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Review

Perioperative hemodynamic monitoring techniques: a narrative review

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Abstract

Hemodynamic monitoring is an integral part of the perioperative care of the patient. Over the years, several different tools and techniques have been developed. The current contribution reviews the various currently available hemodynamic monitoting techniques.

Keywords: **Hemodynamic monitoring, pressure, flow, echocardiography, near-infrared spectroscopy.**

Introduction

Continuous assessment of the hemodynamic status is an essential part of the perioperative care of patients. Already in the first Belgian Standards for Patient Safety in Anesthesia, published in the Acta Anaesthesiologica Belgica in 1989, the importance of perioperative hemodynamic assessment was underscored as being part of the minimal standards for monitoring equipment[1]. A recommendation that was repeated in the 2002 and 2019 updates[2,3].

Ever since the introduction of the sphyngograph, a pulse recorder usable for routine non-invasive monitoring on humans, in 1881 by the Austrian physician Samuel Siegfried Karl Ritter von Basch and the further development of the mercury sphyngomanometer by the Italian physician Scipione Riva-Rocci in 1896[4], the technology for measuring blood pressure, and by extension all aspects of hemodynamic monitoring, has grown exponentially.

In this article we will review the different clinically available perioperative hemodynamic monitoring techniques.

1. Hemodynamic monitoring techniques

In order to keep the review structured, the different hemodynamic monitoring techniques will be discussed based on the technology used: pressure -focused, flow-oriented, tissue oxygenation and ultrasound-based (Figure 1).

A. Pressure-focused monitoring

Among the various monitoring techniques available, pressure-focused monitoring methods are widely utilized due to their ability to provide real-time data on blood pressure dynamics. Pressure monitoring is used to detect hemodynamic alterations associated with a decrease in perfusion pressure and to titrate vasoactive agents to maintain perfusion pressure in cases of hypotension or to limit the risk of bleeding in cases of hypertension. It is obvious that blood pressure measurements should be taken frequently (best continuously if possible) to immediately detect blood pressure changes and specifically reduce/avoid periods of undetected intra-operative hypotension[5].

Automated oscillometric blood pressure measurements

Oscillometric technology detects changes in arterial pressure by analyzing the oscillations generated during inflation and deflation of a cuff mostly

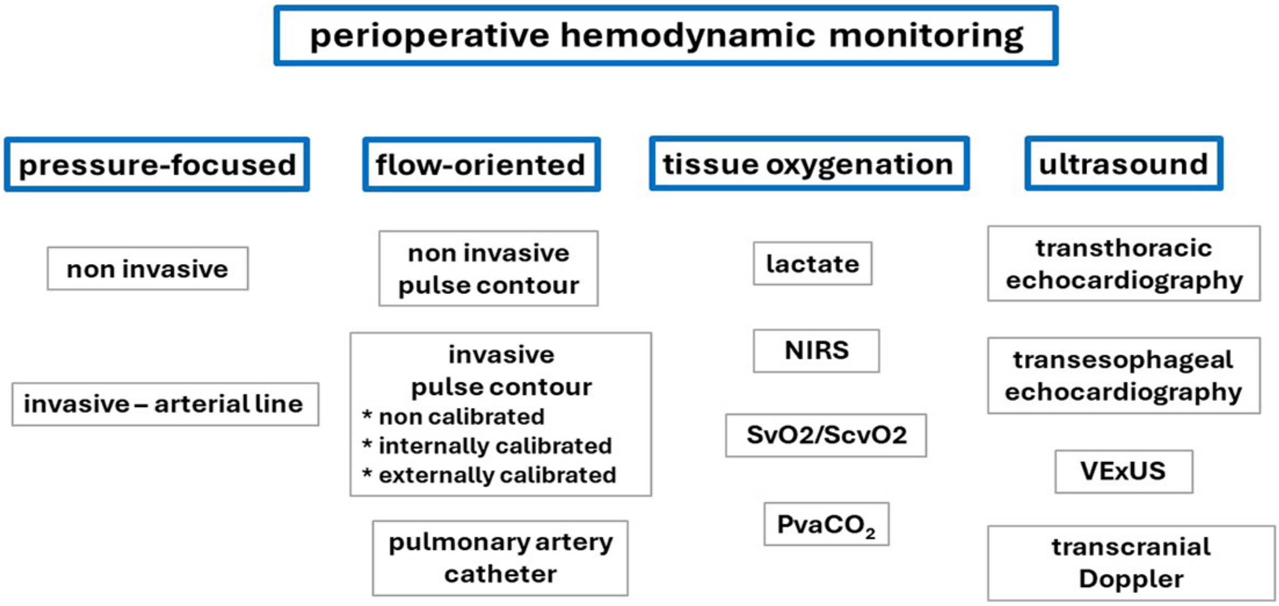

Fig. 1 — Schematic overview of the different monitoring techniques discussed.
NIRS = near-infrared spectroscopy; ScvO2 = central venous oxygen saturation; SmvO2 = mixed venous oxygen saturation; Pv-aCO2 = venous to arterial carbon dioxide tension difference; VExUS = venous excess ultrasound score.

encircling the upper limb. The cuff is inflated beyond the level of systolic arterial blood pressure to fully occlude the brachial artery. As the cuff gradually releases pressure, oscillations manifest within the relaxation curve. These superimposed oscillations are isolated from the relaxation curve and transformed into an oscillometric waveform envelope. Various algorithms are employed to estimate blood pressure based on this envelope, among which the maximum amplitude algorithm is most often used. According to this algorithm, the pressure value corresponding to the highest peak of the envelope represents the mean arterial blood pressure. The systolic and diastolic arterial blood pressure are determined by a predetermined ratio of the maximum amplitude — these fixed ratios are termed characteristic ratios, derived empirically and proprietary to the manufacturer[6].

One of the key advantages of these systems are their simplicity and ease of use. They allow for rapid and non-invasive blood pressure measurements and can provide intermittent blood pressure monitoring during induction, maintenance and emergence from anesthesia and postoperatively. Furthermore, these systems offer the advantage of automatic inflation and deflation of the cuff, reducing the need for manual intervention by healthcare providers.

Oscillometric monitoring systems have several limitations that warrant consideration. Accuracy can be affected by factors such as cuff size, position, and patient movement. Rather than offering continuous blood pressure monitoring, oscillometric systems offer intermittent blood pressure measurements (with measurement intervals set by the user). Moreover, these systems are not as reliable as invasive methods in situations where precise blood pressure measurements are crucial, such as during complex surgical procedures or in patients with severe hemodynamic instability. Also in case of arrhythmias, these systems frequently fail[7].

Continuous non-invasive blood pressure monitoring

Continuous non-invasive blood pressure measurement is based on the so-called volume-clamp method which is a vascular unloading technique. In essence, this technology relies on finger cuffs consistently monitoring the arterial pressure waveform. Volume-clamp methods employ a finger cuff equipped with an integrated infrared photodiode and light detector to gauge the diameter of the finger artery. Relying on an ultrafast feedback mechanism, a control unit dynamically regulates the pressure of the finger cuff to ensure the blood volume in the finger artery remains stable during the entire cardiac cycle. By assessing the pressure changes necessary to uphold a consistent blood volume in the finger artery, it becomes possible to derive and analyze the arterial pressure waveform to estimate arterial pressure as well as cardiac output (applying pulse wave analysis)[7,8].

The volume-clamp method offers several advantages in the perioperative setting, including ease of use, non-invasiveness, and continuous monitoring capabilities. It provides beat-to-beat blood pressure measurements, allowing for the detection of rapid changes in hemodynamics.

This method also has some limitations that must be considered. Accuracy can be affected by factors such as finger temperature, peripheral vascular resistance, and arterial compliance. This technique may not be suitable for patients with peripheral vascular disease or poor peripheral perfusion, as it relies on adequate blood flow to the finger for accurate measurements. As a matter of fact, a recent systematic review and meta-analysis concluded that the values obtained by finger cuff techniques and the reference technique are not interchangeable[8].

Continuous invasive blood pressure monitoring

Arterial catheterization remains the gold standard for invasive blood pressure monitoring in the perioperative period. It involves the insertion of a catheter into an artery, typically the radial or femoral artery, allowing direct measurement of arterial pressure. Arterial catheters offer several advantages over non-invasive methods, including superior accuracy, reliability, and (in contrast to oscillometric monitoring) the ability to continuously monitor blood pressure waveforms. Arterial catheters are particularly valuable in critically ill patients or those undergoing high-risk surgeries where tight hemodynamic control is essential.

Furthermore, arterial catheters enable frequent blood sampling for laboratory analysis, providing valuable information on acid-base status, electrolyte levels, and oxygenation. This integrated monitoring approach facilitates comprehensive hemodynamic assessment and enables prompt intervention in response to changes in patient status. Additionally, arterial catheters can be used to guide titration of vasoactive medications, such as vasopressors or inotropes, to optimize tissue perfusion and hemodynamic stability.

However, arterial catheterization is not without risks and limitations. The invasive nature of the procedure carries a risk of complications, including bleeding, infection, arterial thrombosis, and nerve injury. Moreover, arterial catheters require specialized training for insertion and maintenance, and their use may be relatively contraindicated in patients with coagulopathy or peripheral vascular disease. Additionally, arterial catheterization may be difficult or even not feasible in certain patient populations, such as those with severe arterial calcification or anatomical anomalies.

Prediction of hypotension

The Hypotension Prediction Index (HPI) is a promising tool that has garnered increasing interest in the field of anesthesia and perioperative medicine. Developed as part of advanced hemodynamic monitoring systems, the HPI aims to predict impending hypotension before it occurs, allowing clinicians to intervene proactively and mitigate the risk of adverse outcomes.

The HPI utilizes advanced algorithms to analyze real-time physiological data derived from pressure waveform analysis to generate a predictive score indicating the likelihood of hypotension occurring within a certain time frame[9]. By leveraging machine learning and artificial intelligence techniques, the HPI can identify subtle changes in hemodynamics that may precede overt hypotension, providing an early warning system for clinicians.

Several studies have investigated the performance of the HPI in predicting hypotension across various patient populations and clinical settings. These studies have demonstrated promising results, with the HPI showing good sensitivity and specificity in identifying patients at risk of hypotension[9]. Meanwhile, these validation studies have been criticized by some authors to over-estimate accuracy due to selection bias[10].

The initial assumption was that by integrating multiple physiological variables and using dynamic modeling techniques, the HPI can capture subtle changes in hemodynamics that may not be apparent with conventional monitoring methods. This dynamic approach should allow for earlier detection of impending hypotension and provide clinicians with valuable time to intervene and prevent adverse outcomes. It remains to be studied though whether more simple approaches such as setting the lower alarm for mean arterial pressure at 75 mm Hg[11] or using linear extrapolation of mean arterial pressure might be even effective[12].

HPI monitoring has also become attractive as it supports the clinician by guiding intraoperative management strategies, such as fluid administration, vasopressor and inotrope titration, or adjustments to anesthetic depth. Whether early interventions based on HPI predictions may reduce the incidence and severity of hypotensive episodes, is, however, controversial[13,14]. It also remains to be demonstrated that the use of the HPI may contribute to a reduction in perioperative morbidity and mortality, leading to improved overall healthcare outcomes.

Despite its promising potential, the HPI is not without limitations. Like any predictive tool, the HPI relies on the accuracy and reliability of input data, which may be influenced by factors such as sensor placement, signal quality, and patient-specific variables. Inaccurate or noisy data inputs can affect the performance of the HPI and lead to false-positive or false-negative predictions. Moreover, the HPI may not be applicable to all patient populations or clinical scenarios. Its performance may vary depending on factors such as patient comorbidities, surgical complexity, and anesthetic technique. Additionally, the optimal threshold for triggering interventions based on HPI predictions remains uncertain and may require further validation in prospective clinical trials.

B. Flow-oriented monitoring

Pressure monitoring can detect alterations in perfusion pressure but does not indicate the cause of this impairment: decrease in vascular tone, decrease in flow, or combination of both. Importantly, tissue perfusion can be altered even when blood pressure in maintained. In addition, perfusion to organs may be preserved even when cardiac function is altered. Accordingly, monitoring cardiac output, as a crucial determinant of tissue perfusion, may be indicated in selected cases.

The flow-oriented techniques aim at estimating stroke volume/cardiac output. Three main methodologies can be used: the analysis of the arterial waveform, thermodilution and echocardiography. Echocardiography will be covered in a separate section of this article.

Analysis of arterial pulse wave to derive cardiac output

The arterial pulsatility is generated by the irruption of stroke volume at each systole. While pulse pressure, representing the difference between diastolic and systolic pressure, is proportional to stroke volume, this relation is not straightforward as pulse pressure also depends on aortic compliance and vascular tone. Accordingly, it is difficult to derive stroke volume from pulse pressure. Pulse pressure can be used to track changes in stroke volume. While aortic compliance does not change acutely, vascular tone is a highly dynamic component. In conditions where vascular tone remains unchanged, as over one respiratory cycle or over a few seconds during acute changes in preload, pulse pressure is directly proportional to stroke volume and may track changes in stroke volume. During vena cava clamping, pulse pressure reflected beat by beat changes in stroke volume[15]. Also during fluid administration, changes in pulse pressure are correlated with changes in stroke volume but this correlation is at best loose[16] and not confirmed in other studies[17]. On the contrary, changes in stroke volume observed during changes in vasomotor tone cannot be tracked by changes in pulse pressure[16].

The relationship between arterial pulse and stroke volume is further complexified by the presence of reflected waves. The propagation of pulsatile flow generates reflected waves at branchpoints, so that the arterial waveform in proximal large arteries (e.g. femoral artery) differs from peripheral arteries (e.g. radial)[18]. Additionally, reflected waves are affected by vascular tone[19], resulting in a higher dicrotic notch during vasoconstriction and a lower one in vasodilatory states[20].

To improve the reliability of the estimation of stroke volume, analysis of arterial waveform is preferred over pulse pressure. Different proprietary algorithms have been developed. Most derive aortic compliance from anthropometric characteristics. To take into account vascular tone the device is either internally calibrated or an external calibration is used[21]. Internal calibration refers to the ability of the algorithms to estimate vascular tone by analyzing the pulse wave morphology (FloTrac® and MostCare®)[22,23]. The essential differences between calibrated and uncalibrated devices are shown in Table I.

Noninvasive pulse contour

In this technique the arterial pressure waveform is derived from pressure changes detected at the level of an inflatable finger-cuff. The reconstructed arterial pressure is then analyzed using a non-calibrated or internally calibrated algorithm. If combined with internally calibrated algorithm, it

Table I. — Essential differences between calibrated and uncalibrated pulse wave derived cardiac output monitors.

	Main characteristics	Notes
Non Calibrated	* Non precise measurement of CO * Track changes in CO (if no significant change in vascular tone) * Stroke volume variations	* Not reliable to track changes in CO concurrent to changes in vascular tone
Internally calibrated	* Precise measurements of CO * Track changes in CO * Stroke volume variations	* Not valid for acute changes in vascular tone (require several minutes to equilibrate) * Accuracy may depend on version
Externally calibrated	* Precise measurements of CO * Track changes in CO * Stroke volume variations * Additional measurements (GEDV/EVLW) provided by TPTD	* Require recalibration every 6-8h * Require recalibration when vascular tone is altered

CO = cardiac output; GEDV = global end-diastolic volume; EVLW = extravascular lung water; TPTD = transpulmonary thermodilution.

provides accurate cardiac output measurements and allows to track changes in cardiac output. It also allows functional hemodynamic measurements, whatever the algorithm[24].

The major advantage of this technique is the fully noninvasive technique aspect. Accordingly, it is convenient for cases where an arterial line is not mandated for other purposes but nevertheless submitted to surgery at potential risk of hemodynamic deterioration. Also, it can be applied easily if the patient deteriorates during surgical procedure. The main disadvantage is that it requires a good pulsation in the finger arteries. Finger arterial pulsatility may be impaired in severely vasoconstricted patients (e.g. circulatory shock, high-dose vasopressors, hypothermia, vascular diseases, sclerodermia,…).

Invasive pulse contour

In these techniques, the arterial waveform is directly measured on an arterial line. A dedicated catheter is mandatory for the device, externally calibrated by thermodilution[25,26]. These catheters are mostly inserted in femoral arteries even though other accesses are feasible. For noncalibrated, internally calibrated, or externally calibrated using other methods than transpulmonary thermodilution, regular arterial catheters can be used in radial or femoral position. Importantly, a good arterial signal and adequate zeroing are mandatory for adequate cardiac output measurement[27].

Non-calibrated

The pulse wave analysis does not attempt to evaluate vascular tone. Accordingly, the cardiac output measurement has limited precision. Nevertheless, these techniques allow to track changes in cardiac output provided that vascular tone remains stable during the observation period. This implies that these techniques are adequate to evaluate the effects of fluids or can be used for predicting fluid responsiveness using functional hemodynamics (e.g. respiratory variations in stroke volume, passive leg raising test,…). However, tracking changes in cardiac output during acute changes in vascular tone (e.g. at induction of anesthesia or during changes in vasoactive agents) is not reliable.

Among the advantages, their simplicity in use and often cheaper aspect make these systems attractive. In addition to the above-mentioned limitations, the lack of additional measurements (volumes/pressures) may also make this system less attractive in severely ill patients.

Internally calibrated

Internally calibrated systems have developed algorithms that allow to provide reliable measurements of cardiac output even in patients with low vascular tone[22]. However, these algorithms require some time to equilibrate so that major errors in cardiac output measurements may be reported during very acute changes in vascular tone as observed after a bolus of phenylephrine or epinephrine[28]. Nevertheless, after a few minutes, the system equilibrates and again provides accurate measurements.

Among the advantages of these systems, the reliable measurements in broad range of vascular tone. These allow to track changes induced by fluids and inotropes, and after a lag time, vasopressors. The main limitations are the difficulty to track changes in cardiac output during acute changes in vascular tone and the lack of additional hemodynamic measurements.

Externally calibrated

External calibration can be provided with transpulmonary thermodilution (PiCCO® and EV1000®), lithium dilution (LiDCO®), or input of a cardiac output value obtained with an alternative technique (often echocardiography). The reliability of the different calibrated techniques is quite similar. The interest of transpulmonary thermodilution may reside in the additional measurements that provide important information on the hemodynamic state[29]. Regarding reliability of measurements, the PiCCO® device has been the most extensively evaluated. The interval between two calibrations is usually around 6-8 hours. Up to 6 hours, the percentage error remains below the accepted limits[30]. However, in patients experiencing changes in vascular tone occur within this interval, a significant error in cardiac output may occur[26], so that recalibration is required. Of note, one technique (the EV1000®) applies an internally calibrated algorithm between calibrations. However, even in this case one may still consider that performing transpulmonary thermodilution may be of interest in assessing the patient's hemodynamic status..

The main advantage of the calibrated technologies is the provision of an accurate cardiac output measurement and, with transpulmonary thermodilution, additional measurements for assessing the hemodynamic state. The main limitation is the mandatory use of a specific catheter for transpulmonary thermodilution and the need for recalibration.

Right-sided thermodilution by pulmonary artery catheter

The pulmonary artery catheter has been around for more than 50 years. Cardiac output is measured using the temperature changes detected at the tip of the catheter after injection of a cold bolus of saline. The technique must be standardized and, provided these requirements are met, thermodilution is one of the most robust methods of cardiac output measurement in critically ill patients.

The bolus thermodilution is intermittent. A semi-continuous cardiac output measurement is obtained with modified catheters equipped by a heating filament which allow automated cardiac output measurements. New generation pulmonary artery catheters allow continuous cardiac output measurement through combination of pulse wave analysis applied to the arterial pressure tracing in combination to calibration by thermodilution[31].

The major advantage of this technique is the robustness of measurements. It is often used as the standard to which alternative techniques are compared. In addition, the pulmonary artery catheter also provides a comprehensive hemodynamic evaluation, including intravascular pressures and mixed-venous oxygen saturation. Given the ability to measure pulmonary artery pressure, it is particularly useful for the management of patients with right ventricular dysfunction[32]. The disadvantage is mostly the invasiveness, so that it is often restricted to the most severe cases and for cardiac surgery.

C. Tissue oxygenation monitoring

The crucial function of blood is oxygen (O_2) transport from the red blood cells to the surrounding tissues. Tissue oxygenation depends on tissue perfusion which is the balance between O_2 delivery and O_2 consumption. Tissue oxygenation is however a complex phenomenon involving various physical and chemical processes and refers to adequate O_2 delivery and O_2 consumption within the macro- and microcirculation.

Monitoring tissue oxygenation in the perioperative period can be performed by non-invasive as well as invasive methods. In this section we discuss the most common techniques to assess tissue oxygenation at bedside.

Lactate

Increased blood lactate level is generally considered as a marker of impaired tissue oxygenation and its measurement is widely used in the perioperative as well as postoperative period. This is called type A lactic acidosis.

In normal states of oxygenation glucose is converted by glycolysis to pyruvate, 90% of which enters the Krebs cycle to generate adenosine triphosphate (ATP) by pyruvate dehydrogenase and 10% is metabolized to lactate. In cases of tissue hypoperfusion and lack of O_2, pyruvate cannot enter the Krebs cycle. It is shifted toward the production of lactate by lactate dehydrogenase (LDH). In addition, severe tissular hypoperfusion by itself can alter mitochondrial function and decrease lactate clearance. There are however other known mechanisms that increase blood lactate concentrations. Lactic acidosis is categorized as type B when it is due to other causes than tissue hypoxia. Increased aerobic glycolysis mostly by hyperglycemia and β2 adrenoreceptor stimulation is one example of type B lactic acidosis. Otherwise, severe liver and kidney disease can decrease lactate clearance. Drugs such as metformin, epinephrine, and linezolid antibiotic can also induce type B lactic acidosis. Rarely, inherited metabolic disorders cause elevated lactate levels due to buildup of pyruvate concentrations.

Differential diagnosis between a type A and a type B lactic acidosis can be difficult and both can be present. Sepsis is one clinical condition where in addition to tissue hypoxia, lactate levels increase due to endogenous as well as exogenous β2 adrenoreceptor stimulation. Liver and kidney hypoperfusion may additionally decrease lactate clearance in septic patients[33,34].

In the setting of critical illness, even mild elevations of lactate have been associated with poor outcome and early resuscitation with lactate clearance improved outcome[35].

Interestingly, a large retrospective study including more than 2,000 intensive care unit patients in whom lactate measurements and central venous oxygen saturation ($ScvO_2$) or mixed venous oxygen saturation ($SmvO_2$) at ± 1 hour from lactate measurement were available, could not show any correlation between these parameters[36]. Lactate showed a U-shaped relationship with $ScvO_2$/ $SmvO_2$ with the highest lactate levels at the lowest and highest percentage values of $ScvO_2$/ $SmvO_2$. Lactate should thus not be used interchangeably with $ScvO_2$/ $SmvO_2$ as a marker of tissue hypoxia.

Near-infrared spectroscopy (NIRS)

NIRS is a bedside non-invasive monitoring of tissue oxygenation and hemodynamics. It reflects the balance between tissue O_2 supply and demand. It is based on the unique ability of light in the near-infrared range (700-1000 nm) to measure the concentration of specific chromophores (oxyhemoglobin/deoxyhemoglobin/cytochrome-C-oxidase) and to detect the oxygenation state of the living tissue.

NIRS devices are based on the principles of modified Beer-Lambert law. The Beer's Law states that the intensity of the transmitted light decreases exponentially as the concentration of a substance the light passes through increases. The Lambert's law states that the intensity of transmitted light decreases exponentially as the distance travelled by the light through a substance increases. Based on these laws and applied in the clinical practice, when the transmitted infra-red light reaches hemoglobin within a tissue, depending upon the oxygenation status of the hemoglobin molecule, a change in the light spectrum occurs. This reflected light returns towards the tissue surface and is detected by NIRS devices. In order to decrease the contribution of superficial tissue layers (skin, fat, extracranial tissue, scalp,…) and enhance the contribution of the interested tissue, different source-detector infrared light separations are used. The latter is based on the spatially resolved spectroscopy and is currently used by the commercially available NIRS devices. In general, one source of emitting light and two sources of detecting light are used to differentiate between the superficial and the deeper layers. The tissue oxygenation measured by NIRS devices is a combination of arterial blood, venous blood, and capillaries. Depending on the studied tissue, this contribution can thus vary. At cerebral level, this measure is predominantly venous as approximately 75% of cerebral blood volume is venous.

In the last decades the use of cerebral and somatic oximetry devices has dramatically increased in the perioperative period. Although cerebral oximetry is the major application of NIRS technology particularly in cardiac surgery, the use of somatic (muscle, kidney, abdomen, ..) oximetry in addition to cerebral oximetry has gained popularity. However, in 2020 the American Society for enhanced recovery and Perioperative Quality Initiative joint consensus statement agreed that although cerebral oximetry can detect malperfusion events in specific cases, there is no evidence that it will reduce organ specific morbidity in cardiac as well as non-cardiac surgery[37]. Indeed, during early stages of systemic hypoperfusion (shock, low cardiac output, sepsis,..) perfusion of the heart and the brain is maintained at the expense of perfusion of other organs such as kidneys, liver and intestines. A monitoring strategy exclusively based on the brain may not inform about the global tissue oxygenation status of the patient. Combining a somatic and cerebral oximetry device may somehow unmask this situation. Unfortunately, the use of somatic NIRS in adults is often influenced by the amount of fat tissue that will increase the distance of the penetrating light into the tissue and as such falsely lower the values[38]. In the pediatric population this combination is best possible and of paramount use[39].

Combining cerebral and muscular oximetry may be also useful in specific cases[40]. Otherwise, monitoring muscular oxygenation and assessment of a vascular occlusion test (VOT) is a unique opportunity to dynamically assess microcirculation[41]. In a study in patients undergoing cardiac and thoracic aortic surgeries, a VOT was performed at baseline, at the end of surgery and on postoperative day 1. The primary endpoint was a composite of major adverse complications including death. Microvascular reactivity, assessed by VOT recovery slope, decreased during cardiac surgery. It recovered on postoperative day 1 in patients without complications, but in a significantly less degree compared to those who showed complications[42].

It was demonstrated that somatic oxygenation values significantly vary depending on the monitored organ[43]. A study performed in patients undergoing laparoscopic gynecological procedure and assessing microcirculation based on NIRS showed that even muscle oximetry values differ between the forearm and the calf [44].

Altogether, due to its non-invasive, continuous and easy to use character, cerebral oximetry alone may provide important information regarding tissue oxygenation in major surgery and in high-risk patients, especially when combined with a depth-of-anesthesia monitor[45]. Nevertheless, one should keep in mind that NIRS is a trend monitor and will not provide absolute tissue oxygenation values[2]. Additionally, different commercially available devices use different algorithms and technologies with as result that these devices are not interchangeable[38,47].

Central venous oxygen saturation ($ScvO_2$) / mixed venous oxygen saturation ($SmvO_2$)

Measurement of $SmvO_2$ is based on the Fick's Equation whereby cardiac output can be estimated by calculating the ratio of O_2 consumption (VO_2), measured from the expired gases to the arterio-venous O_2 difference. $SmvO_2$ is measured in the pulmonary artery by means of a pulmonary artery catheter. $SmvO_2$ reflects the balance between O_2 delivery and O_2 consumption[48].

Cardiac Output = VO_2/ arterial O_2 content-mixed venous O_2 content

To calculate arterial/mixed venous O_2 content the following formula is used whereby the hemoglobin (Hb) concentration should be known:

O_2 content in ml/100 ml blood = Hb bound O_2 + dissolved O_2

O_2 content = [1,39 x O_2 saturation as a fraction x Hb in g/dL] + [0.0031 x PO_2 in mmHg]

1,39 being the maximum O_2 - carrying capacity per gram of Hb and 0.0031 being the solubility constant for O_2 at body temperature, which results that the amount of dissolved O_2 can be neglected.

Low $SmvO_2$ reflects low or insufficient cardiac output in response to the metabolic needs, if Hb and arterial O_2 saturation are within the normal range. This assumption however is not true in every patient and studies in various clinical scenarios have shown a poor correlation between cardiac output and $SmvO_2$[49-51]. A single measurement of $SmvO_2$ does not necessarily describe the cardiac output as low values may be due to low cardiac output, a high tissue metabolic demand or low arterial O_2 content. As the insertion of a pulmonary artery catheter is more and more abandoned in clinical practice, measurement of $SmvO_2$ is nowadays replaced by central venous O_2 saturation ($ScvO_2$) reflecting superior cava venous oxygen saturation. Indeed, the use of $ScvO_2$ has been proposed in the hemodynamic management of patients in septic shock[52,53]. Interestingly, supranormal $ScvO_2$ values have been associated with worse outcome in sepsis[54], and in cardiac surgery patients[55] indicating alterations in O_2 extraction by the tissues as result of microvascular malperfusion or abnormal mitochondrial structure and function.

Of note, $ScvO_2$ does not consider the influence of blood from inferior vena cava and coronary sinus, and the correct positioning of the tip of the catheter may influence the obtained result[56]. A small study in patients undergoing cardiac surgery with cardiopulmonary bypass showed a large mean bias between the two measurements. It also demonstrated a large interindividual variability in the bias from one patient to another and even for a single patient over the study period, illustrating that $ScvO_2$ cannot replace $SmvO_2$ in the management of cardiac surgery patients[57].

As the perioperative use of cerebral oximetry has increased over the last decades, several attempts have been made in different clinical situations to compare the relationship between $ScvO_2$/ $SmvO_2$ and cerebral oxygenation values, but the results are inconsistent[58,59]. An elegant study performed in patient undergoing off-pump coronary artery bypass graft surgery compared $SmvO_2$ with cerebral oxygenation obtained from two different NIRS devices[60]. The study showed that there was a poor correlation between $SmvO_2$ and cerebral oximetry values due to a substantial time delay between mean arterial pressure values and $SmvO_2$ in conditions of hemodynamic instability, while no time delay was observed for cerebral oxygenation variations when mean blood pressure values varied. Cerebral NIRS might thus represent a more reliable variable than $SmvO_2$ to assess the effects of blood pressure changes on tissue perfusion.

Venous-to-arterial carbon dioxide tension difference ($PvaCO_2$)

The $PvaCO_2$ or gap is the difference between PCO_2 in mixed venous blood from a pulmonary artery catheter and the PCO_2 in arterial blood. The mixed venous blood sampling from a pulmonary catheter is often replaced by a measurement from a central venous catheter. $PvaCO_2$ is correlated with cardiac output according to modified Fick's equation, meaning that a decrease in cardiac output results in an increase in $PvaCO_2$. Normal values are between 2 and 6 mmHg[61]. However, the gap is more a marker of adequacy of venous blood flow to remove CO_2 produced rather than a marker of tissue hypoxia. CO_2 is the end product of aerobic metabolism. It is 20 times more soluble than O_2, so it more easily diffuses out of ischemic tissues into the venous effluent making it a sensitive marker of low flow states independently of PaO_2. $PvaCO_2$ has been extensively used in septic shock studies[61,62]. Its increase in the setting of major surgery has been associated with poor postoperative outcome[63,64]. A recent trial randomized patients undergoing major surgery to either a control group or to a group receiving goal-directed hemodynamic management based on $ScvO_2$ and on $PvaCO_2$ difference from a central venous catheter. The primary endpoint was organ dysfunction in the postoperative period. The study showed that compared to the control arm, patients in the intervention group had significantly better tissue oxygenation and shorter intensive care unit stay but did not have a significant difference in organ dysfunction[65].

D. Ultrasound-based monitoring

Echocardiography

Medical pioneers emphasize the vast potential of ultrasound (US)-based imaging in anesthesiology, particularly in enhancing the safety and efficacy of several invasive procedures and the noninvasive monitoring of vital organ function and anatomy[66-68]. The mounting clinical evidence for the point-of-care US (POCUS) value in the perioperative setting, growing affordability of US equipment, and a few associated perioperative US in everyday clinical practice[69-71]. Hemodynamic instability unresponsive to initial treatment is a class I indication for performing a timely echocardiographic examination for accurate assessment of cardiovascular therapy to maintain hemodynamic stability.

According to the respective practice guidelines, echocardiography should be used (1) when the nature of the planned surgery or the patient's cardiovascular pathology might result in severe hemodynamic, pulmonary, or neurological compromise or (2) when unexplained life-threatening circulatory instability persists despite corrective therapy[72].

Although such conditions are frequently encountered in the perioperative setting, considerable variations in practice still exist. The use of US depends on the individual anesthesiologist's level of competence and experience with the technique; this indicates the need for structured echocardiography training programs if the potential benefits of this monitoring tool extend beyond cardiac anesthesia practice[73]. Notably, a consensus paper from the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists emphasized the significant role of basic perioperative echocardiography, defining it as an "intraoperative monitoring technique focusing on cardiac causes of hemodynamic or ventilatory instability, including ventricular size and function, valvular anatomy and function, volume status, pericardial abnormalities and complications from invasive procedures, and the clinical impact or etiology of pulmonary dysfunction"[74]. The aforementioned societies delineate the knowledge and training requirements, as well as the indications and scope of a basic echocardiographic examination, which is distinct from an advanced-level (cardiac-diagnostic) examination, but holds value. Although the incorporation of POCUS into everyday clinical care has decreased the "skill gap" for using US among anesthesiologists, the transition toward a standard of care will require more time and training[75]. In Belgium, national standards for training and certification in perioperative POCUS are currently being developed, with POCUS training being incorporated into the education of residents under training[76].

Basic echocardiography offers the same value in the postoperative setting as in the intraoperative setting. The ability to use the transthoracic echocardiographic (TTE) approach further lowers the threshold for its use in postanesthesia units and is considered appropriate for conducting a focused cardiac examination especially when rapid diagnosis is needed during hemodynamic instability. Considering that the information obtained is noncontinuous, its value is determined primarily by user proficiency.

A drawback of the use of transesophageal echocardiography (TEE) approach is its increased invasiveness, along with a longer "start-up" time, limiting its use to specific indications or situations where vital information cannot be obtained via transthoracic windows in the pre- and postoperative period. The use of TEE is considered more quickly intraoperatively, when surgery or the patient's cardiovascular pathology may result in severe cardiovascular, pulmonary, or neurologic compromise.

Hemodynamic-focused echocardiography is an excellent technique for direct cardiac anatomical and functional assessment of the heart by acquiring images of the primary cardiac windows (TTE: subcostal, apical, and parasternal versus TEE: deep transgastric, transgastric, midoesophageal and upper oesophageal). The use of echocardiography as a monitoring tool in this setting requires quantitative echocardiographic monitoring of specific Doppler hemodynamics (transmitral flow, left ventricular outflow tract velocity, tissue Doppler measurements etc.) and right and left ventricular size and systolic function.

This approach provides detailed information on the mechanism of cardiorespiratory failure, leading to a pathophysiological approach and treatment of the underlying causes. Moreover, it supports clinicians in estimating right- and left-sided atrial filling pressures and predicting fluid responsiveness.

The reproducibility of echocardiographic measurements allows for the sequential monitoring of cardiac function, guiding therapeutic interventions to optimize hemodynamics. Extensive research has shown that hemodynamic optimization among high-risk patients can reduce postoperative complications. Most available standard (non-US) monitoring techniques used in clinical practice are invasive and only measure essential surrogate variables for cardiovascular function.

Lung ultrasound

Lung US uses US to examine the chest based on real-time dynamic two-dimensional imaging and artifacts from the interplay between ultrasonic waves and air, lung tissue, pleura, fluids, and bone. This approach has gained considerable attention in recent years because of its value in screening, diagnosis, and monitoring during clinical perioperative practice[77-79]. Lung US is noninvasive, readily available in most operating rooms, reduces the need for X-rays[80,81], and can be used as an adjunct to echocardiography.

Excessive fluid administration can cause volume overload, particularly in patients with impaired cardiopulmonary reserve. Lung US identifies early signs of volume overload much earlier before any clinical signs occur and is able to determine whether dyspnea and/or hypotension are of cardiac origin[82,83]. Concerning volume resuscitation, such a finding could justify the cessation of fluid therapy and the initiation of diuretics, vasodilators, or inotropic support. If hypotension persists and is unresponsive to fluid resuscitation, TTE/TEE can be used to exclude specific causes of hemodynamic instability, such as right ventricular dysfunction, cardiac tamponade, or sepsis[84]. Lichtenstein's FALLS protocol uses an applicable therapeutical algorithm, which can also be used perioperatively[82,83,85].

Venous excess ultrasound score (VExUS)

Anesthesiologists often rely on the inferior vena cava (IVC) measurements to determine whether patients are fluid-deficient or -overloaded. However, a dilated IVC may be present without comorbidities and does not necessarily indicate that the individual is fluid overloaded[86]. In addition, the extent of venous congestion in organs cannot be determined by measuring IVC dilation alone. The VExUS is a recently established US-based scoring modality that diagnoses and quantifies clinically significant organ congestion[87-89]. The protocol is feasible in most patients and can be performed by anesthesiologists throughout the perioperative period[90].

The principle of VExUS is simple: when the limits of the systemic venous compliance of larger veins are exceeded, venous hypertension will occur, resulting in abnormal venous waveforms. The latter are transmitted to organ-specific veins, including the hepatic, portal, and intrarenal veins.

VExUS quantifies systemic congestion using Doppler flow indices of the hepatic and portal veins in addition to the IVC assessment, which has some limitations, including alterations related to right ventricular dysfunction and varying breathing patterns. VExUS parameters are easily obtained and provide an objective marker; consequently, a clinician can adjust intravenous fluids or provide decongestive therapy. A potential limitation of VExUS is its use in chronic liver disease wherein low hepatic pulsatility can be present even with significant systemic congestion. In the perioperative setting, this can help guide decongestive therapy in patients with heart failure, facilitate the management of right ventricular dysfunction, and potentially reduce the risk of postoperative acute kidney injury and pulmonary edema[87,91,92].

Transcranial Doppler

Transcranial Doppler ultrasonography (TCD), which allows for the continuous noninvasive monitoring of cerebral blood flow velocity, represents an important advancement in monitoring intracranial hemodynamics. TCD can assess the adequacy of cerebral blood flow in real time, identify cerebral emboli, and estimate intracranial and cerebral perfusion pressures[93,94].

TCD monitoring throughout the perioperative period may focus on sharp changes in cerebral blood flow velocity, suggesting equivalent changes in cerebral blood volume. Of particular interest are abnormally low cerebral blood flow rate or emboli that travel toward the brain via the bloodstream during surgery. A surgeon's ability to modify surgical actions during surgery can avoid important changes in the cerebral blood flow or reduce the number of emboli during surgical manipulations. Studies have shown that combining TCD with other neuromonitoring modalities (e.g., electroencephalography and NIRS) enables a more comprehensive view of cerebral physiology during surgery[94,95].

Although alterations in cerebral perfusion are associated with postoperative delirium and cognitive disorders regardless of the surgical approach, the recommendation for the use of TCD during carotid endarterectomy and cardiovascular surgery remains poor (Class IIIC)[96].

Practical limitations to the routine intraoperative application of TCD have been noted, including dependency on the examiner's skills and experience in operating TCD within the relatively small environment of the operating room, the absence of an acoustic window in 10%–20% of patients, and the lack of standardized scanning protocols in the perioperative setting[93,97,98].

2. Which hemodynamic monitoring tool should I use ?

Table II summarizes the purpose of the various hemodynamic monitoring tools discussed in this paper. In the decision making of which monitoring tool to use, the point of prime importance is to understand that hemodynamic monitoring tools are designed to capture signals and translate these via all kind of algorithms into numbers, waveforms and images. They are not designed to perform a diagnosis and even less to decide on treatments. As already stated by Pinsky and Payen, almost 20 years ago: " … no monitoring tool, no matter how accurate, by itself has improved patient outcome"[99]. Indeed, monitoring tools only deliver information, which then should be interpreted by the treating medical teams. Patient outcome will depend on the appropriateness and quality of these decisions. Of course it is essential that the information obtained from these monitoring tools is accurate and reliable.

Decisions on type of hemodynamic monitoring tool thus depend on which type of information is expected, which in turn will largely depend on the health status of the patients and their comorbidities together with the type of the planned surgical intervention. Another aspect to be considered is that perioperative patient management represents a continuum of care. Therefore, it is important that

Table II. — Purpose of the measured hemodynamic monitoring variable.

Variable	Purpose
Blood pressure	Detect events associated with decrease in blood pressure *Vasoplegia *Decrease in blood flow
	Monitor organ perfusion pressure
	Target to titrate vasoactive agents *Risk of bleeding *Impaired tissue perfusion
Cardiac output	Determinant of tissue perfusion
	Target to titrate fluids and inotropic agents
Tissue oxygenation	
SvO2 / SmvO2	Adequacy of oxygen delivery according to oxygen consumption
NIRS O2 saturation	Adequacy of regional oxygen delivery according to regional oxygen consumption
Lactate	Adequacy of oxygen consumption to oxygen requirements
PvaCO2	Adequacy of flow
Ultrasound based	
Echocardiography	Evaluate cardiac function
	Evaluate volume status
	Measure cardiac output
Lung ultrasound	Lung edema (hydrostatic or non-hydrostatic cause)
	Pneumothorax
	Pleural effusion/hemothorax
VExUS	Venous stasis

NIRS = near-infrared spectroscopy; ScvO2 = central venous oxygen saturation; SmvO2 = mixed venous oxygen saturation; Pv-aCO2 = venous to arterial carbon dioxide tension difference; VExUS = venous excess ultrasound score.

compatibility is maintained among hemodynamic monitoring technologies between different departments in the hospital. Finally, financial and other constraints make that departments and hospitals cannot afford to have all existing systems available. Consequently, decisions on hemodynamic (and other) monitoring systems should integrate all clinical pathways within the hospital. It has therefore been underscored that such decisions should be taken at institutional level[100].

Conclusion

While it is expected from the hemodynamic monitoring tools that they provide an accurate and reliable display of the actual hemodynamic status, it is essential that their use is paired with clearly defined treatment protocols[100]. In this respect, it is essential to remember the famous quote: “treat the patient, not the numbers”. In other words, when the treating physician is confronted with an abnormal numerical (or other) value (or reading), the first step (after having excluded possible technical problems with the monitoring device) should always be to unravel the pathophysiological cause for the “abnormal value” and only then treat the underlying cause and not promptly try to restore the abnormal value with a-perhaps-inappropriate treatment.

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