

REVIEW

Clinical review: Does it matter which hemodynamic monitoring system is used?

Davinder Ramsingh, Brenton Alexander and Maxime Cannesson*

Abstract

Hemodynamic monitoring and management has greatly improved during the past decade. Technologies have evolved from very invasive to non-invasive, and the philosophy has shifted from a static approach to a functional approach. However, despite these major changes, the critical care community still has potential to improve its ability to adopt the most modern standards of research methodology in order to more effectively evaluate new monitoring systems and their impact on patient outcome. Today, despite the huge enthusiasm raised by new hemodynamic monitoring systems, there is still a big gap between clinical research studies evaluating these monitors and clinical practice. A few studies, especially in the perioperative period, have shown that hemodynamic monitoring systems coupled with treatment protocols can improve patient outcome. These trials are **small** and, overall, the corpus of science related to this topic does **not yet fit the standard of clinical research methodology** encountered in other specialties such as cardiology and oncology. **Larger randomized** trials or quality improvement processes will probably answer questions related to the real impact of these systems.

Introduction

Does it matter **which** hemodynamic **monitoring** system is used? While the question may sound simple, the answer is actually far from being clear. The purpose of a monitoring system is not to treat, but rather to provide clinical information that may impact medical decision-making. To quote Michael Pinsky and Didier Payen: 'Finally, no monitoring tool, no matter how accurate, by itself has improved patient outcome' [1]. If we were discussing a medication and asking the question 'Does it

matter which drug is used?', the obvious answer would be 'Of course it matters! We should use the drug that has demonstrated the best positive impact on patients' outcome in large randomized controlled trials, the least side effects, and the best price.' This would be a straightforward question with a straightforward answer. So why does the same question lead to so much confusion when it refers to hemodynamic monitoring systems?

Hemodynamic monitoring systems are measurement tools and their effects on outcomes are only as good as the protocols they are used to drive. Hemodynamic monitoring in the critical care setting and in the perioperative period has been studied for decades and has generated a still increasing number of publications. It is probably one of the most frequently featured topics in scientific journals and meetings, and one of the most popular focuses for symposiums. During the past 50 years we have observed dramatic changes in technologies available for hemodynamic monitoring, ranging from very invasive to mini-invasive and eventually totally non-invasive technologies [2-4]. At the same time, we have observed a conceptual **shift** in philosophy from the monitoring of **static** parameters to **functional** and **dynamic** approaches of hemodynamics [5]. Despite all these changes and 'improvements', it is still unclear whether or not it **matters which** hemodynamic monitoring system we use in clinical practice. We will see that the answer to this question may actually be **context dependent** [6-8]. The outcome most probably **depends** on the **clinical setting** (emergency department, operating room or ICU), on the hemodynamic situation the clinician tries to solve, and partially on the institution, the country and on the healthcare system where the clinician is practicing. Of course, it also **depends** on the **protocol** the clinician aims to apply to his or her patient and on the specific **goal** he or she wants to target (touching on the concept of **goal-directed** therapy [8-10]).

Eventually, the question remains as to **how** a hemodynamic monitoring system should be **evaluated**. Of course, evaluating the impact on patient outcome should be the most important factor [11]. However, can we reasonably **expect** a hemodynamic monitoring system to **improve** patient **outcome** in the critical care setting? For

*Correspondence: mcannesson@uci.edu
Department of Anesthesiology & Perioperative Care, University of California, Irvine,
101 S City Drive, Orange, CA 92868, USA

instance, the pulse oximeter, which has been evaluated in randomized controlled trials conducted in more than 20,000 patients in the anesthesiology setting, has never been shown to improve patient outcome [12,13]. In the same vein, there is no large randomized controlled trial showing that transesophageal echocardiography can improve patient survival even in the cardiac surgery setting [14]. Do we interpret this to mean that these devices should not be used in the clinical setting?

A few studies, especially in the perioperative period, have suggested that hemodynamic monitoring systems coupled with treatment protocols can improve patient outcome. These trials are small and, overall, the corpus of science related to this topic does not yet fit the standard of clinical research methodology encountered in other specialties such as cardiology and oncology. Larger randomized trials, quality improvement processes, and comparative effectiveness research studies will probably answer questions related to the real impact of these systems.

The term hemodynamic monitoring system is very broad and many concepts could be included under this terminology. The definition could range from micro-circulation and mitochondrial function monitoring to arterial pressure and heart rate monitoring. In the present article, we will focus our discussion on systems monitoring cardiac output (CO) and functional hemodynamic parameters. Several review articles have been published recently detailing the different hemodynamic monitoring systems available, and we refer the readers to these manuscripts for an in-depth technological understanding of these systems [3,4,8,15].

The present paper is divided into three parts. In the first part we will describe the evolution of hemodynamic monitoring in the critical care environment during the past 50 years (from the pulmonary artery catheter (PAC) to the most recent functional hemodynamic monitoring). In the second part, we will analyze how these systems have been evaluated in the clinical practice (accuracy for CO monitors and predictive value for functional hemodynamic parameters) and we will analyze the impact of these systems on patient outcome. Lastly, in the third section, we propose a plan for the use of hemodynamic monitoring systems in critical care settings based on the specific clinical situation, the protocol to be applied, and on the patient. This approach is based on the model of clinical pathways and quality improvement processes implementation.

Hemodynamic monitoring in the critical care setting: from past to present

Pulmonary artery catheter

Intermittent thermodilution obtained through the PAC has been considered the gold standard for CO monitoring

in the clinical setting since the late 1960s [16-18]. This system was widely used until the 1990s [19], when it started to dramatically decrease in all settings [20] secondary to a shift in philosophy, replacement by newer technologies [21], and also probably due to the widespread use of transesophageal echocardiography. Most studies focusing on the PAC and outcome have shown no positive association between PAC use for fluid management and survival in the ICU [22-24] or in the high-risk surgery patient [25]. This conclusion combined with the extreme level of invasiveness, advanced level training for placement, and incorrect parameter interpretation have lead to declining use of this system [26]. However, the PAC still holds utility in the assessment of right ventricular CO, pulmonary arterial pressures [6,8], and mixed venous oxygen saturation monitoring [8,27]. The lack of positive impact of the PAC on patient outcome does not preclude its use in a selected sample of patients by adequately trained physicians. In addition, most new CO monitoring systems are still evaluated against the intermittent thermodilution technique in the clinical research practice [8].

Esophageal Doppler

Simultaneous to the decline of PAC use, development of less invasive hemodynamic monitoring systems started in the 1990s. One of the first systems to be described and developed was the esophageal Doppler system allowing for non-invasive monitoring of CO [28]. This approach was described in the mid-1970s [29,30] and gained popularity in the 1990s after several small studies demonstrated a positive impact on postoperative outcome in patients undergoing high-risk surgery [31-34]. The waveform is highly dependent on correct positioning and requires frequent adjustments of depth, orientation, and gain to optimize the signal [35] and, while esophageal Doppler has demonstrated utility in aiding the assessment of the hemodynamic status of critically ill patients, this technology has been slow to be adopted [36]. This system has the most evidence regarding improvement of outcome in patients undergoing high-risk surgery and therefore should be strongly considered in such a setting [37-41]. The National Health Service in the UK has recently recommended the use of this device during high-risk surgery [42,43].

Transpulmonary thermodilution

One of the most successful systems to be described has been transpulmonary thermodilution together with the concept of pulse contour analysis. This system was developed in the 1990s by a German company, Pulsion, who commercialized the PiCCO system (Pulsion, Munchen, Germany) [44]. This system, which requires the use of a dedicated arterial line (preferentially femoral)

and a central venous catheter in the superior vena cava, achieved reasonable acceptance in Europe but is still relatively unknown in the USA [36]. Recently, Edwards Lifesciences released a similar transpulmonary thermodilution system (Volume View; Edwards Lifesciences, Irvine, CA, USA) [45,46]. CO measurements obtained using these systems correlate well with the PAC measurements [47-50]. These systems allow for continuous CO measurements using the calibrated pulse contour analysis method. While interesting, this method remains invasive [51] and requires frequent recalibration when the vasomotor tone changes [52-55]. Today, these systems have gained popularity in the ICU but are still rarely used in the operating rooms. Additionally, few outcome studies have been published using this system [56] and it is not clear whether their benefits outweigh the risks associated with femoral line placement.

Mini-invasive and non-invasive cardiac output monitoring systems

More recently, mini-invasive and non-invasive hemodynamic monitoring systems have been developed and deployed [57]. Most mini-invasive systems rely on the analysis of the arterial pressure waveform combined with the patients' demographics [58]. The systems are not user dependent and are very easy to use (plug-and-play). The main drawback of these systems is that they are highly dependent on vasomotor tone and on vascular compliance. Any acute change in these variables impacts the accuracy of these systems [54,59,60]. There are limited, but positive, outcome studies using these systems [61,62].

Finally, totally non-invasive systems have been developed. Bioimpedance and, more recently, bioreactance systems are back in the game (bioimpedance was actually developed very early on, before esophageal Doppler, but was never quite successful in the critical care setting) [63-68]. Ultrasound techniques such as the USCOM device have been proposed in the intensive care and emergency department settings (USCOM, Sydney, Australia). More innovative, uncalibrated and non-invasive CO measurements obtained through the analysis of a non-invasive arterial pressure waveform have also been released recently [69,70]. However, we need more evidence regarding the accuracy of these systems in order to use the output variables for clinical decision-making.

Table 1 summarizes the different CO monitoring systems clinically available today.

Functional hemodynamic monitoring parameters

Apart from the technological development of CO monitoring systems, most of the recent medical literature focusing on hemodynamic monitoring in the critical care setting has focused on the so-called functional hemodynamic monitoring parameters [1]. Instead of monitoring a given

parameter, functional hemodynamic monitoring assesses the effect of a stressor on a hemodynamic parameter. For the assessment of preload dependence, the stress has been established as a fluid challenge and the parameter monitored is the stroke volume or one of its surrogates (for example, arterial pressure) [71]. The effects of positive pressure ventilation on preload and stroke volume are used to detect fluid responsiveness in mechanically ventilated patients under general anesthesia [5]. If mechanical ventilation induces prominent respiratory variations in stroke volume [5], systolic pressure [72-74] or in arterial pulse pressure (PPV) [75], the patient's heart is more likely to be working on the steep portion of the Frank-Starling relationship and is thus preload dependent. These effects can also be assessed by measuring the variability on the inferior [76,77] or superior [78] vena cava diameter. When these parameters cannot be used because one limitation is present (spontaneous ventilation [79], arrhythmia [80], tidal volume <7 ml/kg [81], open chest conditions [82]), the effects of passive leg raising on the stroke volume can be used to detect preload dependence instead [83].

Monnet and colleagues have also described the effects of a tele-expiratory occlusion on arterial pulse pressure to predict the effects of volume expansion on CO [84]. The tele-expiratory occlusion test consists of a 15-second end-expiratory occlusion in patients under mechanical ventilation. Patients presenting a more than 5% increase in pulse pressure (systolic pressure – diastolic pressure) are more likely to be responders to volume expansion (in these patients, the increase in venous return induced by the decrease in intrathoracic pressure induces an increase in stroke volume and pulse pressure because the patient's heart is working on the steep portion of the Frank-Starling curve). These maneuvers (passive leg raising and tele-expiratory occlusion tests) are more appropriate for the ICU setting while stroke volume variation, PPV or respiratory variations in the plethysmographic waveform [85] are more suited for the operating room setting.

These dynamic parameters have consistently been shown to be superior to static parameters for the prediction of fluid responsiveness [75,86]. Moreover, some studies have suggested that minimization of the respiratory variations in the arterial pressure or in the plethysmographic waveforms could improve fluid management and postoperative outcome [10,87,88]. Table 2 presents the various functional hemodynamic parameters available for the prediction of fluid responsiveness as well as the monitors available for their display.

Evaluation of hemodynamic monitoring systems and how to choose among them?

Now that we have discussed the different hemodynamic systems available, the question remains as to whether or

Table 1. Available cardiac output monitoring systems with their respective advantages and disadvantages

Technology	System	Invasiveness	Mechanism	Advantages	Disadvantages	Outcome studies
Pulmonary artery catheter	Vigilance	+++	Thermodilution	Gold standard for continuous/intermittent cardiac output monitoring. Allows measuring pulmonary pressures and mixed venous oxygen saturation.	No dynamic parameters of fluid responsiveness, Provides cardiac output information every few minutes.	–
Calibrated pulse contour analysis	PiCCO plus	++	Transpulmonary thermodilution + pulse contour analysis	Continuous cardiac output monitoring. Central venous oxygen saturation with specific device. Good accuracy.	Remains significantly invasive. Requires a specific femoral artery catheter.	0
	VolumeView	++	Transpulmonary thermodilution + pulse contour analysis	Continuous cardiac output monitoring. Central venous oxygen saturation with specific device. Good accuracy.	Remains significantly invasive. Requires a specific femoral artery catheter.	0
	LiDCO plus	+	Lithium dilution	Continuous cardiac output monitoring.		+
Uncalibrated pulse contour analysis	FloTrac	+	Pulse wave analysis	Continuous cardiac output monitoring. Mini-invasive, self-calibration systems.	Accuracy of cardiac output has been a concern. Sensitive to changes in vasomotor tone. Requires a specific arterial pressure sensor.	+
	LiDCO Rapid	+	Pulse wave analysis	Continuous cardiac output monitoring. Mini-invasive, self-calibration systems. Can be used with any arterial line and arterial pressure sensor.	Not enough validation studies.	0
	Pulsioflex	+	Pulse wave analysis	Continuous cardiac output monitoring. Mini-invasive, self-calibration systems. Can be used with any arterial line and arterial pressure sensor.	No validation study.	0
	PRAM	+	Pulse wave analysis	Continuous cardiac output monitoring. Mini-invasive, self-calibration systems.	Not enough validation studies. Requires a specific arterial kit.	0
	Nexfin	0	Non-invasive pulse wave analysis	Continuous cardiac output monitoring. Completely non-invasive, self-calibration system.	Not enough validation study. Motion artifact.	0
Ultrasound	Cardio Q	0+	Doppler ultrasound	Less invasive than arterial-based systems, qualifies for billable monitoring in the USA.	Requires frequent manipulation for proper position, significant potential for user variability.	+++
	USCOM	0	Suprasternal ultrasound	Non-invasive cardiac output measurement.	Intermittent. Operator dependent.	0
Bioreactance	NiCOM	0	Bioreactance	Non-invasive continuous cardiac output monitoring.	Few validation studies. Many limitations.	0
Endotracheal bioimpedance	ECOM	+	Bioimpedance	Mini-invasive and continuous cardiac output monitoring.	Few validation studies. Requires a specific arterial kit and a specific endotracheal tube.	0
Thoracic bioimpedance	BioZ	0	Bioimpedance	Non-invasive cardiac output measurement.	Many negative studies in the critical care setting.	0

0, None; 0+, very slight; + slight; ++, intermediate; +++, severe. PiCCO plus, Pulsion Medical Systems, Irving, TX, USA; VolumeView, Edwards, Irvine, CA, USA; LiDCO plus, LiDCO Ltd, London, UK; FloTrac, Edwards, Irvine, CA, USA; LiDCO Rapid, LiDCO Ltd, London, UK; Pulsioflex, Pulsion Medical Systems, Irving, TX, USA; PRAM, Multiple Suppliers; Nexfin, BMEye, Amsterdam, Netherlands; Cardio Q, Deltex Medical Limited, Chichester, West Sussex, UK; USCOM, Uscom, Sydney, Australia; NiCOM, Cheetah Medical, Tel Aviv, Israel; ECOM, ConMed, Irvine, CA, USA; BioZ, CardioDynamics, San Diego, CA, USA.

not it matters which of them is used for the management of critically ill patients. Practically speaking, if we want to reasonably answer this question, we need to define what we expect from these systems, to identify the setting in which the system is going to be used, and to evaluate whether or not these systems accurately achieve what we expect from them.

What do we expect from a hemodynamic monitoring system?

This question depends on the monitor. At the very least, we expect a CO monitoring system to measure CO accurately and we expect a fluid responsiveness monitor to predict fluid responsiveness accurately.

Evaluating the accuracy of a cardiac output monitoring system

The last two decades have seen an explosion in the numbers of manuscripts published aiming at evaluating the accuracy of a hemodynamic monitoring system to measure CO accurately. Dozens of manuscripts have tried to define the methodology that should be used to clearly demonstrate whether or not a monitor can measure and track CO in the clinical setting. After more than a decade of research on this methodology alone, a consensus seems to have been reached [89-92]. The first step is to evaluate the agreement between the new method and the gold standard (most studies still use intermittent thermodilution as the gold standard). For this purpose, Bland-Altman analysis – originally described to assess the agreement between two methods of clinical measurement – should be used [93,94]. This analysis provides the users with a bias and limits of agreement. Unfortunately, little is known with regard to what is considered acceptable or not.

The second step is to calculate the mean percentage error, which is defined as the ratio between the range of the limits of agreement and the mean CO of the gold standard [95]. The idea is that narrow limits of agreement may mean that the system is very precise, but one must acknowledge that this may also only indicate the study was conducted in a sample of subjects presenting with very low CO values. According to Critchley and Critchley, a mean percentage error >30% should allow the conclusion of the new method as being inaccurate [95]. Once again, one must remember that this approach depends on the intrinsic precision of the gold standard [96]. The third step is then to test the concordance between the new method and the gold standard [97,98]. Basically, this approach aims at evaluating whether or not the two techniques follow the same direction when CO is modified. For some, a weak accuracy may not be a problem as long as the ability to track changes is accurate. This is theoretically true since most goal-directed therapy

Table 2. Systems allowing for monitoring dynamic parameters of fluid responsiveness

Dynamic parameter of fluid responsiveness	Monitor available for their display
Systolic pressure variation	Can be eyeballed accurately
Pulse pressure variation	Cannot be eyeballed Philips Intellivue Monitors LiDCO Rapid LiDCO Plus PiCCO Plus PulsioFlex PRAM Nexfin CNAP General Electric Monitors
Stroke volume variation	LiDCO Rapid LiDCO Plus PiCCO Plus Pulsioflex PRAM Vigileo FloTrac EV1000 VolumeView ECOM BioZ NICOM
Pleth variability index	Masimo Radical 7
Passive leg raising	Demonstrated with esophageal Doppler, PiCCO plus, Echocardiography, NICOM, and Vigileo FloTrac

PiCCO plus, Pulsion Medical Systems, Irving, TX, USA; VolumeView, Edwards, Irvine, CA, USA; LiDCO plus, LiDCO Ltd, London, UK; FloTrac, Edwards, Irvine, CA, USA; LiDCO Rapid, LiDCO Ltd, London, UK; Pulsioflex, Pulsion Medical Systems, Irving, TX, USA; PRAM, Multiple Suppliers; Nexfin, BMEye, Amsterdam, Netherlands; Cardio Q, Deltex Medical Limited, Chichester, West Sussex, UK; USCOM, Uscom, Sydney, Australia; NiCOM, Cheetah Medical, Tel Aviv, Israel; ECOM, ConMed, Irvine, CA, USA; BioZ, Cardiodynamics, San Diego, CA, USA; CNAP, CNS Systems, Graz, Austria; General Electric Monitors, General Electric Company, Fairfield, Connecticut, USA; EV1000 VolumeView, Edwards, Irvine, CA, USA; Masimo Radical 7, Masimo, Irvine, CA, USA; esophageal Doppler, Deltex Medical Limited, Chichester, West Sussex, UK; Echocardiography, Multiple Suppliers.

protocols for fluid management rely on relative changes in CO, as opposed to absolute values. However, a perfect trending ability together with a weak accuracy would essentially indicate that further calibration would solve the problem. Unfortunately, it is more likely that the bias and the limits of agreement drift over time. According to Critchley and colleagues, concordance <92% should be considered unacceptable.

Evaluating the predictive value of a functional hemodynamic parameter

The use of functional hemodynamic monitoring in the clinical practice is, in a way, simpler to evaluate. The goal of most functional hemodynamic monitoring parameters

is to **predict fluid responsiveness** in critically ill patients. For this purpose, the methodology is quite straightforward and has for a long time relied on the use of **receiver operating characteristics** curve analysis [99]. This analysis results in a **single** threshold value associated with a high sensitivity and specificity for the prediction of fluid responsiveness. For example, it was shown initially that **PPV >13%** in septic patients was able to predict fluid responsiveness with sensitivity and specificity **>90%** [100]. However, this methodology is very **old** and may not reflect the actual clinical setting where such **polarized situations** do **not** often exist.

Significant **improvements** have recently been made in the methodology used for the evaluation of a biomarker or diagnostic tool [101]. For instance, the **gray zone** approach has been proposed to **avoid** the **binary** constraints resulting from the **black-or-white** nature of the **receiver operating characteristics** curve that often does **not** fit the **reality** of **clinical** or screening practice [101]. The **gray zone** technique proposes **two** **cutoff** values that constitute the borders of the gray zone. The **first** **cutoff** allows the practitioner to **exclude** the **diagnosis** (fluid responsiveness in the present case) with **near-certainty** (that is, **privilege sensitivity** and **negative predictive** value), whereas the **second** **cutoff** is chosen to indicate the value **above** which the **selected diagnosis** can be **included** with **near-certainty** (that is, **privilege specificity** and **positive** predictive value) [101]. **Intermediate** values included in the gray zone correspond to a prediction value **not** **precise** enough for a diagnostic decision [102]. This approach has recently been applied to test the ability of PPV to predict fluid responsiveness in the perioperative setting, and it was shown, in more than 400 patients, that the **gray** zone for **PPV** is between **8 and 13%** and that about **25%** of the patients are **within** this **gray** zone. If this approach was used in the ICU setting, the **majority** of patients would more likely be **within** this **gray** zone. This type of approach should help to better define the clinical application of these functional hemodynamic parameters. In any case, these **dynamic** parameters have **consistently** been shown to be the **best** **predictors** of fluid responsiveness [75,86].

Evaluating the impact on outcome

Finally, the **ultimate** **test** is to evaluate whether or not the use of a monitor to guide hemodynamic management can **improve** patient **outcome**.

The problem is that **none** of the **CO** **monitoring** systems available today **consistently** present with **<30%** mean **percentage** **error**, **>92%** **concordance**, and **positive** **outcome** **studies**. Most widely used CO monitoring systems demonstrate a mean **percentage** **error** of around **40** to **45%** [103] and most of these devices present with **concordance** **<92%**. Interestingly, despite these very

disappointing results, these systems have **still** been **tested** in clinical **outcome** studies and **some** have demonstrated **positive** results [37,104]. Let us stress this point and be a little bit provocative: it is **surprising** to observe that a professional discipline such as medicine is able to conduct clinical **studies** **using** **devices** that have been **consistently** **demonstrated** to be **inaccurate**. One may argue that the methodology used to evaluate these systems (mean percentage error, concordance) is not appropriate and presents intrinsic limitations. However, **would** **any** other **industry** dealing with **life** and **death** situations **accept** such a shortcoming? Would an **altimeter** be used on a commercial passenger **plane** despite the fact that it has been demonstrated to be **inaccurate** according to the most commonly accepted standards from the Federal Aviation Administration? Why would we, as physicians, accept what other industries would clearly consider **unacceptable**?

The reason for this shortcoming is probably related to the fact that **human** **physiology** and physiopathology is an **incredibly** **complex** model. This explains why it is so **difficult** to **reliably** **measure** **physiological** variables, and it also explains why it is so **difficult** to make good **clinical** **decisions**. As a matter of fact, when dealing with complex situations, medical decision-making can be **completely** **different** from one **physician** to the next [26]. This **lack** of **standardization** in patient management is probably one of the major factors influencing patient outcome and, coincidentally, one of the only factors that we can influence for the **improvement** of patient care. This has been **beautifully** **demonstrated** during the past 10 years by studies in the critical care setting focusing on protocol implementation and quality improvement processes aiming at standardizing patient care. Goal-directed therapy protocols or **checklist** implementations exemplify this type of approach [105-107]. Studies such as those conducted by **Rivers** and colleagues in septic patients showing the impact of **standardizing** hemodynamic management on survival have opened the field to such approaches [9]. Most recently, studies have demonstrated that applying a simple **checklist** in the **ICU** and in the operating room can significantly impact outcome [108,109]. These studies are **repeatedly** concluding that **decreasing** the **variability** of care can **save** **lives**.

Concerning hemodynamic monitoring systems, the same approach could be applied. Clearly, **despite** the **lack** of **precision** of most CO monitoring systems available, **some** **positive** outcome studies have been published, especially in the perioperative setting with patients undergoing **high-risk** **surgery**. These studies have shown that the **optimization** of fluid administration based on CO monitoring can **decrease** postoperative **morbidity** and decrease the **length** of **stay** in the hospital and in the ICUs (Figure 1) [37,104]. Since fluid and hemodynamic

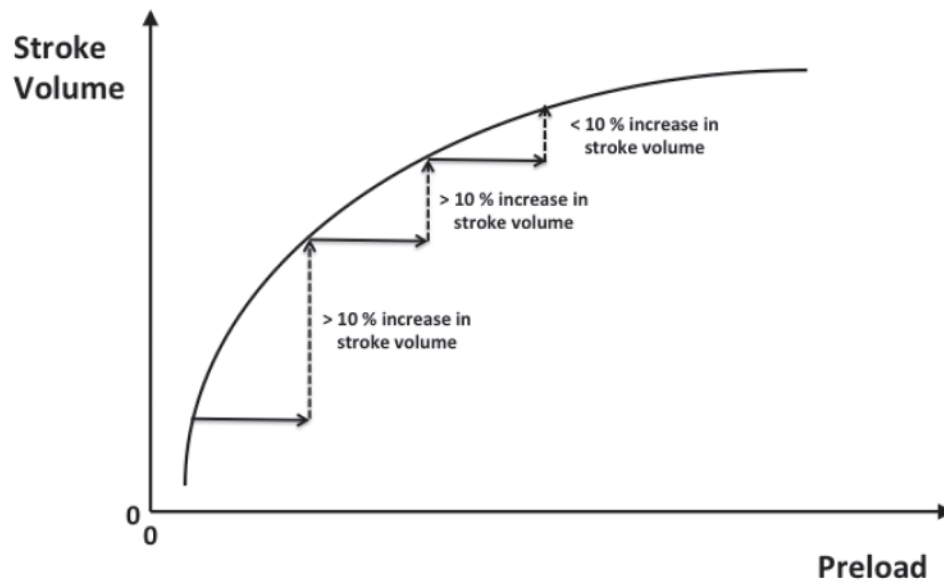


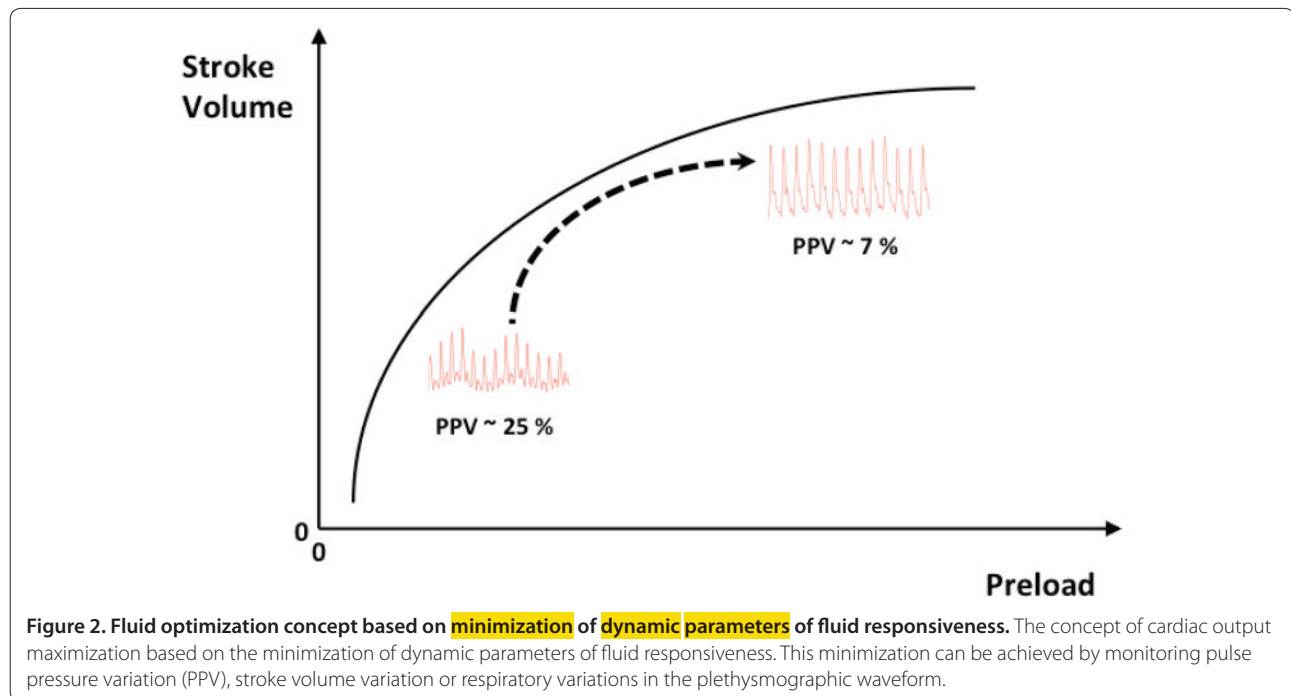
Figure 1. Fluid optimization concept based on stroke volume monitoring. The concept of cardiac output maximization based on fluid administration and stroke volume monitoring. Small boluses of fluid are administered intravenously (200 to 250 ml at a time) until the stroke volume increases by <10%.

management have been shown to impact postoperative outcome and because these two major focuses of our field have been shown to be widely nonstandardized [110,111], it would then be reasonable to assume that using a CO monitoring system (even if not a perfect one) to guide fluid administration in a standardized way in the perioperative period has the potential to improve postoperative outcome. This approach consists of titrating fluid, based on CO, until it reaches the plateau of the Frank-Starling relationship (Figure 1), which has been shown in several small clinical studies to improve patient outcome.

The evidence has been considered strong enough by the National Health Service in the UK to universally endorse this practice in the high-risk surgery setting [42,43], even though it has created some heated discussion [112,113]. Widespread acceptance of this concept in other countries will probably take longer due to the relative infrequency of large clinical studies. Such evaluations are strongly needed in the perioperative period [11,114]. This is exemplified by Devereaux and colleagues in an editorial recently published in *Anesthesiology* [114]: 'Unlike cardiology, large clinical studies remain uncommon in perioperative medicine [115,116]. Further, there has been a tendency to believe the results of small perioperative clinical studies, especially when they demonstrate statistically significant results. This position is supported by the fact that perioperative guideline committees recommended β -blockers to patients undergoing noncardiac surgery for a decade based upon the results of small trials demonstrating implausibly large treatment

effects.' One should also mention that large quality-improvement programs and comparative effectiveness research studies could also be utilized as an alternative to this approach [40,117].

In addition, while functional hemodynamic parameters can be used as diagnostic tools to answer whether a patient needs fluid or not, another approach consists of using these parameters to guide fluid optimization during high-risk surgery [10]. As a matter of fact, the concept of CO maximization during surgery could be achieved by applying the concept of respiratory variations in arterial pressure or in the plethysmographic waveform minimization (Figure 2) [10]. Conducting CO maximization using CO monitors that have >40% mean percentage error [103] could theoretically be easily achieved by conducting PPV minimization. This would be a cheap and free-of-right way to optimize hemodynamics in the perioperative period. PPV minimization has been suggested and recently described [10,118], and the method could be of major importance in countries or institutions where the use of CO monitoring systems cannot be reasonably expected for all patients undergoing high-risk surgery but where fluid optimization still has the potential to dramatically influence patient outcome [119]. Of course, it may be difficult to determine the clinical effect of minimizing PPV without CO trending ability. However, recent studies strongly suggest that changes in PPV induced by volume expansion reflect changes in CO with excellent sensitivity, specificity, and a very narrow gray zone [120].



Which hemodynamic monitoring system? For which patient? When? How?

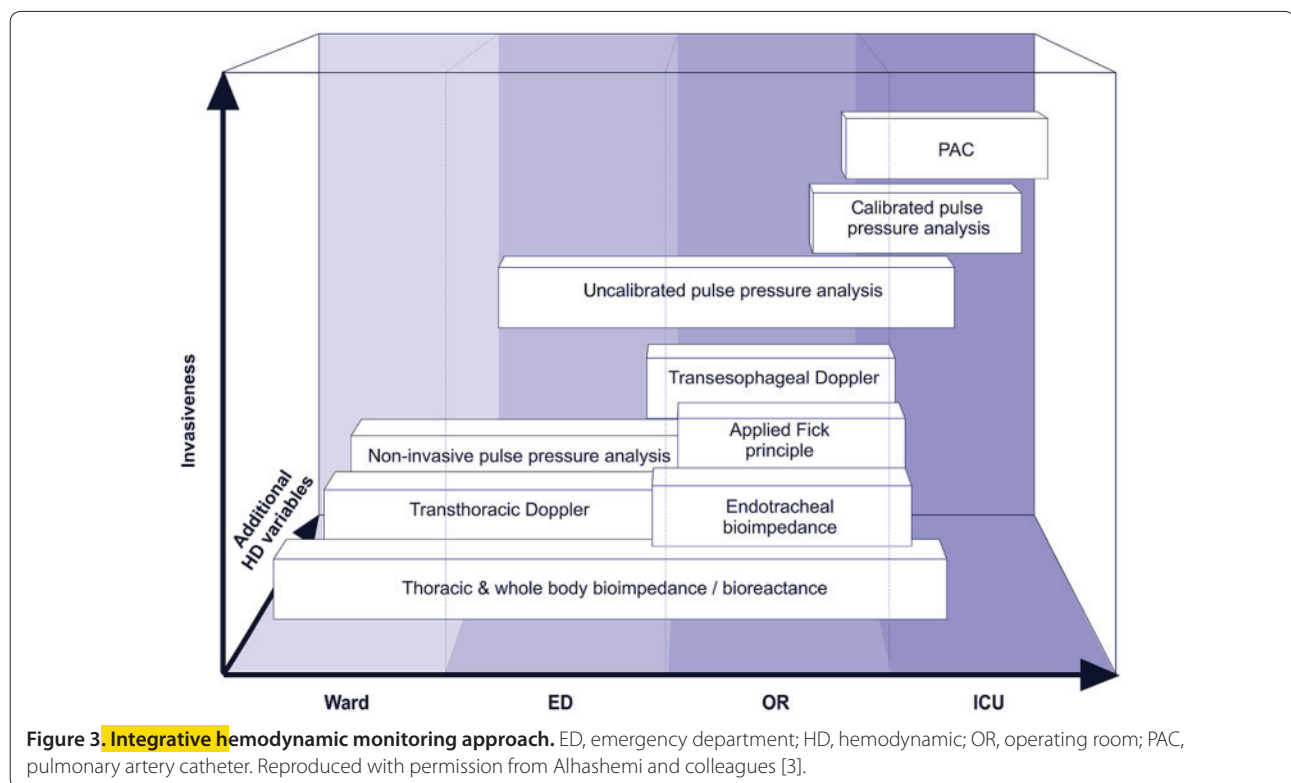
Several parameters must be considered before deciding which hemodynamic monitoring system should be used because, yes, it does eventually matter. Ideally, this decision should be made at the institutional level. Most departments throughout the world cannot afford to buy all of the market-available systems. At the same time, no system available today can effectively be used in all the different sectors of a hospital. Depending on the patient's specific history and course through the hospital, one hemodynamic monitoring system may be more appropriate than the other. Defining a set of systems available that will be adaptable to the various patient populations and clinical pathways will then be essential. This approach has been recently proposed by Alhashemi and colleagues (Figure 3) and has been described as an integrative perspective for the use of CO monitoring systems [3]. The defining approach takes into account the setting (ward, emergency department, operating room, and ICU) as well as the integration of CO monitoring with or without other hemodynamic variables.

The decision should be an institutional decision and should integrate all clinical pathways existing within the institution

Institutions containing emergency departments, operating rooms, and ICUs should have non-invasive, mini-invasive and invasive hemodynamic monitoring systems available to the clinicians and his or her patients. Likewise,

when the institution performs cardiac surgery, it is still highly recommended to have PACs available. This system is well fitted for patients with low ejection fraction (<30 to 35%), moderate to severe pulmonary hypertension, sepsis (endocarditis), and for cardiac transplantation. If the patient spends more than 72 hours in the ICU after surgery, it is recommended to switch from the PAC to a transpulmonary thermodilution system. Of course, transesophageal echocardiography should be available in all institutions performing cardiac surgery. However, this system is not a monitoring system *per se* and does not substitute for a continuous hemodynamic monitoring system.

An important consideration is that patient management is a continuum of care. Consequently, it is essential to maintain compatibility among hemodynamic monitoring technologies between different departments within the institution and to favour systems able to adapt to various clinical pathways. For example, some patients will enter the hospital through the emergency department, will then go to the operating room, and then to the ICU. Ideally, the evolution in hemodynamic monitoring should be made available on an identical platform that will adapt to the changes in hemodynamic status of the patient as well as to the clinical scenario in these different departments. Today, technological platforms allowing for a continuum of care from a totally non-invasive hemodynamic monitoring system to a mini-invasive one and then to an invasive one (or *vice versa*) are just emerging. For an institution to work within a given



system that would be flexible and allow any kind of patient throughout the hospital to be effectively monitored would make perfect sense. Once again, this kind of platform is just starting to emerge and most institutions still have to purchase different systems, from different companies, in order to monitor different patients.

The systems should be paired with clearly defined protocols

As mentioned earlier, the only way to impact patient outcome is to pair the monitoring system with a therapeutic protocol. This approach has been shown to improve perioperative outcome in several small clinical studies and in some quality improvement processes employing the esophageal Doppler [40]. Such standardization of patient care is the only way to change current practice and to pragmatically and positively impact clinical decision-making. Standardization guidelines should also include the indications for hemodynamic monitoring and which hemodynamic monitoring system should be used for what patients (based on the integrative approach described above; Figure 3). Once again, the National Health Service in the UK has exemplified this through its release of National Institute for Health and Clinical Excellence guidance regarding hemodynamic monitoring and optimization during high-risk surgery [42,43]. These guidelines are clear and easy to apply and can easily be applied in any institution.

The system should be adapted to the patient

Of course, the final choice of a hemodynamic monitoring system is patient and pathology dependent. Additionally, whenever possible, a non-invasive system should be used. However, at this stage, non-invasive systems may not be as reliable as invasive ones. There is no doubt that non-invasive systems will eventually take the lead in the future [121], but we are still contemplating the effective length of a development phase [122]. For example, non-invasive systems based on pulse oximeter waveform analysis have been shown to be able to provide useful information regarding fluid responsiveness in healthy patients under general anesthesia [85]. However, these systems may not be reliable in the ICU in septic shock patients [123]. That being said: who would consider managing the hemodynamic status of a septic shock patient based solely on the plethysmographic waveform alone? On one hand, the risk of using a non-invasive technique in a challenging setting is that it will lead to inappropriate clinical decisions. On the other hand, it is unacceptable to expand the indications for invasive monitoring when their risks outweigh their benefits. We should always keep this in mind when choosing the most appropriate hemodynamic monitor for our patients.

Conclusion

Hemodynamic monitoring and management has greatly improved during the past decade. Technologies have

evolved from very invasive to non-invasive, and the philosophy has shifted from a static approach to a functional approach. However, the critical care community still has potential to improve its ability to adopt the most modern standards of research methodology in order to more effectively evaluate new monitoring systems and their impact on patient outcome. Today, despite the huge enthusiasm raised by new hemodynamic monitoring systems, there is still a big gap between clinical research studies evaluating these monitors and clinical practice. A few studies, especially in the perioperative period, have shown that hemodynamic monitoring systems coupled with treatment protocols can improve patient outcome. Unfortunately these trials are small and, overall, the corpus of science related to this topic does not yet fit the standard of clinical research methodology encountered in other specialties such as cardiology and oncology. Larger randomized trials, quality improvement processes, and comparative effectiveness research studies are probably needed. However, some innovative professional societies have considered that this evidence was strong enough to release recommendations regarding hemodynamic monitoring and management during high-risk surgery. For this purpose, strictly speaking, the esophageal Doppler is the device that currently presents with the most positive evidence.

Finally, the choice of the hemodynamic monitoring systems available should be a widespread institutional process and all departments involved should be consulted (emergency department, ward, ICU, and operating room). At the end of the day, the choice depends on the available expertise, on the patient population, and on the clinical pathways. For institutions who cannot afford a proprietary hemodynamic monitoring system for their patients, fluid optimization can be achieved effectively by monitoring respiratory variations in the arterial pressure or in the plethysmographic waveform depending on the clinical context.

This is part of a series on *Perioperative monitoring*, edited by Dr Andrew Rhodes

Abbreviations

CO, cardiac output; PAC, pulmonary artery catheter; PPV, pulse pressure variation.

Competing interests

DR is a consultant and speaker for Edwards Lifesciences. MC is a consultant for Masimo Corp., Edwards Lifesciences, Covidien, Draeger, Philips Medical Systems, Fresenius Kabi, and a speaker for ConMed. MC received research grants from Edwards Lifesciences and Masimo Corp. MC is co-inventor and co-owner on US and International patent applications related to closed-loop fluid administration and hold an equity position in Sironis, a company developing closed-loop medical devices. BA declares that he has no competing interests.

Published: 5 March 2013

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doi:10.1186/cc11814

Cite this article as: Ramsingh D, et al.: Clinical review: Does it matter which hemodynamic monitoring system is used? *Critical Care* 2013, **17**:208.