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Best practice & research clinical anaesthesiology: Advances in haemodynamic monitoring for the perioperative patient
Perioperative cardiac output monitoring

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Less invasive or even completely non-invasive haemodynamic monitoring technologies have evolved during the last decades. Even established, invasive devices such as the pulmonary artery catheter and transpulmonary thermodilution have still an evidence-based place in the perioperative setting, albeit only in special patient populations. Accumulating evidence suggests to use continuous haemodynamic monitoring, especially flow-based variables such as stroke volume or cardiac output to prevent occult hypoperfusion and, consequently, decrease morbidity and mortality perioperatively. However, there is still a substantial gap between evidence provided by randomised trials and the implementation of haemodynamic monitoring in daily clinical routine. Given the fact that perioperative morbidity and mortality are higher than anticipated and anaesthesiologists are in charge to deal with this problem, the recent advances in minimally invasive and non-invasive monitoring technologies may facilitate more widespread use in the operating theatre, as in addition to costs, the degree of invasiveness of any monitoring tool determines the frequency of its application, at least perioperatively. This review

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covers the currently available invasive, non-invasive and minimally invasive techniques and devices and addresses their indications and limitations.

Introduction

Monitoring haemodynamic variables perioperatively or on the intensive care unit (ICU) is one of the present-day essential skills of an anaesthetist and intensive care physician. This article focuses on frequently used monitoring options and aims to optimise the benefits for clinical practice through the presentation of indications and limitations of the different techniques. Herein, we present minimally and non-invasive monitoring techniques (calibrated and uncalibrated pulse contour analysis, pulse wave transit time (PWTT) analysis and oesophageal Doppler method (ODM)) and invasive procedures (pulmonary arterial and transpulmonary thermodilution (TPTD)). As the focus is placed on continuous haemodynamic monitoring, discontinuous methods such as echocardiography are not covered.

Methodological remarks

New devices for CO measurement are introduced into the market with ever-increasing frequency. The manufacturers claim that these devices are 'easy to use', 'plug-and-play' and 'reliable' and offer significant savings due to beneficial effects on both morbidity and costs.

The clinician is left with the question whether these devices indeed are accurate and precise, i.e. if the mean difference (=bias) between the new device and the chosen clinical gold standard comparator (mostly thermodilution) and the precision of the new method (1 standard deviation [SD] above and below the bias) are acceptable. At present, method comparison studies mostly are performed using Bland-Altman statistics, which offer a graphical representation of bias and the limits of agreement (LOA, which are linked to the precision of the method by the equation 1.96·precision = limits of agreement, representing an area where 95% of all values are expected to lie) [1].

However, Bland-Altman statistics calculates only the intervals of agreements, but it does not say whether those limits are clinically acceptable or not. Whether the bias and LOAs are indeed 'acceptable' must be defined by the clinician, based on methodological considerations, clinical requirements and a cost-benefit analysis. In this regard, Critchley and coworkers proposed the use of the percentage error (PE), which is calculated by LOA divided by the mean value of the reference method multiplied by 100 (%) [2,3]. Based on an arbitrarily chosen mean CO of 5 L min^{-1} and Pythagorean analysis, if both methods have a coefficient of variation (CV) not exceeding 20%, then the resulting PE is below 30%. In other words, if method comparison yields a PE of <30% compared to an accepted reference standard, the new technique would be judged 'interchangeable' with the reference standard and therefore considered clinically acceptable. While this concept is intuitive and relatively easy to apply, it has been criticised mainly for two reasons [4,5]: first, the larger the CO, the larger becomes the absolute error (e.g. 30% of 5 L min^{-1} versus 30% of 8 L min^{-1}); second, the CV of neither the test method nor the reference method is normally reported in method comparison studies. If the reference method is imprecise, a PE >30% may be calculated even though the test method is both accurate and precise. However, as thermodilution has been shown to have a CV below 20% in carefully controlled studies, this is not a big problem in clinical research [6].

Another issue is the correct determination of changes in CO. From a clinical point of view, absolute CO values are much less informative than CO changes during therapeutic interventions [7]. In this regard, several statistical methods have been proposed, with the four–quadrant plot (concordance analysis) currently being the most popular [8]. Concordance is defined as the agreement of the direction of change obtained from paired measurements of both the test and the reference method. This agreement is graphically displayed by plotting the CO change of the test method against the CO change of the reference technique on a four-quadrant scatter plot. The concordance rate is then calculated as

the percentage of the number of data points lying in the upper right and the lower left quadrant of the scatter plot divided by the total number of data points. As data scattered around the centre of the plot represent only small and probably random changes of CO, an exclusion zone of (mostly) ± 15% change in CO is defined and values in this zone are excluded from analysis. According to the recommendations recently proposed by Critchley et al., a clinically acceptable concordance to assume interchangeability is given with a concordance rate >90%–95% [9]. Additionally, this method has been criticised because the percentage magnitude of CO changes is not represented in the graph and that the chosen percentage changes defining the exclusion zone (e.g. 5% versus 10% versus 15%) and the percentage values indicating an acceptable trend following characteristics are chosen arbitrarily [10]. Recently, a refinement of the four–quadrant plot has been proposed using an error grid that assigns each area of the plot an importance based on the therapeutic consequences of erroneous readings on clinical management [8].

Despite the limitations cited above, for the purpose of this review, we define interchangeability of methods by a PE <30% for absolute CO values and a concordance rate >90% for trend following characteristics, as these numbers are reported in the majority of studies and therefore allow for at least approximately comparing the performance of different devices.

Invasive techniques (pulmonary and transpulmonary thermodilution)

Thermodilution: advantages and limitations

At present, thermodilution (either pulmonary arterial or transpulmonary) is still widely accepted as the clinical 'gold' standard for CO measurement [11].

The main advantage of the technique is its relative intuitive and easy-to-understand physiological rationale. The technique allows for an instantaneous calculation of flow in an individual patient at a distinct time point, integrating all influencing factors and confounders (e.g. myocardial contractility, characteristics of the vasculature and ventilatory settings) at that very moment. Therefore, thermodilution is very often used as the reference technique in method comparison studies, and accuracy and precision of a new method are judged according to its performance against thermodilution. The main disadvantages are the relatively time-consuming setup and the invasiveness, which make it a less favourable alternative for perioperative CO measurement. It has been criticised that thermodilution is not interchangeable with a true experimental gold standard such as transit time ultrasound due to PE exceeding the 30% limit in both experimental and clinical studies [12,13]. However, if instrument-related systematic errors, random errors induced by operator dependency (including inappropriate or inconsistent injectate temperature, varying volume of the injectate and speed/regularity of injection) and errors introduced by the inherent physiological variability in the patient studied are carefully controlled, the precision of pulmonary artery thermodilution may be just below 20% and therefore in the range suggested by Critchley and coworkers in their model yielding the PE threshold of 30% [6,14].

Transpulmonary thermodilution

TPTD was developed in Germany at the end of the past century and is quite popular particularly in the German-speaking countries. Presently, it is marketed by Getinge/Maquet ($PiCCO_2$; Pulsion Medical Systems, Feldkirchen, Germany) and by Edwards (VolumeView; Edwards LifeSciences, Irvine, USA) [15].

Principle of function

For CO measurement by TPTD, a cold indicator (ice-cold saline) is injected in a central venous line. The path of the indicator as it travels through the circulation, however, is not detected by a probe positioned in the pulmonary circulation (as with pulmonary artery thermodilution) but after passage of the pulmonary circulation by a detector placed in the femoral artery ("transpulmonary") [16]. The commercially available systems combine TPTD (CO and intrathoracic and pulmonary volumes

intermittently) with pulse contour analysis (CO continuously in real time). For the pulse contour-derived CO, the same limitations outlined in the chapter on devices using minimal/non-invasive pulse contour analysis are applied. The main difference is that the pulse contour in both the $PiCCO_2$ and the VolumeView device is calibrated by the intermittently performed TPTD. This enables updated and reliable values even during rapidly changing respective high and low vascular resistance, at least if calibration is performed repeatedly during these periods of haemodynamic instability [17].

The indicator dilution yields a curve displaying the appearance of the cold indicator over time. The Stewart–Hamilton equation enables CO calculation based on this indicator dilution curve. CO determination by pulmonary artery thermodilution is still considered the clinical gold standard, especially in the English-speaking countries. Pulmonary artery thermodilution is based on injecting an indicator (usually ice-cold saline) in the distal port of a pulmonary artery catheter (PAC) [11]. The travel of the indicator through the right heart is then detected using a thermistor at the tip of the catheter. The resulting thermodilution curve is analysed using an equation proposed by Stewart and Hamilton, yielding the integral under the curve and thus representing CO. As a rule of thumb, a small area under the curve is associated with a high CO, while the converse holds true for a large area. TPTD is based on the same principle, but indicator detection is accomplished using a thermistor in the femoral artery after travelling through all cardiac chambers and the descending aorta. Thus, CO obtained by TPTD represents a systemic CO, while pulmonary artery thermodilution technically speaking represents only right heart CO. As the basic principle is very similar, it is not surprising that both techniques yield comparable values. Numerous studies have shown a very good agreement between these two methods, and they are considered interchangeable [18]. TPTD accuracy is only slightly distorted by heart valve pathologies [19,20]. During very hypodynamic periods, however, displayed values are often unreliable.

TPTD-based goal-directed algorithms

Despite widespread use of TPTD in the German-speaking countries, only few studies deal with TPTD-guided algorithms compared with 'standard of care', reporting mixed results. Two trials enrolling patients undergoing cardiac surgery (one with a historic control group and the other, randomised and controlled) showed a reduced vasopressor use and a shorter ICU stay in patients treated according to the TPTD-based algorithm [21,22], while this could not be confirmed by in patients on the ICU and in major abdominal surgery [23,24] – albeit with a completely different algorithm. This emphasises that the algorithm used is of paramount importance regarding the efficacy of TPTD-based variables. In addition, incorporating several variables derived from both TPTD and pulse contour analysis (including the dynamic variables of fluid responsiveness pulse pressure variation (PPV) and stroke volume variation (SVV)) in an algorithm adds to complexity and hampers application in daily clinical routine.

Limitations

It has been shown that TPTD values are reliable even during veno-venous haemofiltration [25]; during extracorporeal membrane oxygenation (ECMO), however, TPTD does not work anymore.

TPTD is a widespread and established monitoring technology. Accuracy is comparable with that of the clinical gold standard pulmonary artery thermodilution. TPTD-driven algorithms may improve patients' outcome but are not routinely used in clinical practice.

Pulmonary arterial thermodilution

This section presents a short and concise overview regarding pulmonary arterial thermodilution, as this technique is covered in a separate chapter in this Best Practice issue. Still a PAC is widely used during cardiac surgery procedures and during a highly major surgery (e.g. for liver transplantation) [26].

Cardiac output may be obtained using a PAC either by bolus thermodilution (see chapter on transpulmonary thermodilution) or semi-continuously by randomly applied thermal energy generated by a heating filament built in the distal end of the catheter [27]. While bolus thermodilution is still considered as the clinical 'gold' standard for CO determination, semi-continuous CO determination shows a larger PE than the reference technique bolus thermodilution [28].

Following an observational study published in 1996 by Connors and co-workers and reporting an excess mortality of patients equipped with a PAC, the use of this device was increasingly questioned and criticised [29]. Quite recently published meta-analyses, however, suggest that the PAC, if implemented as part of a goal-directed therapeutic approach aiming at an optimised oxygen delivery, may decrease morbidity and mortality in critically ill patients [30,31]. Consequently, the PAC is still recommended by the most recent version of the interdisciplinary S3 guideline on the intensive care of patients following cardiac surgery [32]. Therefore, the PAC is still a valuable tool for haemodynamic monitoring, also in the perioperative setting.

Minimally invasive monitoring (calibrated and uncalibrated pulse contour analysis, oesophageal Doppler)

In the past few years, there was a remarkable trend with regard to perioperative haemodynamic monitoring in favour of less invasive techniques. These less invasive techniques are thought to enable a better tailoring of fluids, inotropes and vasopressors to the individual patient needs by providing flow-based variables such as stroke volume and cardiac output continuously in real time. Regardless of performing haemodynamic monitoring, in addition to preservation of myocardial contractility and afterload, one of the major goals should be to adjust the volume status of the patient close to 'normovolemia' to avoid both occult hypoperfusion and hypervolemia [33]. In this regard, cardiac output is the major determinant influencing oxygen supply in addition to haemoglobin and arterial oxygen content (Fig. 1).

None of the available minimally invasive techniques is able to measure stroke volume (SV) and CO directly; they can provide only an indirect estimation of these variables. If we list the key features of an ideal monitoring device, such a device should have the following features:

- Easy to use
- Readily available
- Cause no complications
- Reliable and yield reproducible values
- Non-invasive
- Investigator independent
- Easy to interpret

At present, these features are not completely met by the minimally invasive monitoring techniques available for daily clinical routine.

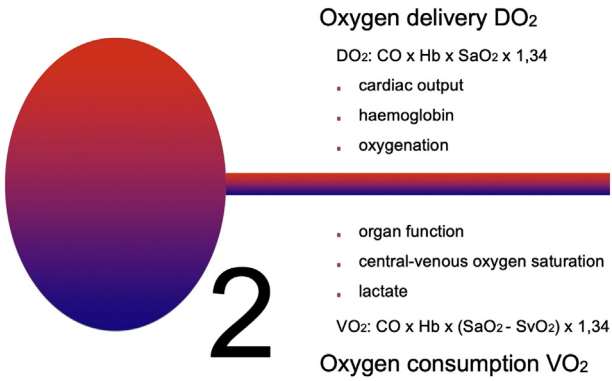

Fig. 1. Determinants of oxygen supply and demand.

From the numerous present-day minimally invasive devices, we have chosen those that are widely used in clinical routine. There is certainly softness with regard to categorisation of devices to the different degrees of invasiveness, which will be addressed subsequently (Fig. 2).

Generally, pulmonary-arterial and thermodilution are considered as (maximal) invasive techniques. With regard to minimally invasive haemodynamic techniques, several methods and devices are currently available on the market, such as uncalibrated pulse contour analysis, pulse power analysis and ODM. Completely non-invasive techniques are based either on the 'Volume-Clamp' method (which generates values also by an uncalibrated pulse contour analysis), PWTT analysis or bioimpedance.

Pulse contour analysis: advantages and limitations

The majority of uncalibrated less invasive or non-invasive devices are based on pulse contour analysis for calculation of CO and derived variables, even though proprietary labelling such as 'pulse power analysis' may suggest an alternative or more sophisticated approach.

The main advantage of pulse contour analysis is the uncomplicated and easy-to-use setup, which facilitates application in the OR environment. Calibration of the device with a reference technique is not mandatory (albeit possible with certain devices), and the measurement starts right upon feeding in biometric patient data such as gender, age, weight and height in the respective haemodynamic monitor. The main limitation is that the basic assumption, namely, that calculation of CO is possible using the shape (and specific changes of the shape) of the arterial pressure waveform may not be true in several clinical situations. The Windkessel model applied for calculation of CO from the pressure waveform is fitted to the conditions present in an individual patient applying a limited set of biometric data. These data are used in the different algorithms to account for the patient's aortic properties, including the aortic compliance, which, in turn, among other factors, yield Windkessel compliance and its characteristic impedance [34]. It is well conceivable that the assumptions made by the applied model are violated in individual patients, especially in clinical situations that have not or not sufficiently be incorporated in method derivation. Further, biometric information has some influence on waveform analysis, as manipulating these data may result in significant changes of the obtained CO [6].

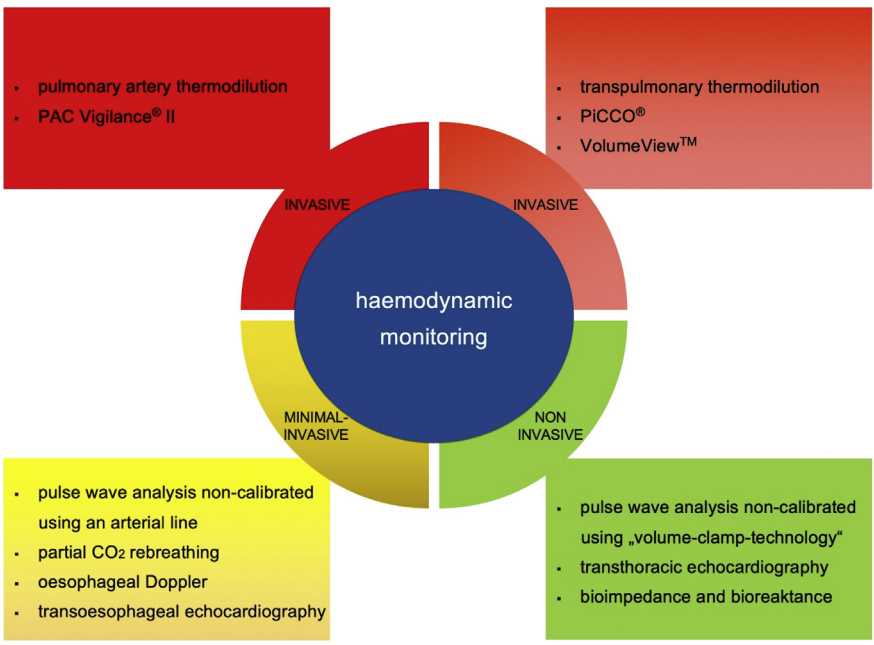

Fig. 2. Invasiveness of different monitoring techniques.

It is therefore not surprising that recent meta-analyses investigating minimally and non-invasive devices reported PEs well above 40% for each of the studied devices [35,36]. On the other hand, it has been shown that meticulous experimental setup and the avoidance of commonly found confounders such as haemodynamic instability significantly improve the performance of the new devices [6,37]. From a clinical point of view, monitoring devices should be able to cope with these confounders, as monitoring, especially during haemodynamic instability, may be most beneficial to the patient.

FloTrac (Vigileo/EV 1000/hemosphere)

The underlying principle of uncalibrated pulse contour analysis is explained using the FloTrac™ system, which is marketed since 2005 by Edwards Lifesciences (Irvine, CA, USA).

CO is calculated by multiplying heart rate (HR) and SV according to the equation $CO = HR \cdot SV$. The Flotrac algorithm uses this equation in a modified version; $CO = PF \cdot (\sigma AP \cdot \chi)$, where PF represents pulse frequency, σAP the standard deviation of pulse pressure (PP) and χ the conversion factor Khi. HR is substituted by pulse frequency (PF) to only consider heart beats generating a pulse wave (and thereby tissue perfusion) in the calculation [38]. This is accomplished by counting the systolic peaks of the pulse curve in 20 s intervals with a frequency of 100 Hz (generating 2.000 data points). Use of the standard deviation σAP instead of PP yields a variable that is more robust against short-term changes of vascular tone and is therefore preferred for calculation.

In contrast, SV is not measured directly but obtained from the product of σAP with the conversion factor χ and is therefore estimated from the above-mentioned variables. The conversion factor serves two objectives: First, it holds the dimension ml/mmHg; multiplying it with σAP, which is given in mmHg, enables conversion to the unit ml. Second, χ offers further information with regard to vascular resistance and compliance, respectively, thereby modifying their influence on PP, which, in turn, is used for estimation of SV. The conversion factor itself is calculated using a polynomic equation consisting of several variables (according to the manufacturer) among others: PF, mean arterial pressure (MAP), σAP, body surface area (BSA), compliance of the great vessels C(P) and skewness (μ_{3ap}) and kurtosis (μ_{4ap}) of the pressure curve. χ is a mean value of a 60 s interval and therefore refreshed minute by minute. An important prerequisite for a reliable, minimally invasive measurement of CO based on uncalibrated pulse contour analysis is a high-quality arterial pressure curve, as its quality is essential for an accurate analysis.

In addition to the above explained formula, further factors are considered for CO calculation by the FloTrac system. According to the manufacturer, the system is able to identify several circulatory states based on an integrated databank and consequently adjusts the performed calculations. In this regard, different software versions of the FloTrac algorithms exist; version 4.0 is marketed at present [39].

The FloTrac system has been assessed in several studies, which shows that the development of the software program from versions 1 to 4 yielded at least partially an improvement with regard to the interchangeability with thermodilution as the reference technique [39,40]. Particularly, the arrhythmia detection has been improved with third-generation software. However, patients with high as well as with low and rapidly changing systemic vascular resistance still are a challenge, also for the latest and most sophisticated software version [41–45]. In such patients, haemodynamic monitoring based on uncalibrated pulse contour is still not recommended. Two recent meta-analyses on the FloTrac-Vigileo-system suggest that in patients with preserved systemic vascular resistance and a hypo- or normodynamic circulation (which can be normally observed in patients undergoing elective surgery), both PE and trending capabilities may be sufficient for use in daily clinical practice, while in critically ill patients with low SVR and/or a hyperdynamic state, precision and trending are significantly worse [40,46]. Because of the principal shortcomings of uncalibrated systems, this pertains to all devices using uncalibrated pulse contour algorithms [47–49].

ProAQT™ (Pulsioflex)

Another uncalibrated minimally invasive monitoring device based on pulse contour analysis is the ProAQT-system (PULSION Medical Systems SE, Feldkirchen, Germany). The device offers continuous estimation and trending of SV and CO. Further, dynamic variables of fluid responsiveness such as PPV and SVV, the calculated systemic vascular resistance index and the cardiac power index as an indicator of cardiac contractility are calculated. Additionally, calibration with a reference CO is possible.

According to the manufacturer, the ProAQT-system uses the pulse contour algorithm originally developed for the PiCCO device, and another proprietary algorithm for initial 'calibration' based on patients' demographic data. One problem of this approach may be that the PiCCO device is intended for use in the femoral artery, while the ProAQT is usually connected to a radial line. As the pulse contour differs between the femoral and the radial site, disappointing results of a study comparing the ProAQT with calibrated TPTD with the $PiCCO_2$ may be due to this inconsistency [50]. Currently, only few data are available with regard to the validity of the ProAQT-derived variables. Monnet et al. analysed the effects of fluid administration and the reduction or increase in norepinephrine dose in an ICU setting on CO measured by ProAQT and FloTrac compared to TPTD [47]. They summarised that ProAQT and FloTrac are not able to reliably estimate the absolute values of CO, but volume-induced changes and norepinephrine-induced changes in CO were tracked reliably by both systems. The possibility to autocalibrate the system did not improve its reliability. In a recently published bi-centre clinical study regarding the accuracy of the ProAQT technology in patients who underwent cardiac surgery, the device showed poor accuracy compared with TPTD regarding CO measurements [50]. However, the authors reported an acceptable reliability for tracking changes in CO, especially after cardiopulmonary bypass (concordance rate of 94%). Biais and colleagues found a large PE and a low concordance rate (62%) between the ProAQT algorithm and continuous pulmonary artery thermodilution during liver transplant surgery, and they attributed this result to the high impact of SVR on ProAQT readings [51]. To date, there are no CO comparison studies for the ProAQT with a PE below 30%, regardless of the patient population enrolled. In a trial applying a goal-directed therapy (GDT) protocol in a major abdominal surgery with the ProAQT, however, patients in the intervention group had less postoperative complications than those in the standard care group [52].

$LiDCO_{rapid}$

The $LiDCO_{rapid}$ monitoring system (LiDCO Group Ltd, London, UK) represents another approach of beat-to-beat cardiac output determination, the pulse power analysis. The algorithm calculates a nominal aortic volume from a nomogram, in which age, gender, height and other parameters are considered. The obtained volume is multiplied by an exponential function, which, in turn, is modified by arterial blood pressure and aortic compliance (derived from an internal reference). The pulse power algorithm originally required calibration by lithium indicator dilution to determine the individual vascular compliance. The lithium dilution-derived CO has been evaluated in different clinical and experimental scenarios with ambiguous results [53–55]. The newly developed software program ($LiDCO_{rapid}$) uses a nomogram to assess the patient's specific aortic compliance. Therefore, a prior lithium dilution calibration for the calculation of SV/CO and dynamic variables of fluid responsiveness is not necessary. However, alternatively, an external calibration with a reference technique can still be performed.

The $LiDCO_{rapid}$ requires only a standard arterial line. As generally no calibration is performed, the above outlined limitations for uncalibrated or autocalibrated arterial pressure waveform analysis do apply, such as rapid changes in vascular tone [56]. Our group has performed a study evaluating the $LiDCO_{rapid}$ technology against TPTD in 42 patients undergoing cardiac surgery, in which CO determination by pulse power analysis was significantly influenced by MAP, yielding an unacceptable high bias [57]. With regard to patients at higher surgical risk, Nordstrom et al. compared the $LiDCO_{rapid}$ technology with an ODM in a setting of intraoperative SV optimisation in patients undergoing major abdominal surgery [58]. They concluded that the $LiDCO_{rapid}$ and the ODM cannot be used interchangeably and that $LiDCO_{rapid}$ SVV and PPV add little value to a GDT protocol.

Although the $LiDCO_{rapid}$ technology is principally comparable with the FloTrac/Vigileo-system, there is less evidence regarding its accuracy and precision. It should be noted, however, that the largest trial on GDT in major abdominal surgery performed so far used the $LiDCO_{rapid}$ as its haemodynamic monitor [59].

Oesophageal Doppler

The ODM measures blood flow in the descending part of the aorta. Using the pulsed-wave Doppler principle, a velocity-time integral, the so-called 'stroke distance', is displayed. As a product of stroke distance and the cross-sectional area of the aorta (based on empirical data), SV and CO can be

calculated automatically. As approximately 30% of blood flow leaving the left ventricle supplies the coronaries, the upper limbs and the brain, only 70% of the total CO can be measured in the descending aorta (which is compensated for by the system). The basic principle of ODM-derived CO measurement has been described in detail elsewhere [60,61]. As the obtained velocity-time waveform is highly dependent on the correct position of the probe, the clinician often has to re-adjust the probe to keep the angle of insonation as small as possible, i.e. to keep the accuracy of measurements as best as possible. The higher the angle of insonation, the higher the degree of underestimating the real CO. Anatomically, the descending aorta and the oesophagus run in parallel at the level where the oesophageal probe should be positioned, causing an angle of insonation of approximately 45°, which has to be considered for ODM-derived variables [60,62]. There are some data available regarding the relationship between learning curve and achieving high diagnostic quality. Lefrant et al. demonstrated that a period of training involving no more than 12 patients is required to enable reliable CO measurements using an ODM [63]. To address problems due to a lost Doppler signal, the manufacturer (Deltex Ltd., Chichester, Great Britain) has recently launched an enhanced monitor that enables Doppler-calibrated pulse contour analysis (CardioQ-ODM+). By using a research monitor incorporating nine different pulse contour algorithms, our group and others found that the well-known Zander-Liljestrand algorithm performed best [64,65]. This algorithm was subsequently mounted in the ODM+. Although it is a less invasive approach of monitoring CO, the ODM has to be inserted blindly into the oesophagus in sedated and most often in mechanically ventilated patients, and in general, the risk of harm to oesophageal structures with potentially serious complications must be kept in mind [66].

There is increasing evidence that ODM-guided fluid optimisation will improve patients' outcome [67–70]. Consequently, the British National Institute of Health and Clinical Excellence has adopted the use of intraoperative oesophageal Doppler monitoring in the National Health Service (NHS) in patients undergoing major or high-risk surgery or other surgical patients in whom the clinician would consider using invasive haemodynamic monitoring [71]. However, a recent meta-analysis questioned the beneficial effects of ODM-driven SV optimisation protocols on patients' outcome [72]. The authors concluded that ODM-guided fluid optimisation in colorectal surgery did not influence length of stay in hospital or postoperative complications. Results favouring this approach were seen only in early studies, whereas more recent trials did not show any beneficial effects [73].

Non-invasive technologies (volume clamp technique, bioreactance, pulse wave transit time)

Finger cuff-based techniques

The finger cuff-based technologies such as ClearSight (Edwards Lifesciences, Irvine, USA) and CNAP (CNAPTM Monitor 500, CNSystems Medizintechnik AG, Graz, Austria) are able to continuously determine non-invasive arterial blood pressure and CO by an inflatable cuff around the index and/or the middle finger. This technology in principle is based on the 'volume clamp method' first introduced in the early 1970s by Jan Penaz [74]. The basic principle of the 'volume clamp method' relies on 'clamping' the diameter of a finger artery by a dynamic counter-pressure inflation of the finger cuff, therefore keeping the diameter of the artery constant. Consequently, the pressure effected on the finger by the cuff corresponds to the pressure in the finger arteries, which can be registered and converted to central arterial pressure [75,76]. The basic principle of calculating SV/CO in both systems is based on the pulse contour method, which is described in detail above and elsewhere [77,78].

ClearSight (formerly known as Nexfin)

With regard to CO measurements, ClearSight technology has been developed on the basis of a large human database including non-invasive and invasive arterial finger pressure tracings together with thermodilution CO during cardiac surgery [79], passive head-up tilt in healthy subjects [80] and patients in shock [34]. Currently, a large pool of data is available dealing with the accuracy and precision of ClearSight-derived flow variables, with inhomogeneous results. Our group studied 40 patients undergoing elective coronary artery bypass grafting during the intraoperative period including a

passive leg-raising manoeuvre and situations with changing systemic vascular resistance. In this study, the ClearSight device proved to be a reliable technology for CO estimation during cardiac surgery [37]. Regarding the validation of the ClearSight device in the operating room (OR), our results have been confirmed in 25 patients monitored with an ODM, yielding a strong correlation of ClearSight-CO with CO measured by ODM [81]. Monnet et al. studied the ClearSight device in 45 haemodynamically unstable patients. The aim of this study was to evaluate whether the ClearSight device was able to accurately track changes in CO due to a fluid challenge. Unfortunately, estimation of CO in septic shock patients was not reliable, neither for absolute values of CO nor for tracking changes induced by volume expansion [82]. These results have been confirmed in another study on post-cardiac surgery patients in the ICU [83]. Comparably to minimally invasive devices such as the FloTrac-Vigileo, the ClearSight device performs best in patients undergoing elective surgery. In a very well-controlled study in patients undergoing cardiac surgery, PE of ClearSight (compared to pulmonary artery thermodilution) was below 30% during stable haemodynamics; performance during periods of haemodynamic instability, however, was unacceptable [6].

Several studies showed a fair ability of the ClearSight device in tracking changes in CO [37,81,82,84–86]. Presently, the use of the ClearSight device may be most beneficial in the OR and the PACU, especially in patients at intermediate risk who normally would not be equipped with a CO monitoring device. However, the high price (comparably to a PAC) is currently counteracting this reasonable approach. Quite recently, two studies demonstrated that haemodynamic optimisation protocols using non-invasive devices are feasible and able to reduce postoperative complications [87,88].

CNAP

Comparable to the ClearSight device, the CNAP system (CNSystems Medizintechnik AG, Graz, Austria) offers the ability to continuously measure blood pressure, SV/CO and PPV/SVV. Data of the ability of the CNAP device to estimate CO are scarce [78]. A proof-of-concept-study enrolling approximately 38 patients in the ICU showed that this technology is feasible in critically ill patients [78]. There was an acceptable agreement between CNAP-CO and TPTD if the CNAP device had been calibrated with thermodilution; data produced from the autocalibrated algorithm (using demographic data), however, were above the accepted PE. In a more recent study from the same group, similar results were reported with a too large PE for autocalibrated values; trending characteristics, however, were acceptable (concordance rate of 100%) [89].

Thoracic bioimpedance

Thoracic bioimpedance is a non-invasive method for CO measurement analysing the variations in voltage in each beat in response to the application of a high-frequency, transthoracic current. The most promising monitoring device in this field might be the NICOM device (Cheetah Medical Inc., Wilmington, Delaware, USA). In brief, this technology tracks the phase of the electrical current traversing the chest. The underlying scientific phenomenon is that the higher the SV, the more significant these phase shifts become. The underlying principle of thoracic bioimpedance is described in detail elsewhere [90]. There are a lot of validation studies available showing in principle promising results regarding accuracy and precision of NICOM-CO compared to TPTD and pulmonary artery thermodilution, even in the presence of atrial and/or ventricular arrythmias [91–93]. However, a few studies showed controversial results, especially in infants and neonates and in critically ill patients [94,95].

One main limitation of this technology seems to be the application in the OR, as electrocautery interferes with the thoracic bioimpedance signal. Whenever electrocautery is used for more than 2/3 of the time period, NICOM-CO is not displayed. To date, the clinical impact of this technology in daily clinical routine is limited, and a widespread use of this technology in perioperative medicine seems unlikely at present.

Pulse wave transit time (esCCO)

The esCCO technology (Nihon Kohden®, Tokyo, Japan) is a non-invasive haemodynamic monitoring platform that requires an ECG signal and the plethysmographic wave [96]. As already described previously, one main approach for calculating CO is based on the information provided by PP:

$$CO = SV \times HR = (K \times PP) \times HR$$

[CO, cardiac output; SV, stroke volume; K, constant value; PP, pulse pressure; HR, heart rate].

The esCCO technology is based on the observation that the correlation between SV and the PWTT is superior compared to the correlation between SV and PP [97], yielding the following formula:

$$CO = SV \times HR = K \times (\alpha \times PWTT + \beta) \times HR = esCCO$$

[CO, cardiac output; SV, stroke volume; HR, heart rate; K, constant value; PWTT, pulse wave transit time; α, β: experimental constant].

The PWTT is the sum of the pre-ejection period and the pulse wave arrival time from the ascending aorta to the peripheral plethysmographic wave. PWTT is calculated from the interval between the R wave of the ECG and the peripheral SpO2 pulse wave arrival when ECG and SpO2 are simultaneously recorded. The initial need for external calibration has been replaced by the possibility to adjust measurements to biometric data incorporated in the most recent software program [98].

Unfortunately, after a first multicentre validation study showing promising results [99] – albeit with the esCCO calibrated with pulmonary artery thermodilution – further studies using the 'auto-calibrated' algorithm based on patients' biometric data failed to show acceptable agreement compared with thermodilution or echocardiography, especially in critically ill patients; further, trending abilities were not sufficient to guide adequate therapeutic decisions [100–102]. Consequently, this device is currently not recommended.

In conclusion, monitoring devices provide values useful for the diagnosis of the underlying pathophysiology. Fig. 3 presents a matrix that displays the recommended haemodynamic monitoring depending on the specific risks of the surgical procedure and the patient. Therapeutic decisions derived

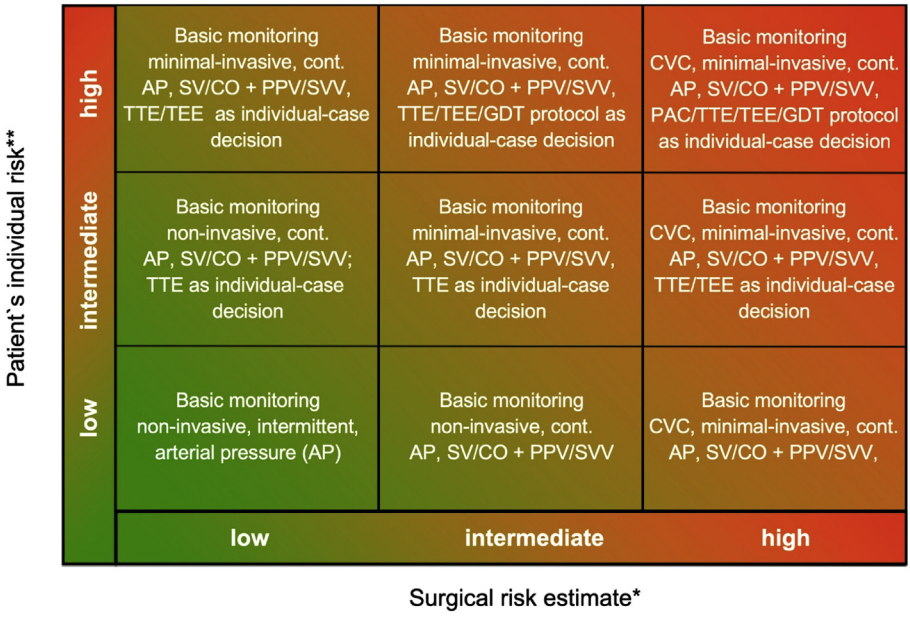

Fig. 3. Decision matrix presenting the recommended haemodynamic monitoring based on the risk of the specific surgical procedure and the patient. *based on surgical risk estimation. ** based on different institutional standard operating procedures, i.e. ASA physical status classification system, revised cardiac risk index, metabolic equivalent threshold (MET) etc. BP, blood pressure; CVP, central venous line; CO, cardiac output; GDT, goal-directed therapy.

from these values must first be assessed by an expert physician. In-depth knowledge of the advantages and limitations of the monitoring devices used is required for proper use of these devices.

Practice points

- Recently introduced minimally invasive and non-invasive monitoring technologies provide useful information regarding acute changes of the cardiocirculatory system.
- Calibrated monitoring technologies provide higher accuracy and precision with regard to cardiac output determination compared with uncalibrated techniques.
- The higher the risk to the patient and the more complex the type of surgery performed, the more advanced and invasive monitoring is both justified and needed.
- Monitoring per se will not improve patients' outcome, unless coupled to a defined treatment.

Research agenda

- The value of minimally invasive and non-invasive monitoring technologies, especially in extreme patient populations such as octogenarians and the severely obese, as well as in infants and neonates, should be further established.
- There is a need for multicentre, randomised, controlled trials in an appropriate number of patients to investigate the impact of non-invasive-driven haemodynamic optimisation protocols in the perioperative setting of high-risk patients.

References

[1] Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1(8476):307–10.
*[2] Critchley LA. Bias and precision statistics: should we still adhere to the 30% benchmark for cardiac output monitor validation studies? Anesthesiology 2011;114(5):1245. author reply 1245-1246.
[3] 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(2):85–91.
[4] Fischer MO, Diouf M, Wilde RB, et al. Evaluation of cardiac output by 5 arterial pulse contour techniques using trend interchangeability method. Medicine (Baltimore) 2016;95(25):e3530.
*[5] Lorne E, Diouf M, de Wilde RBP, et al. Assessment of interchangeability rate between 2 methods of measurements: an example with a cardiac output comparison study. Medicine (Baltimore) 2018;97(7):e9905.
*[6] Truijen J, Westerhof BE, Kim YS, et al. The effect of haemodynamic and peripheral vascular variability on cardiac output monitoring: thermodilution and non-invasive pulse contour cardiac output during cardiothoracic surgery. Anaesthesia 2018;73(12):1489–99.
[7] Critchley LAH. Meta-analyses of Bland-Altman-style cardiac output validation studies: good, but do they provide answers to all our questions? Br J Anaesth 2017;118(3):296–7.
*[8] Montenij LJ, Buhre WF, Jansen JR, et al. Methodology of method comparison studies evaluating the validity of cardiac output monitors: a stepwise approach and checklist. Br J Anaesth 2016;116(6):750–8.
[9] 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(5):1180–92.
[10] Fischer MO, Lorne E. The trend interchangeability method. Br J Anaesth 2016;117(6):826–8.
*[11] Reuter DA, Huang C, Edrich T, et al. Cardiac output monitoring using indicator-dilution techniques: basics, limits, and perspectives. Anesth Analg 2010;110(3):799–811.
[12] Botero M, Kirby D, Lobato EB, et al. Measurement of cardiac output before and after cardiopulmonary bypass: comparison among aortic transit-time ultrasound, thermodilution, and noninvasive partial CO_2 rebreathing. J Cardiothorac Vasc Anesth 2004;18(5):563–72.
[13] Stetz CW, Miller RG, Kelly GE, et al. Reliability of the thermodilution method in the determination of cardiac output in clinical practice. Am Rev Respir Dis 1982;126(6):1001–4.
[14] Metzelder SM, Coburn M, Stoppe C, et al. Accuracy and precision of calibrated arterial pulse contour analysis in patients with subarachnoid hemorrhage requiring high-dose vasopressor therapy: a prospective observational clinical trial. Crit Care 2014;18(1):R25.
[15] Kiefer N, Hofer CK, Marx G, et al. Clinical validation of a new thermodilution system for the assessment of cardiac output and volumetric parameters. Crit Care 2012;16.

[16] Sakka SG, Rühl CC, Pfeiffer UJ, et al. Assessment of cardiac preload and extravascular lung water by single transpulmonary thermodilution. Intensive Care Med 2000;26:180–7.
*[17] Hamzaoui O, Monnet X, Richard C, et al. Effects of changes in vascular tone on the agreement between pulse contour and transpulmonary thermodilution cardiac output measurements within an up to 6-hour calibration-free period. Crit Care Med 2008;36.
[18] Sakka SG, Reinhart K, Meier-Hellmann A. Comparison of pulmonary artery and arterial thermodilution cardiac output in critically ill patients. Intensive Care Med 1999;25:843–6.
[19] Hilty MP, Franzen DP, Wyss C, et al. Validation of transpulmonary thermodilution variables in hemodynamically stable patients with heart diseases. Ann Intensive Care 2017;7:86.
[20] Staier K, Wilhelm M, Wiesenack C, et al. Pulmonary artery vs. transpulmonary thermodilution for the assessment of cardiac output in mitral regurgitation. Eur J Anaesthesiology 2012;29:431–7.
[21] Goepfert MS, Richter HP, Zu Eulenburg C, et al. Individually optimized hemodynamic therapy reduces complications and length of stay in the intensive care unit. Anesthesiology 2013;119:824–36.
[22] Goepfert MSG, Reuter DA, Akyol D, et al. Goal-directed fluid management reduces vasopressor and catecholamine use in cardiac surgery patients. Intensive Care Med 2007;33:96–103.
[23] Schmid S, Kapfer B, Heim M, et al. Algorithm-guided goal-directed haemodynamic therapy does not improve renal function after major abdominal surgery compared to good standard clinical care: a prospective randomised trial. Crit Care 2016;20:50.
[24] Trof RJ, Beishuizen A, Cornet AD, et al. Volume-limited versus pressure-limited hemodynamic management in septic and nonseptic shock. Crit Care Med 2012;40.
[25] Dufour N, Delville M, Teboul J-L, et al. Transpulmonary thermodilution measurements are not affected by continuous veno-venous hemofiltration at high blood pump flow. Intensive Care Med 2012;38:1162–8.
[26] Ikuta K, Wang Y, Robinson A, et al. National trends in use and outcomes of pulmonary artery catheters among medicare beneficiaries, 1999–2013. JAMA Cardiol 2017;2(8):908–13.
[27] Vincent JL. The pulmonary artery catheter. J Clin Monit Comput 2012;26(5):341–5.
[28] Cho YJ, Koo C-H, Kim TK, et al. Comparison of cardiac output measures by transpulmonary thermodilution, pulse contour analysis, and pulmonary artery thermodilution during off-pump coronary artery bypass surgery: a subgroup analysis of the cardiovascular anaesthesia registry at a single tertiary centre. J Clin Monit Comput 2016;30:771–82.
[29] Connors Jr AF, Speroff T, Dawson NV, et al. The effectiveness of right heart catheterization in the initial care of critically ill patients. SUPPORT Investigators. JAMA 1996;276(11):889–97.
[30] Gurgel ST, do Nascimento Jr P. Maintaining tissue perfusion in high-risk surgical patients: a systematic review of randomized clinical trials. Anesth Analg 2011;112(6):1384–91.
[31] Hamilton MA, Cecconi M, Rhodes A. A systematic review and meta-analysis on the use of preemptive hemodynamic intervention to improve postoperative outcomes in moderate and high-risk surgical patients. Anesth Analg 2011;112(6):1392–402.
[32] Habicher M, Zajonz T, Heringlake M, et al. S3 guidelines on intensive medical care of cardiac surgery patients : hemodynamic monitoring and cardiovascular system-an update. Anaesthesist 2018;67(5):375–9.
[33] Shin CH, Long DR, McLean D, et al. Effects of intraoperative fluid management on postoperative outcomes: a hospital registry study. Ann Surg 2018;267(6):1084–92.
[34] Jellema WT, Wesseling KH, Groeneveld AB, et al. Continuous cardiac output in septic shock by simulating a model of the aortic input impedance: a comparison with bolus injection thermodilution. Anesthesiology 1999;90(5):1317–28.
*[35] Joosten A, Desebbe O, Suehiro K, et al. Accuracy and precision of non-invasive cardiac output monitoring devices in perioperative medicine: a systematic review and meta-analysisdagger. Br J Anaesth 2017;118(3):298–310.
[36] 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(5):1220–35.
[37] Broch O, Renner J, Gruenewald M, et al. A comparison of the Nexfin(R) and transcardiopulmonary thermodilution to estimate cardiac output during coronary artery surgery. Anaesthesia 2012;67(4):377–83.
[38] Metzelder S, Coburn M, Fries M, et al. Performance of cardiac output measurement derived from arterial pressure waveform analysis in patients requiring high-dose vasopressor therapy. Br J Anaesth 2011;106(6):776–84.
[39] Suehiro K, Tanaka K, Mikawa M, et al. Improved performance of the fourth-generation FloTrac/vigileo system for tracking cardiac output changes. J Cardiothorac Vasc Anesth 2015;29(3):656–62.
[40] Slagt C, Malagon I, Groeneveld AB. Systematic review of uncalibrated arterial pressure waveform analysis to determine cardiac output and stroke volume variation. Br J Anaesth 2014;112(4):626–37.
[41] Eisenried A, Klarwein R, Ihmsen H, et al. Accuracy and trending ability of the fourth-generation FloTrac/EV1000 system in patients with severe aortic valve stenosis before and after surgical valve replacement. J Cardiothorac Vasc Anesth 2019 May;33(5):1230–6.
[42] Hattori K, Maeda T, Masubuchi T, et al. Accuracy and trending ability of the fourth-generation FloTrac/vigileo system in patients with low cardiac index. J Cardiothorac Vasc Anesth 2017;31(1):99–104.
[43] Maeda T, Hamaguchi E, Kubo N, et al. The accuracy and trending ability of cardiac index measured by the fourth-generation FloTrac/Vigileo system and the Fick method in cardiac surgery patients. J Clin Monit Comput 2018 Nov 7. https://doi.org/10.1007/s10877-018-0217-1.
[44] Maeda T, Hattori K, Sumiyoshi M, et al. Accuracy and trending ability of the fourth-generation FloTrac/Vigileo System in patients undergoing abdominal aortic aneurysm surgery. J Anesth 2018;32(3):387–93.
[45] Shih BF, Huang PH, Yu HP, et al. Cardiac output assessed by the fourth-generation arterial waveform analysis system is unreliable in liver transplant recipients. Transpl Proc 2016;48(4):1170–5.
[46] Suehiro K, Tanaka K, Matsuura T, et al. The Vigileo-FloTrac system: arterial waveform analysis for measuring cardiac output and predicting fluid responsiveness: a clinical review. J Cardiothorac Vasc Anesth 2014;28(5):1361–74.
[47] 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(2):235–43.

[48] van Drumpt A, van Bommel J, Hoeks S, et al. The value of arterial pressure waveform cardiac output measurements in the radial and femoral artery in major cardiac surgery patients. BMC Anesthesiol 2017;17(1):42.
[49] Weil G, Motamed C, Eghiaian A, et al. Comparison of Proaqt/Pulsioflex((R)) and oesophageal Doppler for intra-operative haemodynamic monitoring during intermediate-risk abdominal surgery. Anaesth Crit Care Pain Med 2019 Apr;38(2):153–9. https://doi.org/10.1016/j.accpm.2018.03.011.
[50] Broch O, Carbonell J, Ferrando C, et al. Accuracy of an autocalibrated pulse contour analysis in cardiac surgery patients: a bi-center clinical trial. BMC Anesthesiol 2015;15:171.
[51] Biais M, Mazocky E, Stecken L, et al. Impact of systemic vascular resistance on the accuracy of the pulsioflex device. Anesth Analg 2017;124(2):487–93.
[52] 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(5):R191.
[53] Gruenewald M, Renner J, Meybohm P, et al. Reliability of continuous cardiac output measurement during intra-abdominal hypertension relies on repeated calibrations: an experimental animal study. Crit Care 2008;12(5):R132.
[54] Mowat I, Todman E, Jaggar S. Validation of the LiDCO pulse contour system in patients with impaired left ventricular function. Anaesthesia 2012;67(2):188. author reply 188-189.
[55] O'Loughlin E, Ward M, Crossley A, et al. Evaluation of the utility of the Vigileo FloTrac(™) , LiDCO(™) , USCOM and CardioQ(™) to detect hypovolaemia in conscious volunteers: a proof of concept study. Anaesthesia 2015;70(2):142–9.
[56] Bein B, Meybohm P, Cavus E, et al. The reliability of pulse contour-derived cardiac output during hemorrhage and after vasopressor administration. Anesth Analg 2007;105(1):107–13.
[57] Broch O, Renner J, Hocker J, et al. Uncalibrated pulse power analysis fails to reliably measure cardiac output in patients undergoing coronary artery bypass surgery. Crit Care 2011;15(1):R76.
[58] Nordstrom J, Hallsjo-Sander C, Shore R, et al. Stroke volume optimization in elective bowel surgery: a comparison between pulse power wave analysis ($LiDCO_{rapid}$) and oesophageal Doppler (CardioQ). Br J Anaesth 2013;110(3):374–80.
*[59] Pearse RM, Harrison DA, MacDonald N, et al. Effect of a perioperative, cardiac output-guided hemodynamic therapy algorithm on outcomes following major gastrointestinal surgery: a randomized clinical trial and systematic review. JAMA 2014;311(21):2181–90.
[60] Schober P, Loer SA, Schwarte LA. Transesophageal Doppler devices: a technical review. J Clin Monit Comput 2009;23(6):391–401.
[61] Singer M. Oesophageal Doppler. Curr Opin Crit Care 2009;15(3):244–8.
[62] Colquhoun DA, Roche AM. Oesophageal Doppler cardiac output monitoring: a longstanding tool with evolving indications and applications. Best Pract Res Clin Anaesthesiol 2014;28(4):353–62.
[63] Lefrant JY, Bruelle P, Aya AG, et al. Training is required to improve the reliability of esophageal Doppler to measure cardiac output in critically ill patients. Intensive Care Med 1998;24(4):347–52.
*[64] Broch O, Bein B, Gruenewald M, et al. Accuracy of cardiac output by nine different pulse contour algorithms in cardiac surgery patients: a comparison with transpulmonary thermodilution. Biomed Res Int 2016;2016:1–13.
*[65] Monge Garcia MI, Romero MG, Cano AG, et al. Impact of arterial load on the agreement between pulse pressure analysis and esophageal Doppler. Crit Care 2013;17(3):R113.
[66] Schober P, Loer SA, Schwarte LA. Perioperative hemodynamic monitoring with transesophageal Doppler technology. Anesth Analg 2009;109(2):340–53.
[67] Noblett SE, Snowden CP, Shenton BK, et al. Randomized clinical trial assessing the effect of Doppler-optimized fluid management on outcome after elective colorectal resection. Br J Surg 2006;93(9):1069–76.
[68] Abbas SM, Hill AG. Systematic review of the literature for the use of oesophageal Doppler monitor for fluid replacement in major abdominal surgery. Anaesthesia 2008;63(1):44–51.
[69] Mowatt G, Houston G, Hernandez R, et al. Systematic review of the clinical effectiveness and cost-effectiveness of oesophageal Doppler monitoring in critically ill and high-risk surgical patients. Health Technol Assess 2009;13(7). iii-iv, ix-xii, 1-95.
[70] Singer M. Oesophageal Doppler monitoring: should it be routine for high-risk surgical patients? Curr Opin Anaesthesiol 2011;24(2):171–6.
[71] Ghosh S, Arthur B, Klein AA. NICE guidance on CardioQ(TM) oesophageal Doppler monitoring. Anaesthesia 2011;66(12):1081–3.
[72] Srinivasa S, Lemanu DP, Singh PP, et al. Systematic review and meta-analysis of oesophageal Doppler-guided fluid management in colorectal surgery. Br J Surg 2013;100(13):1701–8.
[73] McKenny M, Conroy P, Wong A, et al. A randomised prospective trial of intra-operative oesophageal Doppler-guided fluid administration in major gynaecological surgery. Anaesthesia 2013;68(12):1224–31.
[74] Penaz J, Voigt A, Teichmann W. Contribution to the continuous indirect blood pressure measurement. Z Gesamte Inn Med 1976;31(24):1030–3.
[75] Bogert LW, van Lieshout JJ. Non-invasive pulsatile arterial pressure and stroke volume changes from the human finger. Exp Physiol 2005;90(4):437–46.
[76] Fortin J, Marte W, Grullenberger R, et al. Continuous non-invasive blood pressure monitoring using concentrically interlocking control loops. Comput Biol Med 2006;36(9):941–57.
[77] Wesseling KH, Jansen JR, Settels JJ, et al. Computation of aortic flow from pressure in humans using a nonlinear, three-element model. J Appl Physiol (1985) 1993;74(5):2566–73.
[78] Wagner JY, Grond J, Fortin J, et al. 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 2016 Aug;30(4):487–93. https://doi.org/10.1007/s10877-015-9744-1.
[79] Jansen JR, Schreuder JJ, Mulier JP, et al. A comparison of cardiac output derived from the arterial pressure wave against thermodilution in cardiac surgery patients. Br J Anaesth 2001;87(2):212–22.

[80] Harms MP, Wesseling KH, Pott F, et al. Continuous stroke volume monitoring by modelling flow from non-invasive measurement of arterial pressure in humans under orthostatic stress. Clin Sci (Lond) 1999;97(3):291–301.
[81] Chen G, Meng L, Alexander B, et al. Comparison of noninvasive cardiac output measurements using the Nexfin monitoring device and the esophageal Doppler. J Clin Anesth 2012;24(4):275–83.
[82] Monnet X, Picard F, Lidzborski E, et al. The estimation of cardiac output by the Nexfin device is of poor reliability for tracking the effects of a fluid challenge. Crit Care 2012;16(5):R212.
[83] Fischer MO, Avram R, Carjaliu I, et al. Non-invasive continuous arterial pressure and cardiac index monitoring with Nexfin after cardiac surgery. Br J Anaesth 2012;109(4):514–21.
[84] Ameloot K, Van De Vijver K, Broch O, et al. Nexfin noninvasive continuous hemodynamic monitoring: validation against continuous pulse contour and intermittent transpulmonary thermodilution derived cardiac output in critically ill patients. Sci World J 2013;2013:519080.
[85] Bubenek-Turconi SI, Craciun M, Miclea I, et al. Noninvasive continuous cardiac output by the Nexfin before and after preload-modifying maneuvers: a comparison with intermittent thermodilution cardiac output. Anesth Analg 2013;117(2):366–72.
[86] 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(3):534–9.
[87] Benes J, Haidingerova L, Pouska J, et al. Fluid management guided by a continuous non-invasive arterial pressure device is associated with decreased postoperative morbidity after total knee and hip replacement. BMC Anesthesiol 2015;15:148.
[88] Joosten A, Huynh T, Suehiro K, et al. Goal-Directed fluid therapy with closed-loop assistance during moderate risk surgery using noninvasive cardiac output monitoring: a pilot study. Br J Anaesth 2015;114(6):886–92.
[89] Wagner JY, Korner A, Schulte-Uentrop L, et al. A comparison of volume clamp method-based continuous noninvasive cardiac output (CNCO) measurement versus intermittent pulmonary artery thermodilution in postoperative cardiothoracic surgery patients. J Clin Monit Comput 2018;32(2):235–44.
[90] Keren H, Burkhoff D, Squara P. Evaluation of a noninvasive continuous cardiac output monitoring system based on thoracic bioreactance. Am J Physiol Heart Circ Physiol 2007;293(1):H583–9.
[91] Squara P, Denjean D, Estagnasie P, et al. Noninvasive cardiac output monitoring (NICOM): a clinical validation. Intensive Care Med 2007;33(7):1191–4.
[92] Raval NY, Squara P, Cleman M, et al. Multicenter evaluation of noninvasive cardiac output measurement by bioreactance technique. J Clin Monit Comput 2008;22(2):113–9.
[93] Rich JD, Archer SL, Rich S. Noninvasive cardiac output measurements in patients with pulmonary hypertension. Eur Respir J 2013;42(1):125–33.
[94] Ballestero Y, Lopez-Herce J, Urbano J, et al. Measurement of cardiac output in children by bioreactance. Pediatr Cardiol 2011;32(4):469–72.
[95] Fagnoul D, Vincent JL, Backer de D. Cardiac output measurements using the bioreactance technique in critically ill patients. Crit Care 2012;16(6):460.
[96] Ishihara H, Okawa H, Tanabe K, et al. A new non-invasive continuous cardiac output trend solely utilizing routine cardiovascular monitors. J Clin Monit Comput 2004;18(5–6):313–20.
[97] Sugo Y, Ukawa T, Takeda S, et al. A novel continuous cardiac output monitor based on pulse wave transit time. Conf Proc IEEE Eng Med Biol Soc 2010;2010:2853–6.
[98] 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(6):465–71.
[99] 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(1):82–7.
[100] 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(6):879–86.
[101] Biais M, Berthezene R, Petit L, et al. Ability of esCCO to track changes in cardiac output. Br J Anaesth 2015;115(3):403–10.
[102] Thonnerieux M, Alexander B, Binet C, et al. 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(2):383–91.