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TECHNICAL NOTE

New sensors for the early detection of clinical deterioration on general wards and beyond - a clinician's perspective

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Abstract
The early detection of clinical deterioration could be the next significant step in enhancing patient safety in general hospital wards. Most patients do not deteriorate suddenly; instead, their vital signs are often abnormal or trending towards an abnormal range hours before severe adverse events requiring rescue intervention and/or ICU transfer. To date, at least 10 large clinical studies have demonstrated a significant reduction in severe adverse events when heart rate, blood pressure, oxygen saturation and/or respiratory rate are continuously monitored on medical and surgical wards. Continuous, silent, and automatic monitoring of vital signs also presents the opportunity to eliminate unnecessary spot-checks for stable patients. This could lead to a reduction in nurse workload, while significantly improving patient comfort, sleep quality, and overall satisfaction. Wireless and wearable sensors are particularly valuable, as they make continuous monitoring feasible even for ambulatory patients, raising questions about the future relevance of "stay-in-bed" solutions like capnography, bed sensors, and video-monitoring systems. While the number of wearable sensors and mobile monitoring solutions is rapidly growing, independent validation studies on their sensitivity and specificity in detecting abnormal vital signs in actual patients, rather than healthy volunteers, remain limited. Additionally, further research is needed to evaluate the cost-effectiveness of using wireless wearables for vital sign monitoring both within hospital wards and at home.

Keywords Wireless sensor · Wearable sensor · Continuous monitoring · Remote monitoring · Patient safety

1 Introduction

"Patients admitted to hospital believe that they are entering a place of safety. They feel confident that, should their condition deteriorate, they are in the best place for prompt and effective treatment. Yet there is evidence to the contrary. Patients who become acutely unwell in the hospital may receive suboptimal care. This may be because their deterioration is not recognized or not acted upon sufficiently rapidly". This alarming statement doesn't come from a victim of medical error or a burned-out clinician; it comes from the National Institute for Health & Care Excellence (NICE) in the UK (https://www.nice.org.uk/guidance/CG50).

Many patients die in hospitals on general wards where clinical deterioration can go unnoticed for hours. In the large European Surgical Outcomes Study [1] which included 46,539 patients from 498 hospitals in 28 countries, most patients (73%) who died during their hospital stay were not admitted to an intensive care unit (ICU) at any time after surgery. A national UK audit [2] revealed that out of 23,554 in-hospital cardiac arrests, more than half occurred on general medical or surgical wards.

Importantly, most general ward patients do not deteriorate suddenly; their vital signs are often abnormal or trending towards an abnormal level hours before critical events requiring rescue interventions [3]. However, healthcare professionals may not immediately notice these changes because vital sign spot-checks are typically performed only every 4 to 12 h [4]. Prospective observational studies of patients who had blinded continuous monitoring consistently show that nurses' routine intermittent spot-checks of vital signs miss most hypoxemic and hypotensive events [5,

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6]. Therefore, continuous vital sign monitoring may detect clinical deterioration immediately and thus potentially reduce severe adverse events requiring rapid response team activations and/or ICU admission [7].

2 Why monitor vital signs?

Vital signs typically spot-checked on general wards include heart rate (HR), blood pressure (BP), core body temperature, oxygen saturation (SpO_2), and respiratory rate (RR). Each vital sign holds potential value in detecting clinical deterioration, though their sensitivity and specificity vary. For example, HR is highly sensitive but not specific; it may increase during many situations, including cardiac arrhythmia (e.g. atrial fibrillation), cardiac failure, postoperative bleeding, respiratory failure, and sepsis. On the other hand, some vital signs are more specific than sensitive. For example, SpO_2 typically decreases only in cases of respiratory complications, such as pneumonia, pulmonary edema, or pulmonary embolism.

The effectiveness of vital signs in detecting clinical deterioration varies depending on the clinical situation. For example, among general ward patients receiving opioids, about 10% desaturate ($SpO_2 < 90\%$) and more than one third become bradypneic ($RR < 10$) [8]. In these patients, monitoring respiratory variables, in particular RR, would be particularly important. Conversely, monitoring HR and body temperature may be more useful in detecting sepsis and prompting timely bacteriological sampling and antibiotic therapy. Among general ward patients, cardiac arrest is better predicted by RR and HR (with areas under the ROC curve of 0.72 and 0.68, respectively) than by systolic BP (area under the ROC curve of 0.55) [3]. A study involving over 250,000 patients utilized machine learning methods to predict severe adverse events in ward patients, and found that RR best predicted deterioration, followed by HR, systolic BP, body temperature, and SpO_2 [9]. Supporting these observations, UK's NICE 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*" (https://www.nice.org.uk/guidance/CG50). It is therefore unfortunate that during manual spot-checks RR is rarely checked [10] and often incorrectly measured [11].

When several vital signs are recorded simultaneously, they can be combined to calculate Early Warning Scores (EWSs). EWSs are valuable for detecting and quantifying clinical deterioration and predicting severe adverse events such as ICU admission and cardiac arrest [3, 9]. Implementing monitoring systems that automatically calculate EWS and promptly alert clinicians in case of clinical deterioration has been associated with improved clinical outcomes [12–14]. Moreover, machine learning algorithms that utilize continuous data as input variables show the potential to predict severe adverse events more accurately than classical EWSs [9, 15].

3 Innovative monitoring solutions

Heart rate is classically recorded with surface skin electrodes. Two electrodes are necessary to record HR and one ECG lead. Of note, the two electrodes can be very close to each other (only a few mm apart) so that they both can be housed in a single adhesive patch or device (e.g. the rear side of a wristband) [16]. Continuous HR monitoring allows the detection of cardiac arrhythmia and cardiac arrest [17]. Atrial fibrillation is the most common cardiac arrhythmia. It can impair cardiac performance and cause embolic strokes. Although atrial fibrillation can be suspected from HR monitoring alone (very high heart rate variability), monitoring at least one ECG lead is necessary to confirm the diagnosis (typical pattern with irregular HR and no P wave before the QRS). Several algorithms have been developed and approved for automatically detecting atrial fibrillation. Most have been designed to favor specificity over sensitivity [18].

Oxygen saturation (SpO2) is classically obtained using transductance photoplethysmography with a sensor wrapped around a finger or clipped on the ear lobe, or using reflectance photoplethysmography with a sensor applied on the skin (wristband, smartwatch, or ring sensor). Transductance photoplethymography has been considered the gold standard for many years, but several sensors using reflectance photoplethysmography have also been approved for medical use [19]. Of note, the estimation of pulse rate is possible from the photoplethysmographic waveform. However, pulse rate may differ from HR in case of cardiac arrhythmia and electro-mechanical dissociation (heart rate without pulse rate).

Numerous methods have been proposed for the automatic estimation of RR in general ward patients. They are mainly based on capnographic, acoustic, thoracic impedance and piezo-electric techniques [20]. Capnographic sensors detect expired CO_2 and are considered the reference to measure RR. However, they are part of tethered monitoring systems and nasal prongs may be poorly tolerated by spontaneously breathing patients. Acoustic neck sensors detect tracheal airflow and can be used to compute RR. However, measurements may be influenced by speaking and swallowing [21]. Changes in lung volume during respiration induce proportional changes in electrical thoracic impedance that can also be used 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. Wireless thoracic impedance techniques now exist (Fig. 1), and a recent study suggests high accuracy in measuring RR in general ward patients [22]. Other wearable sensors use accelerometers to detect chest movements [23] and the physiologic respiratory variation in pulse oximetry waveforms to estimate RR [24]. For patients staying in bed, a contact-free piezoelectric sensor, positioned under the mattress, has also been proposed to monitor RR [25].

Several wearables incorporate thermistors to measure skin temperature, which is known to differ from core body temperature. Therefore, various proprietary algorithms have been developed to estimate core body temperature from skin temperature. During surgery, a strong correlation has been reported between temperature values from an axillary wearable sensor and reference esophageal measurements [26].

Blood pressure remains the most challenging vital sign to measure non-invasively and continuously. Volume clamp and tonometric methods have been proposed for continuous finger and radial BP monitoring, respectively [27]. However, these systems have been designed for the operating room; they are bulky, and expensive, and the measurements are easily disturbed by movements. In addition, clinical studies comparing these methods against intraarterial BP measurements suggest that they often do not meet international standards [28]. Other monitoring systems, combining chest electrodes (to detect the ECG R wave) and a finger pulse oximeter (to detect a peripheral pulse), can predict BP from the quantification of the pulse wave transit time (or pulse arrival time) [29]. However, validation studies remain scarce, and regular calibrations by an independent method (typically the oscillometric brachial cuff method) are mandatory. More recently, machine learning algorithms have been proposed to detect changes in blood pressure from pulse oximetry waveform analysis [30, 31]. Such algorithms have been trained to recognize specific patterns associated with a decrease or a rise in BP and may therefore be used to estimate BP after initial oscillometric calibration. This new approach is very promising given the fact that photoplethysmographic sensors are now ubiquitous (Fig. 2).

4 Real-life challenges

4.1 Measurement accuracy

The number of wearable sensors is rapidly increasing, yet independent validation studies assessing their sensitivity and specificity for detecting abnormal vital signs in patients, as opposed to healthy volunteers, are still limited [32]. High sensitivity is essential to ensure that any clinical deterioration is promptly identified, while high specificity is critical to prevent false alarms, which can contribute to alarm fatigue and increase the workload for nursing staff. Several strategies can be employed to enhance specificity. Ensuring sensors remain securely attached to the patient is crucial to minimize artifacts. Adhesive patches on the trunk and wristbands may be more reliable than finger clips or nasal prongs [33]. Smart software solutions, including machine learning

Fig. 1 Example of mobile monitoring system using chest and abdominal electrodes to compute respiratory rate (RR) from cyclic changes in thoracic impedance, and a finger photoplethysmographic sensor to monitor oxygen saturation (SpO2) and pulse rate (PR). Continuous data transfer to the gateway (a smartphone-like device following the patient) is secured by a proprietary connectivity protocol. From GE Healthcare with permission

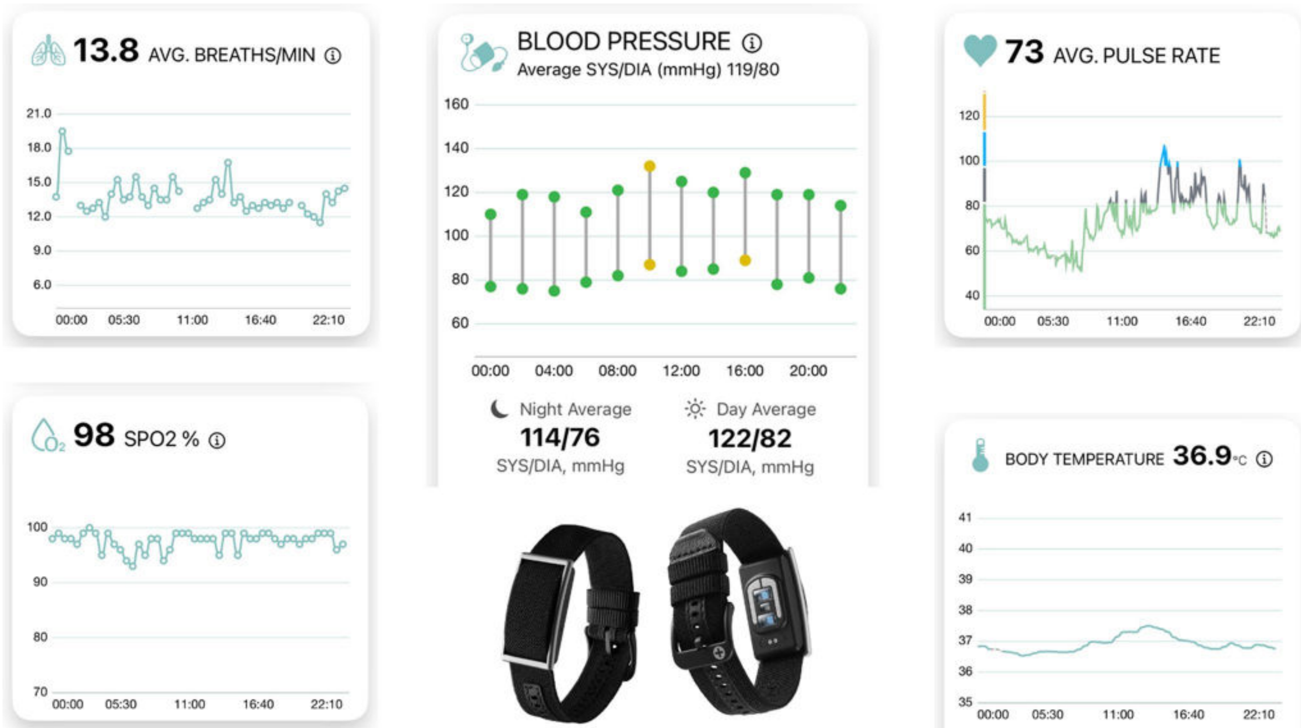

Fig. 2 Example of medical-grade photoplethysmographic wristband enabling the semi-continuous monitoring of 5 vital signs. Abbreviations: AVG., average; SYS, systolic pressure; DIA, diastolic pressure; SpO2, percutaneous arterial oxygen saturation. Wristband picture from Corsano Health with permission

algorithms, can be used to filter out residual artifacts [34]. Alarm thresholds and annunciation delays (the time between crossing a threshold and issuing an alert) should be carefully calibrated and personalized to match the physiological profile of individual patients [7].

Robust connectivity between wireless sensors, viewing, and alarming systems is key [32]. Connectivity protocols must be resilient enough to overcome obstacles like wall or body mass and be optimized to handle large volumes of streaming data. Wireless systems that ensure reliable signal quality and continuous data transmission from the patient to the attending healthcare provider are essential. Additionally, these systems should offer strong cybersecurity, low data latency, and resistance to interference from other nearby devices, making them highly suitable for widespread hospital adoption.

4.2 Clinical usability

Ease of use is crucial to clinical adoption and monitoring systems should be made seamless and intuitive for users, from minimally intrusive sensors to purposeful alarming tools. Alert messages should be automatically directed to the right person, be it the nurse, the ward doctor, the rapid response team, ICU staff, or a command center - depending on the patient's condition and the local care organization. Assuming all the conditions above are met, continuous ward monitoring should not increase workload but rather redistribute it [35]. Ward clinicians, who receive earlier alerts in the event of patient deterioration, can manage more non-severe adverse events, reducing the burden on rapid response teams and intensivists [7, 32]. Continuous, silent, and automatic monitoring of vital signs also offers the opportunity to eliminate unnecessary spot-checks for stable patients, who represent the majority in general wards. This can lead to a reduction in nurse workload, while significantly improving patient comfort, sleep quality, and overall satisfaction.

4.3 Mobility

Early mobilization is a cornerstone of Enhanced Recovery After Surgery (ERAS) programs. Physical movement is crucial for preventing thrombotic complications and bedsores in both medical and surgical patients. To support this, wireless and wearable sensors are highly desirable, as they make continuous monitoring feasible even for ambulatory patients. Given this shift, the future of "stay-in-bed" solutions like capnography, bed sensors, and video-monitoring systems may come into question [7].

4.4 Accessibility

Affordability is another key determinant of hospital adoption. A comprehensive evaluation of the return on investment should consider potential cost savings from reducing ICU transfers and shortening hospital stays. Economic models [36, 37] and real-life assessments [38] have indicated possible savings when continuous monitoring solutions are implemented on hospital wards. Additionally, patient selection using risk stratification tools, including machine learning algorithms, could further optimize the return on investment.

5 Impact of continuous monitoring on clinical outcomes

Early detection of clinical deterioration has potential to improve patient outcomes [39]. To date, at least 10 large clinical studies have demonstrated a significant reduction in severe adverse events when continuous monitoring of vital signs is implemented on general medical and/or surgical wards. These studies [29, 40–48], summarized in Table 1, show clinical benefits ranging from reduced rapid response team activations and ICU admissions to shorter hospital stays and lower mortality rates. Most of these studies are before and after implementation comparison studies, with the majority using wireless wearable sensors (Table 1). The most recent study is a retrospective, propensity-matched analysis conducted in post-surgical patients. It compared the postoperative outcomes of 12,345 patients whose vital signs were intermittently spot-checked (standard practice) with 7,955 matched patients who were continuously monitored using a wireless wearable system [48]. This study found a significant reduction in the composite outcome of ICU admission and death (Fig. 3).

6 Towards home monitoring

An increasing number of sensors and monitoring systems are now being designed for use beyond the hospital. While remote home monitoring presents additional hurdles– particularly in terms of connectivity and ensuring a timely and effective response (Who will respond in case of clinical deterioration at home? How quickly?)– it also offers significant potential benefits. First, with the rise of enhanced recovery after surgery programs, many patients are discharged very soon after their procedures, often on the same day. Wearable sensors could enable the early detection of postoperative complications, such as sepsis, which typically arise during the first week after surgery (Fig. 4). Second, for patients with chronic respiratory diseases or heart failure, early detection of clinical deterioration through continuous

Table 1 Ten large studies (> 1000 patients) reporting outcome benefits with continuous monitoring of vital signs on regular hospital wards

Patients *n*	Monitoring sensors	Continuous monitoring of	Wearable system	Outcome benefits	First author
Surg 5959	Tethered pulse ox.	SpO_2, PR	No	Decrease in rescue events & ICU admissions	Taenzer [40]
Med + Surg 3747	Piezoelectric bed sensor	HR, RR	No	Decrease in calls for cardiac arrest & hospital stay	Brown [41]
Surg 128111	Capnography	RR	No	Decrease in RRT events with naloxone	Stites [42]
Med. 4402	Abdo. patch, brachial cuff, pulse ox.	SpO_2, PR, RR	Yes	Decrease in cardiac arrest, ICU & hospital mortality	Subbe [43]
Med + Surg 1958	Electrodes, brachial cuff, pulse ox.	HR, RR, BP, SpO_2	Yes	Decrease in RRT events	Weller [29]
Med 1119	Electrodes, brachial cuff, pulse ox.	HR, RR, BP, SpO_2	Yes	Decrease in RRT events	Stellpflug [44]
Surg 1450	Pulse ox.	SpO_2, PR, RR	Yes	Decrease in severe adverse events	Tian [45]
Med + Surg 4769	Electrodes, brachial cuff, pulse ox.	HR, RR, BP, SpO_2	Yes	Decrease in RRT events & ICU admissions	Eddahchouri [46]
Med 4497	Pulse ox.	SpO_2, PR, RR	Yes	Decrease in cardiac arrest, hospital LOS and mortality	Balshi [47]
Surg 20300	Electrodes, brachial cuff, pulse ox.	HR, RR, BP, SpO_2	Yes	Decrease in ICU admission and mortality	Rowland [48]

Abbreviations: Surg, surgical; Med, medical; Prosp., prospective; Retro, retrospective; Abdo., abdominal; ox., oximeter; SpO_2, oxygen saturation; PR, pulse rate; HR, heart rate; RR, respiratory rate; BP, blood pressure; RRT, rapid response team; LOS, length of stay

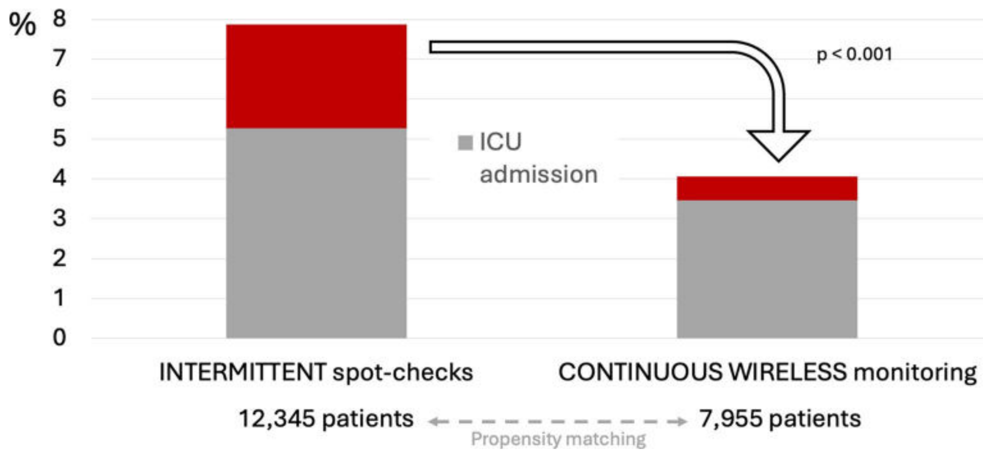

Fig. 3 Large propensity-matched study reporting a significant decrease in mortality and ICU admission in surgical ward patients monitored with wireless wearable sensors. This original figure was created with data published by Rowland et al. [48]

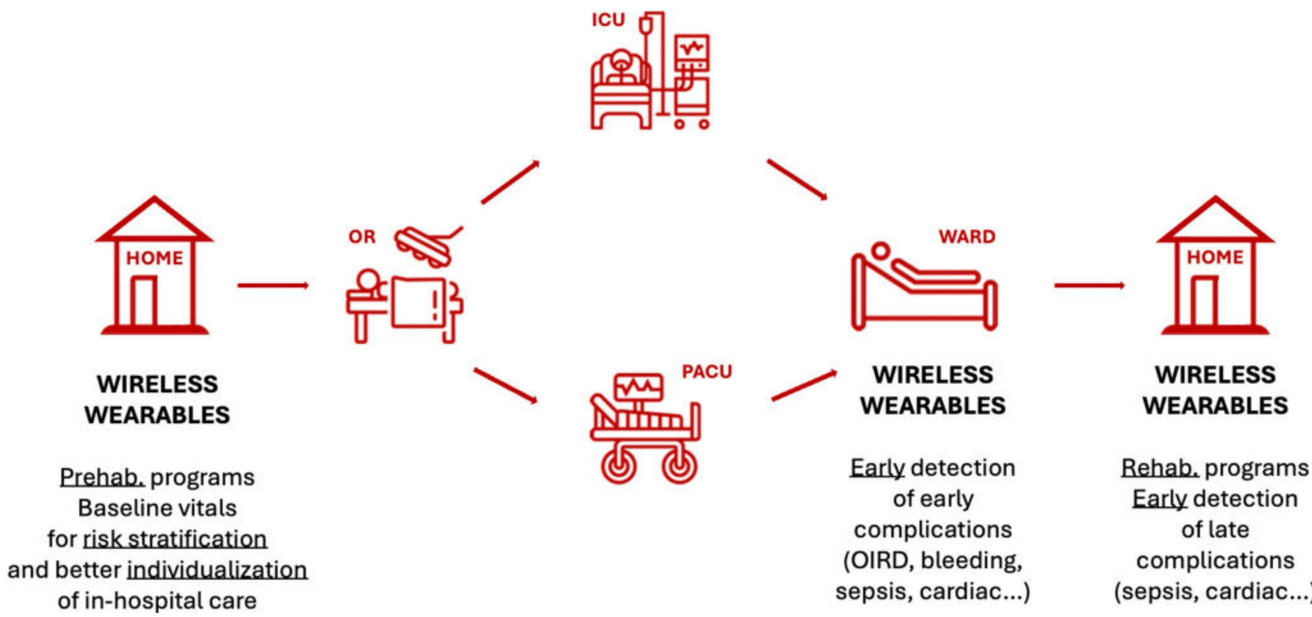

Fig. 4 In surgical patients, wireless wearable sensors may also be useful before hospital admission and after hospital discharge (home monitoring). Abbreviations: ICU, intensive care unit; OIRD, opioid-induced respiratory depression; OR, operating room; PACU, post-anesthesia care unit; Prehab., prehabilitation; Rehab., rehabilitation

monitoring could allow for immediate therapeutic adjustments, potentially preventing hospital admission or readmission. Similarly, in ambulatory oncology patients receiving chemotherapy, wearable sensors could play a role in the early identification and treatment of infectious complications. Importantly, both early discharge and the prevention of readmissions are likely to significantly reduce healthcare costs. This should be carefully considered when evaluating the cost-effectiveness of continuous remote monitoring with wearable sensors.

Finally, home monitoring can also play a valuable role in better characterizing individual physiologic profiles or phenotypes. Currently, patients are often treated with uniform therapeutic goals, even though no two patients are exactly alike. For example, resting HR and BP can vary significantly among individuals, and therapeutic targets should presumably reflect this inter-individual variability [49]. A “physiological identity card” that includes the patient’s baseline vital signs could help clinicians tailor care more precisely to each individual. For instance, wearable devices are increasingly being used to record physiologic profiles before surgery, particularly in the context of prehabilitation programs. The goal is to enhance risk stratification and better personalize both intraoperative and postoperative management, ensuring that treatment plans are as individualized as the patients themselves (Fig. 4).

7 Conclusion

Most patients hospitalized on general wards do not deteriorate suddenly; their vital signs are often abnormal or trending towards an abnormal level hours before a critical event. However, healthcare professionals may not immediately notice these changes because vital sign spot-checks are performed intermittently. To date, at least 10 large clinical studies have demonstrated a significant reduction in severe adverse events when continuous monitoring of vital signs is implemented on general medical and/or surgical wards. Wireless and wearable sensors are highly desirable, as they make continuous monitoring feasible even for ambulatory patients. Continuous, silent, and automatic monitoring of vital signs also offers the opportunity to eliminate unnecessary spot-checks for stable patients. This can lead to a reduction in nurse workload, while significantly improving patient comfort, sleep quality, and overall satisfaction. More independent validation studies are needed to assess the sensitivity and specificity of wireless wearables for detecting abnormal vital signs in patients, as opposed to healthy volunteers. Comprehensive evaluations of the return on investment, considering potential cost savings from reducing ICU transfers and shortening hospital stays, are also warranted. Despite the technical, logistical, and cultural challenges that lie ahead, continuous monitoring with wireless wearables could be the next significant breakthrough in enhancing patient safety.

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Declarations

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