One of the primary goals of this hemodynamic optimization is associated with both, reduced morbidity and intensive care unit length of stay. Recent evidence suggests that an individualized approach to trend CO over time remains a matter of debate.14 In particular, a number of concerns have been raised regarding the ability of the earlier generations of this device to respond in a timely and accurate manner to rapid changes in peripheral vascular resistance during high-risk surgical procedures.10,11 Another non-invasive pulse contour development is the combination of non-invasively measured arterial finger blood pressure with Modelflow (TNO/BMI).12 The Nexfin (BMEYE, Amsterdam, The Netherlands) is a newer device that has recently been introduced into practice. It provides beat-to-beat stroke volume and CO measurements by analysis of a non-invasive finger arterial blood pressure trace, derived continuously from an inflatable finger cuff. A recent study in 40 patients by Broch et al. suggests that this method correlates reasonably well with transcardiopulmonary thermodilution in cardiac surgery patients.13

To what degree pulse contour CO monitors are able to trend CO over time remains a matter of debate.14 In direct comparison with esophageal Doppler CO, the

**LEARNER OBJECTIVES**

After participating in this activity, the learner will be able to:

1. Identify the various means of non-invasive cardiac output monitoring;
2. Recognize the limitations of non-invasive cardiac output monitoring; and
3. Be aware of the clinical utility of non-invasive cardiac-output monitoring in comparison with pulmonary artery catheterization and transesophageal echocardiography.

An historic quote from the 1834 *London Times* may illustrate how an ingenious instrument such as the stethoscope was initially underestimated:

“… that it will ever come into general use … is extremely doubtful, … because its beneficial application requires much time and gives a good bit of trouble both to the patient and the practitioner … and because (it is) foreign and opposed to all our habits and associations.”

Although *Pulmonary artery catheters* (PAC) have long been the clinical gold standard for tracking hemodynamic variability in high-risk surgical patients, the true “gold standard” for the measurement of cardiac output (CO) is the Fick method. While the Fick method is clinically impractical, PACs permit the intermittent or continuous determination of CO as a key variable in the treatment of the cardiovascular system. Advanced cardiovascular monitoring and trending is an essential component of hemodynamic optimization of the perioperative patient and the critically ill. Recent evidence suggests that an individualized hemodynamic optimization is associated with both, reduced morbidity and intensive care unit length of stay.13 One of the primary goals of this hemodynamic optimization is the prevention of inadequate tissue perfusion and oxygenation. While PACs have been shown to provide reliable and continuous information with a reasonable response time, the have also been associated with significant cost and inherent risk due to their invasiveness.4 Furthermore, CO measurements made with the PAC are not as accurate as with the Fick method. Over the last several years, less or non-invasive continuous CO monitors have emerged as reasonable alternative. These non-invasive CO monitors should be reviewed by considering the following characteristics for CO monitoring techniques; accuracy, reproducibility or precision, rapid response time, operator independency, ease of use, continuous use, cost effectiveness, and no increased mortality and morbidity. This text briefly describes the various non-invasive methods to measure CO and discusses some of their individual advantages and disadvantages.

**ARTERIAL PULSE CONTOUR METHODS**

The estimation of CO based on pulse contour analysis is an indirect method, since CO is not measured directly, but is computed from an area under the curve of a pressure pulsation.5 The pulse contour method for estimation of beat-to-beat stroke volume goes back to the classic Windkessel model as described by Otto Frank in 1899 when he published his mathematical formulations.6 Most pulse contour methods are, explicitly or implicitly based on this model.7,8 They relate an arterial pressure or pressure difference to a flow or volume change. Currently, several pulse contour methods are available: the PiCCO (Pulsion Medical Systems), PulseCO™ (LiDCO Ltd., London, UK) and FlowTrac-Vigileo (TNO/BMI). All these three pulse contour methods use an invasively measured arterial blood pressure. Two of these three systems require calibration: PiCCO is calibrated by transpulmonary thermodilution, LiDCO by transpulmonary lithium dilution. The FlowTrac-Vigileo system relies on self-calibrating software and includes a proprietary algorithm that represents the interplay of patient demographics, compliance of the arterial vasculature, and the rapidly changing nature of vasomotor tone. While the FloTrac-Vigileo initially has been embraced as a user-friendly CO monitor, recent validation studies suggest that only a minority of studies demonstrates acceptable limits of agreement (e.g. < 30%).9 In particular, a number of concerns have been raised regarding the ability of the earlier generations of this device to respond in a timely and accurate manner to rapid changes in peripheral vascular resistance during high-risk surgical procedures.10,11

Another non-invasive pulse contour development is the combination of non-invasively measured arterial finger blood pressure with Modelflow (TNO/BMI).12 The Nexfin (BMEYE, Amsterdam, The Netherlands) is a newer device that has recently been introduced into practice. It provides beat-to-beat stroke volume and CO measurements by analysis of a non-invasive finger arterial blood pressure trace, derived continuously from an inflatable finger cuff. A recent study in 40 patients by Broch et al. suggests that this method correlates reasonably well with transcardiopulmonary thermodilution in cardiac surgery patients.13
pulse contour methods do not fully compensate for changes in peripheral vascular resistance and other circulatory changes while Doppler readings appear to be less affected.\textsuperscript{15}

Even though arterial pulse contour methods may not be quite as accurate as the true gold standards, they still have significant advantages. These include, but are not limited to, their minimal invasiveness, their response-time (beat-to-beat), and their ability to predict changes in CO and ultimately to track changes.

**INDICATOR DILUTION TECHNIQUES**

Indicator dilution techniques rely on the injection of an inert, soluble indicator substance into the circulation. Commercially available systems include the transpulmonary thermodilution (PiCCO, Pulsion Medical Systems), the transpulmonary lithium dilution method (LiDCO Ltd., London, UK) and the PAC based continuous thermodilution methods (Vigilance, Baxter; Opti-Q, Abbott; and TruCCOMS, AorTech). Essentially all transpulmonary indicator dilution methods are modifications of the conventional intermittent bolus thermodilution method. CO is calculated based on the Steward method and the Hamilton modification.\textsuperscript{16} The Steward-Hamilton equation is based on the assumption that a) the injected indicator and the blood mix completely, b) that there will be no actual loss of the indicator between the place of injection and place of detection and c) that there is constant blood flow.\textsuperscript{17} Sources of error and variability include loss of indicator before, during or after injection, variation of the injectate temperature and/or volume and recirculation or detainment of indicator.

**FICK PRINCIPLE USING CARBON DIOXIDE**

The NICO (Novametrix) systems is a non-invasive device that applies Fick’s principle on carbon dioxide (CO\textsubscript{2}) and relies on a partial rebreathing technique and airway gas measurement. The systems calculates effective lung perfusion based on the evaluation of CO\textsubscript{2} elimination through integration of the measured gas flow and CO\textsubscript{2} concentration every 3 minutes after a brief period of partial rebreathing. The monitor requires the patient to be intubated. Individual ventilation/perfusion mismatch and the lack of an opportunity for calibration may explain why the accuracy of this method is mixed and why there is a lack of agreement between thermodilution and CO\textsubscript{2}- rebreathing CO.

**BIO-IMPEDANCE METHOD**

The continuous measurement of thoracic electrical bio-impedance (TEB) obtains an informative waveform signal: the portion of the bio-impedance waveform related to the cardiac cycle resembles to a large degree an arterial pressure waveform. For five decades, efforts were undertaken to derive stroke volume and CO of this waveform or its derivatives. These efforts relied on a model that contributes the rapid change of bio-impedance which occurs shortly after aortic valve opening to the expansion of the compliant ascending aorta, assuming that more blood volume temporarily stored in the ascending aorta contributes to a decrease in bio-impedance (or an increase in electrical conductivity of the thorax). Most current bio-impedance systems determine CO on a beat-to-beat time base. Excessive lung water (e.g. pulmonary edema) and acute changes in peripheral vascular resistance may negatively affect the reliability of CO measurements. This may help to explain relatively poor correlations when bio-impedance monitors are compared to a reference method in the critically ill or in septic patients.\textsuperscript{18} Persistence in marketing the bio-impedance method as a low-cost non-invasive approach to calculating CO, paired with the development of newer technologies, has resulted in a recent renaissance of these monitors.

**TRANSESOPHAGEAL ECHOCARDIOGRAPHY AND ULTRASOUND TECHNIQUES**

Transepophageal echocardiography (TEE) represents a clinical monitor that can assist the experienced anesthesiologist in the hemodynamic evaluation and management of surgical patients during general anesthesia. Hemodynamic evaluation with echocardiography consists of both, the qualitative and quantitative assessment. While qualitative assessment includes the description of chamber sizes and shapes, the quantitative approach to TEE allows the determination of blood flow and volumes, pressure gradients, valve areas and intracardiac pressures. Stroke volume (SV) can be calculated knowing the velocity time integral (VTI) and the cross sectional area (CSA) at the point where the VTI was determined. Most commonly, the left ventricular outflow tract (LVOT) is used to calculate echo-based SVs. The CSA equals \(\pi\) \(r^2\), which can be substituted by 0.785 \(d^2\) diameter squared. This leads to:

\[
SV (\text{ml}) = CSA (\text{cm}^2) \times VTI (\text{cm/beat})
\]

Applied for the LVOT:

\[
\Leftrightarrow\ SV = 0.785 \times (\text{diameter LVOT})^2 \times VTI_{LVOT}
\]

**Cardiac output (CO)**

\[
CO (\text{l/min}) = SV (\text{ml}) \times HR (\text{heart rate/min})
\]

And applied for the LVOT:

\[
\Leftrightarrow\ CO = SV_{LVOT} (\text{ml}) \times HR (\text{beats/min})
\]

\[
\Leftrightarrow\ CO = 0.785 \times (\text{diameter LVOT})^2 \times VTI_{LVOT} \times HR
\]

TEE-based CO estimations have been compared to thermodilution techniques under varying conditions. While a large number of studies suggest that TEE based CO measurements have acceptable agreement and accuracy compared with thermodilution using the PAC\textsuperscript{19-21}, other studies have questioned this accuracy, especially in certain subgroups of patients.\textsuperscript{22,23} Of note, accurately estimating CO based on TEE and Doppler quantification requires a significant level of skills.
New developments in 3D echocardiography along with available 3D quantification software utilizing semi-automated endocardial border detection permit fast and accurate measurements of global and regional left ventricular (LV) function. Studies comparing MRI with 3D echocardiography for the assessment of LV mass and function show very good correlation and agreement that is superior to 2D echocardiography. This also holds true for real-time 3D transthoracic echocardiography (RT-3D-TTE) assessment of patients with cardiomyopathies or regional wall motion abnormalities secondary to myocardial infarction with abnormal LV geometry. Global LV function is assessed by 3D analysis of end systolic and end diastolic volumes, EF and stroke volumes, which can be used to calculate CO. In a recent perioperative study, we have demonstrated the feasibility, reliability, and validity of similar volumetric studies based on 3D-TEE of the right ventricle (RV). This work suggests that 3D-TEE can reliably represent the complex geometry of the RV and, therefore, may constitute a valuable tool for dynamic perioperative assessment of RV function, stroke volumes and CO.

Recent technological advances in ultrasound crystals have resulted in new miniature Doppler probes positioned inside the esophagus with their echo window on the thoracic aorta for measuring aortic flow velocity. Aortic cross sectional area is assumed (CardioQ, Deltec or measured simultaneous with 2D-echo (HemoSonic, ARROW). Note, these technologies do not measure CO directly but rather estimate aortic blood flow. However, based on the continuity principle, a fixed relationship between aortic blood flow and CO is assumed to calculate CO. Roeck et al. showed that abrupt changes in CO are much better followed with esophageal Doppler systems than with the PAC based continuous CO systems.

**CONCLUSION**

While a large number of methods for the assessment of CO exist, none combines all eight criteria discussed in the introduction (accuracy, reproducibility or precision, rapid response time, operator independency, ease of use, continuous use, cost effectiveness, and no increased mortality and morbidity). Pulmonary artery thermodilution, lithium dilution and transpulmonary thermodilution provide valid and reliable intermittent information. Pulse contour-derived CO monitors provide the clinicians with a relatively non-invasive option to determine LV contractility and beat-to-beat SVs but remain associated with relatively wide limits of agreement when compared to thermodilution-based techniques. Although Doppler-derived estimation of CO may not be quite as accurate when compared to thermodilution CO, it has been shown to facilitate goal-directed therapies and improve intermediate clinical outcomes. Recent technological improvements in bioimpedance systems may help to improve the accuracy and reproducibility of this non-invasive technique.

**REFERENCES**


