; *calc.*, calculated)

	Critchley et al. [3]	Tan et al. [4]	Chand et al. [5]	Knobloch et al. [6]	Chan et al. [7]
Setting	Animal lab. model, anesthetized dogs	Postcardiac surgery, adult patients	Postcardiac surgery, adult patients	Postcardiac surgery, adult patients	Postcardiac surgery, adult patients
Reference method	Ultrasonic flow probe	Thermodilution	Thermodilution	Thermodilution	Thermodilution
Patients	<i>n</i> = 6	<i>n</i> = 22, mean age: 63.5 years	<i>n</i> = 50, mean age: 59.2 years	<i>n</i> = 36, mean age: 67.2 years	<i>n</i> = 26, mean age: 60.6 years
Simple regression	<i>d.n.a.</i>	<i>d.n.a.</i>	<i>d.n.a.</i>	$R = 0.870, p < 0.01$	$R = 0.46, p < 0.01$
Cardiac output: bias (LOA)	-0.01 l/min (-0.34 to 0.31)	0.18 l/min (-1.43 to 1.78)	-0.14 l/min (-1.43 to 1.58)	-0.23 l/min (-2.52 to 1.79)	0.22 l/min (-1.17 to 1.62)
Mean error	13%	<i>d.n.a.</i>	34% (calc.)	42% (calc.)	54% (calc.)

To our knowledge, this is the first study in pediatric patients validating CO measurement by USCOM with CO measurement by PAC thermodilution considered as gold standard (Table 1). USCOM has demonstrated reliable results of CO measurements in laboratory animal studies by using aortic flow probes in anesthetized dogs. The investigators found 95% limits of agreement of -0.34 and 0.31 l/min over a wide range of cardiac output values [3].

Tan et al. [4] recently evaluated the USCOM vs. thermodilution cardiac output measurements in adult patients after cardiac surgery and found, comparable to our results, 95% limits of agreement for the two techniques of -1.43 and 1.78 l/min. Chand et al. [5] and Chan et al. [7] confirmed this level of agreement of the two techniques in a similar clinical setting with adult patients after cardiac surgery. For both studies we calculated the mean percentage error, which exceeds 30% (Table 1). Although their agreements were less than those obtained in our study, the authors judged the USCOM to be a reliable technique for CO assessment.

The fact that our study included no patients with normal cardiac anatomy included may be considered as limitation of this study. However, cardiac catheterization with the opportunity of PAC thermodilution CO assessment in patients without heart disease is very rare, and limits this type of investigation to pediatric patients with congenital

heart disease or critically ill pediatric patients on the intensive care unit. In this study a single operator performed all USCOM measurements. Further studies must investigate interrater and intrarater reliability of the USCOM method. Since the aortic valve diameter may be a crucial and unknown factor in the calculation of absolute CO value, the USCOM may become a trend monitor rather than a tool for the assessment of absolute CO values. To support this application of USCOM in pediatric patients further research on long-term and repeated CO measurements is needed.

In the future, USCOM may rather serve as a feasible, fast usable, valuable diagnostic tool to measure cardiac output and to demonstrate therapeutic hemodynamic effects, for example, of fluid challenge and inotropic supports in critical ill children, by comparing pre- and posttherapeutic CO values with USCOM. In this clinical settings the absolute value of CO may be rather unimportant as the fact the CO has increased from a "low" CO to a "normal" or even "high" CO.

In conclusion, based on our findings USCOM cannot be recommended for the assessment of absolute CO values in pediatric cardiac patients. Further studies must determine whether the incorporation of measured aortic valve diameter can improve accuracy of the USCOM, and whether the device can be reliably used as a trend monitor for cardiac output assessment.

References

- Egan JR, Festa M, Cole AD, Nunn GR, Gillis J, Winlaw DS (2005) Clinical assessment of cardiac performance in infants and children following cardiac surgery. *Intensive Care Med* 31:568-573
- Webster CS, Merry AF, Emmens DJ, Van Cotthem IC, Holland RL (2003) A prospective clinical audit of central venous catheter use and complications in 1000 consecutive patients. *Anaesth Intensive Care* 31:80-86
- Critchley LA, Peng ZY, Fok BS, Lee A, Phillips RA (2005) Testing the reliability of a new ultrasonic cardiac output monitor, by using aortic flowprobes in anesthetized dogs. *Anesth Analg* 100:748-753
- Tan HL, Pinder M, Parsons R, Roberts B, van Heerden PV (2005) Clinical evaluation of USCOM ultrasonic cardiac output monitor in cardiac surgical patients in intensive care unit. *Br J Anaesth* 94:287-291
- Chand R, Mehta Y, Trehan N (2006) Cardiac output estimation with a new Doppler device after off-pump coronary artery bypass surgery. *J Cardiothorac Vasc Anesth* 20:315-319
- Knobloch K, Lichtenberg A, Winterhalter M, Rossner D, Pichlmaier M, Phillips R (2005) Non-invasive cardiac output determination by two-dimensional independent Doppler during and after cardiac surgery. *Ann Thorac Surg* 80:1479-1484

7. Chan JS, Segara D, Nair P (2006) Measurement of cardiac output with a noninvasive continuous wave Doppler device versus the pulmonary artery catheter: a comparative study. *Crit Care Resusc* 8:309–314
8. Knobloch K, Hubrich V, Rohmann P, Lupkemann M, Gerich T, Krettek C, Phillips R (2006) Feasibility of preclinical cardiac output and systemic vascular resistance in HEMS in thoracic pain—the ultrasonic cardiac output monitor. *Air Med J* 25:270–275
9. Knobloch K, Hoeltke V, Jakob E, Vogt PM, Phillips R (2007) Non-invasive ultrasonic cardiac output monitoring in exercise testing. *Int J Cardiol* 2007 (epub ahead of print: 26 April)
10. Siu CW, Tse HF, Lee K, Chan HW, Yung C, Lee S, Lau CP (2007) Cardiac resynchronization therapy optimization by ultrasonic cardiac output monitoring (USCOM) device. *Pacing Clin Electrophysiol* 30:50–55
11. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurements. *Lancet* I:307–310
12. Tibbals J, Hochmann M, Osborne A, Carter B (1992) Accuracy of the BoMED NCCOM3 bioimpedance cardiac output monitor during induced hypotension: an experimental study in dogs. *Anaesth Intensive Care* 20:326–331
13. Critchley LAH, Critchley JAJH (1999) A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. *J Clin Monit* 15:85–91
14. Dey I, Sprivulis P (2004) Emergency physicians can reliably assess emergency department patient cardiac output using the USCOM continuous wave Doppler cardiac output monitor. *Emerg Med Australas* 17:193–199
15. Nidorf SM, Picard MH, Triulzi MO, Thomas JD, Newell J, King ME, Weyman AE (1992) New perspectives in the assessment of cardiac chamber dimensions during development and adulthood. *J Am Coll Cardiol* 19:983–988
16. Gardin JM, Tobis JM, Dabestani A, Smith C, Elkayam U, Castleman E, White D, Allfie A, Henry WL (1985) Superiority of two-dimensional measurement of aortic vessel diameter in Doppler echocardiographic estimates of left ventricular stroke volume. *J Am Coll Cardiol* 6:66–74
17. Nottermann DA, Castello FV, Steinberg C, Greenwald BM, O’Loughlin JE, Gold JP (1989) A comparison of thermolulution and pulsed Doppler cardiac output measurement in critically ill children. *J Pediatr* 115:554–560
18. Murdoch IA, Marsh MJ, Tibby SM, McLuckie A (1995) Continuous haemodynamic monitoring in children: use of transoesophageal Doppler. *Acta Paediatr* 84:761–764