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Perioperative hemodynamic management 4.0

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Postoperative complications within 30 days represent the third leading cause of death in the world. Multiple solutions have been proposed to tackle the clinical and economic burden of postoperative complications. They include the optimal fluid and hemodynamic management of patients undergoing major surgery. Technological innovations and a better understanding of cardiovascular physiology underlie the evolution of perioperative hemodynamic management, ranging from the mere normalization of heart rate, blood pressure, and central venous pressure to oxygen delivery maximization with a pulmonary artery catheter and individualized fluid management with esophageal Doppler or pulse contour methods. The concept of personalized hemodynamic management recently emerged and may soon become a reality, because of new technologies enabling noninvasive measurement of cardiac output, not only during and after but also before surgery. The monitoring of microcirculation and tissue perfusion may help to fine tune this approach. Importantly, mortality within 30 days after surgery is 1000 times higher than intraoperative mortality. Therefore, continuous ward monitoring with wireless and wearable sensors may be the next major opportunity to improve patient safety.

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Postoperative complications within 30 days occur in approximately 17% of patients undergoing nonambulatory elective surgery [1], and they represent the third leading cause of death in the world [2]. Multiple initiatives have been proposed to tackle the clinical and economic burden of postoperative complications, ranging from the WHO surgical safety checklist to minimally invasive surgery (e.g., laparoscopic procedures), protective mechanical ventilation [3], and enhanced recovery after surgery (ERAS) programs [4]. One of the key components of enhanced recovery pathways is the optimal fluid and hemodynamic management of patients undergoing major surgery.

Evolution of perioperative hemodynamic management

For decades, perioperative hemodynamic management of patients undergoing noncardiac surgery was mainly based on the monitoring of heart rate and blood pressure. A central venous catheter or a pulmonary artery catheter was occasionally used for the highest risk procedures, with the objective to maintain hemodynamic variables within a population-based normal range or close to pre-incision values.

Thirty years ago, Shoemaker et al. [5] introduced the concept of oxygen delivery maximization for patients undergoing major procedures. Although several studies showed that this approach may have value when applied during and/or immediately after surgery [6,7], the adoption remained poor. Reasons include the fear to induce fluid overload, cardiac arrhythmia, and ischemia with aggressive fluid and inotropic therapy, as well as the inception of individualized fluid management at the end of the 90s [8].

Individualizing fluid management means tailoring fluid administration to individual needs (Fig. 1) by ensuring that patients' hearts are operating close to the inflexion point of the Frank-Starling relationship, i.e., away from the dangerous hypovolemic and fluid overload zones. In practice, small fluid boluses (200–250 ml) are given until stroke volume approaches a plateau value (bolus-induced increase in stroke volume <10%). An alternative method consists of quantifying the arterial pulse pressure variation (PPV) induced by mechanical ventilation, which is known as a marker of the position on the Frank-Starling curve [9]. Regardless of the method used, individualized fluid management

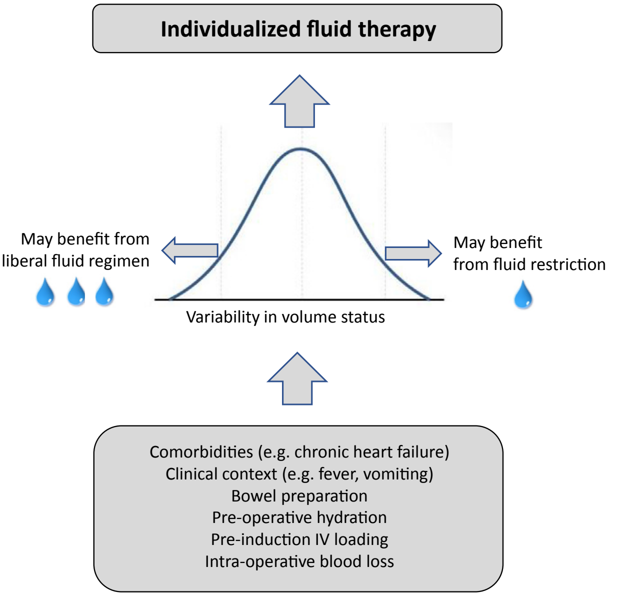

Fig. 1. Individualized fluid management. There are no two patients alike with regard to volume status and hence to fluid requirements. Fluid administration should be tailored to individual fluid needs.

strategies have repeatedly been associated with a decrease in postoperative complications and hospital length of stay in patients undergoing major surgery [10–12]. They are currently recommended by several consensus statements and anesthesia societies [13,14], whereas large randomized trials (Floela, GAS-ART, iPEGASUS, and Optimise II) are still ongoing. Of note, the superiority of individualized fluid management over a zero-fluid balance approach has not been established in head-to-head comparisons [15]. However, it was recently demonstrated that one-size-fits-all fluid restriction increases the risk of hypovolemia-related complications such as acute kidney injury [16].

The future of hemodynamic management: new concepts

Personalized hemodynamic management

The concept of personalized hemodynamic management recently emerged [17]. The idea is to ensure perioperative hemodynamic targets are consistent with individual physiological status. Futier et al. [18] proposed an intraoperative blood pressure management strategy based on personal preoperative resting values. By maintaining intraoperative systolic arterial pressure close to baseline preoperative values – using continuous norepinephrine administration after fluid optimization – they significantly decreased postoperative organ dysfunction. Ackland et al. [19] used a similar approach for oxygen delivery during the 6 h postoperative period of high-risk surgery. Patients who achieved preoperative oxygen delivery values in the postoperative phase sustained less morbidity, in particular less infectious complications. Saugel et al. (clinicaltrials.gov: NCT02834377) have recently completed a clinical study where personal cardiac output values are measured the day before surgery with a noninvasive pulse contour technique and subsequently used as target values during the procedure. Results should be published in 2019.

Optimization of tissue perfusion

Restoring or preserving tissue perfusion and oxygenation is the ultimate goal of hemodynamic management. Several methods have been proposed to assess tissue perfusion and microcirculation. They include near-infrared spectroscopy (NIRS) with forehead adhesive sensors to assess brain oxygenation and video microscopy techniques to quantify sublingual microcirculation. The former enables continuous monitoring, and several studies suggest a significant decrease in postoperative delirium when maintaining brain oxygenation close to baseline values [20]. The latter are intermittent and operator-dependent techniques, precluding their use beyond research purposes [21]. In the near future, smart Foley catheters containing a photoplethysmographic sensor may allow the continuous monitoring of urethral perfusion index (Fig. 2). These tools may enable the detection of a possible

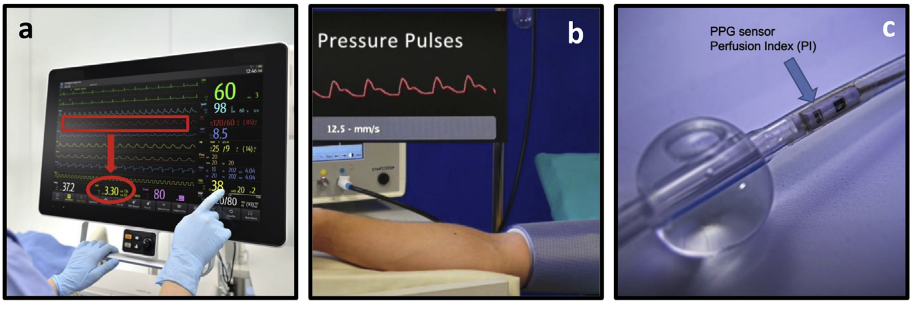

Fig. 2. Future easy-to-use techniques for intraoperative hemodynamic monitoring. In the future, multi-parameter bedside monitors could continuously display cardiac output values next to other physiological variables, oscillometric brachial cuffs could record blood pressure waveforms (from UP-Med/Philips with permission), and smart Foley catheters could provide continuous information about microcirculation (from Advanced Perfusion Diagnostics with permission).

dissociation (aka lack of coherence) between macrocirculation (e.g., mean arterial pressure) and microcirculation and open the door to the individualization of vasopressor therapy by identifying the optimal level of mean arterial pressure for any given patient.

Decision support systems and predictive analytics

Visual decision support systems or target screens are already available to guide clinicians following hemodynamic protocols [22]. Hemodynamic variables and targets can be customized by clinicians who have to adapt their hemodynamic goals to specific clinical situations (e.g., liver resection) and the individual patient. These decision support tools are useful to quantify the time spent in target [23] and to enhance protocol adherence [24].

Predictive analytics are statistical methods analyzing current and historical data to make prediction about the future. They are susceptible to detect specific patterns or signatures of clinical deterioration before it becomes visible to clinicians. Predictive algorithms have recently been proposed to predict intraoperative hypotension. Studies have yielded conflicting results, with sensitivities and specificities within the 65–85% range [25–27]. These findings may be explained, at least in part, by the fact that any external intervention, by definition unknown from the predictive system, is susceptible to impact hemodynamic stability (e.g., a bolus of propofol would likely decrease blood pressure whatever the prediction, whereas a bolus of ephedrine would increase it) [28]. In addition, it remains to be determined whether the prediction of hypotension would result in its prevention and better clinical outcomes.

Automation

The automation of perioperative hemodynamic management is difficult to envision. Most goal-directed therapy protocols recommend stopping fluid boluses if they do not increase stroke volume (nonresponder patients), but truly hypovolemic patients may not respond to a fluid bolus by an increase in stroke volume if they are bleeding at the same time. A clinician would obviously notice and continue to give fluid, whereas an automated system designed to fluid optimize stroke volume would not. Two recent randomized controlled trials investigating the clinical impact of a closed loop system delivering fluid boluses (according to a predefined protocol) failed to show significant benefits [29,30]. The automatic titration of vasopressors to ensure a stable blood pressure during surgery is also technically feasible [31], but it does not mean that vasopressors are always the right therapeutic answer to a decrease in blood pressure. Depending on the root cause of hypotension, it may actually be better to administer fluid, or red blood cells, or inotropes, or simply to decrease the depth of anesthesia [32].

In contrast, because of its potential to make clinicians life easier with no additional risk for patients, automation of simple diagnostic tests may soon become available. Assessing the hemodynamic impact of respiratory maneuvers (transient increase in tidal volume, end-inspiratory or expiratory pause, and lung recruitment maneuver) is known to be useful to predict fluid responsiveness [33,34]. Patients who do not experience significant changes in hemodynamics during such maneuvers should not receive fluid boluses. These simple tests could be automatized on anesthesia machines and mechanical ventilators (Fig. 3) so that anesthetists and intensivists would know at regular intervals, and without any additional workload, about the fluid responsiveness status of their patient [35].

The future of hemodynamic management: new techniques

Before surgery

One of the key challenges of the personalized approach is to determine the personal hemodynamic values for any given patient. Indeed, blood pressure may vary at daytime, and cardiac output values at rest are classically unknown. To limit the influence of stress and premedication on baseline blood pressure values, Futier et al. [18] used the patient's usual resting systolic pressure, and Saugel et al. [36] recently proposed to use ambulatory measurements made a few days before surgery. It is now possible to quickly spot-check cardiac output noninvasively during the preoperative consultation or on the

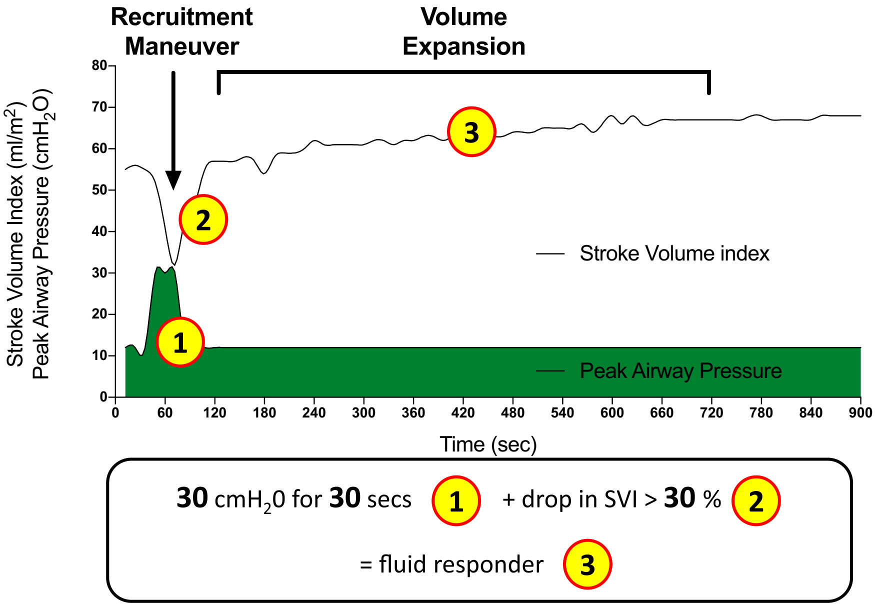

Fig. 3. The automatic detection of fluid responsiveness. The "3 × 30" maneuver is useful to predict fluid responsiveness and could be automatized on anesthesia machines.

surgical wards the day before surgery. Noninvasive and reusable tools include echocardiography, suprasternal Doppler, finger arterial pulse contour techniques, and bioimpedance necklaces (Fig. 4).

During surgery

Because pulse contour techniques are easy to use and not affected by electro-cautery, they have become the preferred choice for anesthetists to monitor patients undergoing major noncardiac surgeries [16,37]. Despite their limited accuracy and precision when compared to reference methods (e.g., thermodilution and echocardiography), the use of uncalibrated pulse contour methods has been shown to be associated with a significant decrease in postoperative complications [38]. However, surveys suggest that only 1/3 of eligible patients are monitored [39], and a recent real-life audit done in France reveals it may actually be much less (<1/10 of eligible patients) [40]. Because the cost of monitoring techniques may be a significant barrier to hospital adoption, several hemodynamic monitoring companies are now offering "low-cost" solutions with either reusable sensors or a flat fee for monitoring an unlimited number of patients. Given the growing body of evidence supporting the clinical value of uncalibrated pulse contour methods, one may also imagine that bedside monitoring companies will develop or acquire pulse contour algorithms so that cardiac output values, or at least trends, will soon become available next to blood pressure numbers in all patients with a radial catheter in place (Fig. 2).

For patients without an arterial line, oscillometric upper-arm cuffs have recently been revisited to include a rigid conic shell and a hydraulic sensor pad. They may improve the accuracy of blood pressure measurements and enable the recording of an arterial pressure waveform for about a minute [41]. In the future, these new-generation cuffs could also be used to compute PPV and cardiac output from the arterial pressure waveform (Fig. 2).

Continuous ward monitoring

In the large (>46,000 patients) EUSOS study conducted in 28 European countries, most patients (73%) who died before hospital discharge were not admitted to critical care at any stage after surgery [42]. Importantly, vital signs are often abnormal, or trending toward abnormal range, hours before

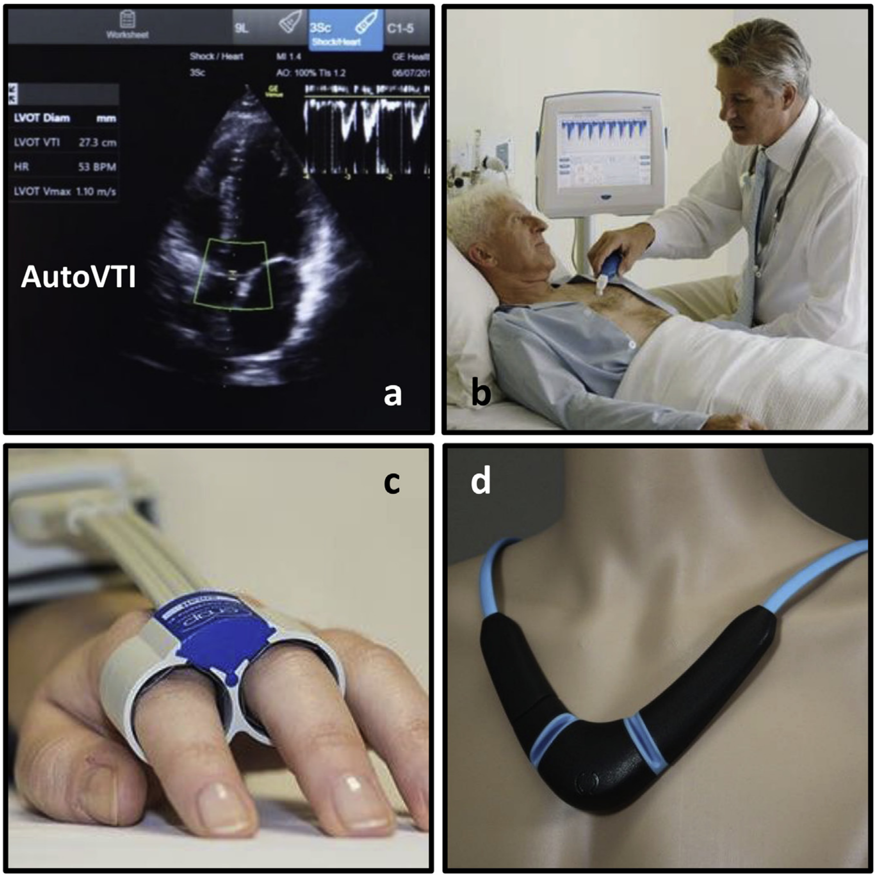

Fig. 4. Personalized hemodynamic management. Examples of noninvasive and reusable techniques that could be used to measure cardiac output during the preoperative anesthesia consultation or on the wards before surgery. a = Echocardiography-Doppler with software enabling the semi-automatic measurement of the velocity time integral (autoVTI) in the left ventricular outflow tract (from GEhealthcare.com), b = Suprasternal Doppler (from Uscom.com.au), c = Volume clamp pulse contour technique (from CNSystems.com), d = Bioimpedance necklace (from Tosense.com).

death [43]. Nurses who spot-check vital signs every 4–6 h may detect clinical deterioration with delays [44]. A recent and prospective observational study conducted in a leading US hospital, where patients were continuously but blindly monitored, revealed that nurses who were checking blood pressure every 4 h missed about half of hypotensive events [45]. Another study from the same group showed that hypotensive events between days 1 and 4 after surgery (when most patients are on the wards) are associated with a 183% increase in myocardial infarction and death [46]. Therefore, continuous monitoring of blood pressure may help to improve quality of care [47]. Unfortunately, blood pressure remains a variable that is difficult to measure noninvasively and continuously. Several volume clamp and tonometric methods have been developed to measure finger or radial blood pressure, respectively [48]. However, these tethered monitoring systems have been designed for the operating room, not for ambulatory ward patients. Other monitoring systems, such as a combination of chest electrodes (to detect the ECG R wave) and a finger pulse oximeter (to detect a peripheral pulse), are able to predict blood pressure from the estimation of changes in pulse wave transit time [49]. Weller et al. [50] used such a system in ward patients and reported a significant decrease in the number of rapid response team calls. In the future, adhesive and wireless patches may become available for the continuous monitoring of carotid, brachial, or radial blood pressure and derived parameters [51]. The pulse oximetry waveform analysis also has potential to gather blood pressure information [52].

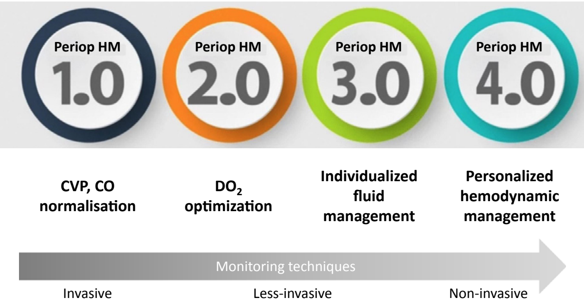

Fig. 5. Evolution of perioperative hemodynamic management. Periop HM, perioperative hemodynamic management; CVP, central venous pressure; CO, cardiac output; DO_2, oxygen delivery.

Conclusion

Technological innovations and a better understanding of cardiovascular physiology explain the evolution of perioperative hemodynamic management from the mere normalization of heart rate, blood pressure, and central venous pressure, to oxygen delivery maximization with a pulmonary artery catheter, and individualized fluid management with esophageal Doppler or pulse contour methods (Fig. 5).

The concept of personalized hemodynamic management recently emerged and may soon become a reality because of new technologies enabling noninvasive measurement of cardiac output, not only during and after but also before surgery. Monitoring microcirculation and tissue perfusion may help to identify the optimal blood pressure and flow for any given patient and at any given time.

Mortality within 30 days after surgery is 1000 times higher than intraoperative mortality [53]. Therefore, continuous ward monitoring with wireless and wearable sensors may be the next major opportunity to decrease the clinical and economic burden of postoperative complications and deaths.

Conflicts of interest

FM is the founder and managing director of MiCo, a Swiss consulting firm. MiCo does not sell any medical products, and FM does not own shares nor receive royalties from any MedTech company. MB declares lecture fees from Getinge and from Edwards Lifesciences. SML has no conflicts of interest to declare. EF declares consulting fees from Drager Medical, GE Healthcare, Edwards Lifesciences, and Orion Pharma and lecture fees from Fresenius Kabi and Getinge.

Practice points

- The optimal fluid and hemodynamic management of patients undergoing major surgery is a key component of enhanced recovery pathways.
- Individualized fluid management is recommended by expert consensus statements and society guidelines.
- Uncalibrated pulse contour techniques are the preferred choice of anesthetists for hemodynamic monitoring during noncardiac surgical procedures.
- Oncoming easy-to-use and low-cost techniques should increase the adoption of hemodynamic monitoring during surgery.
- Noninvasive techniques could be used the day before surgery or during the preoperative visit to determine personal blood pressure and cardiac output targets.
- Ward monitoring with wireless and wearable sensors might be the next major opportunity to improve patient safety.

Research agenda

- Several large randomized controlled trials are ongoing to confirm the clinical and economic benefits of individualized fluid management.
- Further research is warranted to investigate the impact of personalized hemodynamic management on postoperative outcome.
- Studies are needed to clarify how microcirculation and tissue perfusion may be manipulated and what would be the impact on patient outcome.
- Future research should investigate whether predictive analytics may help to prevent adverse events.
- The impact of continuous ward monitoring on clinical outcomes has to be confirmed when using untethered monitoring systems.

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