VIA MEDICA

ARTYKUŁ POGLĄDOWY

Anestezjologia Intensywna Terapia
2015, tom 47, numer 5, 517–532
ISSN 0209–1712
www.ait.viamedica.pl

Hemodynamic monitoring: To calibrate or not to calibrate? Part 2 — Non-calibrated techniques

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Abstract

There is much evidence that fluid overload leads to adverse outcomes in perioperative and critically ill patients. Cardiac output monitoring can help us guiding initial and ongoing fluid resuscitation and can help us to assess whether a patient will be responsive to fluids when hypotensive. In recent years, many sophisticated devices that measure a variety of hemodynamic parameters have evolved on the market. We wanted to provide an overview of the different techniques available today, including their validation in different patient populations. In this second part of the review, we focus on non-calibrated techniques, both invasive and non-invasive. For each technique a short overview of the working principle, together with the advantages, disadvantages and the available validation literature is listed. Many promising minimal invasive monitoring devices can help us to further optimize our hemodynamic treatment in both the perioperative and critical care setting. However, the validation data are scarce for many of these techniques, especially in complex circumstances with changing hemodynamics (preload, afterload and contractility), as with the use of fluids and vasoactive medication. The measurements made by these devices, therefore, need to be interpreted with caution. Further improvements and more validation data are needed before these techniques can be implemented in common day practice. Moreover, in severely shocked hemodynamic unstable patients, calibrated techniques are to be preferred over those which are uncalibrated. Hence, the new techniques not only need to be accurate, but also need to be precise in order to keep track of changes.

Key words: hemodynamic monitoring, calibrated, invasive, less invasive, non-invasive, thermodilution

Anestezjologia Intensywna Terapia 2015, tom 47, nr 5, 517–532

Cardiac output (CO) is believed to be one of the most important hemodynamic parameters in both the perioperative and intensive care unit (ICU) setting. In the last two decades many devices have come on the market aimed at measuring CO by several interesting methods, both invasive and non-invasive. Some of these devices use validated calibration methods, such as thermodilution, in order to reduce bias and correct for patient specific characteristics. Others try to reduce bias by implementing an algorithm based on certain mathematical models or patient demographic parameters. In this second part of the review, we provide the reader with an update on the uncalibrated devices that are on the market today. There is a broad range of techniques being used and these are summarized in Table 1. With this review we try to give the reader an insight into the working principles, advantages and disadvantages together with an overview of the available data with regard to the validation summarized in Table 2. Many of the new devices also assess fluid responsiveness, while most often pulse pressure analysis is used to assess response to a fluid challenge. As such, they can help us to solve therapeutic conflicts (defined as a situation where each of the possible therapeutic decisions carries some potential harm). Therapeutic conflicts are the biggest challenge for protocolized hemodynamic management in critically ill patients and whether or not to calibrate may not be the only issue when trying to solve these complex problems [1]. A therapeutic conflict is a situation where our decisions can make the biggest difference. We have to rec-

Należy cytować wersję: *Bernards J, Mekeirele M, Hoffmann B, Peeters Y, De Raes M, Malbrain MLNG:* Hemodynamic monitoring: To calibrate or not to calibrate? Part 2 — Non-calibrated techniques. Anaesthesiol Intensive Ther 2015; 47: 501–516. doi 10.5603/AIT.a2015.0076.

Table 1. Types of uncalibrated hemodynamic monitoring devices

1. Minimally-invasive pulse contour analysis
a. Vigileo/Flotrac
b. Pulsioflex/ProAQT
c. LiDCOrapid/PulseCO
d. PRAM/Mostcare
2. Respiratory-derived cardiac output monitoring system
a. $NiCO_2$: partial CO_2-rebreathing
3. Non-invasive pulse contour analysis
a. Radial applanation tonometry: T-line
b. Fingercuff ClearSight/Physiocal (formerly known as Nexfin)
c. Fingercuff CNAP/VERIFY
4. Bioimpedance and bioreactance
a. Bioimpedance
b. Bioreactance cardiac output monitoring (Cheetah-NICOM)
c. Endotracheal cardiac output monitoring (ECOM)
5. EsCCO: estimated continuous cardiac output (Nihon Koden)
6. Ultrasound cardiac output monitoring (USCOM)

ognize that CO measurement may be a lot less informative and accurate than we may want (or think) [1]. Continuity of precise CO measurements (and trending ability) offers one vital insights that may be hidden in the analogue signals of our monitors and may be more important than accuracy. As recently stated by Saugel et al., "Physiological Examination" — observing multiple parameters on the monitor in real time — should be considered to be (at least) as important as the classic "Physical Examination" [93]. Moreover, even assuming that correct, precise and accurate measurements can be obtained with these new devices, they will not change outcome unless they are coupled to a personalized individual treatment algorithm that follows physiology [2].

STATISTICAL ANALYSIS

In order to validate a new CO device, it needs to be compared with the gold standard technique usually thermodilution CO obtained with the Swan-Ganz device (Edwards Lifesciences, Irvine, CA, USA) or transpulmonary thermodilution CO with the PiCCO device (Pulsion Medical Systems, Feldkierchen, Germany). Although, classically, a Pearson regression analysis is used when comparing two measurement techniques, the best statistical method to do so is the Bland and Altman analysis. In this analysis the difference between 2 comparative CO measurements, also known as the bias, is plotted against the mean value of the CO measurements. By doing so, one can measure the upper and lower limit of agreement by taking the mean difference and adding or subtracting twice the standard deviation of the differences. If these limits of agreement are acceptable for the parameter measured, one can argue that the two CO measurement techniques can be used interchangeably [3]. These limits of agreement depend on the parameter studied and the reference method being used. When focusing on CO monitoring devices, the accepted limits of agreement in the literature are around 30% with a percentage of error of 25% [4].

With new devices being developed that are capable of continuous CO measurements, there is growing interest in the trending capabilities of the devices. Rather than the CO itself, the possibility of a device to detect changes in CO may even be more important. There are several ways to analyze trending. One method frequently used today is a 4-quadrant scatter plot, first proposed by Perrino *et al.*, where the ΔCO of two measuring techniques are plotted against each other [5]. Investigators then measure the percentage of concordance between the two studies. A central portion of the plot is usually eliminated because the small changes in ΔCO are less predictive. Although this exclusion zone usually lies between 5–15%, it can be optimized using a receiver operating characteristics (ROC)-curve analysis [6]. Acceptable concordance rates for trending capability in CO monitoring should be above 90%. One of the pitfalls in using four-quadrant plots is that very large changes in CO are virtually always in agreement and thus can falsely augment the concordance rate. While these large changes should ideally be excluded, it is difficult to identify the best cut-off point. A recent publication by Critchley *et al.* suggests a new way to present trend data by using a polar plot analysis after converting data points to an angle indicating the degree of deviation from the ideal line of agreement [6]. When studying trending, with thermodilution being the reference method, a radial limit of agreement of 5° is proposed [7].

MINIMAL INVASIVE PULSE CONTOUR AND PULSE PRESSURE ANALYSIS

Several devices use the technique of pulse pressure analysis to estimate CO. The difficulty is that, to estimate CO from pulse pressure analysis, one would not only need information about the heart rate and blood pressure, but it is also necessary to make an estimate of the pressure-volume relationship of the aorta. Most of the techniques being used today are based on a three-element model integrating aortic characteristic impedance, arterial compliance and systemic vascular resistance. Although these models work relatively well in stable patients, when a patient becomes unstable - as in a shock setting - or when vaso-active drugs are being used, most models lack accuracy [1]. While fine-tuning of the algorithms being used in the monitoring devices try to improve accuracy, further steps need to be taken.

FLOTRAC/VIGILEO

The FlowTrac/Vigileo (hereafter named Vigileo) device by Edwards Lifesciences (Irvine, CA, USA) is a minimally

invasive technique system capable of computing cardiac output, cardiac index, stroke volume, stroke volume index and stroke volume variation using pulse pressure variation measured at the radial or femoral artery. The algorithm begins with the premise that stroke volume is proportional to pulse pressure and vascular tone. Vigileo® analyzes the pressure wave by measuring pressure points at 100 Hz. The cardiac output is then estimated using the following algorithm:

$$CO = HR \times SD_{PP} \times Khi$$

Where HR is heart rate, SD_{pp} is the standard deviation of the pressure points and Khi is a correction factor for the vascular tone. Khi is derived from the patient's gender, age and body-surface area, as well as certain pressure wave characteristics, such as mean arterial pressure, skewness of the pressure wave, and kurtosis of the pressure wave (a quantification of how peaked or flat the pressure wave is). These pressure wave characteristics are constantly analyzed and compared to a database of numerous test patients used to modify Khi continuously.

Vigileo can be connected to standard arterial monitoring devices. In contrast to PiCCO, the Vigileo monitor is uncalibrated which makes it easier to use. However, the lack of calibration does make the Vigileo monitor more prone to errors. Vigileo showed acceptable accuracy when first tested in patients undergoing cardiac surgery [9–12]. However, the method is much less accurate in septic patients with low vascular resistance. Although software updates have made it more accurate, the percentage error is still more than 30% and increases when systemic vascular resistance is decreased [13–17]. Vigileo also lacks accuracy in patients with intracranial haemorrhage [18], severe liver disease [19] and morbid obesity [20].

The trending capability of Vigileo was studied by Monnet *et al.* who showed a low concordance rate of 73% after fluid expansion and only 41% after administration of norepinephrine [21]. Another disadvantage of Vigileo is that it is not possible to "calibrate" cardiac output with a more validated technique such as thermodilution.

PROAQT/PULSIOFLEX

The ProAQT/Pulsioflex method (hereafter named Pulsioflex) by Pulsion Medical Systems (Feldkirchen, Germany, now part of Maquet Getinge Group) continuously measures cardiac output by analyzing the systolic portion of the pressure wave, in a similar way to the PiCCO-device. Before doing so, the Pulsioflex estimates the initial cardiac output by a different algorithm called 'auto-calibration'. For this auto-calibration, Pulsioflex uses the height, weight and age of the patient, mean arterial pressure, heart rate, as well as an abstract value that is based on an analysis of a comprehensive database. With pulse contour analysis this initial cardiac output is continuously adjusted. Pulsioflex also allows you to manually enter a starting cardiac index obtained by a more validated technique, such as echocardiography or thermodilution to make the initial cardiac output as precise as possible.

Currently there are only two studies with the Pulsioflex device. In a study by Monnet *et al.*, the Pulsioflex was compared with Vigileo and transpulmonary thermodilution in critically ill patients. Pulsioflex was unable to accurately predict cardiac output with limits of agreement of −1.5 to 1.4 L $min^{-1}m^{-2}$ and a percentage of error of 40% [21]. After autocalibration, the percentage error stayed at 39%. Pulsioflex showed acceptable tracking capabilities compared to thermodilution after fluid bolus, with a concordance rate of 91%. Surprisingly the concordance-rate declined after auto-calibration. Pulsioflex was unable to track changes in cardiac output after administration of norepinephrine.

In another study by Salzwedel *et al.*, the Pulsioflex device was used for perioperative goal-directed hemodynamic therapy in patients undergoing major abdominal surgery. Using non-invasive hemodynamic monitoring for goal-directed hemodynamic therapy led to a decline in post-operative complications 28 days after surgery [22].

LIDCORAPID/PULSECO

The LiDCO*rapid*/PulseCO system (hereafter named LiDCOrapid) by LiDCO group (London, UK) is an uncalibrated form of hemodynamic monitoring that uses the same algorithm used in LiDCOplus. The PulseCO algorithm calculates a nominal stroke volume from the entire pressure waveform using an autocorrelation algorithm, a method referred to as pulse power analysis. In LiDCOplus, this nominal stroke volume is converted into an actual stroke volume using Lithium dilution techniques for calibration. However, LiDCOrapid makes a robust uncalibrated estimate of stroke volume and cardiac output, based on a large database and using certain patient variables, such as age, length and weight. LiDCOrapid also provides measures of mean arterial pressure, pulse pressure variation and stroke volume variation.

As with the Pulsioflex device, LiDCOrapid can be calibrated at any time using another technique.

Performance studies comparing LiDCOrapid with thermodilution methods show insufficient accuracy. Although Phan *et al.* found minimal bias compared to thermodilution, there were wide limits of agreement with a percentage of error of 54.2% [23]. In another study on liver transplant patients, investigators found a mean bias of −0.1 L min^{-1} with limits of agreement of −2.6 to 2.39 and a percentage error of 39.2% [24]. Broch *et al.* compared LiDCOrapid with thermodilution before and after coronary bypass surgery,

and also found poor accuracy for LiDCOrapid after induction with a mean bias of 0.36 L $min^{-1}m^{-2}$, limits of agreement of −1.73 to 2.46 L $min^{-1}m^{-2}$ and a percentage error of 86% [25].

However, calibration of the device using Lithium dilution did improve the accuracy to an acceptable percentage of error of 28% [25]. In another study, calibration with thermodilution also significantly improved its accuracy [26]. In another study by Cecconi *et al.*, the PulseCO algorithm, after calibration with Lithium dilution, even showed an acceptable accuracy in critically ill patients, but only in the first 4 hours. Afterwards, the accuracy dropped markedly which would make a new calibration necessary [27]. Thus, while uncalibrated measurements of the LiDCOrapid device should be interpreted cautiously, accuracy is improved with calibration.

Looking at tracking capabilities, Costa *et al.* found only moderate concordance using a four-quadrant plot comparing PulseCO with thermodilution techniques, with the highest concordance rate being only 82% [24].

MOST CARE/PRESSURE RECORDING ANALYTICAL METHOD (PRAM)

The Most Care device (hereafter named PRAM) by Vytech Health (Padova, Italy) is a cardiac output monitoring device that uses an algorithm called the pressure recording analytical method. Unlike other pulse contour analysis devices that use either calibration or correlate using previously obtained patient data, PRAM uses a theoretical model developed *a priori* by the theory of perturbing. To do so, analyzation of both the pulsatile and continuous flow is monitored at a frequency sampling of 1000 Hz, which is much higher than with other pulse contour devices. In PRAM, the stroke volume is calculated using the following formula:

$$Stroke\ volume = \frac{A}{\frac{P}{t} \times K}$$

Where A (mm Hg × s) is the area under the systolic portion of the pressure curve, P/t (mm Hg s^{-1}) describes the pressure wave profile as changes of pressure with time and K is a dimensional factor related to the instantaneous acceleration of the vessels cross-sectional area ($s^2\ cm^{-1} \times cm^{-2}$) [28]. For more detailed information about the mathematical model, we refer the reader to the original article. PRAM also provides SVV, PVV and SPV.

A systematic review by Schlöglhofer on semi-invasive cardiac output monitoring devices refers to several reports showing a reasonable performance of Modelflow in stable patients undergoing catheterization (Table 2). Acceptable performance was also reported during and after cardiac surgery, as well as in patients with an intra-aortal balloon pump. A study of 30 septic patients also showed an acceptable accuracy, with a mean cardiac output of 7.66 L min^{-1}, mean bias −0.26 L min^{-1}, 95% limits of agreement of −2.22 to 1.7 L min^{-1} and percentage error of 25%. Accuracy was diminished in patients with atrial fibrillation. The author mentioned that all of the studies were performed on the same study group [29].

In contrast to these studies, two other studies performed on patients after cardiac surgery showed a very large difference in outcome with a high percentage of error of 73% and 87%, respectively. One of these could be contributed to the presence of atrial fibrillation, which has proved to reduce the Modelflow's accuracy in other studies as well [30, 31].

As with other uncalibrated pulse contour analyzing methods, only an invasive arterial catheter is needed. However, since the algorithm is not based on a patient database, other patient parameters are not necessary. This makes the implementation of PRAM very easy. Several studies have shown good accuracy in a wide range of settings (however, most of the results come from the same study group). Thus, more validating data is needed from multicenter studies to confirm the data and elucidate the large discordance between the different studies and eliminate possible bias.

RESPIRATORY DERIVED CARDIAC OUTPUT MONITORING SYSTEM: PARTIAL CO_2-REBREATHING (NICO)

According to the Fick Principle, a special case of mass balance, cardiac output can be measured by the oxygen consumption and the difference in oxygen concentration in the arterial and venous blood. Although considered as the gold standard in cardiac output measurements, it is a relative invasive technique (as the patient needs to be intubated and mechanically ventilated) that is hardly ever used.

Another suitable indicator that could be used instead of oxygen is carbon dioxide (CO_2), which is produced in the body and extracted from the bloodstream by the lungs. This technique is used in the NICO-sensor (Philips Respironics, Eindhoven, the Netherlands) by using a partial rebreathing method. When using CO_2 as an indicator in the Fick formula, the rearrangement yields:

$$CO = \frac{VCO_2}{C_vCO_2 - C_aCO_2}$$

Where VCO_2 represents the CO_2 clearance in the lungs, and C_vCO_2 and C_aCO_2 represent venous and arterial CO_2-concentrations respectively.

We can measure the CO_2-production relatively easily by measuring the exhaled CO_2-content and multiplying it by the minute volume. The arterial CO_2-content can be estimated by measuring the end-tidal CO_2 concentration ($etCO_2$) in combination with the slope of the CO_2-dissociation curve. However, the venous CO_2 concentration is more difficult to measure. We may omit the venous carbon dioxide measure-

ment by using a technique called partial CO_2 rebreathing. The underlying principle is as follows. By assuming cardiac output is stable under normal and rebreathing conditions, we obtain:

$$CO = \frac{VCO_{2N}}{C_vCO_{2N} - C_aCO_{2N}} = \frac{VCO_{2R}}{C_vCO_{2R} - C_aCO_{2R}}$$

Where N is for non-rebreathing, and R is for rebreathing. By subtracting the two, we get the following differential Fick equation:

$$CO = \frac{VCO_{2N} - VCO_{2R}}{(C_vCO_{2N} - C_aCO_{2N}) - (C_vCO_{2R} - C_aCO_{2R})} = \\ = \frac{\Delta VCO_2}{(C_vCO_{2N} - C_aCO_{2N}) - (C_vCO_{2R} - C_aCO_{2R})}$$

By assuming venous CO_2-content stays the same during normal and rebreathing conditions, we can eliminate it from the equation. For arterial CO_2 we will use the end tidal CO_2 -concentration in combination with our previously mentioned slope of the CO_2-dissociation curve that describes the relation between the partial CO_2-pressure and the exhaled CO_2-content [32]:

$$CO = \frac{\Delta VCO_2}{\Delta C_aCO_2} = \frac{\Delta VCO_2}{S \cdot \Delta etCO_2}$$

By using partial CO_2-rebreathing, we can now measure cardiac output without the need of intravascular devices. However, from a theoretical point of view, a few important concerns are to be made:

— The difference between the arterial CO_2 content during normal and rebreathing conditions are very small. Small errors in measurement can thus lead to large changes in cardiac output.
— Changes in ventilation can alter the end-tidal CO_2. NICO can, therefore, only be used in fully sedated patients with volume-controlled ventilation.
— Changes in alveolar gas exchange, for instance in ARDS, will influence the CO_2-diffusion and this can lead to false changes in the cardiac output measured.
— Differences in VCO_2 and end-tidal CO_2 reflect only the parts in the lung that participate in gas exchange. Measurements must be corrected for intrapulmonary shunts. The NICO-monitor compensates for this by using a shunting fraction based on Nunn's iso-shunt tables [33]. However, in ICU patients with important cardiopulmonary disease (pneumonia, atelectasis, intracardial shunts), this may be a problem.

Apart from ventilator-associated data (such as full respiratory mechanics with dynamic compliance and resistance, dead space tidal volume, alveolar minute volume, end-tidal CO_2,…), the NICO system provides the clinician with the CO_2 elimination rate and the pulmonary capillary blood flow (PCBF), defined as the portion of the cardiac output that is effective in gas exchange.

Few data on validation exists for cardiac output monitoring by the NICO-system. To our knowledge, the latest publication on the technique dates back to 2010. At this moment, the NICO-algorithm is implemented in a few Philips Respironics ventilator devices. In a publication by Kotake *et al.* investigating the latest software version (5.0) of the NICO-system, researchers found insufficient data for interchangability with thermodilution, with a mean bias of 0.18 L min^{-1}, limits of agreement of 1.66 L min^{-1} and a percentage of error of 33.2%. Although a newer version of the software did not significantly improve its accuracy, it shortened the rebreathing time needed [34].

In a prospective clinical trial, PCBF was validated against invasive measurement (CO minus venous admixture flow) [35]. PCBF values were reported to be useful in titrating PEEP aimed at improving PCBF in an acute lung injury setting. To the knowledge of the authors, no outcome data has been published on the use of PCBF in any clinical setting.

Although the theory of partial CO_2-rebreathing in measuring cardiac output seems promising, to date insufficient data exists supporting its accuracy compared to reference techniques. Moreover, to use the device, an endotracheal intubation is needed and patients need to be fully sedated and on volume-controlled ventilation. Some cardiopulmonary diseases that change ventilation/perfusion ratios and increase shunting also limit its accuracy. Indeed, such diseases are very common in an ICU population.

NON-INVASIVE PULSE CONTOUR ANALYSIS

T-LINE

The T-line system (TL-300) by Tensys Medical Inc. located in San Diego, CA, USA (hereafter named T-line) is a new non-invasive method based on pulse contour analysis using a technique called applanation tonometry. To do so, a pressure sensor is placed upon the patient's radial artery. After searching the optimal position, the T-line device performs an applanation sweep. The artery is gradually compressed mechanically until the transmural pressure is zero. This will lead to a maximal pulse pressure. Further compression will lead to dampening of the curve and a reduction in pulse pressure. The amount of pressure needed then correlates with the mean arterial pressure. Several studies have showed accurate blood pressure monitoring for the T-line compared to arterial catheter measurements, as well as central aortic blood pressure monitoring in ICU patients, showing acceptable limits of agreement and a percentage of error of 15–17%, according to the AAMI (Association for the Advancement of Medical Instrumentation) criteria for intermittent non-invasive blood pressure monitoring devices [36–39].

A newly developed auto-calibrating algorithm uses the arterial wave to estimate cardiac output. The physiological parameters used are gender, age, height, body weight, systolic arterial pressure, diastolic arterial pressure, mean arterial pressure, pulse pressure, beat-to-beat interval, maximal slope within systole and systolic area under the curve. In a proof-of-concept study, this algorithm was compared to a calibrated pulse contour analysis and showed an acceptable percentage of error of 23% in 22 selected ICU patients [40].

Cardiac output measured by the T-line system was compared to pulmonary artery thermodilution in 50 patients undergoing cardiac surgery. While the authors concluded that there was a reasonable accuracy, the limits of agreement seem a little bit too high, according to the criteria set out by Critchley and Critchley. However, the study did show an acceptable tracking capability with a concordance rate of 95% [41].

Although the T-lines capability to accurately measure cardiac output needs more validation, it is a promising technique that is able to measure cardiac output without the need for intravascular devices.

CLEARSIGHT/PHYSIOCAL SYSTEM

The ClearSight monitoring device (hereafter named ClearSight) produced by Edwards Lifesciences (Irvine, CA, USA), previously known as Nexfin by BMEYE B.V. Amsterdam, the Netherlands, is a non-invasive arterial pressure curve analysis device. Clearsight estimates the blood pressure by a cuff wrapped around the finger. The device then uses photoplethysmography with LED-technology to constantly adjust cuff pressure to keep the arterial diameter, and thus the finger's diameter constant. With the volume of the finger kept the same, the opposing cuff pressure correlates with the arterial pressure, a technique also referred to as the Peñáz-principle. The continuous waveform can then be used to estimate stroke volume, cardiac output, SVV and PPV.

A recent review by Ameloot *et al.* showed an average percentage of error of 22% for the monitoring of mean arterial pressure, which is a little too high according to the AAMI-criteria. For cardiac output monitoring, it showed a mean bias of 0.1 L min^{-1} with an unacceptably high weighted average percentage of error of 44%. Accuracy was less in patients with low cardiac output, finger oedema, hypothermia or a high peripheral resistance. However, ClearSight did show an acceptable tracking capability in a few studies [42].

CNAP/VERIFY

The CNAP/VERIFY technology (hereafter named CNAP) by CNSystems Medizintechnik (Graz, Austria), uses the same technique of photoplethysmography as Clearsight. However, in order to correct for changes in vasomotoric activity, the CNAP device uses an algorithm called "Vasomotoric Elimination and Reconstructed IdentiFication of the Initial setpoint" (VERIFI). The algorithm continuously analyses the shape of the waveform and can distinguish between changes in blood volume due to changes in blood pressure or due to changes in arterial diameter.

To our knowledge, there is only one validation study where the novel cardiac output algorithm was applied retrospectively to a set up database of 36 critically ill patients and was correlated against transpulmonary thermodilution methods [43]. The investigators found a mean cardiac output of 6.4 L min^{-1} for CNAP against 7.8 L min^{-1} for thermodilution with high limits of agreements of –4.9 to + 2.1 L min^{-1} and a percentage of error of 45%. After pre-calibrating the system with the first cardiac output obtained by thermodilution, the percentage of error dropped markedly to an acceptable 25% [43]. Furthermore, these data are only retrospective.

BIOIMPEDANCE AND BIOREACTANCE

BIOIMPEDANCE

Although the bioimpedance method as a way to monitor cardiac output was described in the 1970s, data supporting its validity is scarce. According to a systematic review by Critchley *et al.*, devices on the market today include: BioZ (CardioDynamics, San Diego, CA, USA), PhysioFlow (NeuMeDx, Inc., Bristol, UK), the NICOMON (Larsen and Toubro Ltd., Mumbai, India), NICCOMO (Medis, Ilmenau, Germany) and the CSM3000 (Cheers Sails Medical, Shenzhen, China).

According to Ohm's law, electrical current is equal to a voltage difference divided by the resistance or impedance (Z). Impedance itself is dependent on the cross-sectional area of the conductor (A), the length (l) and the resistivity (ρ).

$$I = \frac{U}{Z} \quad with \quad Z = p\ \frac{l}{A} = p\ \frac{l^2}{V}$$

With the current held constant, changes in voltage across the circuit are caused by changes in impedance. Moreover, with the resistivity being held constant, changes in voltage difference are due to changes in volume of the conducting tissues. Compared to other tissues in the thoracic cavity, blood has a relatively low resistivity. Therefore, though it composes a small portion of the thoracic cavity, the changes in blood volume have a high impact on the impedance.

With this assumption, we can postulate that changes in thoracic impedance are largely dependent on 3 components. A baseline impedance (Z_0) indirectly proportional to the thoracic fluid content, tidal changes in intrathoracic blood volume caused by respiration, as well as small changes in impedance caused by the cardiac cycle [44]. The latter changes are primarily due to changes in aortic volume and this can be used to estimate stroke volume and cardiac output [45].

Table 2. Overview of the validation studies for the non-calibrated cardiac output measuring devices: overview of the studies on the minimal and non-invasive cardiac output measuring devices. Study population, study size and reference method, mean CO of the reference method, mean bias, 95% limits of agreement and percentage error are stated

	Author	Study-population	Reference method	Mean CO (L min^{-1})	Mean bias (L min^{-1})	95% limits of agreement (L min^{-1})	Percentage error (%)	Advantages	Disadvantages
Flotrac/Vigileo	Button et al. [9]	Cardiac surgery (n = 31)	PAC TD	4.2–5.6	0.1–0.6	± 1.8–2.6	NA	Only arterial catheter and patient's characteristics needed. Many validation studies in wide study population, although with large percentages of error	Insufficient studies supporting validation. Not able to calibrate with reference method
	Cannesson *et al.* [10]	Cardiac surgery (n = 11)	PAC TD	4.7	0.26	−1.48 to 2.00	37		
	De Waal *et al.* [11]	Cardiac surgery (n = 22)	TPTD	5.27	0	−1.74 to 1.74	33		
	Mayer *et al.* [83]	Cardiac surgery (n = 40)	PAC TD	3.5 (CI)	0.46	−0.69 to 1.61	46		
	Marqué *et al.* [13]	Septic shock (n = 18)	PAC TD	4.2 (CI)	0.1	−2.2 to 2.0	64		
	Slagt *et al.* [14]	Septic shock (n = 5)	PAC TD	NA	−1.6	−4.8 to 1.6	48		
	Slagt *et al.* [14]	Septic shock (n = 4)	PAC TD	NA	−1.2	−1.0 to 3.4	37		
	De Backer *et al.* [84]	Sepsis (n = 58)	PAC TD	NA	0.2	NA	30.4		
	Sakka *et al.* [17]	Septic shock (n = 24)	TPTD	6.45	0.5	−4.1 to 5.1	71		
	Junttila *et al.* [18]	Intracranial haemorrhage (n = 16)	PAC TD	7.6	1.5	−2.4 to 5.4	58		
	Su *et al.* [19]	Liver transplant (n = 28)	PAC TD	6.4	−0.8	−5.6 to 4.0	75		
	Tejedor *et al.* [20]	Morbidly obese (n = 8)	PAC TD	6.2	NA	NA	28.5		
Pulsioflex/ ProAQT	Monnet *et al.* [21]	Critically ill (n = 20)	TPTD	3.1	−0.1	−1.4 to 1.3	40	Only arterial catheter and patient's characteristics needed Acceptable tracking capabilities for fluid challenge in one study	Insufficient studies supporting validation. Unacceptably high percentage of error in available study. Optional calibration with more validated technique is possible but does not seem to improve accuracy.
LiDCOrapid/ PulseCO	Phan *et al.* [23] Costa *et al.* [24]	Cardiac surgery (n = ?)	PAC TD	NA	NA	NA	54.2	Only arterial line and patient's characteristics needed Optional calibration with more validated technique. Calibration with alternative technique improves accuracy	Insufficient studies supporting validation.
	Broch *et al.* [25]	Liver transplant (n = 20)	PAC TD	7.78	−0.1	−2.6 to 2.39	39.2		
		Cardiac surgery (n = 42)	TPTD	2.47–3.35	0.01–0.36		28–86		
Mostcare/ PRAM	Romano *et al.* [85]	Cardiac surgery (n = 32)	PAC TD	4.0	0.07	−0.73 to 0.87	20	Only arterial catheter needed. Acceptable validating data, although mostly from the same study group	Conflicting data on performance. Poor performance in atrial fibrillation.
	Zangrillo *et al.* [86]	IABP (n = 32)	PAC TD	5.1	0.13	−1.69 to 1.43	30		
	Scoletta *et al.* [87]	IABP (n = 15)	PAC TD	NA	0.2	−1.31 to 0.91	24		
	Franchi [88]	Sepsis (n = 30)	PAC TD	7.7	−0.26	−2.22 to 1.70	25		
	Maj *et al.* [30]	Critically ill with AF (n = 49)	PAC TD	NA	0.13 (CI)	−1.66 to 1.94	73		
	Paarmann *et al.* [31]	Cardiac surgery (n = 23)	PAC TD	5.2	0.0	−4.54 to 4.53	87		

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Table 2. Overview of the validation studies for the non-calibrated cardiac output measuring devices: overview of the studies on the minimal and non-invasive cardiac output measuring devices. Study population, study size and reference method, mean CO of the reference method, mean bias, 95% limits of agreement and percentage error are stated

	Author	Study-population	Reference method	Mean CO (L min^{-1})	Mean bias (L min^{-1})	95% limits of agreement (L min^{-1})	Percentage error (%)	Advantages	Disadvantages
NICO	Kotake et al. [34]	Aortic reconstruction surgery (n = 42)	PAC TD	NA	0.18	−1.48 to 1.84	33.2	No arterial catheter needed. Measurement of pulmonary capillary blood flow	Insufficient studies supporting validation. Less accurate with large shunting (e.g. pneumonia, atelectasis) or changes in alveolar gas exchange (e.g. ARDS) Only works in fully sedated, volume controlled ventilation.
T–line	Saugel *et al.* [40]	Mixed ICU patients (n = 22)	TPTD	7.0	0.1	−1.5 to 1.7	23	Non-invasive technique Acceptable tracking capabilities in one study	Insufficient studies supporting validation.
	Wagner *et al.* [41]	Post–cardiac surgery (n = 50)	PAC CO	4.7	−0.2	−1.8 to 1.4	34		
ClearSight/ /Physiocal	Ameloot *et al.* [42]	Meta–analysis (n = 365)	PAC TD, TPTD or TEE	5.4 *	0.1 *	−2.34 to 2.54 *	44 *	Non-invasive technique. Studies show some accuracy to track hemodynamic changes	Insufficient studies supporting validation.
CNAP/VERIFY	Wagner *et al.* [43]	Critically ill (n = 36)	TDPD	6.4	−1.4	−4.9 to 2.1	45	Non-invasive technique	Insufficient studies supporting validation.
Bioimpedance	Peyton *et al.* [46]	Meta-analysis (n = 435)	PAC TD, TPTD	NA	−0.1	−2.18 to 2.38	42.9	Non-invasive technique	Insufficient studies supporting validation. Prone to error with changes in thoracic fluid content or vascular resistance.
Cheetah–NICOM/ Bioreactance	Squara *et al.* [47]	Post–cardiac surgery (n = 110)	PAC TD	4.7	0,06	−1.36 to 1.48	30	Non-invasive technique	Insufficient studies supporting validation. Prone to error with changes in thoracic fluid content or vascular resistance. Not able to detect sudden changes in cardiac output.
	Marqué *et al.* [48]	Mixed population (n = 29)	PAC TD	4.86	−0.1	−2.3 to 2.5	49		
	Kober *et al.*[49]	Ovarian surgery (n = 15)	TPTD	NA	0.26	−1.39 to 1.92	50.7		
ECOM	Møller-Sørensen *et al.* [50]	Cardiac surgery (n = 25)	PAC TD	4.7	−0.45	−2.4 to 1.49	41	Close proximity to the aorta might improve its accuracy compared to bioimpedance or bioreactance.	Insufficient studies supporting validation. Prone to error with changes in thoracic fluid content or vascular resistance. Patient needs to be intubated.
	Maus *et al.* [51]	Cardiac surgery (n = 30)	PAC TD	4.56	0.02	−2.26 to 2.30	50		
	Ball *et al.* [52]	Cardiac surgery (n = 40)	PAC TD		−0.11 to 0.2		48–53		
	Maass *et al.* [53]	Cardiac surgery (n = 53)	PAC TD	NA	−0.13	NA	40		

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Table 2. Overview of the validation studies for the non-calibrated cardiac output measuring devices: overview of the studies on the minimal and non-invasive cardiac output measuring devices. Study population, study size and reference method, mean CO of the reference method, mean bias, 95% limits of agreement and percentage error are stated

	Author	Study-population	Reference method	Mean CO (L min^{-1})	Mean bias (L min^{-1})	95% limits of agreement (L min^{-1})	Percentage error (%)	Advantages	Disadvantages
EsCCO	Terada T *et al.* [89]	Kidney Transplant (n = 15)	TPTD	NA	1.37	−1.54–0.76	35.6	Completely non-invasive. Easy to use. No catheter-related adverse effects.	Very high bias and percentage error. No hard evidence in favour of EsCCO.
	Thonnerieux M *et al.*[58]	Cardiac surgery (n = 27)	TPTD	NA	+0.7	−2.1 to +3.5	NA		
	Wacharasint P *et al.* [90]	Cardiac surgery (n = 50)	TPTD	NA	1.2	−1.9 to 4.3	NA		
	Permpicul C *et al.* [62]	Sepsis (N = 10)	TPTD	NA	1.2	−2.8 to 5.4	NA		
	Ball TR *et al.* [59]	Cardiac surgery (n = 35)	TPTD	5.4	NA	NA	44–60		
	Tsutsuj M *et al.* [64]	OR and ICU (n = 195)	TPTD	NA	NA	−2.49 to 2.35	NA		
	Yamada T *et al.* [63]	OR and ICU (n = 352)	TPTD	NA	0.13	−2.13 to 2.39	37		
	Sinha A. *et al.* [60]	Mixed Surgery (n = 14)	TPTD		0.13	−4.32 to 4.58	69		
USCOM	Beltramo F *et al.* [67]	Paediatric cardiac KT (n = 31)	PAC TD	4.37	0.2	−1.2 to 1.6	11	Non-invasive technique that has no procedural risks and with a short learning curve.	Sometimes unobtainable echocardiographic imaging. Rather weak evidence with wrong valve area estimations compared to traditional echocardiography.
	Chong SW *et al.* [91]	Meta-analysis ICU and OR	TPTD	NA	−0.39	−0.25 to −0.53	42.7		
	Horster S *et al.* [74]	Ventilated sepsis (n = 70)	TPTD	6.55	−0.36	NA	29		
	Thom O *et al.* [71]	Intensive care (n = 94)	PAC TD	5.5	−0.09	+/−2.92	19		
	Boyle M *et al.* [72]	mixed ICU (N = 39)	TPTD	3.4	0.6	0.4–0.8	56		
	Su BC *et al.* [78]	Liver transplant ICU (n = 15)	TPTD	NA	0.13	−0.65 to 0.92	NA		
	Wong LS *et al.* [79]	Liver transplant ICU (n = 12)	PAC TD	NA	0.39	−1.47 to 2.25	NA		
	Knirsch W *et al.* [69]	Paediatric cardial pts (n = 24)	PAC TD	3.6	−0.13	1.3–5.3	36.4		
	Arora D *et al.* [80]	CABG (n = 30)	TPTD	4.63	−0.13	−0.86 to 0.59	NA		
	Chan JS *et al.* [81]	Cardiac surgery (n = 30)	PAC TD	NA	0.22	−1.17 to 1.62	52		
	Tan HL *et al.* [82]	Cardiac surgery (n = 24)	TPTD	NA	0.18	−1.43 to 1.78	NA		

NA — not available; (CI) — cardiac index; PAC TD — pulmonary artery catheter thermodilution; TPTD — transpulmonary thermodilution; TEE — transesophageal echocardiography; * pooled data. Data were calculated, if possible, according to Critchley and Critchley

Bioimpedance monitoring has had much attention in the past and present. The theory seems very attractive since it is very cheap and practical to use, while only a few electrodes are needed. This has led to the production of several devices that all use slightly modified algorithms based on the principle explained above.

The theoretical concept does have important limitations. Impedance is influenced by all changes in thoracic fluid composition, such as lung oedema and pleural effusions. Changes in systemic vascular resistance will influence the volume changes in the aorta and will, therefore, interfere with cardiac output measurements. Electrical interference, for instance during electrocautery, makes the technique not useful during surgery.

There is very little data supporting the use of bioimpedance. A meta-analysis by Peyton *et al.* found a mean bias of 0.1 L min^{-1} with 95% limits of agreement of 2.28 L min^{-1} and a percentage error of 42.9% [46].

CHEETAH-NICOM/BIOREACTANCE

The CHEETAH-NICOM (hereafter named Cheetah) by Cheetah Medical (Newton Center, MA, USA) is a non-invasive cardiac output monitoring device that uses a technique called Bioreactance based on the principal of thoracic electrical bioimpedance. To improve the signal-to-noise ratio, Cheetah not only measures changes in voltage amplitude, but rather phase-shifts in the alternating current. According to the authors, this phase-shift depends almost exclusively on pulsatile flow and, therefore, should be more closely related to aortic blood flow and, thus, cardiac output.

Cheetah was compared to thermodilution using a pulmonary artery catheter in 110 patients following cardiac surgery. The authors of this study reported a mean bias of 0.06 L min^{-1} with limits of agreements of 1.42 L min^{-1} and a percentage of error of 30% which is close to the acceptable range [47]. Another study, in a mixed population, found a low bias of 0.01 L min^{-1} with wide limits of agreement of ± 1.68 L min^{-1}. Although a percentage of error was not mentioned, from the data presented this can be calculated to roughly 49% [48]. A final study on patients treated for ovarian cancer, showed a mean bias of 0.26 L min^{-1} with a percentage of error of –1.39 to 1.92 L min^{-1} and a high percentage error of 51% [49].

The same disadvantage of interference by electrical activity for bioimpedance applies to the bioreactance algorithm. Moreover, because it uses averaged cardiac output readings over a longer period, it is not able to detect sudden changes in cardiac output.

Despite the bioreactance algorithm, there is still insufficient data supporting the validity of Cheetah/NICOM. Hopefully, further adjustments will make the device more accurate in the future. With its shortcomings kept in mind, its practicality makes the concept very attractive.

ENDOTRACHEAL CARDIAC OUTPUT MONITOR (ECOM)

Another technique based on bioimpedance is the endotracheal cardiac output monitoring device (hereafter named ECOM) by ConMed Corp, from Utica, USA. Unlike other bioimpedance techniques, ECOM uses electrodes that are attached to an endotracheal tube. The idea is that because of the close proximity of the trachea to the aortic arch, this should improve its signal to noise ratio.

Four studies have been performed comparing ECOM with thermos dilution techniques on patients scheduled for cardiac surgery. None of them showed acceptable accuracy, with limits of agreements between 40 and 51% [50–53]. In one study, investigators did show an acceptable trending capability with 83% of cardiac output changes lying within the 0.5 L min^{-1} limit of agreement and 95% within 1 L min^{-1} limit of agreement. This means a change in cardiac of 1 L min^{-1} will be detected 95% of the time [51]. However, this was not confirmed by another study which only found a concordance rate of 30% in a four-quadrant plot [50].

ESCCO: ESTIMATED CONTINUOUS CARDIAC OUTPUT

EsCCO is the abbreviation of estimated continuous cardiac output. It is a non-invasive device, introduced in 2004 by Nihon Koden (Tokyo, Japan) to estimate the cardiac output with an algorithm that continuously produces such estimates based on patient characteristics and measurements of electrocardiography, peripheral saturation and non-invasive measured blood pressure. The main idea is that, with these measurements, a pulse wave transit time can be determined. This pulse wave transit time in combination with the heart rate is proposed to be able to estimate the cardiac output.

Concerning the evidence, quite a few articles do not compare EsCCO to a gold (invasive) standard but make a comparison with echocardiographic cardiac output measurements [54–57]. While most articles suggest an unacceptable disconcordance in reported cardiac output compared to the used gold standard between 30 and 80% [54, 56–61], some articles claim better global concordance by adapting data, such as changing the threshold of fluid responsiveness to raise of cardiac output in the EsCCO-arm to 11% compared to the usual 15% [55]. While others report an unacceptable gap in the results between estimated cardiac output by EsCCO, they conclude, strangely enough, that there is a good correlation [62]. Only two articles, both from the same authors with only abstracts available, showed a strong positive linear relationship between EsCCO and continuous cardiac output measurement in operating room

and ICU patients [63, 64]. Remarkably, in the methodology it is shown that at the start of measurements being taken, there is a calibration of the EsCCO with invasive cardiac output.

Therefore, we may state that EsCCO is an unreliable technique for measuring cardiac output. Especially during septic shock and fluid resuscitation, the available data seem devastating. However, there might be a use for it during the de-escalation phase. In this particular setting, while single calibration with the removed invasive measurement of cardiac output could be interesting, at present there are no data about the duration of the reliability of calibration.

As possible advantages, we may keep in mind that EsCCO is a non-invasive continuous way to estimate cardiac output. This has the benefit of being easy to use and the absence of catheter-related complications. The major disadvantage is that EsCCO remains an estimation of cardiac output. The vast majority of studies suggest an unacceptably high deviation from cardiac output measurements by a more validated method.

ULTRASONIC CARDIAC OUTPUT MONITORING

USCOM (Sydney, Australia) is the abbreviation for ultrasonic cardiac output monitoring. By applying ultrasound to suprasternal and intercostal sites, a cross sectional view of the aortic and pulmonary outflow tract can be achieved. Via USCOM the flow velocity in these vessels is measured. USCOM combines this information with pre-calculated valve areas based on patient height and weight. A crucial point, in this approach is the correct estimation of the valve area by USCOM. However, some data point out that this often fails to be true [65]. Especially with aging, starting at 50 years and even more after the age of 60, USCOM becomes less reliable in the estimation of valve area [66]. Moreover, with increasing age, the visibility of the outflow tracts decreases. It is remarkable that in almost all studies, cardiac output cannot be measured by USCOM in around 10% of patients for this reason. Perhaps this is why many such articles focus on children and pregnant women [67–69].

Concerning young patients, some authors claim children tend to have reliable USCOM measurements, as long as they are not critically ill or suffer from a structural heart disease [67, 69]. A third study confirms this statement, yet reports a percentage error of 58% compared to TTE [70]. In critically ill (paediatric and adult) patients, almost all studies agree that USCOM appears to be totally unreliable [71–73]. Only two articles claim otherwise [74, 75]. The first has a borderline borderline acceptable percentage error of 29% [74] while the other paper reports good average correlations. However, this average seems to be based on the reciprocal elimination of overestimations and underestimations while the percentage error was not reported [75].

The learning curve in order to obtain a reproducible USCOM evaluation is rather short. One study states that application of USCOM for five times is sufficient to master the technique [76]. Other studies suggest 20 investigations or more. Indeed, a good inter- and intra-observer measurement is obtained in most studies [77].

There are some indications where USCOM may provide reproducible data. The first is in liver transplantation where USCOM is reported to be reliable in all dedicated articles [78, 79]. However, one of the authors reported that the use of USCOM in this setting is nonetheless limited since pulmonary pressure, which is only available invasively, is more relevant as a parameter during transplantation [79]. The second situation where USCOM may be promising is after a coronary bypass procedure, not involving valvular lesions, although further validating studies are required for this matter [80–82].

An important advantage is that it is a truly non-invasive technique that has no procedural risks. The technique is easy to learn with very short learning curve. The major disadvantage is that there is quite a proportion of unobtainable imaging by USCOM. The difference between reported cardiac output and the gold standard is in most circumstances too great. The proposed cardiac valve measurements are often significantly different from the echocardiographic-measured valve area.

DISCUSSION

In this review we have tried to give the reader an overview of the presently available cardiac output monitoring devices. There is a large and interesting spectrum of devices that each work by different technology. All of them have their advantages and disadvantages. None of the devices consistently shows a percentage error in the acceptable range according to the criteria set by Critchley and Critchley. Therefore, at this moment, there are insufficient data for any of the devices with regard to interchangeability with a gold standard calibrated technique, such as (transpulmonary) thermodilution. As stated previously, in cases of refractory shock with significant changes in preload, afterload and contractility, calibrated techniques are preferred. On the other hand, they require either invasive catheters or a skilled operator (in the case of echocardiography) to accurately measure cardiac output. Therefore, we believe that there is a place for less invasive devices in today's clinical practice. Moreover, as some patients can be stabilized with just an arterial and central venous line, we suggest a stepwise approach with escalation in hemodynamic monitoring. Escalation should be performed in any situation of persistent shock, new organ failure (e.g. development of respiratory insufficiency or evolution to ARDS) or when confronted with a therapeutic dilemma. A therapeutic dilemma is a situation

Table 3. Escalation in hemodynamic monitoring from arterial line to more invasive techniques, with a list of different parameters and information that can be obtained, as well as the therapeutic options

Device	Hemodynamic parameters	Clinical information	Treatment options
A-line	MAP	Afterload	Vasopressors
A-line + PPV	PPV	Fluid responsiveness	Fluids
PLR/EEO tests	Dynamic test	Fluid responsiveness	Fluids
CVL	CVP, $S_{cv}O_2$	Barometric preload, tissue O_2	Fluids, inotropes
Uncalibrated CO	CO, SV, SVV, dPmax	Contractility, flow	Fluids, vasopressors, inotropes
Calibrated CO	GEDVI, EVLWI, GEF	Contractility, flow, volumetric preload, organ function	Fluids, vasopressors, inotropes, de-resuscitation
PAC	PAP, PAOP	Flow, barometric preload, organ function	NO, inotropes (PDI)

A-line — arterial line; CO — cardiac output; CVL — central venous line; CVP — central venous pressure; EEO — end-expiratory occlusion; EVLWI — extravascular lung water index; GEDVI — global end-diastolic volume index; GEF — global ejection fraction; NO — nitric oxide; PAOP — pulmonary artery occlusion pressure; PAP — pulmonary artery pressure; PDI — phosphodiesterase inhibitors; PLR — passive leg raising; PPV — pulse pressure variation; SV — stroke volume; SVV — stroke volume variation

where each of the possible therapeutic options carries some possible harm and forms the greatest challenge in critical care. Escalation should be seen with respect to the monitoring technique, the parameters that can be obtained and the different therapeutic options linked to the hemodynamic profile. With regard to treatment options, the main choices are starting, increasing or withdrawing fluids, vasopressors and/or inotropes. Table 3 lists the different escalation options, assuming baseline monitoring in all patients with an arterial line and central venous line in combination with transthoracic echocardiography. De-escalation can be performed when the patient responds to initial treatment and stabilizes.

The exact choice of the device to use depends on the situation. In the initial setting, such as the emergency department where invasive arterial pressure monitoring is not readily available (because of time constraints), non-invasive techniques using tonometry such as T-line, Clearsight or CNAP can give valuable information about a patient's hemodynamic status and fluid responsiveness. Transthoracic echocardiography should always be seen as an adjunct. In this setting, tracking capabilities to readily evaluate a response to fluid resuscitation therapy may be sufficient. The inability of uncalibrated devices to deal with changes in vascular tone makes them less useful and reliable in the ICU setting. In situations of shock with the need for vasoactive medication, calibrated devices are recommended.

In the perioperative setting, choosing the best device depends not only upon the suspected severity and duration of the surgery and underlying patient comorbidities but also on the length of the procedure to place the device and how much access one has to the patient. It is evident that monitoring techniques, such as TTE, have no place if the only uncovered area is the head or feet of one's patient.

Preferably, in low risk surgery with healthy patients, only non-invasive techniques should be used.

When large hemodynamic changes and fluid shifts are expected and the use of vasoactive medication is probable, a device that is accurate in order to assess fluid responsiveness but fails to adapt to changes in vascular tone, will not prove useful. Here, the risk of complications from more invasive devices must be weighed against the need for accurate and reliable parameters.

Larger interventions (e.g. laparotomies or thoracotomies) in otherwise healthy patients, or smaller surgery in at-risk patients with high ASA scores, can generally be managed with minimally invasive techniques, such as pulse contour analysis or esophageal Doppler. Pulse contour analysis can also be used to measure fluid responsiveness and continuous cardiac output. However, once again the question arises whether the technique needs to be accurate and interchangeable with the gold standard or whether a precise technique is preferred that allows good tracking of changes in hemodynamics (Fig. 1). More invasive techniques, such as PiCCO will give the added value of volumetric preload (GEDVI) and extravascular lung water. Practically, however, it is more time-consuming to calibrate this device. The clinician will also not have the option of choosing where they want to place the catheters. Depending on the site of operation, this may cause lively discussions between surgeons and anaesthetists. Choosing a less favourable site for the catheter may result in less accurate readings. In these settings, it may be favourable to use a simpler and less invasive pulse-contour analysis device, such as Vigileo or Pulsioflex.

Recent studies have shown that the oesophageal Doppler devices are more cost-effective compared to their counterparts. Although the CardioQ is recommended by the NICE guidelines, the Hemosonic does offer the advantage of M-mode, which provides more accurate readings of aortic volume (which in turn provides more accurate cardiac output measurements) and more reproducible probe po-

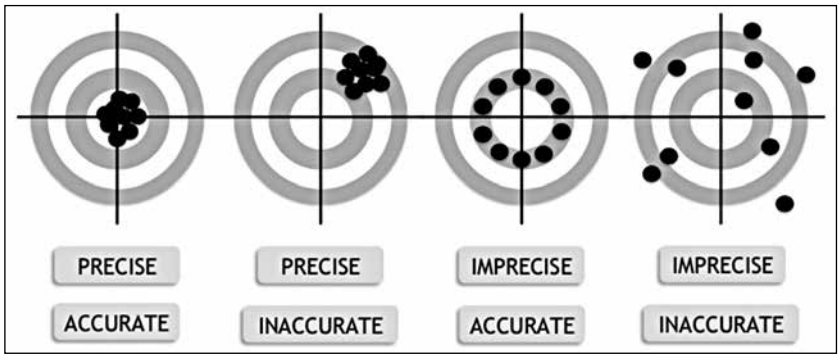

Figure 1. Cartoon showing difference between precision and accuracy. A new cardiac output technique needs to be both precise and accurate in order to be used interchangeably with the gold standard CO measurement method. However, in order to keep track of changes (and to assess the effect of diagnostic and therapeutic interventions), precision is more important than accuracy. See text for explanation. Adapted from Cecconi et al. (add reference 92)

sitioning. Although these devices require less experience than actual transesophageal echocardiography, they also dislocate more easily. Moreover, they are very susceptible to artifacts (especially during coagulation). Furthermore, just as with pulse contour analysis, the results are less accurate when cardiac arrhythmias are present (e.g. atrial fibrillation, frequent SVES of VES).

Septic or otherwise-critically ill patients undergoing high-risk surgery may need even more invasive monitoring techniques. Here, the choice between PAC and transesophageal echocardiography is usually decided by the experience of the anaesthetist. TEE has a very steep and long learning curve. A PAC, on the other hand, may be more feasible when the patient will need a central line anyway. While TEE gives an actual view of the problem, PAC leaves us to wonder, and acts like a politician, i.e. although it seems to perform well, you are never sure that what it tells you is true. Recent decades' TPTD techniques have replaced the PAC in complicated high-risk surgery. Of course, in cardiac and large vascular or thoracic surgery, the use of TEE is the new standard of care. Indeed, these days it can hardly be replaced by any other technique, not only for monitoring CO and fluid responsiveness but, in many cases, also to aid and assist the surgeon in visualizing areas of interest (insertion of cannulas or balloons, crossing the atrial septum during percutaneous valve implant, assessment of residual valve leakage after valve replacement surgery etc.).

In the end, it all comes down to the same conclusions: different patients have different needs and many surgical interventions come with their own challenges. The choice between non-, less- minimallly- and invasive monitoring needs to be evaluated for every case individually, while the risk for complications must be weighed against the benefits of having advanced hemodynamic monitoring.

The same rules apply to the ICU patient population. Especially during the most critical period of severe shock with ever changing preload (fluids), afterload (pressors) and contractility (inotropes), a calibrated cardiac output monitoring device (with volumetric preload and fluid responsiveness parameters) is the only method of choice. There is just too little evidence to support less or minimally invasive techniques. De-resuscitation should be guided by volumetric indices like extravascular lung water. After the de-resuscitation phase (when the patient stabilizes), de-escalation to a less invasive cardiac output measurement method can be evaluated especially when removal of catheters is preferable (in case of suspected line infection). The most accurate measurements in this setting can be reached by using transthoracic echocardiography; therefore TTE training in order to acquire the required skills should be incorporated in the core critical care curriculum. In absence of this expertise, one of the above-mentioned uncalibrated methods could be used. There is not one method which may be promoted as the best, since all have comparably high percentages of error. It is important to keep in mind that with all these devices the exact value is certainly not to be trusted. The trend could, however, offer an opportunity to the ICU clinician to re-evaluate the patients' response to treatment (Fig. 1). However, clinical data in this setting is often lacking.

CONCLUSIONS

After the scientific earthquake caused by the negative studies on the use of the PAC in critically ill patients in the 1990s, critical care physicians started using fewer PACs in their ICUs, especially in Europe. However, not using any kind of invasive or less-invasive monitoring may lead to a literal and figurative dead-end. Although it may sometimes be better to have a lucky doctor instead of a smart one (especially if the patient survives), as Samuel Shem nicely stated: "If you don't take a temperature, you can't find a fever" (in "The House of God" ISBN 0-440-13368-8). Thus, by defini-

tion, if you want to treat a patient with shock, you should measure cardiac output. Some believe one is always better off trying to do something even if one fails, rather than doing nothing and succeeding; therefore, doing some kind of hemodynamic monitoring will preserve our knowledge base and keep us intelligent human beings, not because we think we know everything without questioning it, but rather because we question everything we think we know. Moreover, in an analogy with medication where there are no bad antibiotics but only bad bugs, we conclude that many of the less or non-invasive hemodynamic monitoring technologies available nowadays can provide the clinician with useful additional and new information that can help or alter our decision-making and treatment strategies. The main issue is that a new technique needs to be both precise and accurate if we want to use it interchangeably with the gold standard CO measurement method. However, in order to keep track of changes (and to assess the effect of our therapeutic interventions), precision is more important than accuracy (Fig. 1). Each technology is different, needs to be assessed on its own merits and has a certain learning curve.

Advanced hemodynamic monitoring is recommended in complex situations or patients with shock who do not respond to initial fluid resuscitation. Calibrated techniques offer the best precision and accuracy, while the volumetric estimates of preload status that can be obtained with some of them, such as GEDVI, are of significant value in the hemodynamic optimization of traumatically injured patients. This volumetric assessment is especially useful in patients with increased intra-abdominal pressure or patients with changing ventricular compliance and elevated intrathoracic pressure in whom traditional intracardiac filling pressure measurements, such as PAOP and CVP, may be erroneously elevated and difficult to interpret as they are zero-referenced against atmospheric and not intrathoracic pressure. Reliance on such pressures to guide resuscitation can lead to inappropriate therapeutic decisions, under- or over-resuscitation, and subsequent organ failure. Pulse contour analysis has the potential to significantly improve the speed and accuracy of patient resuscitation following surgery or traumatic injury. The functional hemodynamic parameters of PPV and SVV may even prove to be superior in the assumption that the patient is in regular sinus rhythm and fully sedated under controlled mechanical ventilation.

ACKNOWLEDGEMENTS

1. The authors declare no financial disclosure.
2. Manu L.N.G. Malbrain is founding president and current Treasurer of the World Society of Abdominal Compartment Syndrome (WSACS, www.wsacs.org) and member of the medical advisory board of Pulsion Medical Systems (Maquet Getinge group). The other authors declare no potential conflict of interest with regard to the content of this paper.

References:

1. *Cecconi M, Malbrain ML:* Cardiac output obtained by pulse pressure analysis: to calibrate or not to calibrate may not be the only question when used properly. Intensive Care Med 2013; 39: 787–789. doi: 10.1007/s00134-012-2802-y.
2. *Malbrain ML, Reuter DA:* Hemodynamic treatment algorithms should follow physiology or they fail to improve outcome. Crit Care Med 2012; 40: 2923–2924. doi: 10.1097/CCM.0b013e31825f6cd0.
3. *Bland JM, Altman DG:* Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307–310.
4. *Critchley LA, Critchley JA:* A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. J Clin Monit Comput 1999; 15: 85–91.
5. *Perrino AC, O'Connor T, Luther M:* Transtracheal Doppler cardiac output monitoring: comparison to thermodilution during noncardiac surgery. Anesth Analg 1994; 78: 1060–1066.
6. *Critchley LA, Lee A, Ho AM:* A critical review of the ability of continuous cardiac output monitors to measure trends in cardiac output. Anesth Analg 2010; 111: 1180–1192. doi: 10.1213/ANE.0b013e3181f08a5b.
7. *Critchley LA, Yang XX, Lee A:* Assessment of trending ability of cardiac output monitors by polar plot methodology. J Cardiothorac Vasc Anesth 2011; 25: 536–546. doi: 10.1053/j.jvca.2011.01.003.
8. *Manecke GR, Jr.:* Edwards FloTrac sensor and Vigileo monitor: easy, accurate, reliable cardiac output assessment using the arterial pulse wave. Expert Rev Med Devices 2005; 2: 523–527.
9. *Button D, Weibel L, Reuthebuch O, Genoni M, Zollinger A, Hofer CK:* Clinical evaluation of the FloTrac/Vigileo system and two established continuous cardiac output monitoring devices in patients undergoing cardiac surgery. Br J Anaesth 2007; 99: 329–336.
10. *Cannesson M, Attof Y, Rosamel P, Joseph P, Bastien O, Lehot JJ:* Comparison of FloTrac cardiac output monitoring system in patients undergoing coronary artery bypass grafting with pulmonary artery cardiac output measurements. Eur J Anaesthesiol 2007; 24: 832–839.
11. *de Waal EE, Kalkman CJ, Rex S, Buhre WF:* Validation of a new arterial pulse contour-based cardiac output device. Crit Care Med 2007; 35: 1904–1909.
12. *Mayer J, Boldt J, Schollhorn T, Rohm KD, Mengistu AM, Suttner S:* Semi-invasive monitoring of cardiac output by a new device using arterial pressure waveform analysis: a comparison with intermittent pulmonary artery thermodilution in patients undergoing cardiac surgery. Br J Anaesth 2007; 98: 176–182.
13. *Marqué S, Gros A, Chimot L, Gacouin A, Lavoué S, Camus C, Le Tulzo Y:* Cardiac output monitoring in septic shock: evaluation of the third-generation Flotrac-Vigileo. J Clin Monit Comput 2013; 27: 273–279. doi: 10.1007/s10877-013-9431-z.
14. *Slagt C, Beute J, Hoeksema M, Malagon I, Mulder JW, Groeneveld JA:* Cardiac output derived from arterial pressure waveform analysis without calibration vs. thermodilution in septic shock: evolving accuracy of software versions. Eur J Anaesthesiol 2010; 27: 550–554. doi: 10.1097/EJA.0b013e3283333a92.
15. *Slagt C, de Leeuw MA, Beute J et al.:* Cardiac output measured by uncalibrated arterial pressure waveform analysis by recently released software version 3.02 versus thermodilution in septic shock. J Clin Monit Comput 2013; 27: 171–177. doi: 10.1007/s10877-012-9410-9.
16. *De Backer D, Marx G, Tan A et al.:* Arterial pressure-based cardiac output monitoring: a multicenter validation of the third-generation software in septic patients. Intensive Care Med 2011; 37: 233–240. doi: 10.1007/s00134-010-2098-8.
17. *Sakka SG, Kozieras J, Thuemer O, van Hout N:* Measurement of cardiac output: a comparison between transpulmonary thermodilution and uncalibrated pulse contour analysis. Br J Anaesth 2007; 99: 337–342.
18. *Junttila EK, Koskenkari JK, Ohtonen PP, Ala-Kokko TI:* Uncalibrated arterial pressure waveform analysis for cardiac output monitoring is biased by low peripheral resistance in patients with intracranial haemorrhage. Br J Anaesth 2011; 107: 581–586. doi: 10.1093/bja/aer170.
19. *Su BC, Tsai YF, Chen CY, Yu HP, Yang MW, Lee WC, Lin CC:* Cardiac output derived from arterial pressure waveform analysis in patients undergoing liver transplantation: validity of a third-generation device. Transplant Proc 2012; 44: 424–428. doi: 10.1016/j.transproceed.2011.12.036.

20. *Tejedor A, Rivas E, Ríos J et al.:* Accuracy of Vigileo/Flotrac monitoring system in morbidly obese patients. J Crit Care 2015; 30: 562–566. doi: 10.1016/j.jcrc.2015.01.015.
21. *Monnet X, Vaquer S, Anguel N et al.:* Comparison of pulse contour analysis by Pulsioflex and Vigileo to measure and track changes of cardiac output in critically ill patients. Br J Anaesth 2015; 114: 235–243.
22. *Salzwedel C, Puig J, Carstens A et al.:* Perioperative goal-directed hemodynamic therapy based on radial arterial pulse pressure variation and continuous cardiac index trending reduces postoperative complications after major abdominal surgery: a multi-center, prospective, randomized study. Crit Care 2013; 17: R191. doi: 10.1186/cc12885.
23. *Phan TD, Kluger R, Wan C, Wong D, Padayachee A:* A comparison of three minimally invasive cardiac output devices with thermodilution in elective cardiac surgery. Anaesth Intensive Care 2011; 39: 1014–1021.
24. *Costa MG, Chiarandini P, Scudeller L et al.:* Uncalibrated continuous cardiac output measurement in liver transplant patients: LiDCOrapid™ system versus pulmonary artery catheter. J Cardiothorac Vasc Anesth 2014; 28: 540–546. doi: 10.1053/j.jvca.2013.12.027.
25. *Broch O, Renner J, Höcker J et al.:* Uncalibrated pulse power analysis fails to reliably measure cardiac output in patients undergoing coronary artery bypass surgery. Crit Care 2011; 15: R76. doi: 10.1186/cc10065.
26. *Cecconi M, Dawson D, Casaretti R, Grounds RM, Rhodes A:* A prospective study of the accuracy and precision of continuous cardiac output monitoring devices as compared to intermittent thermodilution. Minerva Anestesiol 2010; 76: 1010–1017.
27. *Cecconi M, Fawcett J, Grounds RM, Rhodes A:* A Prospective study to evaluate the accuracy of pulse power analysis to monitor cardiac output in critically ill patients. BMC Anesthesiol 2008; 8: 3. doi: 10.1186/1471-2253-8-3.
28. *Scolletta S, Romano SM, Biagioli B, Capannini G, Giomarelli P:* Pressure recording analytical method (PRAM) for measurement of cardiac output during various haemodynamic states. Br J Anaesth 2005; 95: 159–165.
29. *Schloglhofer T, Gilly H, Schima H:* Semi-invasive measurement of cardiac output based on pulse contour: a review and analysis. Can J Anaesth 2014; 61: 452–479. doi: 10.1007/s12630-014-0135-8.
30. *Maj G, Monaco F, Landoni G et al.:* Cardiac index assessment by the pressure recording analytic method in unstable patients with atrial fibrillation. J Cardiothorac Vasc Anesth 2011; 25: 476–480. doi: 10.1053/j.jvca.2010.09.027.
31. *Paarmann H, Groesdonk HV, Sedemund-Adib B et al.:* Lack of agreement between pulmonary arterial thermodilution cardiac output and the pressure recording analytical method in postoperative cardiac surgery patients. Br J Anaesth 2011; 106: 475–481. doi: 10.1093/bja/aeq372.
32. *Berton C, Cholley B:* Equipment review: new techniques for cardiac output measurement –– oesophageal Doppler, Fick principle using carbon dioxide, and pulse contour analysis. Crit Care 2002; 6: 216–221.
33. *Benatar SR, Hewlett AM, Nunn JF:* The use of iso-shunt lines for control of oxygen therapy. Br J Anaesth 1973; 45: 711–718.
34. *Kotake Y, Yamada T, Nagata H et al.:* Improved accuracy of cardiac output estimation by the partial CO2 rebreathing method. J Clin Monit Comput 2009; 23: 149–155. doi: 10.1007/s10877-009-9172-1.
35. *de Abreu MG, Geiger S, Winkler T et al.:* Evaluation of a new device for noninvasive measurement of nonshunted pulmonary capillary blood flow in patients with acute lung injury. Intensive Care Med 2002; 28: 318–323.
36. *Langwieser N, Prechtl L, Meidert AS et al.:* Radial artery applanation tonometry for continuous noninvasive arterial blood pressure monitoring in the cardiac intensive care unit. Clin Res Cardiol 2015; 104: 518–524.
37. *Meidert AS, Huber W, Müller JN:* Radial artery applanation tonometry for continuous non-invasive arterial pressure monitoring in intensive care unit patients: comparison with invasively assessed radial arterial pressure. Br J Anaesth 2014; 112: 521–528. doi: 10.1093/bja/aet400.
38. *Meidert AS, Huber W, Hapfelmeier A:* Evaluation of the radial artery applanation tonometry technology for continuous noninvasive blood pressure monitoring compared with central aortic blood pressure measurements in patients with multiple organ dysfunction syndrome. J Crit Care 2013; 28: 908–912. doi: 10.1016/j.jcrc.2013.06.012.
39. ANSI/AAMI. American National Standard for Manual, Electronic or Automated Sphygmomanometers. In.: Association for the Advancement of Medical Instrumentation; 2002.
40. *Saugel B, Meidert AS, Langwieser N:* An autocalibrating algorithm for non-invasive cardiac output determination based on the analysis of an arterial pressure waveform recorded with radial artery applanation tonometry: a proof of concept pilot analysis. J Clin Monit Comput 2014; 28: 357–362. doi: 10.1007/s10877-013-9540-8.
41. *Wagner JY, Sarwari H, Schön G:* Radial artery applanation tonometry for continuous noninvasive cardiac output measurement: a comparison with intermittent pulmonary artery thermodilution in patients after cardiothoracic surgery. Crit Care Med 2015; 43: 1423–1428. doi: 10.1097/CCM.0000000000000979.
42. *Ameloot K, Palmers PJ, Malbrain ML:* The accuracy of noninvasive cardiac output and pressure measurements with finger cuff: a concise review. Curr Opin Crit Care 2015; 21: 232–239. doi: 10.1097/MCC.0000000000000198.
43. *Wagner JY, Grond J, Fortin J, Negulescu I, Schöfthaler M, Saugel B:* Continuous noninvasive cardiac output determination using the CNAP system: evaluation of a cardiac output algorithm for the analysis of volume clamp method-derived pulse contour. J Clin Monit Comput 2015 [Epub ahead of print].
44. *Summers RL, Shoemaker WC, Peacock WF, Ander DS, Coleman TG:* Bench to bedside: electrophysiologic and clinical principles of noninvasive hemodynamic monitoring using impedance cardiography. Acad Emerg Med 2003; 10: 669–680.
45. *Moshkovitz Y, Kaluski E, Milo O, Vered Z, Cotter G:* Recent developments in cardiac output determination by bioimpedance: comparison with invasive cardiac output and potential cardiovascular applications. Curr Opin Cardiol 2004; 19: 229–237.
46. *Peyton PJ, Chong SW:* Minimally invasive measurement of cardiac output during surgery and critical care: a meta-analysis of accuracy and precision. Anesthesiology 2010; 113: 1220–1235. doi: 10.1097/ALN.0b013e3181ee3130.
47. *Squara P, Denjean D, Estagnasie P, Brusset A, Dib JC, Dubois C:* Noninvasive cardiac output monitoring (NICOM): a clinical validation. Intensive Care Med 2007; 33: 1191–1194.
48. *Marqué S, Cariou A, Chiche JD, Squara P:* Comparison between Flotrac-Vigileo and Bioreactance, a totally noninvasive method for cardiac output monitoring. Crit Care 2009; 13: R73. doi: 10.1186/cc7884.
49. *Kober D, Trepte C, Petzoldt M et al.:* Cardiac index assessment using bioreactance in patients undergoing cytoreductive surgery in ovarian carcinoma. J Clin Monit Comput 2013; 27: 621–627. doi: 10.1007/s10877-013-9478-x.
50. *Møller-Sørensen H, Hansen KL, Østergaard M, Andersen LW, Møller K:* Lack of agreement and trending ability of the endotracheal cardiac output monitor compared with thermodilution. Acta Anaesthesiol Scand 2012; 56: 433–440. doi: 10.1111/j.1399-6576.2011.02615.x.
51. *Maus TM, Reber B, Banks DA, Berry A, Guerrero E, Manecke GR:* Cardiac output determination from endotracheally measured impedance cardiography: clinical evaluation of endotracheal cardiac output monitor. J Cardiothorac Vasc Anesth 2011; 25: 770–775. doi: 10.1053/j.jvca.2010.12.017.
52. *Ball TR, Culp BC, Patel V, Gloyna DF, Ciceri DP, Culp WC:* Comparison of the endotracheal cardiac output monitor to thermodilution in cardiac surgery patients. J Cardiothorac Vasc Anesth 2010; 24: 762–766. doi: 10.1053/j.jvca.2010.04.008.
53. *Maass SW, Roekaerts PM, Lance MD:* Cardiac output measurement by bioimpedance and noninvasive pulse contour analysis compared with the continuous pulmonary artery thermodilution technique. J Cardiothorac Vasc Anesth 2014; 28: 534–539. doi: 10.1053/j.jvca.2014.01.007.
54. *Biais M, Berthezene R, Petit L, Cottenceau V, Sztark F:* Ability of esCCO to track changes in cardiac output. Br J Anaesth 2015; 115: 403–410. doi: 10.1093/bja/aev219.
55. *Feissel M, Aho LS, Georgiev S et al.:* Pulse wave transit time measurements of cardiac output in septic shock patients: a comparison of the estimated continuous cardiac output system with transthoracic echocardiography. PLoS ONE 2015; 10: e0130489. doi: 10.1371/journal.pone.0130489.
56. *Fischer MO, Balaire X, Le Mauff de et al.:* The diagnostic accuracy of estimated continuous cardiac output compared with transthoracic echocardiography. Can J Anaesth 2014; 61: 19–26. doi: 10.1007/s12630-013-0055-z.
57. *Bataille B, Bertuit M, Mora M et al.:* Comparison of esCCO and transthoracic echocardiography for non-invasive measurement of cardiac output intensive care. Br J Anaesth 2012; 109: 879–886. doi: 10.1093/bja/aes298.
58. *Thonnerieux M, Alexander B, Binet C, Obadia JF, Bastien O, Desebbe O:* The ability of esCCO and ECOM monitors to measure trends in cardiac output during alveolar recruitment maneuver after cardiac surgery: a comparison with the pulmonary thermodilution method. Anesth Analg 2015; 121: 383–391. doi: 10.1213/ANE.0000000000000753.

59. *Ball TR, Tricinella AP, Kimbrough BA et al.:* Accuracy of noninvasive estimated continuous cardiac output (esCCO) compared to thermodilution cardiac output: a pilot study in cardiac patients. J Cardiothorac Vasc Anesth 2013; 27: 1128–1132. doi: 10.1053/j.jvca.2013.02.019.
60. *Sinha AC, Singh PM, Grewal N, Aman M, Dubowitz G:* Comparison between continuous non-invasive estimated cardiac output by pulse wave transit time and thermodilution method. Ann Card Anaesth 2014; 17: 273–277. doi: 10.4103/0971-9784.142059.
61. *Ishihara H, Sugo Y, Tsutsui M et al.:* The ability of a new continuous cardiac output monitor to measure trends in cardiac output following implementation of a patient information calibration and an automated exclusion algorithm. J Clin Monit Comput 2012; 26: 465–471. doi: 10.1007/s10877-012-9384-7.
62. *Permpikul C, Leelayuthachai T:* Non-invasive estimated continuous cardiac output (escCO) during severe sepsis and septic shock resuscitation. J Med Assoc Thai 2014; 97 (Suppl 3): S184–188.
63. Yamada T, Tsutsui M, Sugo Y et al.: Multicenter study verifying a method of noninvasive continuous cardiac output measurement using pulse wave transit time: a comparison with intermittent bolus thermodilution cardiac output. Anesth Analg 2012; 115: 82–87. doi: 10.1213/ANE.0b013e31824e2b6c.
64. *Tsutsui M, Yamada T, Sugo Y et al.:* Comparison of continuous cardiac output measurement methods: non-invasive estimated CCO using pulse wave transit time and CCO using thermodilution. Masui 2012; 61: 1011–1017.
65. *Van den Oever HL, Murphy EJ, Christie-Taylor GA:* USCOM (Ultrasonic Cardiac Output Monitors) lacks agreement with thermodilution cardiac output and transoesophageal echocardiography valve measurements. Anaesth Intensive Care 2007; 35: 903–910.
66. Huang L, Critchley LA: Study to determine the repeatability of supra–sternal Doppler (ultrasound cardiac output monitor) during general anaesthesia: effects of scan quality, flow volume, and increasing age. Br J Anaesth 2013; 111: 907–915. doi: 10.1093/bja/aet254.
67. *Beltramo F, Menteer J, Razavi A et al.:* Validation of an ultrasound cardiac output monitor as a bedside tool for pediatric patients. Pediatr Cardiol 2015 [Epub ahead of print].
68. *McNamara H, Barclay P, Sharma V:* Accuracy and precision of the ultrasound cardiac output monitor (USCOM 1A) in pregnancy: comparison with three-dimensional transthoracic echocardiography. Br J Anaesth 2014; 113: 669–676. doi: 10.1093/bja/aeu162.
69. *Knirsch W, Kretschmar O, Tomaske M et al.:* Cardiac output measurement in children: comparison of the Ultrasound Cardiac Output Monitor with thermodilution cardiac output measurement. Intensive Care Med 2008; 34: 1060–1064. doi: 10.1007/s00134-008-1030-y.
70. *Zheng ML, Sun X, Zhong J et al.:* Clinical study of neonatal cardiac output measurement methods. Zhonghua Er Ke Za Zhi 2013; 51: 58–63.
71. *Thom O, Taylor DM, Wolfe RE et al.:* Comparison of a supra-sternal cardiac output monitor (USCOM) with the pulmonary artery catheter. Br J Anaesth 2009; 103: 800–804. doi: 10.1093/bja/aep296.
72. *Boyle M, Steel L, Flynn GM et al.:* Assessment of the clinical utility of an ultrasonic monitor of cardiac output (the USCOM) and agreement with thermodilution measurement. Crit Care Resusc 2009; 11: 198–203.
73. Nguyen HB, Banta DP, Stewart G et al.: Cardiac index measurements by transcutaneous Doppler ultrasound and transthoracic echocardiography in adult and pediatric emergency patients. J Clin Monit Comput 2010; 24: 237–247. doi: 10.1007/s10877-010-9240-6.
74. Horster S, Stemmler HJ, Strecker N et al.: Cardiac Output Measurements in Septic Patients: Comparing the Accuracy of USCOM to PiCCO. Crit Care Res Pract 2012; 67: 177–185. doi: 10.1155/2012/270631.
75. *Corley A, Barnett AG, Mullany D, Fraser JF:* Nurse-determined assessment of cardiac output. Comparing a non-invasive cardiac output device and pulmonary artery catheter: A prospective observational study. Int J Nurs Stud 2009; 46: 1291–1297. doi: 10.1016/j.ijnurstu.2009.03.013.
76. *Patel N, Dodsworth M, Mills JF:* Cardiac output measurement in newborn infants using the ultrasonic cardiac output monitor: an assessment of agreement with conventional echocardiography, repeatability and new user experience. Arch Dis Child Fetal Neonatal Ed 2011; 96: F206–211. doi: 10.1136/adc.2009.170704.
77. *Dhanani S, Barrowman NJ, Ward RE, Murto KT:* Intra- and inter-observer reliability using a noninvasive ultrasound cardiac output monitor in healthy anesthetized children. Paediatr Anaesth 2011; 21: 858–864. doi: 10.1111/j.1460-9592.2010.03480.x.
78. *Su BC, Lin CC, Su CW et al.:* Ultrasonic cardiac output monitor provides accurate measurement of cardiac output in recipients after liver transplantation. Acta Anaesthesiol Taiwan 2008; 46: 171–177. doi: 10.1016/S1875-4597(09)60005-9.
79. Wong LS, Yong BH, Young KK et al.: Comparison of the USCOM ultrasound cardiac output monitor with pulmonary artery catheter thermodilution in patients undergoing liver transplantation. Liver Transpl 2008; 14: 1038–1043. doi: 10.1002/lt.21483.
80. *Arora D, Chand R, Mehta Y, Trehan N:* Cardiac output estimation after off-pump coronary artery bypass: a comparison of two different techniques. Ann Card Anaesth 2007; 10: 132–136.
81. *Chan JS, Segara D, Nair P:* Measurement of cardiac output with a non-invasive continuous wave Doppler device versus the pulmonary artery catheter: a comparative study. Crit Care Resusc 2006; 8: 309–314.
82. *Tan HL, Pinder M, Parsons R, Roberts B, van Heerden PV:* Clinical evaluation of USCOM ultrasonic cardiac output monitor in cardiac surgical patients in intensive care unit. Br J Anaesth 2005; 94: 287–291.
83. *Mayer J, Boldt J, Schöllhorn T, Röhm KD, Mengistu AM, Suttner S:* Semi-invasive monitoring of cardiac output by a new device using arterial pressure waveform analysis: a comparison with intermittent pulmonary artery thermodilution in patients undergoing cardiac surgery. Br J Anaesth 2007; 98: 176–182.
84. De Backer D, Marx G, Tan A et al.: Arterial pressure-based cardiac output monitoring: a multicenter validation of the third-generation software in septic patients. Intensive Care Med 2011; 37: 233–240. doi: 10.1007/s00134-010-2098-8.
85. *Romano SM, Scolletta S, Olivotto I et al.:* Systemic arterial waveform analysis and assessment of blood flow during extracorporeal circulation. Perfusion 2006; 21: 109–116.
86. *Zangrillo A, Maj G, Monaco F et al.:* Cardiac index validation using the pressure recording analytic method in unstable patients. J Cardiothorac Vasc Anesth 2010; 24: 265–269. doi: 10.1053/j.jvca.2009.09.019.
87. *Scolletta S, Franchi F, Taccone FS, Donadello K, Biagioli B, Vincent JL:* An uncalibrated pulse contour method to measure cardiac output during aortic counterpulsation. Anesth Analg 2011; 113: 1389–1395. doi: 10.1213/ANE.0b013e318230b2de.
88. *Franchi F, Silvestri R, Cubattoli L et al.:* Comparison between an uncalibrated pulse contour method and thermodilution technique for cardiac output estimation in septic patients. Br J Anaesth 2011; 107: 202–208. doi: 10.1093/bja/aer123.
89. *Terada T, Maemura Y, Yoshida A, Muto R, Ochiai R:* Evaluation of the estimated continuous cardiac output monitoring system in adults and children undergoing kidney transplant surgery: a pilot study. J Clin Monit Comput 2014; 28: 95–99. doi: 10.1007/s10877-013-9501-2.
90. *Wacharasint P, Kunakorn P, Pankongsap P, Preechanukul R:* Clinical validation of pulse contour and pulse wave transit time-based continuous cardiac output analyses in Thai patients undergoing cardiac surgery. J Med Assoc Thai 2014; 97 (Suppl 1): S55–60.
91. *Chong SW, Peyton PJ:* A meta-analysis of the accuracy and precision of the ultrasonic cardiac output monitor (USCOM). Anaesthesia 2012; 67: 1266–1271. doi: 10.1111/j.1365-2044.2012.07311.x.
92. *Cecconi M, Rhodes A, Poloniecki J, Della Rocca G, Grounds RM*: Bench-to-bedside review: The importance of the precision of the reference technique in method comparison studies — with specific reference to the measurement of cardiac output. Critical Care 2009; 13: 201. doi:10.1186/cc7129.
93. *Saugel B, Wagner JY, Wendon J, Perel A:* Getting the full diagnostic picture in intensive care medicine: a plea for "physiological examination". Ann Am Thorac Soc 2015; 12: 1738–1739. doi: 10.1513/AnnalsATS.201509-571LE.

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Otzrymano: 26.08.2015 r.
Zaakceptowano: 13.11.2015 r.