Arterial-pressure-based Continuous Cardiac Output Monitoring in Paediatric Patients

a report by
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DOI: 10.17925/EOH.2008.02.1.93

Advanced haemodynamic monitoring is of key importance in the management of children with circulatory failure.[1] Therefore, the measurement of cardiac output in children could be of great benefit. Arterial pressure-based continuous cardiac output (APCCO) is an exciting technology that provides cardiac output (CO) monitoring based on the arterial pressure curve, and its use in children is slowly evolving. This article concerns basic haemodynamic principles and describes the basis of APCCO and its current available use in paediatric patients.

> Critically ill children often suffer from a low cardiac output, which is associated with increased mortality and requires advanced haemodynamic support.

Basic Haemodynamics and Why Cardiac Output Should Be Monitored

CO is the amount of blood pumped by the heart into the ascending aorta (l/minute). In order to compare the CO between different individuals its value is indexed to the body surface area. *Figure 1A* depicts the basic relationship between CO, heart rate and blood pressure. For instance, by administering a fluid bolus the pre-load increases, and only when the ventricle is on the steep part of the Frank-Starling curve does the cardiac stroke volume (SV) also increase. This situation is called fluid responsiveness (see *Figure 1B*). The blood pressure is controlled by our vascular control system in order to guarantee optimal organ perfusion. The body is not capable of detecting changes in CO, although local changes in blood flow can be detected by the endothelium.[2] Therefore, when systemic vascular resistance (SVR) changes, a subsequent change in CO might be left unnoticed unless its value is measured.

Critically ill children often suffer from a low CO, which is associated with increased mortality and requires advanced haemodynamic support.[1,3] For most children and adults in the initial resuscitation phase, fluid therapy is mandatory.[4,5] However, during intensive care treatment in adults half of the fluid boluses do not seem to lead to the desired increase in CO.[6] Furthermore, overzealous fluid therapy seems to aggravate clinical conditions in both adults and children.[7–9] Unfortunately, clinical assessment of haemodynamic variables in children agrees poorly with invasive techniques.[10,11] CO cannot be predicted by easily obtainable variables such as blood pressure and heart rate.[12] In young children, the general belief is that stroke volume is rather fixed, and that CO is predominantly determined by heart rate. However, there is growing evidence that the paediatric heart is more capable of varying its stroke volume than previously believed.[13] Therefore, CO monitoring enabling fluid and inotropic therapy could be beneficial in critically ill children, although this has not been confirmed in a randomized clinical trial.

How to Measure Cardiac Output in Children

In contrast to adults, the pulmonary artery catheter (PAC) is infrequently used in infants. This technique has several limitations as it requires a rather large introducing sheath and has several specific complications. Currently, the transpulmonary thermodilution technique (TPTD) can be considered the gold standard for measuring CO in children.[14,15] Although reliable, this technology is rather invasive since it requires a specific arterial catheter in the femoral position and a central venous catheter. Furthermore, measurements must be performed using at least three consecutive dilution measurements with ice-cold saline. Therefore, it is not suitable for the detection of fast changes in CO. Other available CO measurement techniques in children are lithium dilution[16] and the less reliable oesophageal or transjugular doppler techniques.[17,18] CO Fick-based techniques have also been described.[19]

Arterial-pressure-based Continuous Cardiac Output

With each heartbeat a volume of blood is pumped into the vascular system. As a result, this ejection volume, in combination with vascular resistance, leads to an increase and subsequent decrease of the arterial pressure in the aorta. The magnitude of this change in pressure is a reflection of the actual stroke volume. Therefore, the arterial pressure curve reflects cardiac stroke volume. The APCCO method is based on the windkessel function of the aorta. The windkessel model implies that blood enters the ascending aorta only during systole but blood flows from the aorta during both systole and diastole. The windkessel function thus provides us with the

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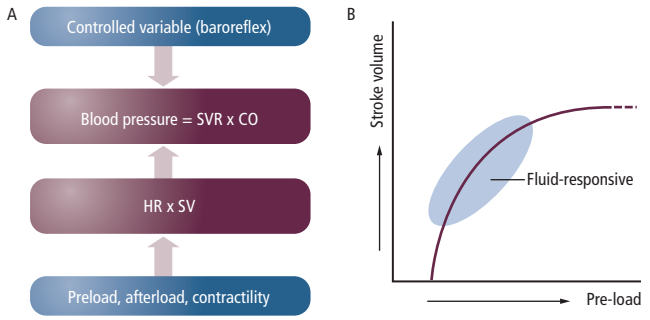
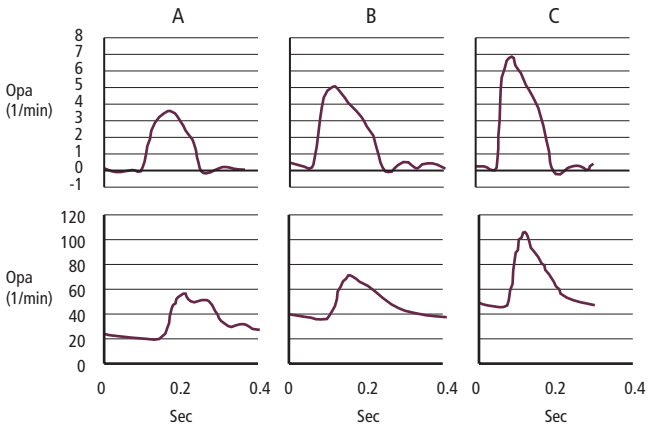
Figure 1: Basic Haemodynamics



CO = cardiac output (l/minute); HR = heart rate; SV = stroke volume.

Figure 2: Flow and Pressure Recording of a 5.7kg Lamb at Hypovolemic Shock (A), After Fluid Resuscitation (B) and During Dobutamine Therapy (C)



Qpa = flow pulmonary artery; Pao = aortic pressure.

opportunity to decrease the afterload of the left ventricle during the ejection phase, while at the same time helping to increase diastolic pressure, enabling diastolic flow through, for instance, the left coronary artery. However, the windkessel function is strongly influenced by the (individually different) compliance of the aorta.

Figure 2 shows an example of an animal experiment. A 5kg lamb is subjected to hypovolaemia, subsequent volume resuscitation and dobutamine therapy. The flow measured with an ultrasound flow probe around the pulmonary artery reflects actual CO. It can clearly be seen that the arterial curve shows an increase in absolute pressure and pulse pressure concomitant with the increase in CO. However, the curve itself also changes in shape and magnitude. This change is caused by alterations in peripheral vascular resistance, resonance, pulse pressure and CO. These effects can be incorporated into an algorithm to calculate absolute cardiac stroke volume. A simple model is shown in *Figure 3*. A method of determining CO using the arterial pressure curve was described long ago.[20] A simple research device was built by Wesseling et al.[21]

As a result of the unknown individual characteristics of the aorta, a second CO technique is often used to calibrate an APCCO method. There are currently two methods that require calibration with an established CO method. The pulse contour method (PCCO) that is incorporated into the PiCCO device (Munich, Germany) calculates the

Figure 3: Example of a Model of the Circulation

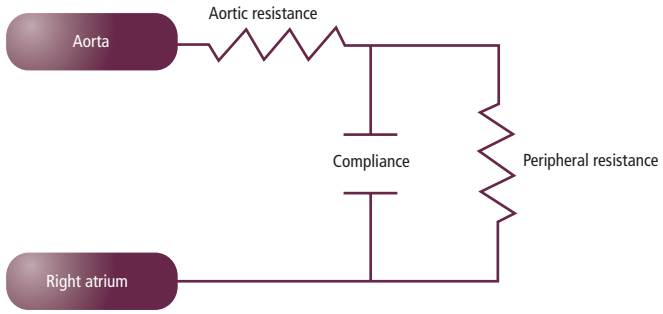
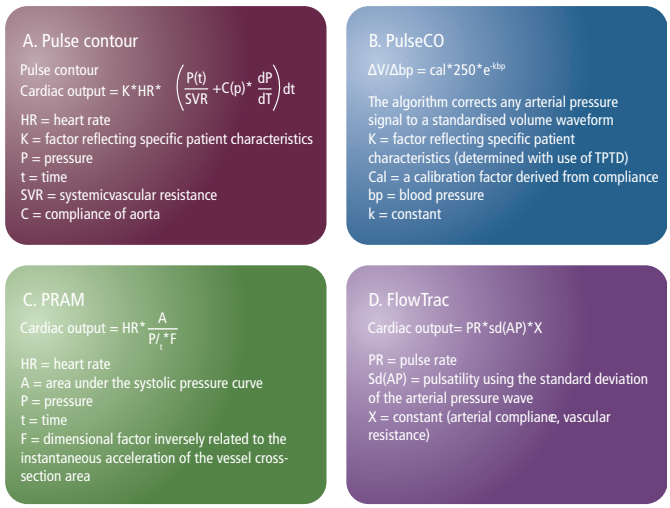


Figure 4: Arterial-pressure-based Continuous Cardiac Output Methods



area under the systolic portion of the arterial pressure waveform and applies an equation as shown in *Figure 4A*. It requires calibration using transpulmonary thermodilution in order to establish the individual characteristics of the aortic compliance. The PulseCO method is incorporated in the LidCO device (LidCO, Cambridge, UK) and uses a pulse power analysis to derive the SV. This method uses measurements of the beat and ejection duration and a series of approximations regarding the relationship between radial artery pressure, aortic pressure, aortic flow and CO. By using the entire pressure waveform rather than just the systolic portion of the curve, the PulseCO system incorporates the influence of peripheral resistance and the reflected wave from the periphery (see *Figure 4B*). The derived SV is corrected using a calibration factor based on the transpulmonary lithium dilution technique.

Currently, there are two systems that do not require calibration. The pressure recording analytical method (PRAM, Mostcare, BioSi, Florence, Italy) uses a routine that identifies the characteristic points of the pressure wave during each beat (diastolic, systolic, dicrotic notch and resonant pressure points during the systolic and end-diastolic phases). The morphological analysis of the beat allows determination of the stroke volume (see *Figure 4C*).[22] In the FloTrac system (Vigileo, Edwards, US) SV is derived using the patient's vascular resistance and arterial compliance based on sex, height, weight and age and the pulse pressure (PP) waveform characteristics, while pulsatility is derived from continuous analysis of the shape of the arterial pressure waveform (see *Figure 4D*).

Table 1: Validation Studies Concerning Arterial-pressure-based Continuous Cardiac Output in Children

Study	Method	Circumstances	Subjects	Gold Standard	Mean CO	Bias	Limits of Agreement	Percentage Error	Correlation
Fakler et al.[33]	PCCO	Congenital cardiac surgery	24 patients 1.4–15.2 years	TPTD	4.5l/min/m^2	0.05l/min/m^2	0.7l/min/m^2	16%	r^2=0.86
Mahajan et al.[27]	PCCO	Congenital cardiac surgery	16 patients 1–36 years	TPTD	3.7l/min/m^2	0.1l/min	1.97l/min/m^2	53%	r=0.7
Kim et al.[34]	PulseCO	Cardiac catheterisation	20 patients 2.6–15.5 years	PATD	3.3l/min/m^2	0.2l/min/m^2	0.3l/min/m^2	10%	r=0.94
Calamandrei et al.[35]	PRAM	Critically ill children	48 patients	Doppler echocardiography	2.7l/min	0.12l/min	0.6l/min	21%	r=0.99
López-Herce et al.[36]	PCCO	Animal study	51 pigs 9–16 kg	TPTD	1.73l/min	0.04l/min	1l/min	57 %	r=0.7
Piehl et al.[37]	PCCO	Animal study	10 piglets 24–37 kg	PATD	2.8l/min	0.1l/min	0.4l/min	14%	r^2=0.97 calibrated r^2=0.22 uncalibrated

*Min = minute; CO = cardiac output (CO); TPTD = transpulmonary thermodilution; TPLD = transpulmonary lithium dilution technique; PATD = pulmonary artery thermodilution; PCCO = pulse contour cardiac output (Pulsion, Munich, Germany); PulseCO (LidCO, Cambridge, UK); PRAM = pressure recording analytical method (Mostcare, BioSi, Florence, Italy). Limits of agreement = 1.96. Percentage error = limits of agreement/mean CO value. * standard deviation (SD) of differences between two techniques.*

Performance of Arterial-pressure-based Continuous Cardiac Output Methods

In general the systems that use calibration have the advantage that CO can always be intermittently measured using a reliable system when there are doubts concerning the APCCO value.[14-16] Although the lithium dilution technology has been validated in children, the manufacturer states that a bodyweight of less than 40kg is a contraindication for its use (www.lidco-ir.co.uk/html/technology/faqs.asp).

The PulseCO method incorporated into the LiDCO device and the pulse contour method (PCCO) incorporated into the PiCCO device have been studied extensively in adults. They show comparable and acceptable results, although regular recalibration improves their performance.[23,24] The Flotrac system has been introduced more recently. In adults its bias is relatively small but the percentage error varies considerably.[25,26] It seems that newer software versions perform better. Studies using this system in children have not been performed. It must be remembered that none of these systems are designed for a paediatric population.

Studies in Children

Table 1 depicts published paediatric studies concerning the APCCO methods. Unfortunately, all published studies analysed only absolute values of CO reflected in bias and limits of agreement (with or without percentage error). Specific capabilities to track changes in CO have not been studied so far. However, it is this capability to track changes in CO that makes these techniques most powerful. All studies had different set-ups and patient groups. One study even included children with cardiac shunts.[27] Shunts influence the pulse pressure and thereby the APCCO method. Apart from validation, the successful clinical use of APCCO in children has also been described.[28]

One of the problems with these validation studies is the gold standard. Since CO is not easy to measure reliably in children it is difficult to study APCCO in children. The calibrated APCCO methods can also only be studied in between two calibrations. In animal experiments a gold standard is readily available using preferably ultrasound flow probes. However, APCCO methods in animals cannot automatically be translated to children since the vascular characteristics of animals can be different to humans.

Specific Considerations with Arterial-pressure-based Continuous Cardiac Output in Children

The difference between systolic and diastolic pressure is called pulse pressure. An increase in pulse pressure causes an increase of windkessel volume in the aorta, and thus a larger stroke volume. However, there is no linear relationship between pressure and volume in the aorta. A pulse pressure of 40mmHg at a level of 80/40 will probably be accompanied by a larger stroke volume than the same pulse pressure at a level of 120/80mmHg. Therefore, a simple linear model will not give accurate results. Furthermore, aortic compliance increases with age, but normalised for body surface area it decreases. This is caused by a developmental increase in arterial size combined with a decreasing arterial wall distensibility with age (most importantly between three and seven years of age).[29] Also, systemic vascular resistance decreases more than twofold during development.[30] The distance between the heart and the femoral (or radial) artery is much shorter than in adults. As in adults, more peripheral collected pulse traces must be compensated for resonance.

Due to the small intra-arterial catheters used in children there is an increased risk of damped waveforms caused by partial occlusion or kinking hampering APCCO performance (specifically when there is no calibration available). On the other hand, sufficient stroke-volume estimation in neonatal waveforms under overdamped pressure waveform conditions has been described.[31] Other factors also influence the reliability of these methods. Heart rate is higher, blood pressure lower and stroke volume much lower. For instance, in a 7kg critically ill child in circulatory shock we measured a systolic blood pressure of 50mmHg and a diastolic pressure of 29mmHg. Heart rate was 168 and cardiac index 2l/minute/m^2 the underlying cardiac stroke volume was 4ml. Specifically under these circumstances we want these systems to work reliably. A measurement error of 1ml represents in these cases an error of 25%.

Algorithms designed for children must take all of the above-mentioned factors into account. A 'simple' translation of adult algorithms will probably not be sufficient. Some conditions render APCCO unreliable or even impossible. This includes cardiac arrhythmias, rapid changes in vascular tone, aortic (vascular or valve) abnormalities and intra- or extra-cardiac shunts.

As a result of the above, care must be taken to direct therapy based on APCCO in children. Technologies with built-in and proven reliable calibration seem most appropriate at this moment.

Future Perspectives

Although the application of the APCCO method in adults is evolving and seems to be gaining reliability, its development in children advances more slowly. This may be because of technical difficulties regarding specific paediatric characteristics and validation problems. A lack of financial benefit in designing these systems for a small subset of patients may play an important role. This would be unfortunate because it is specially in critically ill children where a minimally invasive cardiac output technique is most wanted.

Although arterial catheters are the standard of care in adult and paediatric intensive care, their use in children is more difficult.

Although arterial catheters are the standard of care in adult and paediatric intensive care, their use in children is more difficult. Therefore, a non-invasive APCCO technique would be of great benefit. A completely non-invasive APCCO technique already exists. Based on the former finapres method the Nexfin device (BMEYE, Amsterdam, The Netherlands) already provides an uncalibrated continuous blood pressure and cardiac output using just a finger cuff. Validation of Nexfin CO in adults is promising.

This technology even has a potential benefit over intra-arterial pressure wave systems because it is not hampered by damping of the pressure signal or technical problems with fluid filled pressure recording systems. However, this technique is currently not available for small children. Beta-type small finger cuffs and specially adapted software have been tested in children with promising results.[32] However, further technical developments and more clinical studies are needed.

Conclusion

APCCO monitoring is an evolving technique in adult critical care medicine and anaesthesia. However, in children its performance is still questionable. Much work needs to be done to further adapt algorithms for the paediatric population. Current APCCO systems in children need to be used with caution and should preferably include a known reliable calibration method. Less invasive systems are currently in development. ■

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