REVIEW

Cardiac output monitoring: how to choose the optimal method for the individual patient

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Purpose of review
To review the different methods available for the assessment of cardiac output (*CO*) and describe their specific indications in intensive care and perioperative medicine.

Recent findings
In critically ill patients, persistent circulatory shock after initial resuscitation is an indication for the assessment of *CO* to monitor the response to fluids and vasoactive agents. In patients with circulatory shock associated with right ventricular dysfunction, pulmonary artery hypertension, or acute respiratory distress syndrome, invasive *CO* monitoring using indicator dilution methods is indicated. Calibrated and uncalibrated pulse wave analysis enable absolute or relative *CO* changes to be monitored in real-time during the assessment of fluid responsiveness. In patients undergoing open-heart and thoracic aortic surgery, transesophageal echocardiography is recommended. In selected cardiac surgery patients, advanced hemodynamic monitoring using thermodilution methods can be considered. In high-risk noncardiac surgical patients, invasive pulse wave analysis or esophageal Doppler should be used for perioperative hemodynamic management.

Summary
Various invasive, minimally invasive, and noninvasive methods to assess *CO* are available. A profound understanding of the different *CO* monitoring methods is key to define indications for *CO* monitoring in the individual critically ill or surgical patient.

Keywords
hemodynamic monitoring, pulmonary artery catheter, pulmonary artery thermodilution, pulse wave analysis, transpulmonary thermodilution

INTRODUCTION

Cardiac output (*CO*), the product of ventricular stroke volume (SV) and heart rate (HR), is a primary determinant of oxygen delivery [1▪]. Thus, the assessment and optimization of *CO* are recommended in critically ill patients with altered tissue perfusion [2,3] and in high-risk surgical patients [4]. Different methods have been proposed for the assessment of *CO*, but choosing which method to use in the individual patient is challenging. In this article, we briefly review the different methods available to assess *CO* and describe their specific indications in intensive care and perioperative medicine.

METHODS FOR THE ASSESSMENT OF CARDIAC OUTPUT

The calculation of *CO* using oxygen consumption and arteriovenous oxygen content difference (Fick's principle) and the measurement of *CO* with flow meters (experimental reference method) cannot be routinely applied in clinical practice, so alternative methods have been developed. When choosing among these techniques, several factors need to be taken into account, including their invasiveness [invasive, minimally invasive, and noninvasive methods (Fig. 1)], measurement performance (accuracy, precision, trending), ability to provide real-time continuous *CO* readings, ability to calibrate

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KEY POINTS

- A profound understanding of the different *CO* monitoring methods is key to define indications for invasive, minimally invasive, and noninvasive *CO* monitoring.
- In critically ill patients, persistent circulatory shock after initial resuscitation is an indication for the assessment of *CO*.
- In patients with circulatory shock associated with right ventricular dysfunction or acute respiratory distress syndrome, invasive *CO* monitoring using indicator dilution methods is indicated.
- Pulse wave analysis enables absolute or relative *CO* changes to be monitored in real-time during the assessment of fluid responsiveness.
- In high-risk noncardiac surgical patients, invasive pulse wave analysis or esophageal Doppler should be used for perioperative hemodynamic management.

the *CO* readings to a reference method, and ability to provide additional hemodynamic variables [5–8].

Invasive methods for the assessment of cardiac output

Invasive methods are based on the principle of indicator dilution and include pulmonary artery thermodilution (PATD), transpulmonary thermodilution (TPTD), and lithium dilution.

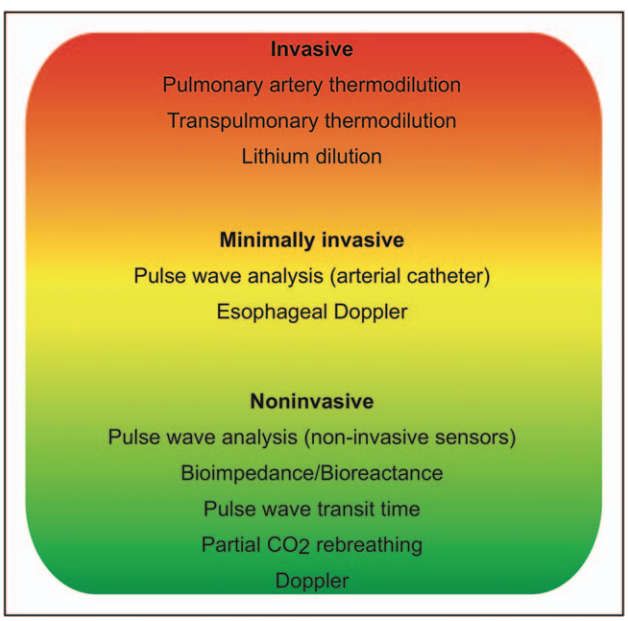

FIGURE 1. Methods for the assessment of cardiac output. Methods for the assessment of cardiac output can be classified according to their invasiveness into invasive, minimally invasive, and noninvasive methods.

Pulmonary artery thermodilution

Intermittent PATD [using a pulmonary artery catheter (PAC) as first described by Swan *et al.* [9] and Ganz *et al.* [10]] enables right ventricular (RV) *CO* to be determined using a modified Stewart–Hamilton equation after injection of a fluid bolus of known volume and temperature (thermal indicator) into the right atrium via the proximal port of the PAC [11]. The subsequent change in blood temperature is recorded by a thermistor located downstream at the tip of the PAC.

The measurement of *CO* with intermittent PATD has been validated against experimental gold standard methods in numerous method comparison studies in animals and humans [8], and, although far from perfect, it remains the clinical reference method for the assessment of *CO* at the bedside [12].

PATD can be limited by physical factors related to the indicator injection (e.g., loss of indicator, variation in injectate temperature or injection rate, change in baseline temperature), patient-specific pathophysiologic factors (e.g., intracardiac shunts, tricuspid regurgitation, low-flow states), variations in *CO* readings over the respiratory cycle, and mathematical factors related to the *CO* algorithms [11,13–16]. Moreover, pulmonary artery catheterization is an invasive procedure associated with rare but severe complications.

PATD using electric heating filaments in the proximal part of the PAC to induce changes in blood temperature enables *CO* to be estimated continuously but with a significant time delay [11].

In addition to *CO*, the PAC can be used to assess pulmonary artery pressures, cardiac filling pressures, and mixed venous oxygen saturation. Additional variables, including pulmonary vascular resistance and RV work, can be derived.

Transpulmonary thermodilution

TPTD-based *CO* assessment requires a central venous catheter for thermal indicator injection into the central venous circulation and a dedicated thermistor-tipped arterial catheter that is usually placed in the abdominal aorta through the femoral artery for the recording of the thermodilution curve. Left ventricular (LV) *CO* is calculated based on a modified Stewart–Hamilton equation [17,18■■].

In validation studies, TPTD-derived *CO* values showed good agreement with PATD-derived values in critically ill and surgical patients [11].

The sources of error and variability in the *CO* measurements and the technical limitations regarding indicator loss or recirculation discussed for PATD also apply to TPTD.

In addition to *CO*, several other hemodynamic variables including extravascular lung water, pulmonary vascular permeability index, and global end-diastolic volume can be assessed using TPTD [17,18■■].

Lithium dilution

The assessment of *CO* by lithium dilution uses isotonic lithium chloride injected into the central venous circulation or a peripheral vein as the indicator [11]. The lithium bolus travels through the right heart, the pulmonary circulation, the left heart, and the aorta; the concentration–time curve used to calculate *CO* is recorded at a peripheral arterial catheter using a flow-through cell with an integrated ion-selective electrode [11].

Lithium dilution-derived *CO* measurements have been validated against PATD in critically ill and surgical patients [11].

In addition to the limitations all indicator dilution methods have in common, the lithium dilution method cannot be used in patients under lithium therapy and carries the risk of lithium accumulation if many measurements are repeatedly performed over short periods of time [18■■].

Minimally invasive methods for the assessment of cardiac output

The analysis of the arterial pressure waveform obtained with an arterial catheter (invasive pulse wave analysis) and the esophageal Doppler technique are usually classified as minimally invasive methods.

Invasive pulse wave analysis

Pulse wave analysis enables SV and thus *CO* to be continuously estimated from the arterial pressure waveform using mathematical algorithms that analyze characteristics of the waveform assuming that the systolic part is proportional to the SV and inversely related to arterial compliance [19–22, 23■■]. The characteristics of the arterial pressure waveform are determined by various factors, including the LV SV, contractility of the heart, vascular compliance, aortic impedance, and peripheral vascular resistance. Available pulse wave analysis systems are either calibrated (sometimes called 'less-invasive') or uncalibrated (usually called 'minimally invasive'). Calibrated systems use an external *CO* value (e.g., *CO* value obtained with an indicator dilution method) as a reference to calibrate the pulse wave analysis-derived *CO* [21,23■■]; uncalibrated systems (perhaps better described as 'autocalibrated') estimate *CO* solely using characteristics of the arterial pressure waveform and biometric and demographic data [21,23■■].

A meta-analysis including data from 24 validation studies comparing invasive pulse wave analysis with thermodilution methods to assess *CO* in critically ill and surgical patients reported a pooled weighted percentage error of 41% [24]. A systematic review emphasized that the measurement performance of pulse wave analysis depends on the patient population, with better performance in general critically ill, surgical, cardiac, and cardiac surgery patients than in patients with liver disease or septic shock [25].

In general, pulse wave analysis-derived *CO* readings must be interpreted with caution in patients with cardiac arrhythmias and in those with marked alterations or rapid changes in vascular tone (such as those with distributive shock). Pulse wave analysis also depends on a perfect arterial pressure signal, which can be disturbed by technical problems related to the arterial catheter, the tubing system, or the pressure transducer.

Pulse wave analysis allows not only the estimation of SV and *CO* but also the assessment of dynamic preload responsiveness variables, including pulse pressure and SV variation.

Esophageal Doppler

The esophageal Doppler method can be used to estimate SV (and thus *CO*) from the blood flow velocity waveform in the descending aorta recorded using a Doppler transducer placed at the tip of a flexible probe [26–28]. SV is estimated from the stroke distance [i.e., the area under the aortic flow velocity waveform (velocity time integral)] and the cross-sectional area of the aorta, which is either measured or estimated from nomograms [26–28].

Estimates of *CO* using esophageal Doppler ultrasonography have been validated against those using PATD in critically ill and surgical patients [29] and a pooled weighted percentage error of 42% has been reported [24].

Although considered as a minimally invasive method, esophageal Doppler ultrasonography requires the probe to be inserted in the esophagus and is thus limited to patients under sedation or general anesthesia. In addition, Doppler measurements can be disturbed by movement and are operator-dependent. Moreover, the estimation of SV relies on a number of assumptions including a fixed distribution of blood flow between the upper and lower parts of the body [26–28].

Esophageal Doppler provides additional hemodynamic variables including corrected flow time and SV variation.

Noninvasive methods for the assessment of cardiac output

During recent years, various technologies for noninvasive *CO* estimation have been proposed and evaluated. These include bioimpedance/bioreactance, pulse wave transit time, partial carbon dioxide rebreathing, Doppler methods, and noninvasive pulse wave analysis [6–8,30▪].

Noninvasive pulse wave analysis uses a noninvasive sensor placed on the finger (finger cuff methods, vascular unloading technology, volume clamp method) [31–33] or over the radial artery (automated radial artery applanation tonometry) [34,35]. The arterial pressure waveform obtained from the sensors is recorded and analyzed continuously to derive *CO*. A recent meta-analysis reported that the pooled mean percentage error of noninvasive pulse wave analysis-derived *CO* compared with thermodilution-derived *CO* was 45% [36▪▪].

It is beyond the scope of our article to discuss the principles, advantages, and limitations of all the available technologies for noninvasive *CO* estimation [6–8]. For all noninvasive technologies, validation studies using bolus thermodilution as the reference method have given conflicting results [7,24,31,36▪▪]. Although most noninvasive systems have been shown to provide accurate and precise *CO* estimations compared with reference methods under clinical study conditions, they all have technology-specific and device-specific problems when used in routine clinical practice [7].

INDICATIONS FOR DIFFERENT METHODS OF CARDIAC OUTPUT ASSESSMENT IN CRITICALLY ILL PATIENTS WITH ACUTE CIRCULATORY SHOCK

Indications for the different methods of *CO* assessment in critically ill patients with circulatory shock are shown in Fig. 2.

In these patients, clinical examination and the placement of an arterial catheter and a central

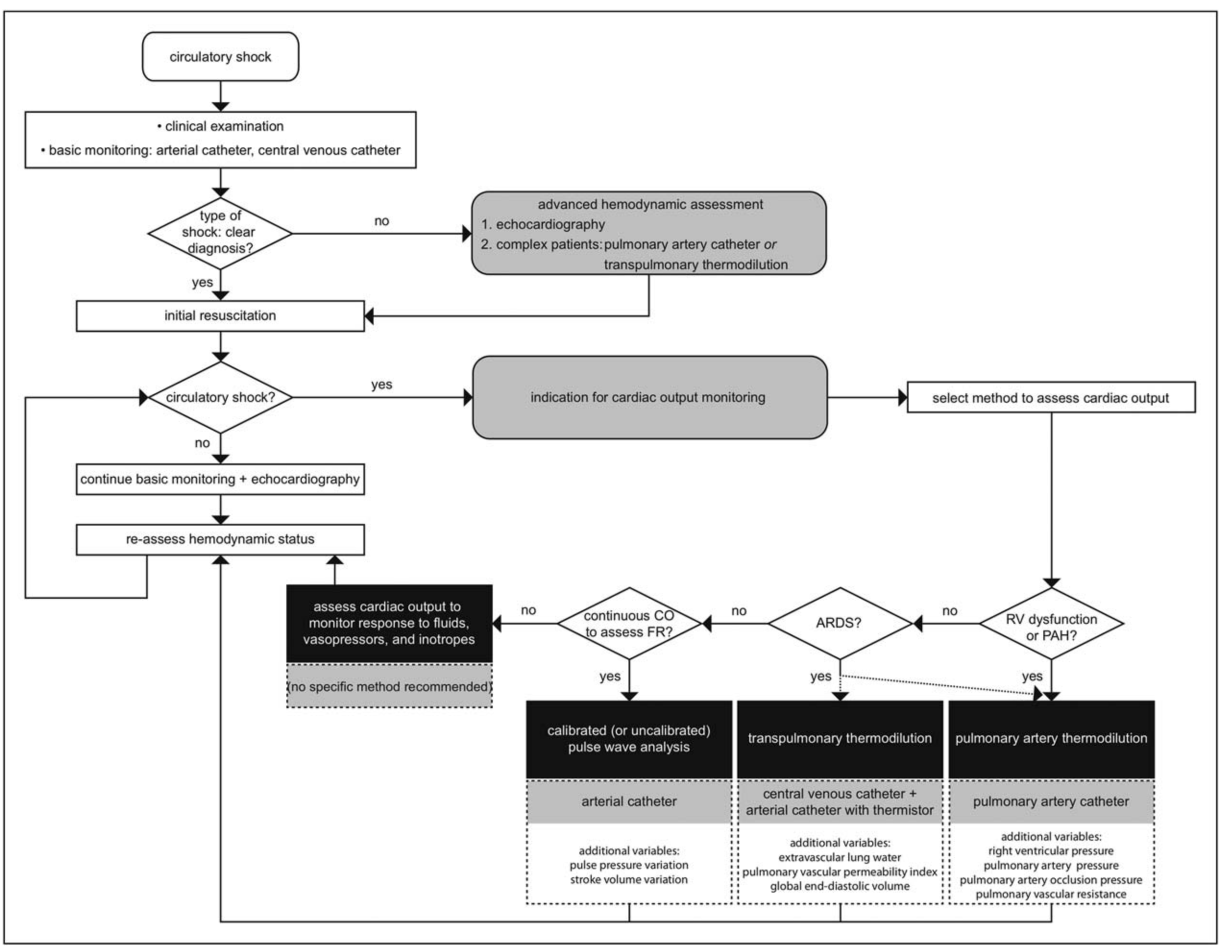

FIGURE 2. Indications for different methods of cardiac output assessment in critically ill patients with acute circulatory shock. ARDS, acute respiratory distress syndrome; *CO*, cardiac output; FR, fluid responsiveness; PAH, pulmonary arterial hypertension; RV dysfunction, right ventricular dysfunction.

venous catheter are recommended as the first step in the diagnostic workup and initial resuscitation [3,30▪]. If the type of circulatory shock [37] cannot be clearly recognized clinically, advanced hemodynamic assessment can be helpful [3]. In this context, echocardiography should be the first-line approach for the assessment of cardiac function, whereas invasive hemodynamic monitoring technologies such as the PAC or TPTD should be restricted to complex patients [3]. The hemodynamic status should be reassessed after initial resuscitation using clinical examination, basic monitoring, and echocardiography.

In patients with persistent or reoccurring circulatory shock after initial resuscitation, *CO* needs to be assessed and optimized. The choice of the *CO* monitoring method in the individual patient depends on medical, institutional, and organizational factors [2,38] and can be facilitated by using the following three key questions:

(1) Is the patient's circulatory shock associated with severe RV dysfunction or pulmonary artery hypertension?
If yes, invasive *CO* assessment using PATD is indicated. In addition to *CO* assessment, other PAC-derived hemodynamic variables, including right atrial and ventricular pressure, pulmonary artery pressure, pulmonary artery occlusion pressure, and mixed venous oxygen saturation, can help to guide hemodynamic therapy.

(2) Is circulatory shock associated with acute respiratory distress syndrome (ARDS)?
If yes, invasive *CO* assessment using PATD or TPTD is indicated. TPTD additionally provides extravascular lung water and pulmonary vascular permeability. Extravascular lung water reflects the amount of water in the lungs outside the pulmonary vasculature, increases in ARDS, and is a predictor of outcome [39,40,41▪,42–44]. The pulmonary vascular permeability index enables differentiation of the pathophysiologic reasons for the increased extravascular lung water [45,46].

(3) Does the *CO* need to be monitored continuously for the assessment of fluid responsiveness?
The assessment of fluid status and fluid responsiveness is recommended in patients with circulatory shock [3,47]. During a fluid challenge [48] or passive leg raising test [49], continuous real-time monitoring of SV and *CO* is required to assess the short-term changes in *CO* in response to the increase in cardiac preload. In patients with circulatory shock, calibrated and uncalibrated pulse wave analysis can be used to assess absolute and relative *CO* changes for the assessment of fluid responsiveness.

Even if not associated with severe RV dysfunction, pulmonary artery hypertension, or ARDS, circulatory shock not responding to initial therapy requires the assessment of *CO* to monitor the response to therapeutic interventions including the administration of fluids and vasoactive agents [3]. It has been recommended that less invasive devices are used only when they have been validated in the context of patients with shock [3]. Completely noninvasive methods are currently not recommended for the estimation of *CO* in patients with circulatory shock [30▪].

INDICATIONS FOR DIFFERENT METHODS OF CARDIAC OUTPUT ASSESSMENT DURING PERIOPERATIVE HEMODYNAMIC MANAGEMENT

Indications for the different methods of *CO* assessment during the perioperative hemodynamic management of surgical patients are shown in Fig. 3.

In noncardiac surgery patients, indications for *CO* monitoring depend on the presence of various patient-related and surgery-related risk factors for perioperative complications. The routine use of PATD or TPTD to assess *CO* is not recommended [50]. In addition, transesophageal echocardiography is only recommended in patients with acute sustained severe hemodynamic instability in the perioperative period [50].

Low-risk noncardiac surgical patients can be monitored using basic hemodynamic monitoring (i.e., HR and rhythm, noninvasive arterial pressure, and peripheral oxygen saturation).

In high-risk noncardiac patients, monitoring of *CO* is indicated [4] as (goal-directed) hemodynamic management using fluids and inotropes to optimize *CO* (and oxygen delivery) has been shown to improve outcome [51–55]. In high-risk noncardiac surgical patients without marked alterations in vascular tone, invasive uncalibrated pulse wave analysis or esophageal Doppler can be used to guide *CO* optimization [23▪▪,55]. Whether noninvasive uncalibrated pulse wave analysis can also be used for the assessment of *CO* in this category of patients is a subject of current research [56]. In high-risk noncardiac surgical patients with marked alterations in vascular tone (e.g., patients with liver failure or sepsis), *CO* can be assessed using invasive calibrated pulse wave analysis or esophageal Doppler [23▪▪,55].

In patients undergoing open-heart and thoracic aortic surgery, transesophageal echocardiography is indicated [57,58]. Transesophageal echocardiography may also be considered in coronary artery bypass graft surgery [57,58]. In selected cardiac surgery patients, advanced hemodynamic assessment

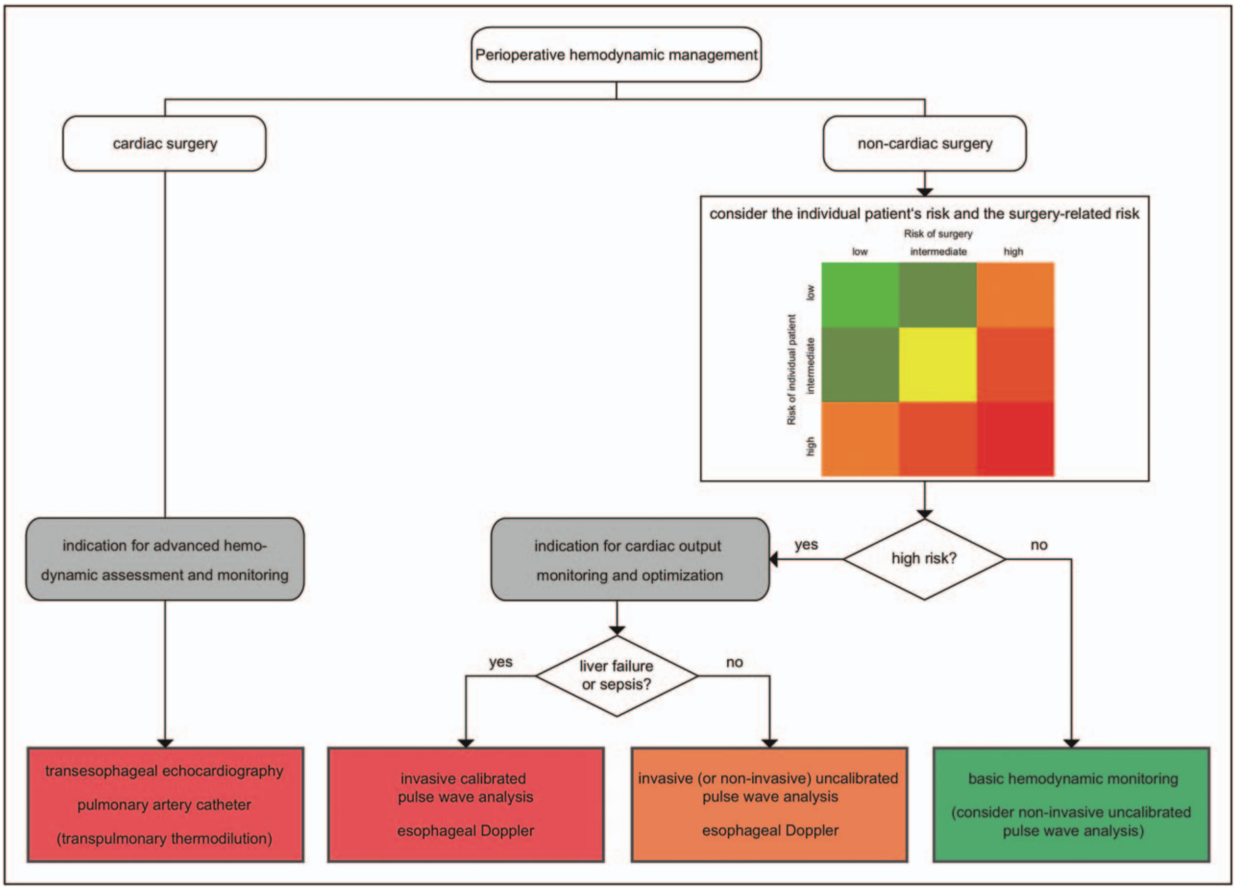

FIGURE 3. Indications for different methods of cardiac output assessment during the perioperative hemodynamic management of surgical patients.

and monitoring using a PAC (or TPTD) may be considered.

CONCLUSION

It is important to understand the measurement principles and indications for the different invasive, minimally invasive, and noninvasive methods available to assess *CO*, so that the optimal *CO* monitoring method can be chosen for the individual critically ill or surgical patient.

In critically ill patients, persistent or reoccurring circulatory shock after initial resuscitation is an indication for the assessment of *CO* to monitor the response to fluids and vasoactive agents. In patients with circulatory shock and RV dysfunction or pulmonary artery hypertension, PATD is indicated. If the circulatory shock is associated with ARDS, *CO* should be assessed using PATD or TPTD. To monitor *CO* continuously during the assessment of fluid responsiveness, calibrated (or uncalibrated) pulse wave analysis can be used to assess absolute or relative changes in *CO*.

In noncardiac surgery patients, indications for the different methods of *CO* monitoring during perioperative hemodynamic management depend on patient-related and surgery-related risk factors. In high-risk noncardiac surgical patients, invasive pulse wave analysis or esophageal Doppler should be used to optimize *CO* and guide hemodynamic therapy. In patients undergoing open-heart and thoracic aortic surgery, transesophageal echocardiography is recommended. In selected cardiac surgery patients, advanced hemodynamic assessment and monitoring with a PAC (or TPTD) can be considered.

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Conflicts of interest

BS collaborates with Pulsion Medical Systems SE (Feldkirchen, Germany) as a member of the medical

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