

Minimally Invasive Monitoring of Cardiac Output in the Cardiac Surgery Intensive Care Unit

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Published online: 10 July 2010
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Abstract Cardiac output monitoring in the cardiac surgery patient is standard practice that is traditionally performed using the pulmonary artery catheter. However, over the past 20 years, the value of pulmonary artery catheters has been challenged, with some authors suggesting that its use might be not only unnecessary but also harmful. New minimally invasive devices that measure cardiac output have become available. In this paper, we review their operative principles, limitations, and utility in an integrated approach that could potentially change patients' outcome. However, it is now clear that it is how the monitor is used (ie, the protocol

or therapy associated with its use, or its lack thereof), and not the monitor per se, that should be questioned when a patient's outcome is being evaluated.

Keywords Cardiac output monitoring · Minimally invasive · Cardiac surgery · Intensive care · Pulse wave analysis · Pulse contour analysis · Esophageal Doppler · Bioreactance · Partial CO₂ rebreathing · Preload · Functional hemodynamics

Introduction

Cardiac output (CO) measurement in the cardiac surgery patient is commonplace and helps in making informed therapeutic decisions when faced with hemodynamic perturbations in the perioperative period. Traditionally, the pulmonary artery catheter (PAC) has been used to measure CO in this patient population, and there are many centers around the world that still use this clinical standard. However, there is a growing body of evidence that suggests that new noninvasive devices that estimate CO in the cardiac surgery population are equally effective when compared with PAC. Although the utilization of PAC has decreased remarkably over the past 20 years following the publication of several studies that questioned the impact of its use on patient outcome [1, 2], the PAC still has a role in patient management under certain clinical conditions where the reliability of the currently available minimally invasive devices is questionable. In fact, some of the first studies demonstrating the benefit of hemodynamic optimization were conducted using PAC [3]; however, discussing the PAC is beyond the scope of this review. Nonetheless, before describing the new less invasive devices that measure CO, it is important to remember that it is the

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protocol or therapy guided by the monitor, and not the monitor itself, that changes patient outcome. This hemodynamic truth has been shown in different randomized controlled trials conducted in the past years [4].

Minimally invasive CO monitoring devices use one of four main principles to measure CO: pulse contour analysis, pulsed Doppler technology, applied Fick's principle, and bioimpedance/bioreactance. Devices that use pulse contour analysis also may be classified into uncalibrated and calibrated systems. Regardless of their classification and their underlying operative principles, the ease of use of these minimally invasive devices and the additional hemodynamic variables that they provide have made them very attractive compared with the traditional PAC. This potentially could result in their widespread application in any group of patients with potential hemodynamic perturbations in whom goal-directed hemodynamic optimization is of paramount importance. However, before adopting any particular technology and using it in daily clinical practice, one has to consider different institution-, device-, and patient-related factors.

The aim of this article is to review the most commonly used minimally invasive devices that measure CO continuously in the cardiac surgery intensive care unit (ICU). In addition, an integrated approach for the use of these different devices in cardiac surgery patients will be presented, taking into consideration not only their invasiveness and typical limitations, but also any additional hemodynamic variables that these new minimally invasive devices may offer.

Factors Influencing Selection of Cardiac Output Monitoring Devices

A variety of factors may affect the selection of CO monitoring devices in a cardiac surgery ICU setting. These factors can be classified into three major groups (Table 1). Institutional factors often are considered the most important ones in daily practice. A specific technique of minimally invasive CO monitoring already may be available, a certain level of standardization between different ICUs within the same institution may be intended, or the integration of the CO measurement monitor into an existing hospital standard monitoring system may be required. Moreover, large teaching institutions may have different needs compared with smaller units with skilled and trained staff. In contrast, device- and patient-related factors are crucial in ensuring consistent and reliable measurements. It is important that the device is easy to handle and that it provides accurate CO measurement and additional hemodynamic variables, given its technical limitations, and that it also meets specific clinical requirements. Often, patient-related factors in combination with the limitations of the particular device dictate its use.

Table 1 Factors driving individual selection of cardiac output monitoring devices

Institution	Size and type of institution Availability of devices Level of uniformity/standardization Integration into standard monitoring systems Number of staff Level of experience Availability of teaching program
Device	Ease of handling Clinical requirements Technical limitations Operator dependency Accuracy and repeatability Valid trend analysis Availability of additional information Economic aspects
Patient	Type of cardiac disease Severity of disease Heart rhythm Contraindications for specific cardiac output device Type of intervention Type of perioperative protocol

Overview of Minimally Invasive Cardiac Output Monitoring Techniques

Pulse Contour Analysis

Pulse contour analysis is a minimally invasive CO monitoring technique based on the principle that stroke volume can be continuously estimated by analyzing the arterial pressure waveform obtained from an arterial line. The characteristics of the arterial pressure waveform are affected by the interaction between stroke volume and individual vascular compliance, aortic impedance, and peripheral arterial resistance. Currently, there are different commercially available devices that measure CO based on the pulse contour analysis method. The most frequently used ones are the calibrated PiCCOplus system (PULSION Medical Systems, Munich, Germany); the LiDCO monitoring system (LiDCO Ltd., London, UK), which is available as either a calibrated (LiDCOplus) or uncalibrated device (LiDCOrapid); and the uncalibrated FloTrac/Vigileo device (Edwards Lifesciences, Irvine, CA). In the near future, uncalibrated and calibrated systems will be available from PULSION Medical Systems and Edwards Lifesciences, respectively.

The PiCCOplus System

The PiCCOplus system employs a dedicated thermistor-tipped catheter, which is typically placed in the femoral

artery, to track changes in stroke volume on a beat-to-beat basis. As an alternative, a radial or brachial catheter may be used; however, such catheters have to be longer than the femoral one to assess aortic pressure wave signal adequately. A central venous line is required to perform CO system calibration using transpulmonary thermodilution. This thermodilution also is used for the adjustment of the individual aortic impedance. Device calibration is necessary every 8 h in hemodynamically stable patients and needs to be done more frequently (eventually every hour) during situations of hemodynamic instability [5]. Nevertheless, a variety of studies have successfully validated the PiCCO*plus* system (by comparing it with PAC) in different patient populations including the cardiac surgery patients [6, 7].

The LiDCO Systems

CO measurement using the LiDCO*plus* system relies on pulse power analysis, which is based on the principle of mass/power conservation in a system and the assumption that, following the correction for compliance and calibration, there is a linear relationship between net power and net flow in the vascular system. Using this device, the entire pulse wave, with its systolic and diastolic components, is analyzed by autocorrelation, a mathematical function that assesses repetitive signals in cycles over time. This is required to determine the change in power caused by the heart, and thus, it captures changes in stroke volume over time. The advantage of such an algorithm is that it takes into account wave reflection in the vascular system. However, the system needs to be calibrated using transpulmonary lithium indicator dilution technique, which can be performed via a peripheral venous line [8]. Clinical studies have demonstrated reliable estimation of CO using this technique as long as no major hemodynamic changes are observed [9, 10]. The reliability of the LiDCO*plus* system may be negatively affected by changes of electrolytes and hematocrit and by high peak doses of muscle relaxants, which crossreact with the lithium sensor. In addition, the system cannot be used in a patient who is taking lithium or weighs less than 40 kg.

Recently, an uncalibrated version of this device that can use any existing arterial line, the LiDCO*rapid*, has been released. The primary indication for this device is stroke volume optimization in the perioperative setting. Therefore, in LiDCO*rapid*, trend analysis is more important than absolute CO values (which may differ when compared with CO assessed by PAC).

FloTrac/Vigileo System

This system requires a proprietary transducer, the FloTrac, which is attached to a standard nonproprietary radial or

femoral arterial catheter and is connected to the Vigileo monitor. In contrast to the PiCCO*plus* and the LiDCO systems, the FloTrac/Vigileo system does not require external calibration, and therefore, it is less invasive. To estimate CO, the standard deviation of pulse pressure sampled during a time window of 20 s is correlated with normal stroke volume based on the patient's demographic data (age, gender, height, and weight) and a built-in database containing information about CO assessed by PAC in a variety of clinical scenarios. Impedance also is derived from these data, whereas vascular compliance and resistance are determined using arterial waveform analysis. In the first generation algorithm, adjustment for the vascular status was performed every 10 min. However, based on the results of the early validation studies, a major modification of the algorithm (generation 2 software) was a reduction of this time window to 1 min [11]. Studies using this modified algorithm showed improved CO estimation [12–14]. Newer software modifications (generation 3) addressing the issue of limited accuracy during hyperdynamic situations (eg, severe sepsis or septic shock) are currently being tested. Preliminary data showed improved performance of the device under these specific conditions.

For reliable CO measurement using all devices that employ pulse wave analysis technology, optimal arterial waveform signal (ie, eliminating damping or increasing tubing resonance) is a prerequisite. Moreover, it cannot be overemphasized that severe arrhythmias may reduce the accuracy of CO measurement, and that the use of an intraaortic balloon pump precludes adequate performance of the devices. Furthermore, pulse wave analysis may be limited during periods of hemodynamic instability, thus requiring frequent recalibration of the calibrated systems.

Doppler Measurements

CO can be estimated noninvasively using esophageal or transthoracic Doppler probes. Esophageal Doppler devices measure blood flow in the descending aorta and estimate CO by multiplying the cross-sectional area of the aorta by blood flow velocity (over time). The aortic diameter is obtained from a built-in normogram or by direct measurement using M-mode echocardiography. Several esophageal Doppler probes are available commercially: ODM II (Abbott Laboratories, Maidenhead, UK), CardioQ (Deltex Medical Ltd., Chichester, Sussex, UK), and HemoSonic 100 (Arrow Critical Care Products, Reading, PA). The latter device is a combination of a Doppler and an M-mode probe whose production has been stopped recently. There are several limitations for the use of esophageal Doppler devices. First, the device measures blood flow in the descending aorta and makes an assumption of a fixed partition between flow to

the cephalic vessels and to the descending aorta. Although this may be valid in healthy volunteers, this relationship may change in patients with comorbidities and under conditions of hemodynamic instability. Second, Doppler probes are smaller than the conventional transesophageal echocardiography probes and position may change unintentionally, thus limiting continuous CO assessment. Because probe position is crucial to obtaining an accurate measurement of aortic blood flow, this device is operator dependent [15], and studies have shown that 10 to 12 insertions are required to obtain accurate measurements [16] with an intraobserver and interobserver variability of 8% to 12% [17]. Third, aortic cross-sectional area is not constant, but rather dynamic, in any individual patient. Thus, the use of a nomogram may result in less accurate CO estimation. Nevertheless, a meta-analysis of 11 clinical trials concluded that esophageal Doppler-derived CO has a high validity in monitoring CO in critically ill patients [18]. However, these studies generally were performed in patients under stable hemodynamic conditions. In contrast, esophageal Doppler had poor agreement with PAC in patients undergoing off-pump coronary artery bypass surgery [19, 20]. Based on these inherent limitations of esophageal Doppler devices, their utility appears to be limited to patients in the cardiac surgery population who are hemodynamically stable and in the presence of skilled operators. Alternatively, the transthoracic approach may be used to assess CO, albeit intermittently. The USCOM device (USCOM, Sydney, Australia) targets the pulmonary and aortic valves accessed via the parasternal and suprasternal windows to assess CO. Validation studies have revealed conflicting results [21–23], which could be explained primarily by the inherent problem of variable signal detection. Another limitation of this device is the fact that CO only can be assessed intermittently; therefore, the utility of the USCOM device is limited in the cardiac surgery ICU, where continuous measurement of CO often is desirable.

Bioimpedance and Bioreactance

Electrical bioimpedance uses electric current stimulation for identification of thoracic or body impedance variations induced by cyclic changes in blood flow caused by the heart beating. CO is continuously estimated, using skin electrodes, by analyzing the occurring signal variation based on different mathematical models. Despite many adjustments of the mathematical algorithms, clinical validation studies continue to show conflicting results [24–27]. Recently, however, bioreactance (NICOM; Cheetah Medical, Portland, OR, USA), a modification of the thoracic bioimpedance, has been introduced [28]. In contrast to bioimpedance, which is based on the analysis of

transthoracic voltage amplitude changes in response to high-frequency current, the bioreactance technique analyzes the frequency spectra variations of the delivered oscillating current. This approach is supposed to result in a higher signal-to-noise ratio, and thus, result in improved performance of the device. Indeed, the initial validation studies look promising [28, 29]. However, more clinical studies are required to address the typical limitations of this technology; namely, situations of large fluid shifts, open chest conditions, and electrical interference.

Applied Fick's Principle

The NICO system (Novamatrix Medical Systems, Wallingford, CT) applies the Fick's principle to carbon dioxide (CO₂) to obtain CO measurement in intubated, sedated, and mechanically ventilated patients using a proprietary disposable rebreathing loop that is attached to the ventilator circuit. The NICO system consists of a mainstream infrared sensor to measure CO₂, a disposable airflow sensor, and a pulse oximeter. CO₂ production is calculated as the product of CO₂ concentration and airflow during a breathing cycle, whereas arterial CO₂ content is derived from end-tidal CO₂ and its corresponding dissociation curve. Every 3 min, a partial rebreathing state is generated by the machine using the attached rebreathing loop, which results in an increased end-tidal CO₂ and reduced CO₂ elimination. Assuming that CO does not change significantly between normal and rebreathing states, the difference between normal and rebreathing ratios are used to calculate CO. There are several limitations to this device, including the need for intubation and mechanical ventilation with fixed ventilator settings and minimal gas exchange abnormalities [30]. Variations in ventilator settings, mechanically assisted spontaneous breathing, the presence of increased pulmonary shunt fraction, and hemodynamic instability have been associated with decreased precision of the device [31, 32]. In addition, validation studies have shown poor agreement between the NICO device and PAC [33, 34]. Accordingly, this modality for measuring CO may not be useful in the cardiac surgery ICU.

Additional Hemodynamic Variables

In addition to stroke volume and CO estimation, some minimally invasive devices that use pulse contour analysis provide one or more additional hemodynamic variables (Table 2); namely, static preload variables, functional hemodynamic variables, and central venous oxygen saturation (ScvO₂). These variables are discussed in the following section together with their clinical utility in the cardiac surgery ICU.

Table 2 Overview of minimally invasive cardiac output monitoring techniques compared to pulmonary artery catheter

Techniques			Cardiac output		Additional variables		
Groups	Examples	Requirements	Invasiveness	Intermit/ cont	Static preload	Functional	SvO ₂ /ScvO ₂
PAC	Catheterization	Right heart	+++	+/+ PAOP	CVP	NA	SvO ₂ catheter required
Pulse wave analysis	PiCCO ^a	Central venous line, thermistor-tipped arterial catheter	++	+/+	GEDV EVLW	SVV PPV	Dedicated ScvO ₂ catheter
	LiDCO ^b	Lithium injection/detection set	+(+)	+/+	NA	SVV PPV	NA
	FloTrac/Vigileo ^c	Specific arterial pressure sensor	+	NA/+	NA	SVV	Dedicated ScvO ₂ catheter
Doppler	TE, TT	Flow probe	+	+/(+)	NA	NA	NA
Bioreactance	NICOM ^d	Cutaneous electrodes	–	NA/+	NA	NA	NA
Applied Fick's principle	PaCO ₂ -Re	Rebreathing loop	–	+/(+)	NA	NA	NA

cont continuous measurements, *CVP* central venous pressure, *EVLW* extravascular lung water, *GEDV* global end-diastolic volume, *intermit* intermittent measurements, *NA* not available, *PAC* pulmonary artery catheter, *PaCO₂-Re* partial CO₂ rebreathing, *PAOP* pulmonary artery occlusion pressure, *PPV* pulse pressure variation, *ScvO₂* central venous oxygen saturation, *SvO₂* mixed venous oxygen saturation, *SVV* stroke volume variation, *TE* transesophageal, *TT* transthoracic

^a Manufactured by PULSION Medical Systems, Munich, Germany

^b Manufactured by LiDCO Ltd., London, UK

^c Manufactured by Edwards Lifesciences, Irvine, CA

^d Manufactured by Cheetah Medical, Portland, OR

Static Preload Variables

Some minimally invasive CO monitoring devices require a central venous line for calibration of the system. Moreover, a central venous line frequently is used in cardiac surgery patients, either in the operating room or in the ICU. Therefore, central venous pressure (CVP) as an additional hemodynamic variable is briefly reviewed here. Traditionally, CVP is monitored as a surrogate marker for cardiac preload because true preload (defined as end-diastolic myocardial fiber tension) cannot be measured at the bedside. However, several factors affect CVP reading, including impaired right ventricular function, severe pulmonary disease, or valvular heart disease. Although most practicing physicians use CVP to guide fluid therapy [35], several studies have shown a lack of correlation between CVP and stroke volume [36–38••], and the fact that absolute CVP cannot be used to assess preload responsiveness cannot be overemphasized. So although readily available, the utility of CVP in guiding fluid therapy is very limited and changes in trend over time, and cyclic changes induced by mechanical ventilation are probably more important than absolute numbers.

In contrast to the static preload variable (ie, CVP), volumetric preload variables are considered to be superior indicators of “true” preload. Global end-diastolic volume (GEDV), intrathoracic blood volume (ITBV), and extra-

vascular lung water (EVLW) are static volumetric parameters that are provided by the PiCCO_{plus} device. These variables are assessed using the transpulmonary thermodilution technique, which is required for the calibration of the device. It is assumed that the injected thermal indicator passes from the site of injection in the central vein to the thermal indicator detection site (usually the femoral artery) through different central compartments that are connected in series. GEDV, ITBV, and EVLW are calculated based on the measured CO and the different indicator passage times. Different studies have shown better correlation between GEDV (or ITBV) and stroke volume than between static pressure preload and stroke volume [36, 39]. GEDV and ITBV could thus be used to guide perioperative fluid therapy better than CVP [40•]. In contrast, EVLW can be used to differentiate between cardiac and noncardiac pulmonary edema, and has been identified as an independent predictor of survival in critically ill patients [41]. Therefore, it may be of value in tailoring therapy in patients with acute respiratory distress syndrome and in the cardiac surgery patient.

Functional Hemodynamic Variables

All commercially available CO monitors that use pulse contour analysis provide an automated quantification of stroke volume variation (SVV), and some also provide

pulse pressure variation (PPV); SVV and PPV are two of the so-called functional hemodynamic variables. The bases of these functional variables are cyclic changes in intrathoracic pressure during positive pressure ventilation, which induce changes in stroke volume and pulse pressure as a result of a reduction in preload (ie, caval vein flow). Under physiological circumstances, the heart operates on the ascending limb of the Frank-Starling curve indicating preload reserve (ie, positive fluid responsiveness [an adequate increase in stroke volume after a volume challenge]) and cyclic changes in intrathoracic pressure during mechanical ventilation result in large changes in stroke volume. In contrast, when the heart is operating on the flat part of the Frank-Starling curve, preload reserve is decreased and there is no adequate cardiac response to volume loading (ie, negative fluid responsiveness). Under these circumstances, mechanical ventilation induces only small changes in stroke volume. Accordingly, SVV and/or PPV may indicate the actual position of an individual on the Frank-Starling curve (large numbers = ascending part of the curve; small numbers = flat part of the curve), and these variables have been shown in various studies to be able to predict fluid responsiveness [42–44], whereas static preload variables have failed to do so [38••]. Nonetheless, it has to be emphasized that cardiovascular and ventilatory limitations like arrhythmias, right HF, spontaneous breathing activity, and low tidal volume (< 8 mL/kg body weight) affect the reliability of these dynamic indices of fluid responsiveness. Under these circumstances, “passive leg raising” could be employed to assess fluid responsiveness because it results in an internal fluid shift from the legs to the central compartment caused by the modified Trendelenburg position. This has been demonstrated to reliably determine fluid responsiveness in critically ill patients [45••].

Central Venous Oxygen Saturation

ScvO₂ is used as a global marker of the balance between systemic oxygen supply and demand [46]. It is easily measured by obtaining a blood sample drawn from a central venous catheter, compared with mixed venous oxygen saturation (SvO₂), which requires the placement of a PAC and the withdrawal of blood from the distal port of the catheter. In addition to intermittent measurements using a blood sample and a blood gas analyzer, both ScvO₂ and SvO₂ can be measured continuously using proprietary central venous catheters and PACs, respectively. There are no outcome studies that compare intermittent versus continuous measurements of ScvO₂ or SvO₂; however, the only study that showed survival benefit using ScvO₂ as a resuscitation endpoint employed its continuous measurements [4]. Using proprietary catheters, continuous measurements of ScvO₂ can be obtained from both the Vigileo and

the PiCCO systems. As far as its clinical utility is concerned, ScvO₂ has been used as a resuscitation endpoint in patients with severe sepsis and septic shock [4] and also in patients undergoing major surgery [47]. In cardiac surgery patients, ScvO₂ never has been used in a clinical trial; however, maintaining SvO₂ at levels of 70% or higher in the perioperative period has been associated with reduced hospital length of stay, primarily as a result of decreased postoperative complications rate in this patient population [48]. It is important to realize that absolute ScvO₂ and SvO₂ values may differ considerably in different clinical situations; however, a strong correlation of their trends over time has been demonstrated [49].

Integrative Concept

When considering the technical features and limitations of all minimally invasive CO monitoring techniques, it is evident that no single device can comply with all clinical requirements in cardiac surgery patients. Therefore, different devices may be used in an integrative concept along a typical clinical pathway in cardiac surgery (Fig. 1) based on the invasiveness of the devices and the available additional hemodynamic variables (Table 2). Bioreactance may be used on the ward and in the emergency department to assess CO initially to confirm a preliminary diagnosis. When more validation data are made available, this technique also may be used in the postoperative setting in high-risk hemodynamically stable patients where no addi-

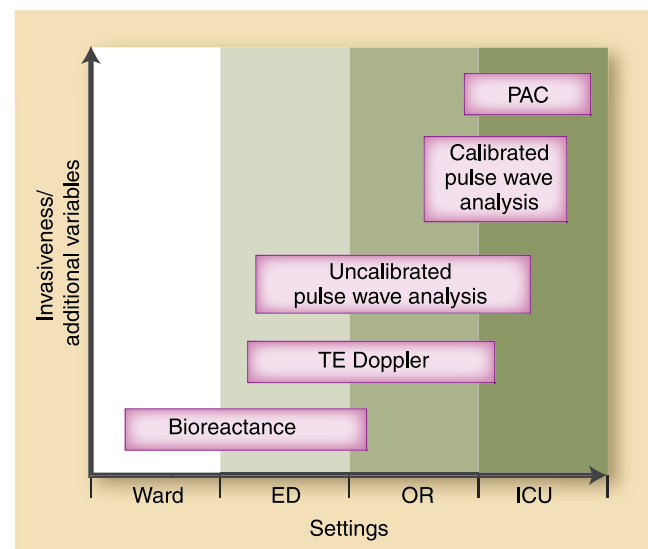


Fig. 1 Integrative concept for the use of cardiac output monitoring devices in cardiac surgery patients. ED—emergency department; ICU—intensive care unit; OR—operating room; PAC—pulmonary artery catheter; TE—transesophageal

tional hemodynamic information is required. Partial CO₂ rebreathing is of limited value in the cardiac surgery patients because this technique requires an intubated and mechanically ventilated patient for CO estimation. Today, sufficient evidence supports the perioperative use of pulse wave analysis devices in cardiac surgery patients. Uncalibrated devices may be the primary choice for the daily routine because they provide functional hemodynamic variables, and thus, allow comprehensive hemodynamic management of the patient. In contrast, calibrated systems may be required when postoperative complications or hemodynamic instability occur and increased device accuracy or volumetric variables are required for improved patient management. In the presence of factors that affect the accuracy of all minimally invasive CO monitoring devices, or when pulmonary artery pressure monitoring or right HF treatment is required, PAC insertion may be warranted for patient-specific therapy.

Reflection on Cost Efficiency

Every hemodynamic monitoring system per se, being invasive or minimally invasive, cannot be cost effective. As mentioned already in this review article, only the hemodynamic monitoring in combination with a treatment protocol may be effective in terms of improved outcome with a reduction of complication and consecutive reduced ICU and hospital lengths of stay [4, 47, 48]. Based on different global price structures for devices and consumables and a variety of financing models (eg, patients monitored per annum), an adequate and precise cost calculation is almost impossible. However, it can be estimated that costs for minimally invasive devices, maintenance and consumables range from roughly \$200 to \$500 per patient. On the other hand, cost savings as a result of an average hospital length of stay reduction of 1 to 2 days may account for up to \$1,000 to \$4,000. Considering these facts and estimates, one may conclude that the use of the minimally invasive hemodynamic monitoring systems can be considered to be cost efficient.

Conclusions

A number of minimally invasive devices that continuously measure the CO are commercially available for use in the cardiac surgery ICU. Their presence does not completely preclude the use of PAC, which continues to serve as the current clinical standard against which all new devices are compared. A number of factors govern the choice of a minimally invasive device; however, the end user has to be familiar with the underlying principles and the inherent

limitations of the particular device available for use. Different minimally invasive devices can be used in an integrative approach in managing cardiac surgery patients with hemodynamic instability and those who have the potential for its development. These devices, in conjunction with ScvO₂ and volumetric preload and dynamic variables that they provide, may obviate the need for PAC in many cardiac surgery ICU patients.

Disclosures Dr. Jamal Alhashemi has received grants or has grants pending, and has received travel compensation, from Edwards Lifesciences. Dr. Maurizio Cecconi has received grants or has grants pending, and has received honoraria, from LiDCO Ltd. and Edwards Lifesciences. Dr. Maxime Cannesson has received consulting fees or honoraria from ConMed Corporation, Covidien, Edwards Lifesciences, Fresenius Kabi, and Masimo Corporation. Dr. Christoph K. Hofer has received grants or has grants pending, and has received honoraria, from Edwards Lifesciences, PULSION Medical Systems, and CSL Behring. No further potential conflicts of interest relevant to this article have been reported.

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