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Ward monitoring 3.0

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> *"Patients who are 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".*

This alarming statement is not from the victim of medical error or a burned-out clinician; it is from the National Institute for Health & Care Excellence (NICE) in the UK.

In fact, patients often die on hospital wards where clinical deterioration can remain unnoticed for hours. In the European Surgical Outcomes Study[1] (EuSOS), which included 46 539 patients from 498 hospitals in 28 countries, most patients (73%) who died were not admitted to critical care at any stage after surgery. In a national UK audit,[2] among 23 554 in-hospital cardiac arrests, more than half occurred on medical or surgical wards.

Ward monitoring 1.0 or intermittent spot-checks

Most ward patients do not precipitously deteriorate. Instead, gradual decline is often detected late because vital signs are usually measured at 4–6 h intervals. A study of continuous clinician-blind oxygen saturation monitoring on surgical wards showed that saturation was <90% for more than 1 h in a third of patients, and <90% for more than 6 h in 10% of patients.[3] Concerningly, nurses who measured vital signs every 4 h missed 90% of the hypoxaemic episodes lasting at least 1 h.[3] Ward hypotension is similarly common, profound, and prolonged—and even more worrisome as postoperative hypotension is associated with nearly a three-fold increase in the risk of myocardial infarction.[4]

Ward monitoring 2.0 or continuous bedside monitoring

As cardiorespiratory deterioration is frequently missed with routine vital sign monitoring, it is reasonable to anticipate that continuous monitoring will improve ward safety. There is at least some evidence to support this. Taenzer and colleagues[5] continuously monitored heart rate and oxygen saturation in 2841 patients recovering from orthopaedic surgery, most of whom were given opioids. There were fewer rescue events and critical care transfers than in parallel control wards. Brown and colleagues[6] used a contact-free sensor put under the mattress to continuously monitor heart rate and ventilatory frequency in 2314 medical–surgical ward patients. The number of calls for cardiac arrest decreased significantly. A recent UK study[7] which included 4402 ward patients reported a significant decrease in cardiac arrest and hospital mortality after implementation of a continuous Early Warning Score surveillance system that used pagers to alert nurses when patients began to deteriorate.

Ward monitoring 3.0

Medical-grade wireless and wearable sensors facilitate continuous monitoring and may improve outcomes in hospital wards. Continuous monitoring of pulse rate and arterial oxygen saturation is available from pulse oximeters, some of which are now wireless. Heart rate and ECG monitoring can be obtained from various chest adhesive patches in which two electrodes are embedded a few centimetres apart (Table 1). Some detect and diagnose cardiac arrhythmias better than classical Holter systems.[8] Ventilatory frequency is the highest-ranked variable in mathematical models predicting clinical deterioration on the wards,[9] and is classically measured from capnographic or acoustic signals. However, ventilatory frequency can also be derived from wireless pulse oximeters and chest patch systems that sense respiratory variation in R-wave amplitude and in RR or pulse intervals (respiratory sinus arrhythmia). Chest patches containing an accelerometer, or a piezoelectric sensor can also estimate ventilatory frequency from chest movement. Several adhesive patches contain a thermistor and measure skin temperature; some are able to accurately estimate central body temperature from the axilla.[10] The finger cuff pulse-decomposition method enables continuous monitoring of blood pressure wirelessly, whereas pulse-wave transit time techniques are useful to track changes in blood pressure (i.e. to detect hypotensive events) and trigger oscillometric brachial cuff measurements.[11] Necklaces equipped with bioimpedance sensors have been cleared to detect changes in thoracic fluid content and may have value to diagnose pulmonary congestion before patients develop symptoms. Untethered monitors also have potential to detect patient location, position, and activity. For example, a supine unmoving patient is expected in bed, but would be a sign of collapse in a bathroom.

Wearables may well make continuous physiologic monitoring practical for ward patients (Table 1). But continuous monitoring will also generate huge amounts of data. Furthermore, wearables seem likely to be less reliable than conventional monitors and nurses who can identify and correct obviously flawed values. Simple threshold alarms for individual data streams will almost surely generate an excessive number of false alarms, but integrated Early Warning Scores could help decrease alarm fatigue.[7] Importantly, future monitoring systems might identify trends and patterns that indicate a failing patient before any particular value exceeds conventional risk thresholds. Decreasing ventilatory frequency and arterial oxygen saturation, for example, might suggest opioid-induced respiratory depression. Increasing ventilatory frequency, heart rate, and temperature with decreasing oxygen saturation and blood pressure may suggest pulmonary sepsis—and might do so before any individual value exceeds a conventional alarm threshold. Data integration should also be able to identify artifact in one data stream by considering normal values from other sensors. Simultaneous development of computing power and predictive analytics will surely help tame the continuous flow of physiologic

Table 1 Examples of medical-grade adhesive patches for physiologic monitoring. BP, blood pressure; HR, heart rate; PR, pulse rate; PWTT, pulse wave transit time; SpO_2, peripheral capillary oxygen saturation; T, temperature

	Company website	Sensor(s)	PR/HR	ECG	Ventilatory frequency	SpO_2	BP	T
	Intelesens.com	Chest patch (x2)	+	+	+			Skin
	Irhythmtech.com	Chest patch	+	+				
	Isansys.com	Chest patch	+	+	+			
	Medicompinc.com	Chest patch	+	+				
	Medtronic.com	Chest patch	+	+				
	Pmd-solutions.com	Chest patch			+			
	Preventicesolutions.com	Chest patch	+	+	+			
	Raiing.com	Axillary patch						Axilla
	Sensium.co.uk	Chest patch, axillary thermistor	+		+			Axilla
	Smartcardia.com	Chest patch	+	+		+	PWTT	Skin
	Vitalconnect.com	Chest patch	+	+	+			Skin

information and provide clinicians with more meaningful and actionable information, less artifact, and fewer false alarms. Machine learning algorithms, for example, have been used with success to distinguish real events from artifact in online multisignal vital sign monitoring data streams.[12] They may also better predict clinical deterioration than current Early Warning Score systems.[9]

Conclusions

Avoidable deaths on hospital wards remain all too common. Many should be prevented by continuous vital sign monitoring. Wireless and wearable sensors can help as patients poorly tolerate tethered monitors.[13] Although many technical solutions already exist to monitor vital signs wirelessly, validation studies remain scarce. Major trials are needed to determine whether wireless and wearable sensors accurately monitor vital signs, avoid excessive false alarms, detect clinical deterioration sufficiently early to allow effective intervention, and reduce serious adverse outcomes.

Authors' contributions

Writing/revising editorial: both authors.

Declaration of interest

Frederic Michard is the founder and managing director of MiCo, a Swiss consulting firm. MiCo does not sell any medical product and Frederic Michard does not own shares from any medtech company. Sotera, Inc provides equipment and funding for the Department of Outcomes Research led by Daniel I Sessler.

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Bedside assessment of lung aeration and stretch

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Knowledge on lung physiology and lung injury mechanisms related to positive pressure ventilation has evolved from animal models advancing the concepts of volutrauma, barotrauma, atelectrauma, and biotrauma[1,2] to applications in