ICU

MANAGEMENT & PRACTICE

INTENSIVE CARE - EMERGENCY MEDICINE - ANAESTHESIOLOGY

VOLUME 19 - **ISSUE** 1 - **SPRING** 2019

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Protecting ward patients

The case for continuous monitoring

Finding patients before they crash might be the next major opportunity to improve patient safety. This article describes recent advances and perspectives for ward monitoring with wearable sensors and smart algorithms.

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Hospital wards are dangerous. Indeed, they are where most unexpected deaths occur within institutions. In a UK national audit study, among 23,554 adult in-hospital cardiac arrests, more than half (57%) occurred on the wards and only 5% in the ICU (Nolan et al. 2014). In the large (>46,000 patients) EUSOS study done in 28 European countries, most patients (73%) who died before hospital discharge were not admitted to critical care at any stage after surgery (Pearse et al. 2012). Importantly, most patients do not suddenly deteriorate. Vital signs are often abnormal, or trending toward abnormal range, hours before cardiac arrest or ICU transfer (Churpek et al. 2012). But healthcare professionals may only suddenly notice this is happening because spot-checks are usually done on a 4-6 hours interval. Prospective observational studies conducted in a leading U.S hospital, where patients were continuously but blindly monitored, revealed that nurses who were checking vital signs every 4h missed 90% of hypoxaemic episodes and about half of hypotensive events (Sun et al. 2015; Turan et al. 2019).

Therefore, the introduction of continuous monitoring has the potential to improve quality of care in traditionally unmonitored settings (Abenstein 2010; Michard and Sessler 2018; Vincent et al. 2018). With the current rise of wearable products developed for health and fitness (e.g. smartwatches detecting arrhythmia or devices monitoring pulse oxygen saturation (SpO_2) and blood pressure (BP) when connected to a smartphone) we are about to reach an unprecedented situation: monitoring may become more intensive at home than in hospital wards so that staying at home may paradoxically be considered safer.

In this article, we summarise which physiologic variables should be monitored, which tools are currently available to do so, and discuss requirements for the future development and adoption of continuous monitoring solutions as standard of care for hospital wards.

Which variables should we monitor?

Vital signs classically spot-checked in ward patients include heart rate (HR), BP, respiratory rate (RR), SpO_2 and temperature. They all have potential value to detect clinical deterioration. Some are more sensitive than specific, like HR that may increase during many situations, including postoperative pain, circulatory shock, respiratory distress, and sepsis. Others are more specific than sensitive. For instance, SpO_2 would decrease only in case of respiratory failure, pending oxygen administration is not automatically titrated to maintain a normal SpO_2 (L'Her et al. 2017). SpO_2 has also been considered a lagging indicator in acute events of respiratory depression.

> **finding patients before they rapidly deteriorate and suffer a major adverse event might be the next major opportunity to improve patient safety**

The ability of vital signs to predict clinical deterioration depends on the clinical context. During patient-controlled analgesia with opioids, rates of desaturation (SpO_2 < 90%) and bradypnoea (RR < 10) lasting >3 min can reach 12% and 41%, respectively (Overdyk et al. 2007). In this context, monitoring respiratory variables, in particular, RR, becomes a priority. In contrast, monitoring temperature and HR would likely be more useful to detect sepsis

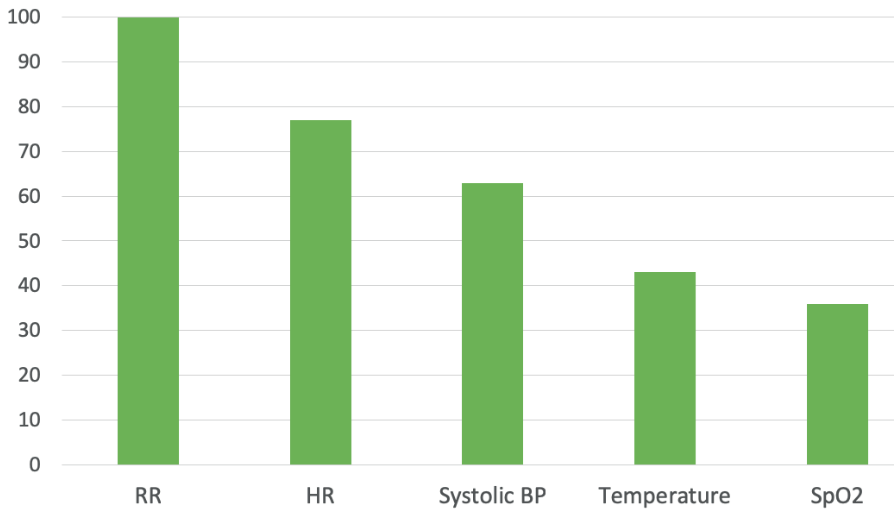

Figure 1. Importance of physiologic variables, scaled to a maximum of 100, in a random forest model developed to predict clinical deterioration on the wards.
Abbreviations: Respiratory rate, RR; heart rate, HR; blood pressure, BP; oxygen saturation, SpO_2. Original figure, with data from Churpek et al. 2016.

and prompt appropriate biological samples and treatments. A recent nationwide study (Michard et al. 2015) including >200,000 patients from >500 US hospitals showed that most common postoperative adverse events are respiratory and infectious complications, emphasising the importance of monitoring RR, SpO_2, HR and temperature.

In the general medical and surgical ward population, studies have repeatedly ranked RR, HR and systolic BP as the top 3 variables to be monitored. To predict cardiac arrest in ward patients, areas under ROC curves of 0.72, 0.68, 0.55 and 0.48 have been reported for RR, HR, systolic BP, and temperature, respectively (Churpek et al. 2012). In a recent study including >250,000 patients and using machine learning methods for predicting clinical deterioration in ward patients (Churpek et al. 2016), RR had the highest "weight" in the predictive algorithm followed by HR, systolic BP, temperature, and SpO_2 (**Figure 1**). In line with these observations, the National Institute for Health and Care Excellence in the UK stated that "RR is the best marker of a sick patient and is the first observation that will indicate a problem or deterioration in condition" (**nice.org.uk/guidance/CG50**).

Current options for continuous ward monitoring

Several methods have been proposed for the automatic estimation of RR in ward patients. They are mainly based on capnographic, acoustic, thoracic impedance and piezo-electric techniques (Michard et al. 2017). Capnographic sensors detect expired CO_2 and are the reference to measure RR in mechanically ventilated patients. In the context of ward monitoring, they are part of tethered monitoring systems sometimes poorly tolerated by spontaneously breathing patients. Acoustic sensors are better tolerated, but measurements may be influenced by speaking and swallowing (Mimoz et al. 2012). Respiration induces changes in electrical thoracic impedance that can be analysed to measure RR. Chest electrodes are classically used to quantify changes in thoracic impedance and have several advantages including ease of use and patient comfort. However, the reliability of RR measurements depends both on the number and the correct positioning of the electrodes. For patients staying in bed, a contact-free piezo electric sensor, left under the mattress, has been used with success to simultaneously monitor RR and HR (Zimlichman et al. 2012). Brown et al. (2014) monitored medico-surgical inpatients with such a system and reported a significant decrease in the number of calls for cardiac arrest.

Heart rate is classically recorded with chest adhesive electrodes. An alternative is the estimation of pulse rate from a pulse oximetry waveform. Of note, the pulse rate may differ from heart rate in case of cardiac arrhythmia and electromechanical dissociation (heart rate without pulse rate). Taenzer et al. used a tethered pulse oximeter to monitor pulse rate and SpO_2 in postoperative orthopaedic patients, many of them receiving opioids (Taenzer et al. 2010). They reported a significant decrease in the number of rescue events and transfers to ICU.

Temperature is classically spot-checked by nurses, and lately adhesive patches have been developed to continuously monitor skin temperature (Michard and Sessler 2018). A recent study showed a good agreement between temperature values from an axillary wearable sensor and reference oesophageal measurements during surgery (Pei et al. 2018). We are not aware of any evaluation conducted on the wards.

Blood pressure remains a variable difficult to measure non-invasively and continuously. Several volume clamp and tonometric methods have been developed to measure finger or radial blood pressure, respectively (Michard et al. 2018a). These systems have been designed for the operating room. Other systems, combining chest electrodes (to detect the ECG R wave) and a finger pulse oximeter (to detect a peripheral pulse), are able to predict BP from the estimation of changes in pulse wave transit time. Weller et al. used such a system to monitor BP, HR, RR and SpO_2 in neurological and neurosurgical ward patients (Weller et al. 2018). They reported a significant decrease in the number of rapid response team calls.

Further, when several variables are recorded together, they can be combined to calculate a single Early Warning Score (EWS). Several have been proposed, and they all include RR, HR, and systolic BP. Some (e.g. the NEWS and the ViEWS) integrate SpO_2 as well. The calculation of EWSs improves

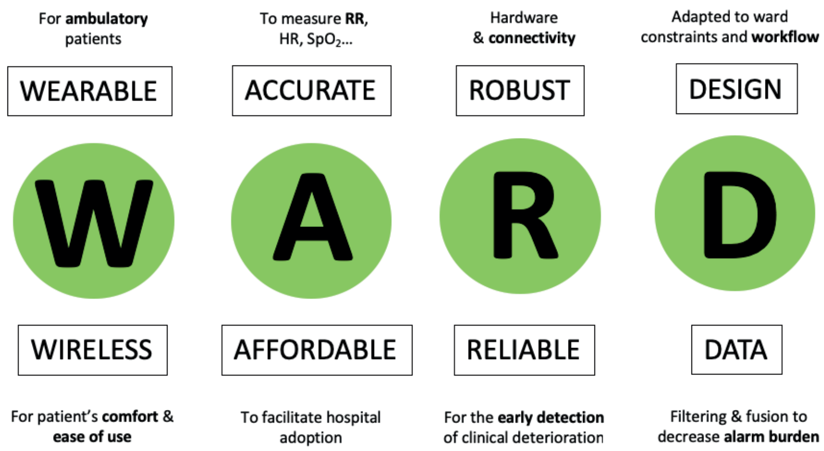

Figure 2. Requirements for future development and successful implementation of continuous ward monitoring techniques.

the prediction of adverse events (Churpek et al. 2012; Churpek et al. 2016). The use of monitoring systems that automatically calculate EWSs and alert clinicians on a pager as soon as patients deteriorate has been shown to be associated with clinical outcome benefits (Bellomo et al. 2012, Schmidt et al. 2015, Subbe et al. 2017, Heller et al. 2018). Machine learning algorithms using continuous data as input have the potential to better predict clinical deterioration and adverse events than classical EWSs (Hravnak et al. 2011).

Requirements for future developments and successful implementation

Wireless and wearable sensors

Early mobilisation is one of the key elements of enhanced recovery after surgery (ERAS) programmes. Physical movement is useful to prevent thrombotic complications and bedsores both in medical and surgical settings. Therefore, wireless and wearable sensors are highly desirable to make continuous monitoring a reality in ambulatory patients (Michard and Sessler 2018). In this respect, robust connectivity between wireless sensors, viewing, and alarming systems is a key requirement (Weenk et al. 2017). Wi-Fi or 3/4/5G connectivity would consume a lot of battery from a wearable, and unpredictable disruptions would remain a safety concern. Bluetooth and Zigbee may not be robust enough for handling wall or body mass obstruction and are not optimised for large amounts of streaming data. A wireless system ensuring robust signal quality and continuous data delivery from the patient's skin to the caring nurse, ensuring a high level of cybersecurity, low data latency, optimised battery life, and resistance to interferences from other devices in proximity would be ideal. Unfortunately, such a system remains to be invented.

> **wireless and wearable sensors are highly desirable to make continuous monitoring a reality**

Accuracy and false alarms

Measurement accuracy is mandatory for ensuring that any deteriorating patient is not missed. The number of wearable sensors is quickly growing, but independent validation studies done in real life conditions remain scarce (Granholm et al. 2016; Weenk et al. 2017; Subbe et al. 2018, Breteler et al. 2018). Core measurement performance is also crucial in preventing false alarms that can lead to additional workload and alarm fatigue (aka desensitisation to alarms). Different non-exclusive solutions can be envisioned. The first one is to minimise artefacts by ensuring sensors remain attached to the patient. In this regard, adhesive patches on the trunk might be preferred to finger clips or nasal sensors. Second, remaining artefacts can be filtered using smart software, such as machine learning algorithms (Chen et al. 2016). Third, both alarm thresholds and annunciation delays (the delay between when an alarm threshold has been crossed and when the alert is given) should be carefully selected (Weller et al. 2018).

Ease of use and impact on workload

Ease of use is key to clinical adoption, and monitoring systems should be made seamless and intuitive for users from minimally intrusive sensors to purposeful alarming tools. As mentioned above, the reliability of wireless connectivity should not become an issue for clinicians, and alert messages should be automatically directed to the right person, be it the nurse, the ward doctor, the rapid response team, an ICU member or a command centre, depending on the patient's condition and the local care organisation. Assuming all above conditions are met, ward monitoring should not increase workload at the hospital level, but rather redistribute it, with more adverse events managed by ward clinicians (since they are alerted earlier) and less by critical care specialists. The opportunity is also to prevent unjustified spot-checks in stable patients who remain the vast majority of ward patients. This may contribute to a decrease in nurse workload, and an improvement in patient comfort, quality of sleep and satisfaction (Michard et al. 2018b).

Affordability

Affordability is another key determinant of hospital adoption (**Figure 2**). A fair evaluation of the return on investment has to take into account potential savings associated with a reduction in the number of ICU transfers and in hospital length of stay. Two economic evaluation studies have shown significant savings when implementing continuous monitoring solutions on the wards (Taenzer et al. 2012; Slight et al. 2014). Patient selection with risk stratification tools may help optimise the return on investment. Machine learning algorithms could identify patients at risk of deterioration and help select those who may benefit the most from continuous monitoring techniques (Schmidt et al. 2015, Churpek et al. 2016).

Conclusion

Finding patients before they rapidly deteriorate and suffer a major adverse event might be the next major opportunity to improve patient safety (Bates and Zimlichman 2015). Thanks to recent hardware (wireless sensors) and software (data filtering and fusion, predictive analytics) innovations, it should become possible to adopt continuous ward monitoring without introducing an unmanageable nurse workload. This, beside the potential clinical benefits (faster recovery, less ICU transfers, and fewer unexpected deaths), could also lead to some logistic (more free beds for new admissions) and economic (shorter hospital stays, fewer complications) benefits. Clinical studies are needed to further investigate the clinical and economic impact of wearable and wireless sensors on medical and surgical wards, and better characterise which patients may benefit the most from these monitoring innovations.

Disclosure

Frederic Michard is the founder and managing director of MiCo, a Swiss consulting firm. Tong J Gan is the founding president of the American Society for Enhanced Recovery (ASER), the president of Perioperative Quality Initiative (POQI) and a consultant for Medtronic. Rinaldo Bellomo has been a consultant for Philips. ■

Key points

- Hospital wards are where most unexpected deaths occur within institutions
- Continuous monitoring has the potential to improve quality of care in traditionally unmonitored settings
- Wireless and wearable sensors are highly desirable to make continuous monitoring a reality in ambulatory patients
- Measurement accuracy is mandatory for ensuring that any deteriorating patient is not missed
- Ease of use is key to clinical adoption, and monitoring systems should be made seamless and intuitive for users
- Ward monitoring should not increase workload at the hospital level, but rather redistribute it, with more adverse events managed by ward clinicians and less by critical care specialists

Abbreviations

ASER	American Society for Enhanced Recovery
BP	Blood pressure
ERAS	Enhanced Recovery after Surgery
EWS	Early Warning Score
HR	Heart rate
POQI	Perioperative Quality Initiative
RR	Respiratory rate
SpO2	Pulse oxygen saturation

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