Best Practice & Research Clinical Anaesthesiology 33 (2019) 229–245

Contents lists available at ScienceDirect

Best Practice & Research Clinical Anaesthesiology

journal homepage: www.elsevier.com/locate/bean

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Postoperative ward monitoring – Why and what now?

Ashish K. Khanna, MD.,FCCP.,FCCM, Associate Professor, Staff Intensivist & Anesthesiologist [a, d, *, 2],
Sanchit Ahuja, M.D. Resident Anesthesiologist [b, d, 1],
Robert S. Weller, MD, Professor, Department of Anesthesiology, Section Head – Regional Anesthesia and Acute Pain Management [c, 2],
Timothy N. Harwood, M.D. Associate Professor of Anesthesiology, Medical Director, DMC Outpatient Surgery Center, Section Head, Ambulatory Anesthesia & Director, Quality Improvement [c, 2]

[a] *Department of Anesthesiology, Section on Critical Care Medicine, Wake Forest School of Medicine, Winston-Salem, NC 27157, USA*
[b] *Department of Anesthesiology, Pain Management and Perioperative Medicine, Henry Ford Health System, Detroit, MI 48202, USA*
[c] *Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC 27157, USA*
[d] *Outcomes Research Consortium, Cleveland Clinic, Cleveland, OH, USA*

Keywords:
ward
continuous monitoring
vital signs
postoperative
machine learning
artificial intelligence

The postoperative ward is considered an ideal nursing environment for stable patients transitioning out of the hospital. However, approximately half of all in-hospital cardiorespiratory arrests occur here and are associated with poor outcomes. Current monitoring practices on the hospital ward mandate intermittent vital sign checks. Subtle changes in vital signs often occur at least 8–12 h before an acute event, and continuous monitoring of vital signs would allow for effective therapeutic interventions and potentially

* Corresponding author. Department of Anesthesiology, Section on Critical Care Medicine, Wake Forest School of Medicine, Winston-Salem, NC 27157, USA.

E-mail addresses: akhanna@wakehealth.edu, ashish@or.org (A.K. Khanna), Sahuja2@hfhs.org (S. Ahuja), rweller@wakehealth.edu (R.S. Weller), tharwood@wakehealth.edu (T.N. Harwood).

[1] Fax: 313-916-9434.
[2] Fax: 336.716.8190.

https://doi.org/10.1016/j.bpa.2019.06.005

avoid an imminent cardiorespiratory arrest event. It seems tempting to apply continuous monitoring to every patient on the ward, but inherent challenges such as artifacts and alarm fatigue need to be considered.
This review looks to the future where a continuous, smarter, and portable platform for monitoring of vital signs on the hospital ward will be accompanied with a central monitoring platform and machine learning-based pattern detection solutions to improve safety for hospitalized patients.

Introduction

In the next generation, demographic changes with increasing complexity of comorbidities will contribute to an increasing number of patients with chronic illnesses in need for high acuity treatment [1]. Additionally, health care institutions worldwide face higher workloads because of shortage of skilled medical/nursing labor and increasing cost [2]. In this setting, sustainable and reliable implementation of advanced electronic wireless technologies may possibly help reduce the burden of this development.

Only 1 in every 100,000 patients receiving an anesthetic suffers from intraoperative mortality, but postoperative patients still have a high risk of acute clinical deterioration.

Depending on the complexity of surgery and burden of comorbidities, 15–45% of patients suffer from postoperative complications—with an overall mortality rate of 1–2% within a month after surgery [3–7]. This 30-day mortality after surgery is the third leading cause of death in the United States [8]. Contrary to expectations, most patients who die during the postoperative period are never admitted to critical care units [4]. A large majority of in-hospital cardiorespiratory events occur on the wards, and when they do occur, outcomes are catastrophic and worse than similar events in monitored environments [9,10]. Up to a third of all postoperative complications and associated mortality are cardiorespiratory [11,12]. The rest are usually a consequence of stroke, sepsis, and hemorrhage, which often lead to unplanned critical care admissions [13,14]. A previous work identified that hypotension is common and may persist for prolonged duration during the immediate postoperative period [15]. This hypotension is strongly and consistently associated with myocardial injury, acute kidney injury, delirium, and stroke [15–18]. Similarly, postoperative hypoxemia is also common and after noncardiac surgery in patients recovering on the general ward [19]. Ventilatory insufficiency, although not commonly measured, is also common and may be more frequent in certain etiologies of postoperative respiratory adverse events in this environment [20].

Acute cardiorespiratory compromise events do not typically occur abruptly. They are usually preceded by an 8- to 12-hour period of subtle changes in vital signs [21–23]. Current monitoring standards on hospital wards require only intermittent “snapshots” of vital sign measurement, usually done at 4- to 6-hour intervals. Therefore, most pattern changes in cardiorespiratory physiology are missed or detected too late to allow for effective interventions to rescue the patient from progressive deterioration. There is, therefore, an obvious need for better, continuous vital sign monitoring on in-patient units.

This narrative review describes the current state of monitoring vital signs on the ward, introduces the need for and the variability of continuous cardiac and respiratory monitoring systems, and addresses challenges associated with converting wards to continuous monitoring units, specifically alarm fatigue and artifactual data. The need for smarter, portable, continuous artificial intelligence-supported and data-driven platforms, along with the need for generation of stronger evidence to support this change in monitoring standards, is also elaborated in some detail.

Current monitoring standards

Integrated information of basic vital signs such as blood pressure, heart rate, temperature, oxygen saturation, and respiratory rate is essential and plays an important role in realizing data-driven clinical decision-making systems. Perturbation in these physiological parameters represents at least one organ dysfunction in a quick and reproducible manner. The conventional practice of vital sign measurement is primarily based on subjective interpretation by medical personnel. This may be associated with potential sources of error with variance related to subject, interobserver, instrument, or technique utilization. Intermittent monitoring of vital signs is currently the standard of care for in-patient wards in most hospital systems in the United States. This periodic monitoring consists of measurement of vital signs every 4–6 h by a nurse or nurse's aide, and validation of the data after the licensed nurse has clinically examined the patient. This longstanding practice has been in existence for more than a hundred years, with limited evidence to suggest the most effective interval of measurements [24,25]. Moreover, evidence suggests that inadequate and poor documentation of vital signs on the wards (presumably due to reasons such as time constraints, increased patient-to-nurse ratio) may be a predictor of preventable deaths [26,27]. Furthermore, based on the subjective judgment of the patient's stability, there appears to be inconsistency in the frequency of evaluations used in clinical practice among hospitals. Manual methods are also prone to a "data smoothing effect," whereby a provider uses preinterpretation of data and averages monitor readings in a situation when a single reading is "out of range." [28,29] This phenomenon was first noticed in a retrospective analysis of abnormal readings [30]. Similarly, another study corroborated the findings and additionally concluded that extreme values were recorded less frequently in manual records than in automated records [31]. In addition, manual recording of pulse oximetry data documented higher values than automated data entry for the same periods [32]. Intermittent monitoring on wards misses large periods of time during which perturbations of vital signs may occur. Hypoxemia (SpO_2 <90%) occurred in a fifth of all patients recovering from noncardiac surgery. Disturbingly, routine ward monitoring missed 90% of these hypoxemic episodes in which oxygen saturation was <90% for at least an hour [19]. Other factors that may lead to suboptimal monitoring includes errors in calculating scores, high work load shifts, high patient-to-nurse ratio, lack of compliance, and inadequate interpretations of worsening variables [33,34].

An inherent problem with periodic monitoring of vital signs on the ward is the lack of interpretation of subtle changes in vital signs or a pattern detection that may occur during "early deterioration." In a review of National Confidential Enquiry of patient outcome and Deaths (NCEPOD) of perioperative patients, it was concluded that only 21% of the identified high-risk surgery patients were admitted to critical care units postoperatively and almost half of the dead patients were never cared for in critical care units [35]. Hospital wards are traditionally considered a safe haven for recovery of patients as they transition to their next destinations (usually out of the hospital); however, they are a common place for the occurrence of unanticipated acute cardiovascular catastrophic events. At least 60% patients have one abnormal vital sign 1–4 h before an acute cardiorespiratory arrest, and there is a stepwise increase in mortality with an increasing number of abnormal vital signs. Mortality approaches 100% with 3 or more abnormal pre-arrest vital signs [36]. A cross-sectional study of 3046 patients concluded that abnormal respiratory rate and heart rate, as both early and late signs, increase the odds of critical care unit transfer [37]. This constitutes the very vital afferent limb of hospital acute medical emergency or "rapid response" teams. A rapid response call from the ward is usually generated only after a nurse-verified set of vital signs meets early warning score criteria [38]. These rapid response teams and the use of effective protocols to run them have showed improved outcomes overall but have been limited by the intermittent nature of data collection as well. Because changes in trends of vital signs begin to occur hours before an untoward event, intermittent monitoring-based early warning scores and rapid response calls may be a retroactive intervention instead of proactive intervention [21] Essentially, most of these teams end up being activated, only when patient deterioration may have progressed beyond the point of effective rescue. An effective efferent limb of rapid response therefore critically depends on an effective afferent response that, in turn, depends on early identification of patient deterioration, which is often not detected in a timely fashion using intermittent monitoring of vital signs.

We now perform surgery on a relatively fragile subset of patients compared to years past. Unfortunately, these patients may be ill-prepared for the procedure, are often not admitted for preoperative optimization, and may be sent home early in the postoperative period. This present-day fast-track approach seems attractive but may not be compatible with periodic monitoring of vital signs on the ward. In fact, the intermittent vital signs approach to ward monitoring was developed decades ago [24,25] when surgery was largely restricted to relatively healthy patients who routinely stayed at least one night before surgery and then remained hospitalized long after surgery. Knowing the commonality of postoperative cardiac and respiratory decompensation and that hypotension surely contributes to myocardial injury (and mortality), current sparse ward monitoring probably misses many potentially important hemodynamic events. The obvious solution is continuous hemodynamic monitoring, which could detect hypotension and lead to diagnosis and treatment. If the effect of this is to reduce the amount of hypotension, this may be expected to improve outcomes, although this theory remains speculative at best and deserves robust investigation.

Why continuous monitoring?

Unplanned critical care unit admissions are associated with increased mortality, length of stay, and a significant economic impact [39,40]. For example, every extra day in the hospital costs approximately $2000 and every additional day in a critical care unit approximately $5000–$7000 [41]. Some authors have named these unplanned, yet potentially preventable ICU admissions as a result of the lack of timely intervention in the absence of continuous ward monitoring, the “4 a.m. phenomenon” (Fig. 1) [42]. Clearly, the precious time lost between the onset of deterioration of vital signs and the detection and intervention of effective therapeutic interventions is clinically significant when comparing continuous with periodic vital signs checks. In this context, a prototypical patient who displays the “4 a.m. phenomenon,” as shown in Fig. 1, is usually in postoperative days 2–3, recovering from a major abdominal surgery, on the general care floor. At around that hour of the night (4 a.m.), the ICU receives this patient as an unprecedented admission from the floor. According to the report from the floor house staff, this patient was found hypoxic and/or hypotensive and he/she is at a point where aggressive therapeutic interventions or respiratory support is not possible on the floor. While a likely explanation of the deterioration is hypoventilation secondary to a combination of pain medications and/or sedative use, the fact that detection is delayed proves costly to the patient and the hospital, resulting in an unplanned and unnecessary ICU admission. Using continuous measurements, trajectories of collected data can be converted into meaningful information of the patient's state in a real-time manner. In this patient's case, this would have resulted in an early detection of impending hypoventilation, effective respiratory support, and a necessary adjustment of pain medicine delivery regimen, to avoid the progressive physiological decline. A study conducted on 2841 postsurgical orthopedics patients demonstrated that continuous surveillance of physiological parameters such as heart rate and oxygen saturation reduced critical care unit transfer from 5.6 to 2.9 per 1000 patients [32]. Another study done on 2314 medical-surgical unit patients showed that continuous monitoring was associated with significant reduction in ICU length of stay and rates of imminent cardiorespiratory arrest events [43]. Recently, a study compared intermittently measured EWS (early warning signs) and continuously recorded vital signs in major abdominal surgeries and reported that clinically relevant hypoxic events of SpO_2 <92% were found in 98% of continuously monitored patients, which remained almost undetected in the intermittent group [44]. Notably, approximately half of all patients experienced severe desaturations, SpO_2<85% that lasted for more than 10 min [44]. Similarly, another study demonstrated that continuous surveillance of vital signs was able to significantly reduce rapid response team calls with acceptable alarm rates when compared with standard ward monitoring [45]. Additionally, comparing continuous or intermittent monitoring with intermittent monitoring alone in surgical ward patients by using scoring systems showed that patients who received continuous monitoring had shorter lengths of stay and reduced readmissions and were administered antibiotic therapy faster than those in the intermittent group [46]. Clinical deterioration in postoperative wards may thus remain undetected for several hours. The “4 a.m. phenomenon” is common and puts immense resource and personnel strain on ICU systems worldwide. Not only does this waste on an ICU bed on a truly avoidable critical care emergency, but it also plays havoc with patient family satisfaction and influences the morale of patient families, patients themselves, and healthcare providers who feel the frustration of burnout in these situations. Clearly, current conventional practice of periodic monitoring of vital signs is suboptimal and may contribute to poor patient

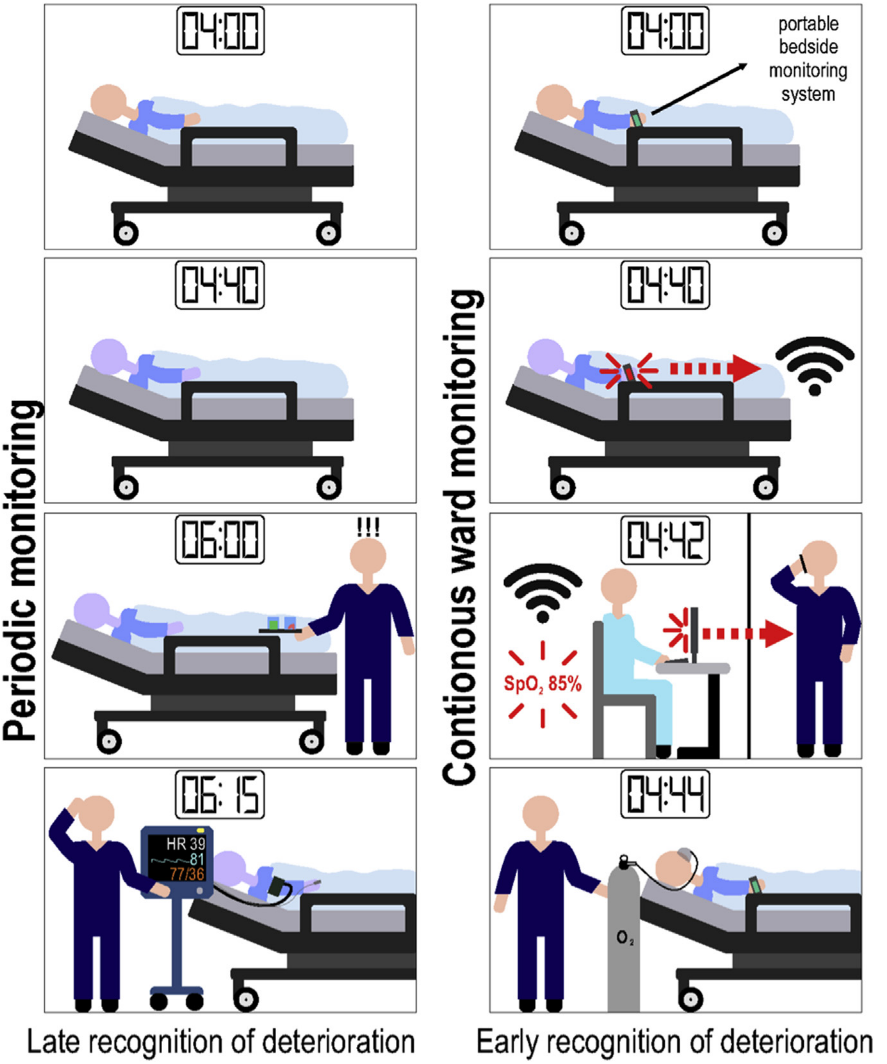

Fig. 1. An illustration depicting an unanticipated acute cardiorespiratory event ("the 4 a.m. phenomenon") on the hospital ward and difference in response times when comparing periodic with continuous monitoring. With permission from: Khanna AK, Hoppe P, Saugel B. Automated continuous noninvasive ward monitoring: Future directions and challenges. Critical Care 2019 23:194 (BMC).

outcomes, whereas continuous monitoring has potential benefits of determining and recognizing perturbations in vital signs early in the postoperative ward patient.

Continuous cardiac monitoring

Cardiac monitoring plays a crucial role in both intra- and postoperative hemodynamics. The perioperative time is particularly a period with susceptibility for myocardial injury. This period is characterized by frequent imbalances in oxygen delivery and consumption secondary to pain, fluid shifts, anemia, and possible secondary insults such as other organ failure and sepsis. Importantly, most myocardial insults during the perioperative period (also known as type II infarctions) are clinically silent.

These patients are likely not to have symptoms such as chest pain and shortness of breath [47]. The only manifestation of ongoing myocardial injury may be a troponin elevation. In fact, troponin elevation after surgery is typically accompanied by neither symptoms nor signs—but the association between troponin elevation and 30-day mortality is nearly as strong without as with symptoms and signs [48,49].

A recent post hoc analysis of POISE-2 trial on 10,010 patients suggests that postoperative hypotension is common and strongly associated with myocardial injury and death during the initial postoperative days [15]. Any duration of hypotension on postoperative days 1–4 had 3 times increased odds of myocardial injury or death compared with nonhypotensive patients during the same time [15]. Therefore, avoidance of hypotension during the postoperative period becomes critically important, with the obvious imperative to first detect such hypotension. Current monitoring standards miss a substantial amount of blood pressure fluctuation on the general hospital ward. Interestingly, an analysis of blinded continuous portable blood pressure recording after abdominal surgery showed that both hypotension and hypertension were common in the immediate postoperative period and often remain undetected by intermittent monitoring in the wards [50]. Specifically, spot checks or periodic monitoring missed approximately 75% of episodes of MAP>110 mmHg and approximately 50% of episodes of MAP<65 mmHg detected by continuous monitoring.

A challenge in this regard has been the development of accurate and portable hemodynamic measurement instruments and technology that may be used to measure blood pressure while patients recover on the hospital ward. The use of intermittent pneumatic blood pressure cuffs is less than optimal in this regard. The new technology that utilizes pulse wave velocity characteristics in relation to elasticity of the arterial wall, by utilizing principles of biomechanics as modeled through Moens-Korteweg equations, appears promising. Blood pressure component estimates are gathered from pulse transit time, measured between ECG and photo plethysmography peak-to-peak calculations [51]. This technology has shown that mean differences in vital signs and EWSs compared with nurse-measured vital signs have been generally found to be within the range of predefined and accepted discrepancies [52]. Further, a randomized trial on 60 medical and surgical ward patients showed that high MEWS, predominantly due to better measurement of respiratory rate-driven changes, can be detected in hospitalized patients around the clock and clinical deterioration at an earlier phase using this portable technology. A maximum of 10 h passed between device-detected high MEWS and next regular nurse measurement in some patients [53].

Total tissue perfusion relies on cardiac output and total oxygen content in blood. Perioperative imbalances in adequate delivery of oxygen are associated with organ injury and mortality [54]. After optimization of adequate oxygen and blood products, assessment and maintenance of cardiac output is another pivotal step. Routine vital signs including blood pressures and heart rate fluctuations are often late manifestations and hence may appear to be normal in the initial stages of acute hypovolemic states as a result of increase in peripheral vascular resistance. Additionally, heart rate perturbations may not be evident immediately after anesthesia exposure [55]. In such situations, among others, the use of continuous cardiac output monitoring may help guide hemodynamic interventions. A previous work suggests that goal-directed therapy improves perioperative outcomes such as length of stay, risk of pneumonia, and pulmonary edema when compared with liberal fluid therapy without hemodynamic goals [56]. As expected, clinical examination does not always estimate volume status, and there is a poor level of agreement regarding cardiac index categories measured with a noninvasive monitoring system and estimated using clinical examination by members of a rapid response team. The authors of this work measured cardiac index noninvasively using a finger cuff technology, which uses the volume clamp method (also known as the vascular unloading technique) to estimate stroke volume using pulse wave analysis and provide real-time cardiac index values [57]. Clearly, the best estimates of cardiac output are measurements guided by validated technology. This general rule is well applicable to the acutely deteriorating ward patient as well [58].

To the extent that even few minutes of hypotension is clinically relevant and needs immediate therapeutic intervention, continuous monitoring may indeed prevent harm. The data obtained from the monitors should be robust and need integration by a system of various algorithms and models before they are available, and reliability of such system still needs to be validated by ongoing research.

Continuous respiratory monitoring

One of the most commonly unrecognized, inappropriately measured, and sometimes neglected vital signs is respiratory rate [59]. In fact, perturbations in respiratory rate are considered a predictor of multisystem adverse events such as cardiopulmonary arrests and an independent predictor of mortality [60–64]. Change in respiratory rate is a better discriminator than change in blood pressure and heart rate in identifying high-risk patients likely to have an acute medical emergency team call for escalation of care [65]. Previous findings also suggest that patients who suffer from adverse events had higher respiratory rates (greater than 24 breaths/minute) up to 24 h before such events [62,66] Despite the accepted importance and the universal utilization of manual measurements, there are several questions regarding the fidelity of manual measurements [67–70]. There is discrepancy in recorded respiratory rates and observed rates and an underrepresentation of lower respiratory rates in manually recorded values. Manual measurement is usually an estimated value of 15 s counted respiratory rate, most of which are likely in range of 18–20 per minute are prone to bias [71]. Additionally, there is minimal correlation between observed and recorded values. In hospital wards, respiratory rate is intermittently measured manually as an approximate estimated value with other subjective parameters of tidal volumes such as "deep or shallow respirations." Continuous monitoring using oxygen saturation and capnography is likely to provide more objective assessment. Pulse oximetry provides an estimation of the degree of hypoxemia, whereas respiratory rate and capnography provide information of minute ventilation. This fact is well supported by a report of surveillance on postoperative orthopedics patients where the authors reported that continuous pulse oximetry leads to fewer rescue events and decreased need to escalate care [32]. It appears that current technology would better and more easily support the use of continuous oximetry and capnography monitoring on the floor than continuous blood pressure, which is still mostly a technological challenge. That said, there remain issues with the fidelity of nasal cannula-detected end-tidal carbon dioxide as a surrogate for ventilatory assessments in nonintubated patients. Literature suggests that ventilatory perturbations may be more common than oxygenation issues in postoperative patients [20]. However, most false alarms, artifacts, and patient noncompliance also come from the current form of end-tidal carbon dioxide detection systems, using nasal cannulas and oral scoops for mouth breathers. In addition, the overall effectiveness of continuous pulse oximetry and capnography monitoring for the detection of postoperative respiratory depression remains a key question [72]. Specifically, does continuous oximetry and capnography make a difference in outcomes? Recognition of desaturation (SpO_2 <90%) is 15 times higher using continuous monitoring than using intermittent monitoring, and identification of ventilatory depression is 6 times higher with continuous capnography than with oximetry alone [72]. There has not been shown, however, to be a reduction in overall patient complications, mortality, or ICU transfer by the addition of ventilatory monitoring to oximetry alone. Continuous oximetry-monitored patients also showed a trend toward less ICU transfers, although mortality outcomes were inconclusive at best [73]. Continuous capnography data are minimal, but what is available shows it to be a valuable tool in patients on supplemental oxygen (a common practice) on the hospital ward [72]. As noted above, the high artifact and false-positive alarm rate limit the utility with current capnography systems. The utility of continuous respiratory monitoring may also extend beyond respiratory outcomes. In postcardiac surgery patients—transferred from ICU to normal wards—rates of postoperative atrial fibrillation are reduced in patients monitored with continuous oxygen saturation through a portable pulse oximetry in contrast to controls [74].

A specific perioperative practice that assumes much importance when considering the use of capnography and ventilatory measurements is that of opioid-based analgesia and consequent respiratory morbidity. Patients who received opioids alone or in combination with sedatives in the inpatient ward environment had a significantly increased odds of mortality compared with those not receiving these drugs. In addition, those who underwent cardiopulmonary resuscitation events had 7.57 more days in the hospital and mean increased total hospital costs of $27,569 [75]. The PRedictiOn of opioiD-Induced respiratory depression in patients monitored by capnoGraphY (PRODIGY) trial prospectively enrolled 1496 patients receiving parenteral opioids on the general care floor and subjected them to continuous monitoring (oximetry and capnography). These data (SpO_2, HR, RR, and $EtCO_2$) was blinded to the bedside provider and adjudicated by an expert committee to separate artifact from true events. The preliminary results showed a 46% incidence of respiratory depressive episodes as defined by preset criteria that were previously undetected by standard monitoring. The

PRODIGY risk score was subsequently derived and internally validated, which showed a combination of variables—age greater than 60 years (in increasing decades), male sex, opioid naivety, sleep disordered breathing, and chronic heart failure to be highly predictive of the occurrence of respiratory depressive episodes in patients on hospital wards [76,77]. Notably, the clinical outcomes of these episodes remain to be determined. Closed claims analysis of catastrophic opioid-induced respiratory depression events that lead to anoxic brain injury or death showed that 42% of these events occur approximately 2 h after the last nursing check, and about 16% occur as soon as 15 minutes after the last nurse visit to a patient's room. Furthermore, nearly all of these events are preventable using continuous monitoring in combination with caregiver education and improved understanding of the detection of these events [78].

These are indicators of urgent need for continuous and accurate respiratory monitoring on postoperative wards. However, this noninvasive monitoring may have a prohibitive effect on the end users (nurses and doctors) in the form of high false alarm rates and related fatigue, which interfere with the expected alarm response and may then limit the effectiveness of continuous monitoring. Nevertheless, current research is focusing on utilizing several filtering techniques such as improvement in biomedical signals design, artificial neural networks, and algorithms to improve artifact detection [79].

Continuous monitoring—pattern detection and waveform data

The real utility of continuous monitoring applications in the postoperative ward setting is the ability to use the multiparameter waveform data to allow for early identification of patient deterioration. This “pattern detection” will be possible only if the clinician has the ability to train and understand basic waveform patterns and recognize early signs of characteristic alterations in waveforms that signal impending harm. An educated provider response to such pattern recognition is assumed, but education in this area is also likely required. In the regard, the role of continuous capnography in combination with continuous oximetry is worth additional mention. These two modalities generate a combination of waveforms that allow for classic patterns under certain pre-existing patient conditions and also in acutely developing respiratory failure.

An example of a utility of the visual recognition of patterns on real-time waveform data is shown in Fig. 2. An early indication of impending deviation from the norm is evident with the multiple episodes of apneas and no breath events (light-blue dashed line), which precede clinical detection (dark-purple dashed line) by at least 15 min. In this patient, the clinical detection of a struggling patient prompted administration of naloxone reversal and correction of ventilatory compromise. Of note, Fig. 2 shows the false sense of satisfaction that is often evident while using the pulse oximeter alone, particularly when supplemental oxygen is being administered, where oxygen desaturation does not occur until very late in the course of events and often occurs when it may be too late for meaningful intervention. This patient was rescued by clinical detection, which occurred 15 min later, rather than through monitor detection. However, the situation could have been much worse had the next ward nursing check not occurred until two hours later, and the patient would have been in extremis and undetected for much longer. Although speculative, exposure to repeated and prolonged episodes of hypoventilation and hypoxemia could possibly lead to myocardial injury and associated mortality in a high-risk patient. Perman and colleagues have demonstrated using a national resuscitation registry that these events result in worse outcomes in an under-monitored ward environment compared to a ward with telemetry and further compared to a critically ill, although continuously monitored, patient in the ICU [9]. Clearly, the lead time (golden period) of 15 min in this case would have allowed for early detection using a central monitoring platform and an effective real-time alert to a bedside provider for timely intervention (Fig. 4) in an ideal continuously monitored ward.

A common patient situation concerns with the postoperative patient who has known or suspected obstructive sleep apnea. These patients (at baseline) typically exhibit cyclical desaturation as part of the definition of sleep disordered breathing. This “saw-tooth” pattern is exacerbated during the postoperative period, especially when on narcotic-based analgesia, importantly with a return to baseline oxygenation in between the cyclical swings. However, as narcotic analgesia increases, these swings in oxygen saturation may become more pronounced and may not return to normoxic levels. A pulse oximeter value in itself may be insufficient to convey this problem to the caregiver, especially in a situation

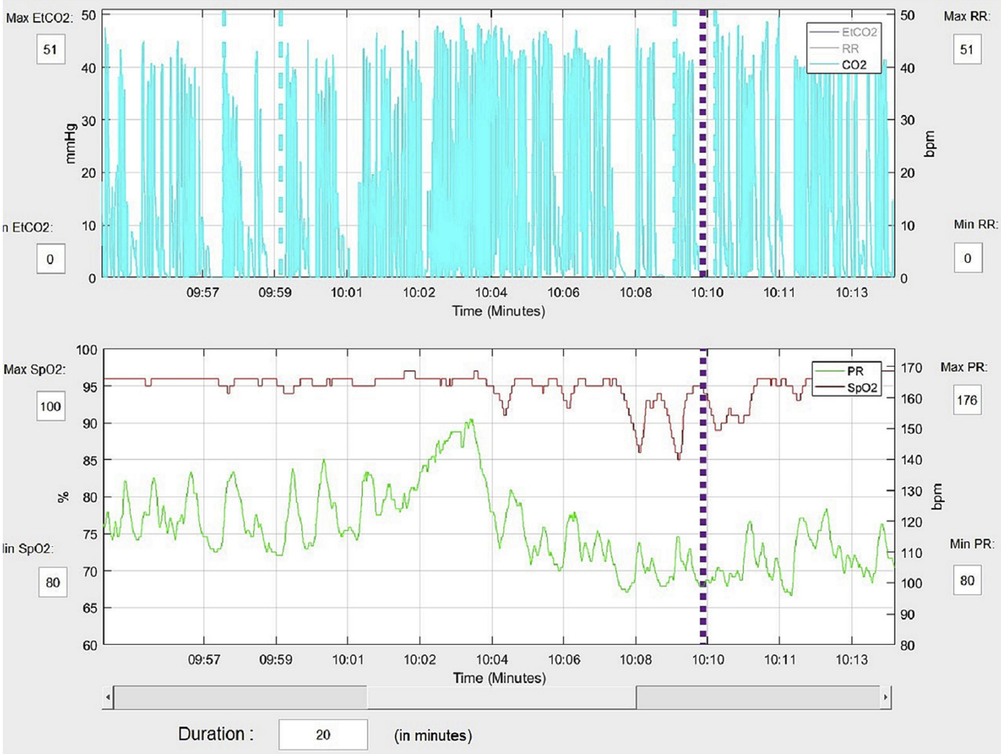

Fig. 2. Real-time waveform data (gathered as part of the PRODIGY trial) showing a rapid-response call (dark purple dashed line), and the period of time (approximately 15 min in this case), where the patient showed repetitive apneas (blue dashed line), wherein timely early intervention may have helped.

where this patient is on supplemental oxygen. Here the utility of continuous capnography, in combination with waveform data from the pulse oximeter, will allow for identification of this characteristic pattern of desaturation in combination with hypoventilation. Fig. 2 shows these frequent apneic and hypoapneic spells that accompany cyclical desaturations in one such patient. An appropriate early clinical intervention in such a patient on the ward, maybe a combination of noninvasive ventilatory support using a continuous positive airway measure (CPAP) device, and an appropriate adjustment of the analgesic regimen to reduce the dose and frequency of these drugs may promote apnea. However, the absence of early recognition of this common occurrence may translate into a future catastrophe, especially when these patients go under-monitored for prolonged periods in a setting of frequent parenteral opioids. The PRODIGY trial showed a very high preponderance of apneas and hypoventilatory monitor-detected events compared with hypoxemic events [77]. The integrated pulmonary index (IPI™), that is, a number generated (0–10 with increasing harm indicated by a higher number) using fuzzy logic as a combination of continuous input into heart rate, respiratory rate, SpO_2, and $EtCO_2$, has also been validated as an accurate indicator of clinical deterioration [80]. The needs of the postoperative ward of the future should allow for visualization of continuous waveform data, either within or outside the ward in a central monitoring unit, and further educate providers in the early identification of dangerous patterns (Fig. 4). The analysis of large volume data to elucidate predictive patterns of vital sign deterioration requiring intervention to prevent adverse outcome should lead to more specific and sophisticated alarm notification in the future. This "smarter" alarm enunciation, coupled with identification of the best alarm responses from providers and education on these responses, should reduce false alarms and alarm fatigue and help direct provider attention to actionable alarms.

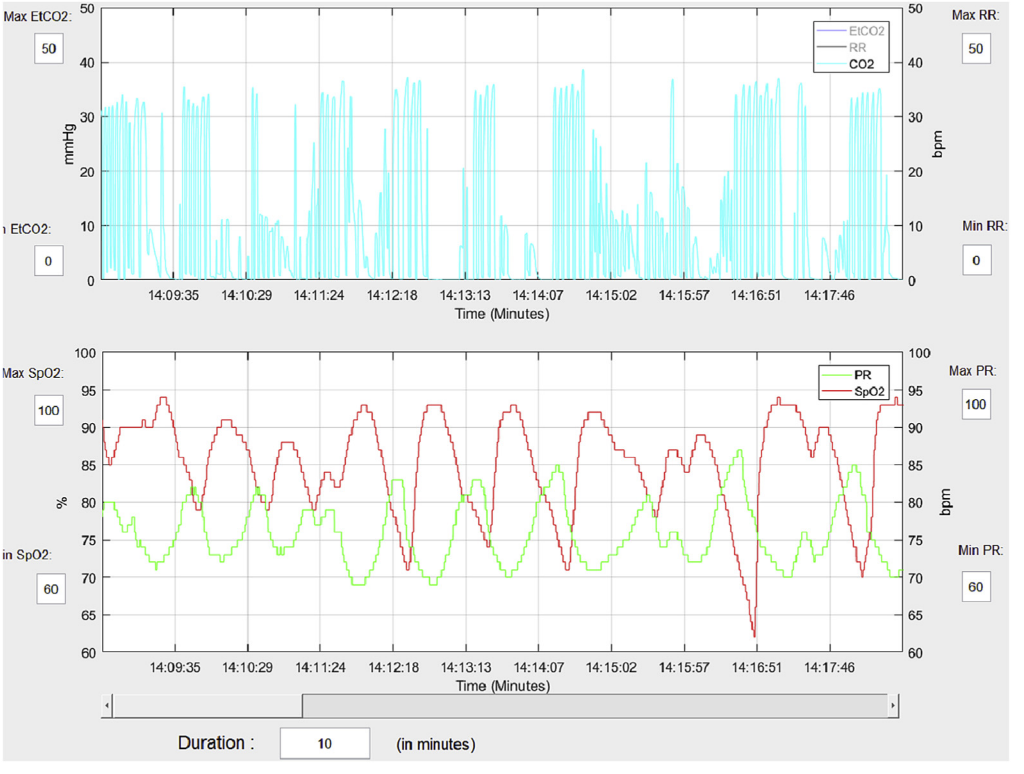

Fig. 3. Real-time waveform data (gathered as part of the PRODIGY trial) showing a typical pattern of repetitive cycles of hypoventilation and apnea accompanied by hypoxemia. This "saw-tooth" pattern would be observed in a patient with obstructive sleep apnea receiving narcotics for pain control.

Continuous monitoring—challenges

While continuous monitoring of everyone on the general care floor or postoperative ward seems a necessary goal, the current technology requires greater sophistication and specificity for detection/prediction of patient deterioration. One of the biggest challenges in the implementation of continuous monitoring systems is that they must be acceptable to patients and caregivers alike. In the past, monitoring systems were bulky, and this led to patient noncompliance and early disconnections, especially on postoperative day 1 or 2, as most patients started ambulating [19]. During the past decade, monitoring systems have evolved in a radical way, moving rapidly from "wire to wireless-wearable" systems and offering efficient ways to decrease workloads and improve outcomes. With wireless devices, however, battery life and patient re-association with the device have become new technical challenges to overcome. Wireless wearable devices would qualify as smarter monitoring in strictly lay terms. Otherwise, these are defined as micro-electronic equipment that does not interfere with routine activities of the user while monitoring various physiological parameters such as vital signs in a continuous robust manner [81]. With advancement, these heterogeneous microsensor systems have gained capability to monitor several patients, store data, transmit to central station, and generate alarms to alert providers for any perturbations.

In terms of usability, nursing staff desire reliably accurate and reactive systems that non-technologically savvy users find intuitively straightforward. Although the implementation of electronic applications in health care dates back more than a decade, usability (efficient, effective, and safe use of technology) is still not fully optimized for clinical use [82,83]. Users remain skeptical of the use of data collection technology in the healthcare environment. In a large national study, physicians' satisfaction

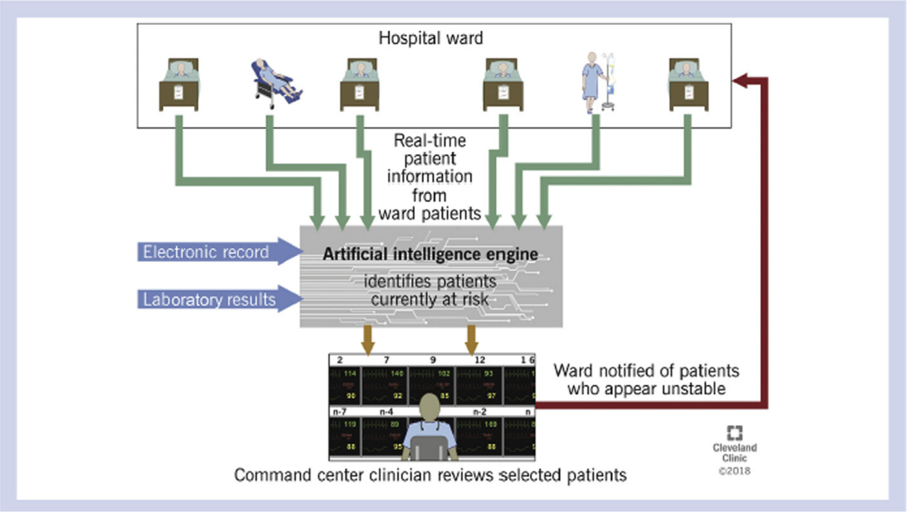

Fig. 4. An illustration of a well-organized continuously monitored hospital ward, with layers of artificial intelligence incorporating patient data from the electronic medical record, and a central monitoring unit with an alert monitoring service that relays true alarms back to providers at the bedside to complete the loop. With permission from: Sessler DI, Saugel B.Beyond 'failure to rescue': the time has come for continuous ward monitoring. Br J Anaesth. 2019 Mar; 122(3):304–306 (Elsevier).

with their EHRs and computer order entry (CPO) was generally low [84]. Physicians who used EHRs and CPOE were less satisfied with the amount of time spent on clerical tasks and were at higher risk for professional burnout. For nurses, they were most dissatisfied approximately 9 months after information technology implementation. However, 18 months after implementation, nurses' perceptions appeared improved. It is not clear whether this is a conditioned, training, or hopelessness response [85]. The prior investigations underline the need to fully incorporate the daily users of these systems during development and implementation.

Wireless monitoring applications should not induce stress in patients and caregivers. The design of these systems should target an interface and backend that a user finds efficient, effective, while providing security. In usability research, simple and relatively low-cost methods exist that should be applied by anyone working in medical device development [86]. The next obstacle, as in Electronic Health Record systems, is to integrate the technologically adept system with an interface that nurses, advanced practice providers, and physicians find intuitive and easy to input and cognate information. A recently introduced, FDA-approved, portable wearable device facilitates continuous collection of vital signs in an uninterrupted fashion. Studies conducted on such portable wearable devices have demonstrated that these devices resulted in higher MEWS (Modified Early Warning Signs) scores than intermittent observation by nurses [53]. Additionally, these devices were well received by patients and nurses; in fact, the quality of data is comparable. These minimally intrusive remote monitoring devices are wireless, and monitoring can be done while patient is ambulatory. Another advantage includes measurements of vital signs uninterrupted without affecting patient's sleep, which have an impact on overall recovery [87]. These wearable devices can then be managed remotely in a central station. Ongoing research is also focusing on machine learning to integrate other physiological parameters that may help filter the artifacts and hence reducing false alarms and associated fatigue (Fig. 4).

Although much awareness exists regarding the problem of false alarms, currently there is no clear solution in place. These alarms to artifactual data are present to the tune of up to 15/patient/hour in a typical continuously monitored environment such as the ICU [88]. A key difference between the ICU and the floor is the available nurse-to-patient ratio that declines from 1:1 or 1:2 in the former to up to 1:8 in the latter. Therefore, if one nurse is to evaluate up to 8 patients and also turn off or adjudicate up to 15 alarms per patient or up to 120 alarms per hour, this alert volume is untenable. The resultant alarm fatigue, distraction, and caregiver burnout could lead to no outcome benefit or even worse patient outcomes.

Appropriate selection of alarm thresholds and persistence before alarm enunciation may help to reduce false alarms and artifact and allow for self-correction. Although some sensitivity is lost with lower alarm threshold and longer duration, the goal is to limit alarms to actionable conditions without having delayed detection of true patient deterioration.

Another challenge of note is the rapid pace in technology advances in this field over the past decade, with the lack of appropriate validation of a number of sensors and devices flooding the market. A major barrier in implementing continuous monitoring in wards (as standard of care) appears to be the validity of sensor device and software, most of which are currently not backed by large randomized trials. Different technologies use distinct sensors (wearable patches) at various placements (such as wrist, chest, head, and hip) and with algorithm configuration, which, at times, may not correlate. Technical dysfunction such as connectivity issues due to nonuniformity of wireless networks, nonintegration of these devices with hospital coding and electronic medical record (EMR) systems leading to non-reimbursement, and the need for manual validation of continuous monitoring data are few others worth mentioning [89,90]. An example is the implementation of continuous monitoring across a hospital system, but the operations arm still needs the bedside nurse to physically enter "validated" data into the EMR. This would occur at present time intervals and negate the perceived benefit of continuous data streams and pattern detection. Unfortunately, most EMRs do store continuous minute-by-minute streams of unverified data for up to 72–96 h but end up purging them for lack of available space. Herein is an important area of intervention and appropriate need to have dedicated continuous data server space to allow hospitals to look at all the available gigabytes of device data at any time from any patient, who was or is being continuously monitored. Furthermore, the data generated by new devices when compared with those generated by gold standard equipment encounter the statistical threat of verification bias [91]. These devices have the ability to estimate idiosyncratic patterns by machine learning, which are potentially unsupervised, and there exists a learning curve in their interpretation. Lastly, legal and ethical issues regarding data protection, data ownership, and affordability upfront pose a challenge [92].

Provider acceptance of the culture change to continuous surveillance monitoring and acceptance of the validity of abnormal data remain additional challenges. While it has been shown in some studies that provider acceptance is good, a tendency to need confirmation of abnormal vital signs with additional equipment can delay treatment and add to provider fatigue [45,53].Finally, there is a significant financial cost to the implementation of widespread continuous monitoring technology in terms of equipment (both disposables and hardware purchasing/damage/loss), wireless networking, software licensing and updates, education, and re-education. Research is desperately needed to compare this cost to the financial and personal cost of adverse patient events, prolonged hospitalization, ICU utilization, and mortality to demonstrate the expected return on investment.

Continuous monitoring—solutions

Continuous monitoring of vital signs offers more proactive approach in determining the trends that might otherwise be missed by intermittent or conventional monitoring in wards. Surely, with advances in sensor technology and filtering mechanisms, the current flaws of the continuous monitoring approach can be overcome. A very basic, although important, mechanism to implement continuous monitoring and integrate it into a workflow system in a hospital ward is based on continuous (portable) bedside data generation, wireless transmission to a central monitoring station/platform, integration of patient data (current clinical, lab, imaging, and demographics) from the EMR (layering machine learning to allow for pattern detection and filtering of artifact) and an efferent arm of implementation of real-time alerts to appropriate tiered layers of providers [93,94]. Some of the other solutions are a direct outcome of implementing this workflow (Fig. 4). Patients would no longer be tethered to boxes with cables, and alarms would be far removed from patient rooms. This would ensure as much patient compliance and lead as minimal a disturbance in sleep wake cycles as possible. This would also allow for dedicated monitoring of alarms and patterns using an e-ICU-like central remote monitoring platform that would ensure that all eyes are always on all alarms, and no alarm is disregarded, especially when filtered through the system as a real alarm.

An important noteworthy mention is the utility of prediction models to help identify those at the highest risk and where continuous monitoring needs to be mandated [76,77]. These models such as the

PRODIGY risk prediction score are derived from continuous monitoring data and are easy to use to allow bedside caregivers an estimate of the risk of deterioration. A high score on such systems should alert the end user to the need for continuous monitoring and, more importantly, early proactive and corrective interventions. Further, education of providers in understanding continuous waveform data (Figs. 2 and 3) to discern patterns and interpret "the EKG of ward monitoring" is of paramount importance. Next, this education will need to be accompanied by a culture change in how we care for our postoperative floor patients, changing practices such as not necessarily just increasing supplemental oxygenation for most respiratory issues, not using sedatives as a surrogate for pain control, and understanding the importance of even a few minutes of exposure to hypotension is necessary at all levels, as is an understanding of the best practices for response to alarm notification and early and effective intervention to rescue patients. Device manufactures and engineers will need to focus on integrated indices such as the IPI™, which take away the difficulty of reading four or five continuous streams of data separately. Rather, the focus would be on one easy-to-interpret number and hopefully color-coded alarm signal that incorporates an amalgamation of physiological alterations coming from different organ systems. Importantly, rapid response teams will see an initial increase in the number of calls and an increase in abnormal variables presented at the time of the call. This may be a transient response as bedside providers are alerted to more abnormal vital signs that reach the threshold for early warning score perturbations [95,96]. Eventually, with better understanding of these alerts and early intervention, this rapid response burden should gradually ease, and if used appropriately, continuous monitoring would help prevent most calls. Finally, data on the need and benefit or utility of continuous monitoring are largely speculative. Among intermittent and continuous monitoring studies, the most studied outcomes include mortality; length of hospital stay; ICU transfers; and adverse events such as stroke, postoperative atrial fibrillation, redo procedures, and functional status. Most of these studies are observational or weaker before and after type trial designs. There are no robust randomized controlled trials (RCTs) showing continuous monitoring makes a difference in serious outcomes such as mortality and or myocardial injury. In the absence of an expensive RCT, there may be alternative research methodology such as alternating interventions model, which has shown by itself to be robust in other studies. In hospitals that are implementing this technology in a graded fashion, an interrupted time series analysis may be better than a standard before and after design. In addition, well-performed cost-effective analysis needs to be included in all trial designs so the utility of investment versus outcomes may be presented and understood.

Mismatches do occur between electronic health record system-dictated workflows and actual workflows of the users of these systems. The obstacles in workflow then negatively influence the efficiency with which we deliver our services to patients. Within an acute care healthcare context, impeded workflows then have a negative impact on the safety and effectiveness of care delivered to these patients [97]. Potentially, other types of health information technology implementation in the inpatient setting may result in savings in labor hours and costs in some non-nursing roles [98].

Enhancing the availability of high-tech services may improve financial performance, especially among not-for-profit hospitals. However, the use of everyday routine patient monitoring systems is not a direct revenue-generating employment of care. Hospitals may experience increased productivity and efficiency using these systems, therefore lowering inpatient operating costs as a result of using these technologies. However, the negative impact on operating costs requires us to strongly be cautious regarding these technologies. Therefore, healthcare managers deciding on these higher technologies should necessarily consider both the cost and revenue implications of these technologies [99]. The added cost burden of additional hospital length of stay in the absence of improved surveillance and intervention, in the era of bundled payments and healthcare cost containment in the United States, may suggest improved monitoring solutions for hospital systems. The data to support this claim need further weight and continuing research endeavors.

Summary

In summary, postoperative periodic monitoring of vital signs on general care wards is currently inadequate for the detection of subtle and early changes in vital signs. This deficiency results in ongoing, undetected deviation of physiological variables from the normal and the potential for organ system injury. Further, imminent cardiorespiratory arrest events continue to occur on our postoperative wards, and in the absence of continuous monitoring, we are unable to regularly detect premonitory signs of deterioration and intervene in a timely fashion to prevent progression to cardiopulmonary arrest. What is needed is continuous, smarter, and portable ward monitoring systems in conjunction with dedicated central monitoring units, adequate artificial intelligence support, and provider education. This combination will pick up true events and decrease artifact and consequent alarm fatigue to a minimum. Finally, we are still awaiting better trial designs to effectively state the case for continuous monitoring in improving serious outcomes, achieving provider acceptance, and reducing overall cost, all of which are necessary to convince hospital systems to adopt this new technology.

Role of funding source

None.

Conflicts of interest

A.K: Consultant for Medtronic.
S.A: None.
R.W: None.
T.H: None.

Practice points

- Postoperative ward patients are vulnerable to acute hemodynamic and respiratory deteriorations, which may lead to catastrophic events. Existing ward monitoring practices are unable to detect subtle vital signs perturbations occurring before such events.
- Continuous, portable monitoring systems integrated with processed data and guided by artificial intelligence seem to be promising but is currently in a stage of evolution. Additionally, several legal and ethical issues regarding data protection, ownership, and affordability upfront pose a challenge. While awaiting the evidence, implementation of a comprehensive surveillance system with proactive interventions to warning signs seems to be a reasonable approach.
- The change in this paradigm from intermittent to continuous monitoring of postoperative ward patients may receive a pushback, and there may be an iterative process toward its implementation. Education and training remain critical in determining success and widespread acceptance.

Research agenda

- Postoperative hemodynamic and respiratory events may be prevented by continuous monitoring and have been shown to be associated with some improved outcomes. The extent to which these relationships are causal remains unknown.
- Utilizing large databases in the construction of models or scoring systems including patient-specific predictive algorithms for impending deterioration of ward patients.
- Research focusing on using filtering techniques such as improvement in biomedical signals design, artificial neural networks, and algorithms to particularly improve artifact detection and reducing false alarms.
- Challenges to implement “continuous monitoring to all” may not be practical. Innovations identifying “whom, what, and where” to monitor remain the cornerstone for future research.

Acknowledgments

None.

References

[1] Zimmerman JE, Kramer AA, Knaus WA. Changes in hospital mortality for United States intensive care unit admissions from 1988 to 2012. Crit Care (London, Engl) 2013;17(2):R81.
[2] Gulland A. Shortage of health workers is set to double, says WHO. Br Med J 2013;347:f6804.
[3] Mokart D, Giaoui E, Barbier L, et al. Postoperative sepsis in cancer patients undergoing major elective digestive surgery is associated with increased long-term mortality. J Crit Care 2016;31(1):48–53.
[4] Pearse RM, Moreno RP, Bauer P, et al. Mortality after surgery in Europe: a 7 day cohort study. Lancet (London, Engl) 2012; 380(9847):1059–65.
[5] Markar S, Gronnier C, Duhamel A, et al. Pattern of postoperative mortality after esophageal cancer resection according to center volume: results from a large European multicenter study. Ann Surg Oncol 2015;22(8):2615–23.
*[6] Smilowitz NR, Gupta N, Ramakrishna H, et al. Perioperative major adverse cardiovascular and cerebrovascular events associated with noncardiac surgery. JAMA Cardiol 2017;2(2):181–7.
[7] Semel ME, Lipsitz SR, Funk LM, et al. Rates and patterns of death after surgery in the United States, 1996 and 2006. Surgery 2012;151(2):171–82.
[8] Bartels K, Karhausen J, Clambey ET, et al. Perioperative organ injury. Anesthesiology 2013;119(6):1474–89.
[9] Perman SM, Stanton E, Soar J, et al. Location of in-hospital cardiac arrest in the United States-variability in event rate and outcomes. J Am Heart Assoc 2016;5(10).
[10] Morrison LJ, Neumar RW, Zimmerman JL, et al. Strategies for improving survival after in-hospital cardiac arrest in the United States: 2013 consensus recommendations: a consensus statement from the American Heart Association. Circulation 2013;127(14):1538–63.
[11] Weiser TG, Regenbogen SE, Thompson KD, et al. An estimation of the global volume of surgery: a modelling strategy based on available data. Lancet (London, Engl) 2008;372(9633):139–44.
[12] Bakker EJ, Ravensbergen NJ, Poldermans D. Perioperative cardiac evaluation, monitoring, and risk reduction strategies in noncardiac surgery patients. Curr Opin Crit Care 2011;17(5):409–15.
[13] Roshanov PS, Rochwerg B, Patel A, et al. Withholding versus continuing angiotensin-converting enzyme inhibitors or angiotensin II receptor blockers before noncardiac surgery: an analysis of the vascular events in noncardiac surgery patIents cOhort evaluatioN prospective cohort. Anesthesiology 2017;126(1):16–27.
[14] Devereaux PJ, Biccard BM, Sigamani A, et al. Association of postoperative high-sensitivity troponin levels with myocardial injury and 30-day mortality among patients undergoing noncardiac surgery. Jama 2017;317(16):1642–51.
*[15] Sessler DI, Meyhoff CS, Zimmerman NM, et al. Period-dependent associations between hypotension during and for four days after noncardiac surgery and a composite of myocardial infarction and death: a substudy of the POISE-2 trial. Anesthesiology 2018;128(2):317–27.
[16] Ng JL, Chan MT, Gelb AW. Perioperative stroke in noncardiac, nonneurosurgical surgery. Anesthesiology 2011;115(4): 879–90.
[17] Meersch M, Schmidt C, Zarbock A. Perioperative acute kidney injury: an under-recognized problem. Anesth Analg 2017; 125(4):1223–32.
[18] Aldemir M, Ozen S, Kara IH, et al. Predisposing factors for delirium in the surgical intensive care unit. Crit Care (London, Engl) 2001;5(5):265–70.
*[19] Sun Z, Sessler DI, Dalton JE, et al. Postoperative hypoxemia is common and persistent: a prospective blinded observational study. Anesth Analg 2015;121(3):709–15.
*[20] Overdyk FJ, Carter R, Maddox RR, et al. Continuous oximetry/capnometry monitoring reveals frequent desaturation and bradypnea during patient-controlled analgesia. Anesth Analg 2007;105(2):412–8.
[21] Schein RM, Hazday N, Pena M, et al. Clinical antecedents to in-hospital cardiopulmonary arrest. Chest 1990;98(6): 1388–92.
[22] Hillman KM, Bristow PJ, Chey T, et al. Duration of life-threatening antecedents prior to intensive care admission. Intensive Care Med 2002;28(11):1629–34.
[23] Vetro J, Natarajan DK, Mercer I, et al. Antecedents to cardiac arrests in a hospital equipped with a medical emergency team. Crit Care Resusc 2011;13(3):162–6.
[24] Zeitz K, McCutcheon H. Evidence-based practice: to be or not to be, this is the question! Int J Nurs Pract 2003;9(5):272–9.
*[25] Mok W, Wang W, Cooper S, et al. Attitudes towards vital signs monitoring in the detection of clinical deterioration: scale development and survey of ward nurses. Int J Qual Health Care – J Int Soc Qual Health Care 2015;27(3):207–13.
*[26] McGain F, Cretikos MA, Jones D, et al. Documentation of clinical review and vital signs after major surgery. Med J Aust 2008;189(7):380–3.
[27] Bianchi W, Dugas AF, Hsieh YH, et al. Revitalizing a vital sign: improving detection of tachypnea at primary triage. Ann Emerg Med 2013;61(1):37–43.
[28] Reich DL, Wax DB. Mind the gap. Anesth Analg 2011;113(2):214–5.
*[29] Taenzer AH, Pyke J, Herrick MD, et al. A comparison of oxygen saturation data in inpatients with low oxygen saturation using automated continuous monitoring and intermittent manual data charting. Anesth Analg 2014;118(2):326–31.
[30] Block FE. Normal fluctuation of physiologic cardiovascular variables during anesthesia and the phenomenon of "smoothing". J Clin Monit 1991;7(2):141–5.
[31] Reich DL, Wood Jr RK, Mattar R, et al. Arterial blood pressure and heart rate discrepancies between handwritten and computerized anesthesia records. Anesth analgesia 2000;91(3):612–6.
[32] Taenzer Andreas H, Pyke Joshua B, McGrath Susan P, et al. Impact of pulse oximetry surveillance on rescue events and intensive care unit transfers: a before-and-after concurrence study. Anesthesiol: J Am Soc Anesthesiologists 2010;112(2):282–7.

[33] Helfand MCV, Anderson J. Technology assessment: early sense for monitoring vital signs in hospitalized patients [Internet]. In: VA evidence synthesis program evidence briefs. Washington (DC): Department of Veterans Affairs (US); 2011–2016.
[34] McGaughey J, Alderdice F, Fowler R, et al. Outreach and Early Warning Systems (EWS) for the prevention of intensive care admission and death of critically ill adult patients on general hospital wards. Cochrane database Syst Rev 2007;(3):Cd005529.
[35] Cain D, Ackland G. Knowing the risk? NCEPOD 2011: a wake-up call for perioperative practice. Br J Hosp Med (London, Engl – 2005) 2012;73(5):262–4.
[36] Molloy WD, Lee KY, Girling L, et al. Treatment of shock in a canine model of pulmonary embolism. Am Rev Respir Dis 1984;130(5):870–4.
[37] Jacques T, Harrison GA, McLaws ML, et al. Signs of critical conditions and emergency responses (SOCCER): a model for predicting adverse events in the inpatient setting. Resuscitation 2006;69(2):175–83.
*[38] Goldhill DR, McNarry AF. Physiological abnormalities in early warning scores are related to mortality in adult inpatients. Br J Anaesth 2004;92(6):882–4.
[39] Haller G, Myles PS, Wolfe R, et al. Validity of unplanned admission to an intensive care unit as a measure of patient safety in surgical patients. Anesthesiology 2005;103(6):1121–9.
[40] Calzavacca P, Licari E, Tee A, et al. The impact of Rapid Response System on delayed emergency team activation patient characteristics and outcomes–a follow-up study. Resuscitation 2010;81(1):31–5.
[41] Gershengorn HB, Garland A, Gong MN. Patterns of daily costs differ for medical and surgical intensive care unit patients. Ann Am Thorac Soc 2015;12(12):1831–6.
*[42] Khanna AK, Hoppe P, Saugel B. Automated continuous noninvasive ward monitoring: future directions and challenges. Crit Care 2019 May 30;23(1).
[43] Brown H, Terrence J, Vasquez P, et al. Continuous monitoring in an inpatient medical-surgical unit: a controlled clinical trial. Am J Med 2014;127(3):226–32.
[44] Duus CL, Aasvang EK, Olsen RM, et al. Continuous vital sign monitoring after major abdominal surgery-Quantification of micro events. Acta Anaesthesiol Scand 2018;62(9):1200–8.
*[45] Weller RS, Foard KL, Harwood TN. Evaluation of a wireless, portable, wearable multi-parameter vital signs monitor in hospitalized neurological and neurosurgical patients. J Clin Monit Comput 2018;32(5):945–51.
[46] Downey C, Randell R, Brown J, et al. Continuous versus intermittent vital signs monitoring using a wearable, wireless patch in patients admitted to surgical wards: pilot cluster randomized controlled trial. J Med Internet Res 2018;20(12):e10802.
[47] Libby P. Mechanisms of acute coronary syndromes and their implications for therapy. N Engl J Med 2013;368(21): 2004–13.
[48] Botto F, Alonso-Coello P, Chan MT, et al. Myocardial injury after noncardiac surgery: a large, international, prospective cohort study establishing diagnostic criteria, characteristics, predictors, and 30-day outcomes. Anesthesiology 2014; 120(3):564–78.
[49] Writing Committee for the Vision Study Investigators, Devereaux PJ, Biccard BM, et al. Association of postoperative high-sensitivity troponin levels with myocardial injury and 30-day mortality among patients undergoing noncardiac surgery. J Am Med Assoc 2017;317(16):1642–51.
[50] Turan A, Chang C, Cohen B, et al. Incidence, severity, and detection of blood pressure perturbations after abdominal surgery: a prospective blinded observational study. Anesthesiology 2019;130(4):550–9.
[51] Chen W, Kobayashi T, Ichikawa S, et al. Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. Med Biol Eng Comput 2000;38(5):569–74.
[52] Weenk M, van Goor H, Frietman B, et al. Continuous monitoring of vital signs using wearable devices on the general ward: pilot study. JMIR mhealth uhealth 2017;5(7):e91.
[53] Weenk M, Koeneman M, van de Belt TH, et al. Wireless and continuous monitoring of vital signs in patients at the general ward. Resuscitation 2019;136:47–53.
[54] Shoemaker WC, Montgomery ES, Kaplan E, et al. Physiologic patterns in surviving and nonsurviving shock patients. Use of sequential cardiorespiratory variables in defining criteria for therapeutic goals and early warning of death. Arch Surg (Chicago, Ill – 1960) 1973;106(5):630–6.
[55] Pizov R, Eden A, Bystritski D, et al. Hypotension during gradual blood loss: waveform variables response and absence of tachycardia. Br J Anaesth 2012;109(6):911–8.
[56] Corcoran T, Rhodes JE, Clarke S, et al. Perioperative fluid management strategies in major surgery: a stratified meta-analysis. Anesth Analg 2012;114(3):640–51.
[57] Eyeington CT, Lloyd-Donald P, Chan MJ, et al. Rapid response team review of hemodynamically unstable ward patients: the accuracy of cardiac index assessment. J Crit Care 2019;49:187–92.
[58] Saugel B, Khanna AK. Managing hemodynamic instability - if you want to know cardiac output, you need to measure it! J Crit Care 2019;49:185–6.
[59] Cretikos MA, Bellomo R, Hillman K, et al. Respiratory rate: the neglected vital sign. Med J Aust 2008;188(11):657–9.
[60] Fieselmann JF, Hendryx MS, Helms CM, et al. Respiratory rate predicts cardiopulmonary arrest for internal medicine inpatients. J Gen Intern Med 1993;8(7):354–60.
[61] Hodgetts TJ, Kenward G, Vlachonikolis IG, et al. The identification of risk factors for cardiac arrest and formulation of activation criteria to alert a medical emergency team. Resuscitation 2002;54(2):125–31.
[62] Cretikos M, Chen J, Hillman K, et al. The objective medical emergency team activation criteria: a case-control study. Resuscitation 2007;73(1):62–72.
[63] Jones AE, Yiannibas V, Johnson C, et al. Emergency department hypotension predicts sudden unexpected in-hospital mortality: a prospective cohort study. Chest 2006;130(4):941–6.
[64] Churpek MM, Yuen TC, Edelson DP. Risk stratification of hospitalized patients on the wards. Chest 2013;143(6):1758–65.
[65] Subbe CP, Davies RG, Williams E, et al. Effect of introducing the Modified Early Warning score on clinical outcomes, cardio-pulmonary arrests and intensive care utilisation in acute medical admissions. Anaesthesia 2003;58(8):797–802.
[66] Goldhill DR, McNarry AF, Mandersloot G, et al. A physiologically-based early warning score for ward patients: the association between score and outcome. Anaesthesia 2005;60(6):547–53.

[67] Hillman K, Chen J, Cretikos M, et al. Introduction of the medical emergency team (MET) system: a cluster-randomised controlled trial. Lancet (London, Engl) 2005;365(9477):2091–7.
[68] Chen L, Reisner AT, Gribok A, et al. Can we improve the clinical utility of respiratory rate as a monitored vital sign? Shock 2009;31(6):574–80.
[69] Lovett PB, Buchwald JM, Sturmann K, et al. The vexatious vital: neither clinical measurements by nurses nor an electronic monitor provides accurate measurements of respiratory rate in triage. Ann Emerg Med 2005;45(1):68–76.
[70] Churpek MM, Yuen TC, Park SY, et al. Derivation of a cardiac arrest prediction model using ward vital signs. Crit Care Med 2012;40(7):2102–8.
[71] Semler MW, Stover DG, Copland AP, et al. Flash mob research: a single-day, multicenter, resident-directed study of respiratory rate. Chest 2013;143(6):1740–4.
[72] Lam T, Nagappa M, Wong J, et al. Continuous pulse oximetry and capnography monitoring for postoperative respiratory depression and adverse events: a systematic review and meta-analysis. Anesth Analg 2017;125(6):2019–29.
[73] McGrath SP, Pyke J, Taenzer AH. Assessment of continuous acoustic respiratory rate monitoring as an addition to a pulse oximetry-based patient surveillance system. J Clin Monit Comput 2017;31(3):561–9.
[74] Kisner D, Wilhelm MJ, Messerli MS, et al. Reduced incidence of atrial fibrillation after cardiac surgery by continuous wireless monitoring of oxygen saturation on the normal ward and resultant oxygen therapy for hypoxia. Eur J Cardiothorac Surg 2009;35(1):111–5.
[75] Overdyk FJ, Dowling O, Marino J, et al. Association of opioids and sedatives with increased risk of in-hospital cardiopulmonary arrest from an administrative database. PLoS One 2016;11(2):e0150214.
[76] Khanna AK, Overdyk FJ, Greening C, et al. Respiratory depression in low acuity hospital settings-Seeking answers from the PRODIGY trial. J Crit Care 2018;47:80–7.
[77] Khanna A, Buhre W, Saager L, et al. 36: Derivation and validation of a novel opioid-induced respiratory depression risk prediction tool. Crit Care Med 2019;47(1):18.
[78] Lee LA, Caplan RA, Stephens LS, et al. Postoperative opioid-induced respiratory depression: a closed claims analysis. Anesthesiology 2015;122(3):659–65.
[79] Takla G, Petre JH, Doyle DJ, et al. The problem of artifacts in patient monitor data during surgery: a clinical and methodological review. Anesth Analg 2006;103(5):1196–204.
[80] Ronen M, Weissbrod R, Overdyk FJ, et al. Smart respiratory monitoring: clinical development and validation of the IPI (Integrated Pulmonary Index) algorithm. J Clin Monit Comput 2017;31(2):435–42.
[81] Jia Y, Wang W, Wen D, et al. Perceived user preferences and usability evaluation of mainstream wearable devices for health monitoring. PeerJ 2018;6:e5350.
[82] Fidler R, Bond R, Finlay D, et al. Human factors approach to evaluate the user interface of physiologic monitoring. J Electrocardiol 2015;48(6):982–7.
[83] Ratwani RM, Hodgkins M, Bates DW. Improving electronic health record usability and safety requires transparency. JAMA 2018 Dec 25;320(24):2533–4.
[84] Shanafelt TD, Dyrbye LN, Sinsky C, et al. Relationship between clerical burden and characteristics of the electronic environment with physician burnout and professional satisfaction. Mayo Clin Proc 2016;91(7):836–48.
[85] Zadvinskis IM, Garvey Smith J, Yen P-Y. Nurses' experience with health information technology: longitudinal qualitative study. JMIR Med Inform 2018;6(2):e38–.
[86] Lopes A, Valentim N, Moraes B, et al. Applying user-centered techniques to analyze and design a mobile application. J Softw Eng Res Dev 2018;6(1):5.
[87] Ulrich RS, Zimring C, Zhu X, et al. A review of the research literature on evidence-based healthcare design. Herd 2008; 1(3):61–125.
[88] Imhoff M, Kuhls S. Alarm algorithms in critical care monitoring. Anesth Analg 2006;102(5):1525–37.
[89] van Waes JA, van Klei WA, Wijeysundera DN, et al. Association between intraoperative hypotension and myocardial injury after vascular surgery. Anesthesiology 2016;124(1):35–44.
[90] Nangalia V, Prytherch DR, Smith GB. Health technology assessment review: remote monitoring of vital signs - current status and future challenges. Crit Care (London, Engl) 2010;14(5):233.
[91] Lyell D, Coiera E. Automation bias and verification complexity: a systematic review. J Am Med Inform Assoc – JAMIA 2017 Mar 1;24(2):423–31.
[92] Bhavnani SP, Parakh K, Atreja A, et al. 2017 roadmap for innovation-ACC health policy statement on healthcare transformation in the era of digital health, big data, and precision health: a report of the American college of cardiology task force on health policy statements and systems of care. J Am Coll Cardiol 2017;70(21):2696–718.
[93] Kamal Maheshwari, Ahuja Sanchit, Mascha Edward J, et al. Effect of sevoflurane versus isoflurane on emergence time and postanesthetic care unit length of stay: an alternating intervention trial. Anesth Analg 2019 [in press].
[94] Michard F, Bellomo R, Taenzer A. The rise of ward monitoring: opportunities and challenges for critical care specialists. Intensive Care Med 2019;45(5):671–3.
[95] Heller AR, Mees ST, Lauterwald B, et al. Detection of deteriorating patients on surgical wards outside the ICU by an automated MEWS-based early warning system with paging functionality. Ann Surg 2018.
[96] Bellomo R, Ackerman M, Bailey M, et al. A controlled trial of electronic automated advisory vital signs monitoring in general hospital wards. Crit Care Med 2012;40(8):2349–61.
[97] Blijleven V, Koelemeijer K, Jaspers M. Identifying and eliminating inefficiencies in information system usage: a lean perspective. Int J Med Inform 2017;107:40–7.
[98] Robinson EJ, Bergey MR, Brady E, et al. The impact of an electronic medication administration record (eMAR) and computerized physician order entry (CPOE) on nurse extender and unit clerk staffing. J Nurs Adm 2017;47(12):610–5.
[99] Zengul FD, Weech-Maldonado R, Ozaydin B, et al. Longitudinal analysis of high-technology medical services and hospital financial performance. Health Care Manag Rev 2018;43(1):2–11.