The impact of continuous versus intermittent vital signs monitoring in hospitals: A systematic review and narrative synthesis

Abstract

Background

Continuous vital signs monitoring on general hospital wards may allow earlier detection of patient deterioration and improve patient outcomes. This systematic review will assess if continuous monitoring is practical outside of the critical care setting, and whether it confers any clinical benefit to patients.

Methods

MEDLINE®, MEDLINE® In-Process, EMBASE, CINAHL and The Cochrane Library were searched for articles that evaluated the clinical or non-clinical outcomes of continuous vital signs monitoring in adults outside of the critical care setting. The protocol was registered with PROSPERO (CRD42017058098).

Findings

Twenty-four studies met the inclusion criteria and reported outcomes on a total of 40,274 patients and 59 ward staff in nine countries. The majority of studies showed benefits in terms of critical care use and length of hospital stay. Larger studies were more likely to demonstrate clinical benefit, particularly critical care use and length of hospital stay. Three studies showed cost-effectiveness. Barriers to implementation included nursing and patient satisfaction and the burden of false alerts.

Conclusions

Continuous vital signs monitoring outside the critical care setting is feasible and may provide a benefit in terms of improved patient outcomes and cost efficiency. Large, well-controlled studies in high-risk populations are required to evaluate the clinical benefit of continuous monitoring systems.

Keywords

Continuous; monitoring, physiologic; patient safety; vital signs

Contribution of Paper

What is already known about the topic?

- Intermittent observation rounds are widely used to identify deteriorating patients in hospital.
- Continuous vital signs monitoring devices promise to allow earlier detection of patient deterioration.
- Little is known about the practical and clinical implications of continuous vital signs monitoring outside critical care wards.

What this paper adds

- Continuous monitoring outside the critical care setting is feasible and may provide a benefit in terms of improved patient outcomes and cost efficiency.
- Patient and staff engagement can influence the impact of the interventions.
- Large, well-controlled studies in high-risk populations are required to evaluate the clinical benefit.

Introduction

Early recognition of patient deterioration in hospital is crucial in reducing morbidity and preventing long term disability. For patients with septic shock, there is an 8% increase in mortality for every hour of delay in antibiotic administration (Kumar et al., 2006). Secondary benefits may include cost savings from reduced high dependency/intensive care and shortened hospital stay.

Prodromal warning signs such as increased respiratory rate or decreased blood pressure precede critical illness (Ridley, 2005). Vital signs monitoring is therefore a common patient care intervention which aims to facilitate the recognition of abnormal physiological parameters in deteriorating patients. Traditional intermittent manual vital signs monitoring, such as early warning score systems, form a standardised approach to assessment and response to critical illness(Day and Oxton, 2014).

Early warning scores have excellent predictive value, but are limited by their intermittent nature (Downey et al., 2017). Vital signs are taken at predetermined intervals (typically 4-hourly), with patient deterioration possible between recordings. It has been suggested that the gap between observations is one of the primary failings of early warning score systems (Tarassenko et al., 2006).

A solution to the problem of inadequate monitoring frequency is continuous monitoring at the bedside. Until recently, continuous vital signs monitoring was limited to intensive care units (ICUs) because it required high staff-to-patient ratios and cumbersome equipment which tethered the patient to the bed space, thereby inhibiting patient mobility and recovery. When ICU-style monitoring was implemented on a general ward, only 16% of patients remained connected in a 72-hour period (Bonnici et al., 2013).

However, minimally-intrusive remote monitoring technologies, aided by wireless data transmission, have the potential to convey the advantages of continuous, ICU-style vital signs monitoring to general wards. It is hypothesised that continuous vital signs monitoring may allow earlier detection of patient deterioration and thereby improve patient outcomes (Tarassenko et al., 2006).

Healthcare systems are becoming increasingly reliant on new technologies but it cannot be assumed that all technology imparts benefit. Continuous monitoring has practical implications which have to be offset. The potential benefit of the additional monitoring may be negated by inadequacies in other areas, such as staffing levels, escalation protocols and nursing compliance (Watkinson et al., 2006). Demonstrating benefit is important as these systems are not without financial cost. System prices are around $1500, and the cost of wearable monitors varies (Hofmann and Welch, 2017). It is important to collate the information available to help inform whether continuous vital signs monitoring offers a significant benefit over intermittent monitoring and can be justified for routine care in terms of cost effectiveness.

The aim of this systematic review is to examine the available, quality evidence to discover if continuous monitoring is feasible outside of the critical care setting, whether it confers any clinical benefit to patients when compared to intermittent vital signs monitoring and what other factors need to be considered during its implementation. Specifically, this review answers the following questions:

- Is continuous vital signs monitoring feasible outside of the critical care setting?
- Does continuous vital signs monitoring improve outcomes in hospital inpatients compared to intermittent vital signs monitoring?
- What are the practical (non-clinical) implications of continuous vital signs monitoring on general hospital wards compared to intermittent vital signs monitoring?

Methods

The protocol for this review was guided by the PRISMA statement(Moher et al., 2009) and was registered with PROSPERO (registration number CRD42017058098).

Eligibility criteria

Studies were selected according to the criteria outlined below.

- Types of studies

Studies were included if they evaluated the practical or clinical outcomes of continuous vital signs monitoring outside of the critical care setting. Study selection was not limited by the vital sign monitored or the outcomes measured. Qualitative, quantitative and mixed-methods studies were included. Study selection was not limited to peer-reviewed publications and included grey literature such as editorials and opinion pieces in order to provide insight into stakeholders' perspectives about the practical implications of continuous vital signs monitoring on general hospital wards.

- Types of participants

Studies were limited to those involving adults patients and staff on general hospital wards.

- Types of interventions/comparators

Of interest are interventions involving continuous monitoring of one or more vital sign parameter. These include heart rate respiratory rate, pulse oximetry, blood pressure and temperature. Selected studies were not limited by specific technologies, including remote technologies. Of particular interest is how continuous vital signs monitoring compares to intermittent monitoring, although single-arm studies were included for completeness.

- Types of outcome measures

Clinical and non-clinical outcomes were examined. Clinical outcome measures included mortality, cardiac arrest events, length of hospital stay and use of high-dependency care. Non-clinical outcomes included staff and patient perceptions, cost effectiveness, alarm buden and predictive value. Outcomes were collected as reported in individual studies.

- Types of setting

Selected studies were limited to hospital studies, outside of the critical care setting. Critical care was defined as a nurse:patient ratio of more than 1:3. Studies relating to outpatient investigations such as long-term cardiac monitoring were excluded. Selected studies were not limited by medical specialty or disease process.

Information sources

- Electronic searches

MEDLINE®, MEDLINE® In-Process, EMBASE, CINAHL and The Cochrane Library were searched for articles published from the dates of inception of the databases (the earliest being 1947) to October 2016.

- Searching other resources

To ensure literature saturation(Bowen, 2008), citations and reference lists of selected studies were reviewed to identify any missed papers.

Search strategy

The search strategy included a combination of keywords and subject headings related to vitals signs (Vital signs OR Vitals OR Heart rate OR Pulse OR Blood pressure OR Respiratory rate OR Temperature OR Oxygen saturation OR Electrocardiograph* OR ECG OR EKG) and monitoring (Observation* OR Monitoring OR Monitor* OR Telemetry OR Oximetry) in combination with keywords Continuous AND Intermittent.

The full search strategies for all databases are provided as Supplementary Material.

Data collection and analysis

- Selection of studies

All retrieved abstracts, studies and citations were collected, stored on an EndNote reference management database (Clarivate Analytics, London, U.K.), and reviewed. Publications were selected using a staged review of titles and abstracts, followed by full text review. Selection decisions were recorded in a Microsoft Excel (2007) document. A second reviewer checked a sample of 100 papers and inter-reviewer selection correlation was calculated.

- Inclusion criteria

The search were not limited by year of publication. Participants were limited to staff and patients of wards admitting adult human inpatients.

- Exclusion criteria

Studies regarding the paediatric, obstetric or neonatal population were excluded because of the specific requirements of these patient groups. Studies describing the development or validation of monitoring models were excluded if they did not report outcomes after implementation.

- Assessment of risk of bias in included studies

The quality of the studies was assessed by two independent researchers (CD and SC) using the Mixed Methods Appraisal Tool (MMAT), Version 2011(Pluye et al., 2009) and the QATSDD tool developed by Sirriyeh *et al*.(Sirriyeh et al., 2012) These tools are applicable to different research designs including qualitative, quantitative and mixed-methods designs, and enable comparison across a diverse range of studies. Inter-assessor agreement was calculated by comparing individual and overall scores for each paper, and discussion following independent scoring facilitated agreement between the two researchers.

- Data synthesis

Quantitative data synthesis was not attempted to avoid units of variance issues and the anticipated effects of excess heterogeneity. A narrative synthesis approach was chosen to summarise the diverse range of selected studies in a structured manner, following the European Social Research Council Guidance on the Conduct of Narrative Synthesis in Systematic Reviews.(Popay et al., 2006) The results of the selected studies were tabulated to highlight important similarities and differences between the studies. The studies were then grouped by type of outcome measure, setting and population. Patterns were identified and common areas between the studies were translated into themes. Each paper was then reassessed in the context of each theme. The themes were further refined using an iterative process. The evidence was then synthesised to provide a narrative, relevant to the research question.

- Data extraction

Data was compiled in a data extraction spreadsheet in Excel, which was tested initially in ten studies to ensure clarity and completeness. Extracted data included the generic and, if applicable, the trade name of the experimental intervention, the mode of application and the intensity and duration of monitoring. Also extracted, if relevant, were the type of intermittent monitoring used in the control arm, for example, early warning scores. In addition, patient characteristics (including disease process) and study setting were recorded. All clinical, non-clinical and feasibility outcome measures were extracted.

- Outcomes and prioritisation

Outcomes were collected as reported in individual studies and were not pre-determined before the literature search. These outcome measures were included in a Summary of Findings table (Tables 1 and 2). No prioritisation of outcome measures was performed to promote a comprehensive review of the available evidence.

Findings

Twenty-four studies were identified that met the eligibility criteria: 12 measured clinical outcomes of continuous monitoring (Table 1), 12 measured non-clinical outcomes (Table 2). Figure 1 illustrates the selection process.

The characteristics of the studies, including study design, intervention(s), comparison groups and outcomes measured are summarised in Tables 1 and 2. Overall, the 24 studies report outcomes on a total of 40,274 patients and 59 ward staff in nine countries. Five were randomised controlled trials (RCTs). All but two studies were single-centre. The study quality scores were generally high, with 18/24 studies scoring 3* or 4* on the MMAT tool. Inter-assessor agreement was 88% which resolved to 100% after discussion.

Outcomes were grouped into one of two categories: clinical outcomes and non-clinical/practical outcomes in order to answer the main questions of this review.

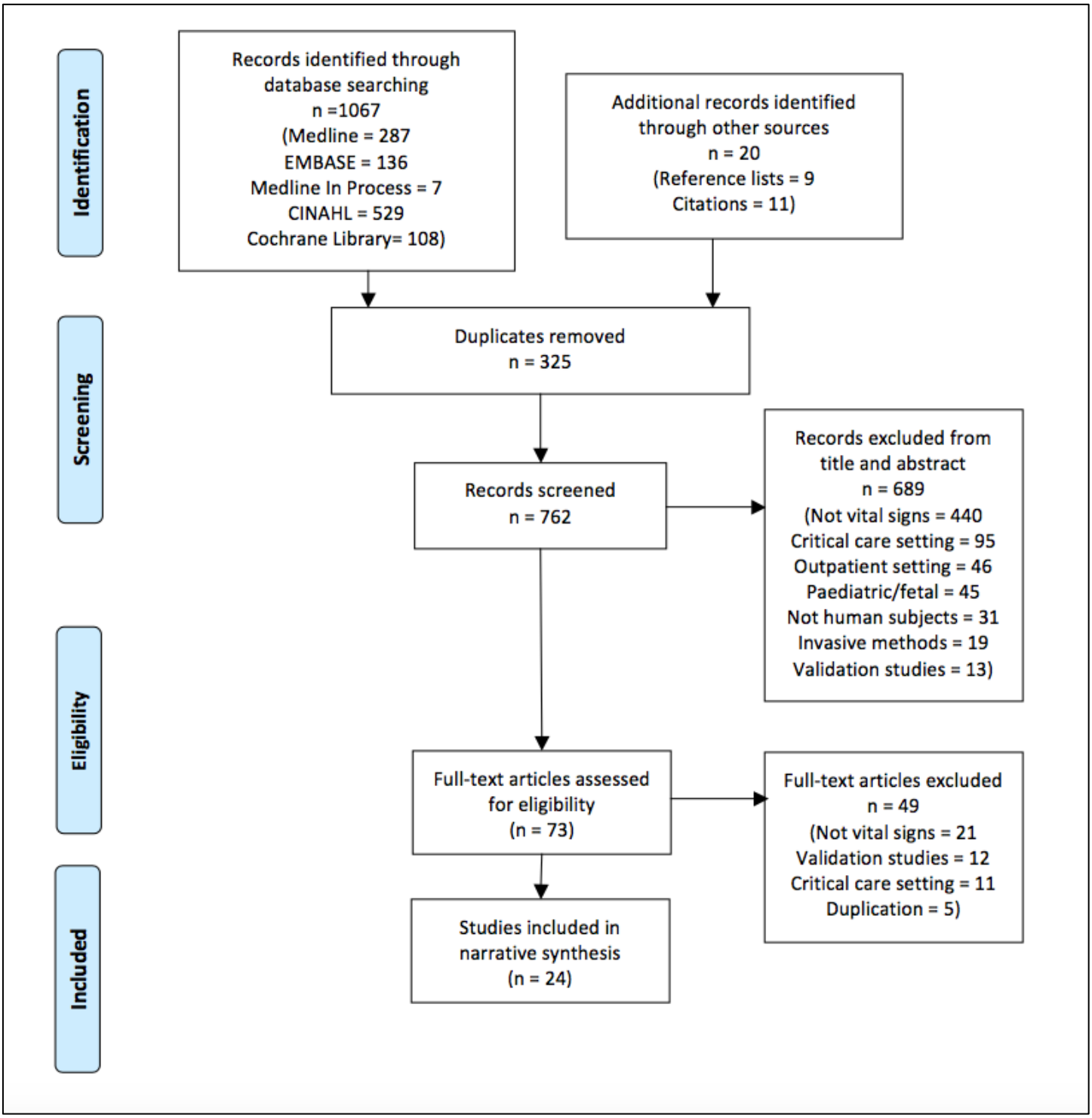

Figure 1: PRISMA diagram of search and eligibility process

Impact of continuous monitoring on clinical outcomes

Twelve studies examined the impact of continuous vital signs monitoring on clinical outcomes. Five of these were randomised controlled trials (Langhorne et al., 2010; Ochroch et al., 2006; Sulter et al., 2003; Tarassenko et al., 2005; Watkinson et al., 2006), one was a non-randomised controlled trial (Cavallini et al., 2003), three were controlled before-and-after studies (Brown et al., 2014; Kisner et al., 2009; Taenzer et al., 2010) and three were prospective observational studies (Taenzer et al., 2014; Varela et al., 2011; Wan et al., 2004). All were single-centre studies.

Outcome measures varied between studies and included mortality, length of hospital stay, ICU admission rate, length of stay on ICU, outcome at discharge and complication rates.

First author, date, country	Study design	Continuous monitoring intervention	Vital signs assessed	Comparison	Number of participants	Participant population	Primary outcome measures	MMAT Quality Score	QATSDD Quality Score
Brown *et al*. (2014), USA	Controlled before-and-after study	EarlySense motion-sensing under-mattress device	HR, RR, movement level	Intermittent vital signs monitoring	Intervention: 2314; Control 5329	Patients admitted to 2 medical-surgical wards	Unplanned ICU admission, ICU LOS, total LOS	***	57.10%
Cavallini *et al*. (2003), Italy	Non-randomised controlled trial	>72 hours of continuous monitoring	BP, ECG, Pulse oximetry, RR, Temp, EEG	4 hourly intermittent vital signs monitoring	Intervention: 134; Control 134	Patients with ischaemic stroke	Mortality, LOS, outcome at discharge, complications	***	69.00%
Kisner *et al*. (2009), Switzerland	Historically-controlled before-and-after study	Auricall wireless continuous pulse oximeter	HR, Pulse oximetry	Intermittent vital signs monitoring	Intervention: 119; Control 238	Patients post-CABG +/- valve surgery	Incidence of post-op AF,	**	33.30%
Langhorne *et al*. (2010), UK	Randomised controlled trial	>72 hours continuous ambulatory monitoring	BP, ECG, Temp, Pulse oximetry	Intermittent vital signs monitoring	Intervention: 16; Control: 16	Patients with ischaemic or haemorrhagic stroke	Mortality, outcome at discharge, complications	***	68.80%
Ochroch *et al*. (2006), USA	Randomised controlled trial	OxiNet II continuous pulse oximetry system	Pulse oximetry	Intermittent pulse oximetry monitoring	Intervention: 589; Control: 630	Patients admitted to one cardiothoracic surgical ward	ICU admission, LOS, LOS on ICU	****	82.20%
Sulter *et al*. (2003), The Netherlands	Randomised controlled trial	>48 hours of continuous monitoring with Marquette Eagle 4000 monitors	BP, ECG, Pulse oximetry, Rectal temp	Intermittent vital signs monitoring	Intervention: 27; Control: 27	Patients with ischaemic stroke	Mortality, outcome at discharge	****	61.90%
Taenzer *et al*. (2010), USA	Controlled before-and-after study	Patient SafetyNet bedside pulse oximetry monitor	HR, Pulse oximetry	Intermittent vital signs monitoring	Intervention: 6392; Control: 7006	Patients on an orthopaedic ward (intervention) compared with other surgical wards (control)	Adverse events, ICU admission	****	79.50%

First author, date, country	Study design	Continuous monitoring intervention	Vital signs assessed	Comparison	Number of participants	Participant population	Primary outcome measures	MMAT Quality Score	QATSDD Quality Score
Tarassenko *et al*. (2005), UK	Randomised controlled trial	BioSign multi-parameter continuous monitoring device	BP, HR, Pulse oximetry, RR, Temp	Intermittent vital signs monitoring	Intervention: 201; Control: 201	High-risk patients admitted to general medical and surgical wards	Mortality, LOS, complications	**	45.20%
Varela *et al*. (2011), Spain	Prospective cohort study	24 hours continuous monitoring of central and peripheral temperature with Holter monitor	Temp	Intermittent temperature monitoring with tympanic thermometer	55	Patients on general medicine ward with pyrexia >38C in previous 24 hours	Detection of deterioration	**	53.30%
Watkinson *et al*. (2006), UK	Randomised controlled trial	72 hours of continuous monitoring with Propaq multiparameter portable monitor	BP, ECG, Pulse oximetry, RR, Temp	Intermittent vital signs monitoring	Intervention: 201; Control: 201	High risk medical and surgical inpatients	Complications, ICU admission, cardiac arrest, mortality	***	66.70%
Wan *et al*. (2004), China	Prospective observational study	72 hours of continuous monitoring with Oxypleth ginger probe pulse oximeter	Pulse oximetry	24 hourly arterial blood gas measurement	39	Patients with long bone fractures and healthy controls	Episodes of inapparent hypoxaemia	***	47.60%

Table 1: Summary of included studies with clinical outcome measures

First author, date, country	Study design	Continuous monitoring intervention	Vital signs assessed	Comparison	Number of participants	Participant population	Primary outcome measures	MMAT Quality Score	QATSDD Quality Score
Banks *et al.* (1999), New Zealand	Observational, non-experimental descriptive pilot study	Flexible monitoring': four portable monitors moved to the patient's bedside	BP, HR, Pulse oximetry, Cardiac waveform monitoring	None	114	Patients requiring intensive surveillance monitoring, but not intensive nursing care.	Feasibility, patient satisfaction, impact on nursing staff, process changes	**	48.90%
Gazarian (2014), USA	Prospective observational study	Continuous ECG monitoring	ECG, Pulse oximetry	None	9	Nurses from medical surgical units	Alarm burden and type	***	66.70%
Gross *et al.* (2011), USA	Retrospective observational study	Intellivue critical care monitoring system	ECG, Pulse oximetry, RR	None	4104	Patients admitted to a subacute medical/surgical floor	Prediction of instability	***	64.20%
Hravnak *et al.* (2011), USA	Prospective longitudinal evaluation	Visensia patient monitoring system	BP, HR, Pulse oximetry, RR	Intermittent vital signs monitoring	632	Patients admitted to a trauma step-down unit	Alarm burden and type	***	84.60%
Jeskey *et al.* (2011), USA	Exploratory action-feedback study using time series surveys and interviews	Multi-parameter wearable transmitter with blood pressure cuff	BP, HR, Pulse oximetry, RR	None	Surveys: 14-25 nurses	Nurses working on 3 medical/surgical wards	Nursing perception	***	54.80%
Morgan *et al.* (2010), USA	Cost-effectiveness evaluation	Patient SafetyNet bedside pulse oximetry monitor	HR, Pulse oximetry	None	Unknown	Post-operative patients admitted to a 36-bed orthopaedic ward	Cost-effectiveness	***	48.10%
Parimi *et al.* (2016), USA	Retrospective observational study	Unknown	Systolic BP, HR	None	10636	Adult trauma patients	Predictive performance	***	72.20%

First author, date, country	Study design	Continuous monitoring intervention	Vital signs assessed	Comparison	Number of participants	Participant population	Primary outcome measures	MMAT Quality Score	QATSDD Quality Score
Prgomet *et al.* (2016), Australia	Mixed-methods study (interviews, surveys, device trial)	VisiMobile wrist-worn continuous monitoring device	BP, ECG, Pulse oximetry, RR, Temp	Intermittent vital signs monitoring	Interviews: 10	8 nurses, 2 doctors from Respiratory and Neurosurgery wards	Perceptions regarding barriers, benefits and concerns	***	64.30%
Slight *et al.* (2014), USA	Return on investment economic analysis	EarlySense motion-sensing under-mattress device	HR, RR, movement level	Intermittent vital signs monitoring	Intervention: 2314; Control 5329	Patients admitted to a medical-surgical ward	Return on investment	***	66.70%
Taenzer *et al*. (2014), USA	Prospective observational study	Patient SafetyNet bedside pulse oximetry monitor	HR, Pulse oximetry	Intermittent pulse oximetry monitoring	16	High-risk patients admitted to 5 general medical and surgical wards	Accuracy of manually recorded data	**	58.30%
Voepel-Lewis *et al.* (2013), USA	Prospective observational study	Continuous pulse oximetry monitoring during patient-controlled analgesia administration	Pulse oximetry	None	103	Post-operative orthopaedic patients	Alarm burden, response times, alarm relevance	****	76.20%
Watkins *et al.* (2016), USA	Prospective observational study based on surveys	Sotera Wireless continuous monitoring system	BP, HR, Pulse oximetry, RR	None	24 nurses	Nurses working on 2 medical/surgical wards across 2 sites	Nursing perception of continuous patient monitoring	**	28.60%
Yong *et al.* (2008), Europe	Retrospective ad hoc observational study	BP every 15 mins for 2 hours, 30 mins for 8 hours and hourly for 24 hours	BP	None	791	Patients with acute hemispheric stroke	Predictive performance	***	57.10%

Table 2: Summary of included studies with non-clinical outcome measures

- Single vital sign studies

Six of the selected papers focussed on continuous measurement of a single vital sign parameter: five examined continuous pulse oximetry (CPOX) alone;(Kisner et al., 2009; Ochroch et al., 2006; Taenzer et al., 2010, 2014; Wan et al., 2004) one study examined continuous temperature monitoring alone.(Varela et al., 2011)

Taenzer *et al.* and Wan *et al.* compared intermittent oxygen saturation measurements with that collected by CPOX.(Taenzer et al., 2010, 2014; Wan et al., 2004) Taenzer reported that manually recorded data was significantly higher than those recorded by CPOX, and did not reflect the patients' physiological state.(Taenzer et al., 2014) Wan *et al.* found that the detection rate of hypoxaemia is poor with arterial blood gas measurement compared to CPOX.(Wan et al., 2004) However, only three of their 20 patients manifested clinical symptoms requiring oxygen therapy, and all three had clinically significant reduction in ABGs, although they did not fall below the threshold of 65mmHg.

Similarly, the study of temperature monitoring found that only 16% of patients had fever 'peaks' identified by continuous monitoring that would not have been found with intermittent tympanic measurements and, in a further 16%, conventional monitoring observed peaks not detected by continuous monitoring.(Varela et al., 2011)

In a retrospective before-and-after study, Kisner *et al.* compared the rates of atrial fibrillation (AF) in cardiac surgical patients who received CPOX, with those who received intermittent monitoring prior to its introduction.(Kisner et al., 2009) No significant difference was detected between the two groups. A single subgroup of patients (those with coronary bypass graft with or without simultaneous valve surgery) demonstrated a significantly reduced incidence of AF (14% versus 26%, p=0.016), but another subgroup (valvular surgery only) demonstrated increased frequency of AF in the CPOX group.

In a well-designed before-and-after study in over 13,000 patients,(Taenzer et al., 2010) continuous pulse oximetry significantly decreased the rate of adverse events and critical care transfers in post-operative orthopaedic patients. Control wards showed no change over the same periods. Similarly, a randomised controlled trial of 1219 cardiothoracic patients found that length of stay on ICU was significantly shorter in patients who were continuously monitored.(Ochroch et al., 2006) This was despite no change in the rate of ICU transfer between the intermittent and continuously monitored groups. When subgroup analysis was performed on a high-risk group of patients, rates of transfer to ICU were decreased, but the study was not powered for this analysis.

- Multi-parameter studies

Studies evaluating continuous monitoring of multiple vital signs parameters have shown mixed results. An industry-funded controlled before-and-after study of 7,643 patients(Brown et al., 2014) found that continuous monitoring on a medical-surgical unit was associated with a total decrease in length of hospital stay from 4.0 to 3.6 days. Although statistically significant, the clinical impact of a 0.4 day reduction in hospital stay was not described. Total ICU days were significantly lower in the continuous monitoring group, but the rate of ICU admission was unchanged. In the control group a concurrent significant increase in length of ICU stay was observed, although the rate of cardiac arrest calls decreased significantly in both control and intervention arms.

Despite promising preliminary results,(Tarassenko et al., 2005) a randomised controlled trial of 402 high risk medical and surgical patients found that continuous multi-parameter monitoring showed no effect on adverse events or mortality.(Watkinson et al., 2006) However, only 16% of the patients were continuously monitored for the full 72 hours intended.

Three of the selected studies specifically involved the monitoring of acute stroke patients.(Cavallini et al., 2003; Langhorne et al., 2010; Sulter et al., 2003) The primary outcome measure was outcome at discharge, as assessed by validated scoring tools. These three studies have been well summarised in a recent Cochrane Review,(Ciccone et al., 2013) which concluded that continuous physiological monitoring significantly reduced death and disability at three months or discharge (odds ratio 0.27, 95% confidence interval 0.13 to 0.56). The significance of these findings were influenced by a non-randomised controlled trial,(Cavallini et al., 2003) which had a high risk of bias due to the method of allocation (consecutive patients admitted to different wards based on availability of beds) and lack of blinding of outcome assessment.

Interestingly, Cavallini *et al.*(Cavallini et al., 2003) found that patients in the continuous monitoring arm of their study had a significantly greater proportion of adverse changes in vital signs, which required acute medical treatment (64% vs 19%). This was echoed in the findings of Langhorne *et al.* (especially hypotension and tachycardia) and Sulter *et al.* (especially hypoxia, hypotension and arrythmias).(Langhorne et al., 2010; Sulter et al., 2003) Despite this, the outcome in patients with complications was found to be better in the continuous monitoring arm than the intermittent monitoring arm, and the length of stay in hospital shorter (9.2 days vs 17.1 days). All three studies concluded that continuous physiological monitoring after acute stroke may reduce the risk of poor outcome and death, and that modern specialised Stroke Units should incorporate such intensive monitoring as standard in the first 48 hours of admission.

Impact of continuous monitoring on non-clinical outcomes

- Cost effectiveness

Slight *et al.*(Slight et al., 2014) performed a return-on-investment analysis based on the results of Brown *et al*.(Brown et al., 2014) who measured unplanned ICU admissions, ICU length of stay and total length of hospital stay in a before-and-after study. Through multiway sensitivity analyses they found a return on investment of 127% for the least favourable conditions, with the most optimistic model returning up to 1739%. Workflow-related issues (e.g. changing nursing practice) were not included in the analysis.

Similar cost-effectiveness studies have been performed based on the results of Taenzer(Morgan J.A., McGrath S.P., 2010) and Ochroch.(Ochroch et al., 2006) Ochroch *et al*. examined the cost of patient care in patients who required ICU transfer and found a difference of $28,195 (p=0.04) in favour of patients who received continuous monitoring. Morgan *et al*.(Morgan J.A., McGrath S.P., 2010) estimated annual cost savings at $817,000 in the first year after the implementation of continuous monitoring at a 400-bed tertiary referral centre, driven by reduced ICU transfers.

- Predictive value

Three studies examined the predictive value of continuous monitoring for patient deterioration in the general ward setting (Hravnak et al., 2013; Parimi et al., 2016; Yong and Kaste, 2008).

Parimi *et al.* analysed the vital signs of 10,636 trauma patients and found that continuous monitoring of heart rate, systolic blood pressure and shock index (heart rate/systolic blood pressure) was predictive of transfusion risk, and that this predictive ability was improved as the duration of continuous monitoring increased.(Parimi et al., 2016)

Yong *et al.* retrospectively examined the systolic blood pressure profiles (readings taken every 15 minutes) of acute stroke patients recruited to a larger randomised controlled trial.(Yong and Kaste, 2008) They found that blood pressure dynamics were independently associated with outcome at 90 days, and recommended that continuous monitoring be used to stabilise blood pressure after stroke.

Hravnak *et al.* performed a prospective study(Hravnak et al., 2013) using an instability score calculated from continuous monitoring of heart rate, respiratory rate, blood pressure and pulse oximetry on a step-down unit. The researchers concluded that the instability score derived from continuous monitoring predicted instability before standard, intermittent vital signs scoring by 9 minutes in 80% of cases. The investigators did not collect data on how the scoring impacted care delivery, and were unable to demonstrate clinical significance.

- Nursing perception

Five studies reported nursing perception(Banks et al., 1999; Jeskey et al., 2011; Langhorne et al., 2010; Prgomet et al., 2016; Watkins et al., 2015) and all identified similar themes.

All studies reported that nursing staff could see the potential for continuous monitoring to enhance patient safety. Nurses perceived that greater 'availability and accessibility' of vital signs information would support their decision-making and provide reassurance to patients.(Prgomet et al., 2016) The value of continuous monitoring was particularly

evident to nurses who were trained and felt confident in its use,(Jeskey et al., 2011; Langhorne et al., 2010) while lack of familiarity with the technology was associated with loss of engagement and the perception of increased workload.(Banks et al., 1999) Banks *et al*. stress the importance of training in time allocated away from clinical duties.(Banks et al., 1999) Interestingly, Jeskey *et al*. found a more positive perception in nurses looking after higher-acuity patients, such as those just back from surgery.(Jeskey et al., 2011)

Prgomet *et al*. reported concerns from both doctors and nurses about over-reliance on continuous monitoring leading to decreased bedside interactions.(Prgomet et al., 2016) Some nurses were worried that visibility of information and alarms would cause patient anxiety, leading to increased time spent to reassure them. Continuous monitoring devices were also considered to provide opportunities for increased engagement of patients in their own care.

- Alarm burden

Eight studies reported concerns about alert burden. Banks found such a problem with nuisance alarms that monitoring had to be abandoned for two patients because of nursing complacency towards the alarms.(Banks et al., 1999) Alarm fatigue and data inaccuracy were also reported by Jeskey *et al.*, who found that excessive false-positive alerts interrupted nurses and distracted them from other responsibilities.(Jeskey et al., 2011) There was also concern that doctors might become overburdened and desensitised to calls.(Prgomet et al., 2016)

Three studies have aimed to quantify alert burden. Average number of alerts per patient per day varies from 7(Voepel-lewis et al., 2013) to 10.8(Watkins et al., 2015) to 95.6.(Gross et al., 2011) False alert rates varied between studies; Gazarian identified 32.9% of alerts as 'nuisance alarms',(Gazarian, 2014) whereas Voepel-Lewis *et al*. found that only one-third of alerts were clinically relevant, and that high alert burden was associated with longer nursing response times.(Voepel-lewis et al., 2013)

Taenzer *et al*. aimed to pre-empt this alert fatigue by adjusting alert thresholds, and allowing adjustment of these limits on a per-patient basis, to account for abnormal baseline physiology.(Taenzer et al., 2010) Similarly, Gross *et al.* were able to reduce their alarm rate by 50% with simple limit adjustments.(Gross et al., 2011)

- Patient perception

Although a number of studies briefly mentioned the comfort of the monitoring devices being tested, only one included patient satisfaction as an *a priori* outcome measure.(Banks et al., 1999) Out of 25 patients interviewed, 22 felt positively about the continuous monitoring system because it gave them a sense of 'security,' whilst other patients found the monitors to be restrictive or uncomfortable.

Discussion

To our knowledge this is the first systematic review to look at both clinical and non-clinical outcome measures to gain a fuller understanding of the impact of continuous vital signs monitoring outside of the critical care setting. A 2016 review by Cardona-Morrell *et al.*(Cardona-Morrell et al., 2016) included quantitative outcome measures such as number of ICU admissions and length of hospital stay, but did not address non-clinical outcomes. The inclusion of a diverse range of interventions, research designs, outcome measures and settings has provided a better reflection of current practices and considerations. However, this heterogeneity precluded data synthesis and so caution must be taken when generalising the results.

The feasibility of continuous monitoring outside the critical care setting is evident by the number of centres that report successful implementation: 10 centres in seven countries have published clinical studies. The majority of studies showed benefits in clinical outcome measures, particularly critical care use and length of hospital stay. Studies with large numbers of participants were more likely to associate the intervention with clinical benefit. Smaller observational studies found that continuous monitoring gave a more accurate reflection of the patient's physiological state, but were unable to demonstrate the clinical significance of this. Although there is limited evidence on the healthcare economics of patient monitoring, it appears that there may be a cost benefit with three studies showing cost-effectiveness of both single- and multi-parameter monitoring devices.

The clinical and non-clinical efficacy of continuous monitoring systems depend on engagement of the nursing staff with the technology and therefore on their satisfaction. In this review, the main barriers to implementation were nursing engagement and alarm burden. In order to ensure maximum benefit from continuous monitoring technologies, it is crucial to engage nursing staff in the implementation and, ideally, development of the intervention(Downey et al., 2017). This should involve the provision of thorough training and assessment and frequent process evaluations to ensure nurses and patients are confident and engaged in their use. Continuous patient surveillance can only be successful if it is not a burden to staff (Taenzer et al., 2010). It is particularly crucial to monitor false alert rates and adjust delays and thresholds accordingly.

Patient satisfaction should also be a consideration in the implementation of new monitoring devices. Although only one study reported patients' views, they were generally positive. This is reflected by the good recruitment rates reported in other studies, up to 98.2%.(Taenzer et al., 2010) Attention to patient comfort and convenience should influence the design of wearable devices to avoid issues with compliance such as those seen by Watkinson et al.(Watkinson et al., 2006) Consideration of patients' experiences throughout can provide universal benefit through the enhancement of patient safety and satisfaction.

Study quality was generally high, although direct comparisons are limited due to the heterogeneous methodologies employed by included studies. A previous review attempted meta-analysis of quantitative studies in this field and was unable to make decisive conclusions due to the heterogeneity of studies included. The use of two quality assessment tools highlighted the fact that many of the selected papers shared common limitations. Due to small sample sizes, studies were often underpowered to detect differences in clinical outcome measures. Some studies reported statistically significant differences found in unpowered subgroup analyses. For instance, Kisner et al. found contradictory results between two small subgroups of cardiac patients that may have been due to multiplicity. The preponderance of observational studies means that causal associations between interventions and patient outcomes have to be interpreted with care. The three largest randomised controlled trials showed conflicting results, illustrating the need for more research in this area. There is always a risk with reporting and publication bias with such a review and care has been taken to highlight industry-funding in one of the largest studies included.

Healthcare institutions must often choose between different patient safety interventions in order to maximise limited resources. These decisions can be based on economic reasons alongside patient benefits. The economic studies all found evidence of extremely cost-effective interventions. However, the results must be interpreted within the limitations of the original study findings. They were limited to small populations in hospitals in the United States, which may limit their generalisability to other healthcare systems.

Many of the clinical studies were limited by the complex nature of the intervention under investigation. Patient and staff compliance may have influenced the impact of the interventions. Demonstrating significant benefit over intermittent monitoring to offset the practical and economic implications of continuous monitoring is difficult, and requires large, well-controlled studies in high-risk populations to demonstrate significant differences in clinical outcomes, such as critical care admissions. Whilst it seems intuitive that continuous monitoring would confer patient benefit, achieving the maximum value from this technology requires consideration of the practical limitations and engagement of the primary stakeholders.

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