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Nursing informatics and patient safety outcomes in critical care settings: a systematic review

Qian Shi[1*], Rosie Wotherspoon[2] and Julia Morphet[3]

Abstract

Aim Conduct a systematic review to analyse how nursing informatics influence patient safety outcomes in critical care settings.

Research methodology/design The following database searches were conducted: Ovid MEDLINE, Cochrane library, Cochrane CENTRAL, CINAHL plus, Ovid Emcare, PsycINFO, and Ovid Embase. Two reviewers conducted the data selection and critical appraisal independently, following the JBI evaluation guidelines. Seventeen articles of high quality were included in this review.

Settings This systematic review focused on critical care settings in healthcare facilities, including Emergency Departments, Intensive Care Units, High Dependency Units and Coronary Care Units in public or private hospitals.

Main outcome measures The overarching outcomes evaluated were patient safety outcomes (e, g, the development of a pressure injury), patient safety outcome measures (i.e., the application of tools used to measure patient safety outcomes e.g. the frequency with which pressure areas are assessed) and the processes of care (e.g. conducting regular pressure area care to prevent pressure injuries).

Results In critical care settings, nursing informatics were associated with promotion of patient safety and prevention of adverse incidents, including reducing the incidence of pressure ulcers and medication errors; helping control blood glucose levels; decreasing the length of hospital stay; and improving compliance with care bundles and overall screening completion rates for risks of pressure ulcers, falls, substance use and agitation in emergency departments.

Conclusion The implementation of nursing informatics in critical care areas has been successful in promoting patient safety. While informatics can be costly to introduce, there is evidence these interventions can reduce costs by preventing adverse events.

Implications for critical practice Electronic health information record systems, clinical decision support systems and telehealth can increase compliance with screening and delivery of care aligned with guidelines across a range of presentations and critical care contexts. With the growing prevalence of nursing informatics, these systems should be considered for more widespread introduction.

Keywords Nursing informatics, Patient safety, Critical care, Quality improvement

*Correspondence:
Qian Shi
qian.shi@monash.edu

Full list of author information is available at the end of the article

Introduction

As the world rapidly evolves into the digital-rich era, the healthcare system has been encompassed by all kinds of technology and computer-based information systems. Nurses play a key role in utilising information technology to provide quality care and as a result, nursing informatics has been introduced as a specialty practice. Nursing informatics aims to optimise the information process, interpretation and management to improve nursing practice and promote patient safety [1]. The introduction of the Technology Informatics Guiding Education Reform (TIGER) initiative in 2004, has resulted in the rapid expansion of nursing informatics in healthcare settings globally [1]. Nursing informatics have subsequently been introduced in critical care settings to enhance the process of care and facilitate evidence-based practice to minimise adverse events, improve clinical decision-making, optimise the effectiveness of interventions and promote patient safety [2]. Patient safety is a priority in critical care settings and there is little room for error [2]. Critically ill patients can be vulnerable and dynamic changes due to compromised physiological status, complex comorbidities and rapid deterioration of health problems [2, 3]. Critical care settings, including Emergency Departments (ED), Intensive Care Units (ICU), High Dependency Units (HDU) and Coronary Care Units (CCU) are designed to provide holistic and appropriate care for those critically ill patients in a timely manner [2, 4].

Patient safety can be defined as "the reduction of risk of unnecessary harm associated with healthcare to an acceptable minimum" ([5] p.14). To clearly identify the main outcome measures in this systematic review, several definitions related to patient safety are explained below. 'Patient safety outcomes' are the patient impacts or results arising from the healthcare interventions and processes of care [6]. For example, the development of a pressure injury is a negative patient safety outcome. In contrast, 'patient safety outcome measures' refer to the tools that measure patient safety outcomes, such as the tools used to measure the frequency or depth of a pressure injury. The 'process of care' is the clinical practice that healthcare providers performed or undertook in the delivery of patient care [6]. The process of care can be affected by healthcare providers' knowledge and resources, such as time, equipment, technologies, the number of staff etc. One example of a process of care is to conduct regular pressure area care to sedated patients, to prevent pressure injuries.

There are a number of nursing informatic applications utilised in clinical nursing care, including the electronic health information record system, clinical decision support systems (CDSSs), telehealth, continuous bedside pressure mapping systems (CBPM), automated drug dispensing systems (ADDS) and continuous glucose monitoring (CGM) devices [1]. These will be explored briefly below.

In this systematic review, the term 'electronic health information record system' will be used to describe both the Electronic Medical Record (EMR) system and Electronic Health Record (EHR). The electronic health information record system is intended to promote information sharing and enhance communication among multidisciplinary team members, which is critical to care delivery [7, 8]. It can also enable nursing staff to easily access and utilise patient data to provide high quality patient-centred care and prevent patient safety incidents, such as identification of an allergy prior to medication administration [7, 8].

A CDSS is a computer-generated tool which consolidates clinical knowledge and information to provide prompts supporting and facilitating decision-making [9, 10]. CDSSs typically contain alerts, guidelines, templates, charts and predictive scoring systems which can help nurses deliver safe healthcare [9, 10]. For example, a CDSS could alert nurses to check for drug-allergy before medication administration [7]. CDSSs can also support as quality control by to automatically detecting any discrepancies or omissions that are generated from the physiological monitoring and medication administration software [11]. Those physiological monitoring and medication administration software are directly connected to CDSSs in real-time via the wireless networks [11]. Once the discrepancies or omissions are detected, this CDSS will send reminders to nurses to either correct data or complete the mandatory nursing activities in order to improve the compliance with evidence-based practice and decrease medication errors [11].

Telehealth is an umbrella term which describes the sharing of data and provision of healthcare interventions via a distance [1]. Telehealth may be provided via telephone or a secure online platform in which the healthcare provider can see the patient. Telehealth enables healthcare provision for people who would otherwise not have easy access to services [1].

Other practical examples of nursing informatics include ADDS, which are computer-controlled drug dispensing units that can maintain secure medication storage, and record medication picking and distribution of medications in healthcare [12]. Another example is a CBPM system, which can display an image of the patient's body, highlighting areas of high pressure via a pressure-sensing mat. This information can be used to guide pressure area care, thereby reducing the incidence of hospital-associated pressure injuries (HAPIs) [13]. A CGM device is aimed at continuously measuring glucose levels in the interstitial fluids every 5 min and send alarms when there are glycaemic changes [14].

However, despite the positive intent of nursing informatics, there is debate regarding the potential risk and unintended consequences these systems may pose to patient safety [15]. For example, the electronic health information record system has been reported to cause anxiety or frustration among nursing staff [15]. A lack of familiarity with electronic health information record systems can increase nursing workload, or delay access to critical patient information, increasing the risk of poor patient outcomes [15]. Nurses also expressed concerns that CDSSs might control or stifle development of their clinical judgement skills [10]. They experienced alert fatigue and consequently did not trust or ignored the data provided by CDSSs due to too much irrelevant information [3, 10]. This is in conflict with the intended purpose of CDSSs and could potentially result in failure to detect signs of patients' deterioration, putting patients in danger [3, 10].

Additionally, there were insufficient reviews that could demonstrate the relationship between nursing informatics and patient safety outcomes in the clinical settings in recent years [16]. The majority of reviews only explored the impacts of one nursing informatics intervention in the clinical setting. For example, Campanella et al. [17] focused on impacts of the electronic health information record system on healthcare quality, while Mebrahtu et al. [18] examined the impacts of CDSSs on patient outcomes. Therefore, the lack of rigorous evidence, and varied outcomes described from the introduction of technology in healthcare, demonstrate the need to conduct a systematic literature review to analyse the impacts of nursing informatics on patient safety in critical care settings.

Review objective

The study objective was to systematically analyse the relationship between nursing informatics and patient safety outcomes in critical care settings.

Methods

The Joanna Briggs Institute (JBI) systematic review methodology was used to guide the protocol development and conduct of this study [19] (supplementary material), including: (1) identifying the review objectives; (2) identifying the inclusion and exclusion criteria; (3) outlining the outcome or intervention measures; (4) outlining search strategies; (5) identifying the whole process of selecting relevant studies; (6) conducting critical appraisal; (7) conducting data extraction and data analysis [19].

Inclusion criteria

Studies were included if nursing informatics were used by nurses, for adult patients who presented or were admitted to critical care settings in healthcare facilities. Critical care settings included ED, ICU, HDU and CCU in public or private hospitals.

No restrictions on outcomes were applied, but were expected to include patient safety, quality improvement, quality of care, and risk assessments. All research methodologies were included. Included papers were limited by year (2004 to 2024) and were written in the English language. 2004 was identified as the start date because the Technology Informatics Guiding Education Reform (TIGER) initiative was formed in 2004 to enable nurses to fully participate and adapt to the information technology environment [20]. Papers were limited to the English language because that is the one language that the three members of the research team had in common.

Exclusion criteria

Studies that did not report patient safety outcomes from nursing staff using information technologies were excluded. Also, studies that exclusively reported on nursing experiences and nursing perceptions regarding the use of nursing informatics applications were excluded.

Search strategy

Databases utilised in this systematic review included Ovid MEDLINE, Cochrane library, Cochrane CENTRAL, CINAHL plus, Ovid Emcare, PsycINFO and Ovid EMBASE [19, 21]. In addition, the cinical practice guidelines portal, ClinicalTrials.gov, Informit, OpenDOAR, Open Grey and Grey Literature Report were utilised to search trial registries and grey literature in order to obtain articles as extensively as possible to eliminate publication bias. The search design and strategy were developed in collaboration with a content expert librarian and the initial search was conducted on 24/03/2021. An updated search was conducted on 19/10/2024, using the same search strategy which retrieved all relevant studies from 24/03/2021 to 19/10/2024. An example of the search strategy in Ovid MEDLINE with all keywords and index terms is presented in Table 1.

Selection of studies

After completing the search, the results were exported to EndNote software and then Covidence [22] in preparation for data screening and subsequent selection. The title and abstract of all retrieved papers were screened by two authors against the selection criteria [19]. Following title and abstract review, the full text of all included papers was retrieved and reviewed, in order to select all relevant research evidence to analyse [19]. The above selection and review processes were conducted by at least two authors (QS, and either RW or JM) independently, to minimise selection bias [19].

Table 1 Ovid MEDLINE -search example

	#	Searches	Fields	Explanations
First Concept	1	Patient	Title & abstract & full text	Keywords or synonyms searching
	2	Patient Safe*	Title & abstract & full text	Keywords or synonyms searching
	3	Safety Management/	Title & abstract & full text	Subject headings are indicated with "/"
	4	Quality of care	Title & abstract & full text	Keywords or synonyms searching
	5	Management	Title & abstract & full text	Keywords or synonyms searching
	6	Quality improvement	Title & abstract & full text	Keywords or synonyms searching
	7	Risk assessment/	Title & abstract & full text	Subject headings are indicated with "/"
	8	Medical error	Title & abstract & full text	Keywords or synonyms searching
	9	Adverse event	Title & abstract & full text	Keywords or synonyms searching
	10	2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9		OR will retrieve all articles from 2 to 9
	11	1 AND 10		AND will combine all research results
Second Concept	12	NURS*	Title & abstract & full text	Keywords or synonyms searching
	13	Nursing informatics	Title & abstract & full text	Keywords or synonyms searching
	14	Information system*/	Title & abstract & full text	Subject headings are indicated with "/"
	15	Electronic medical record OR EMR	Title & abstract & full text	Keywords or synonyms searching
	16	Electronic Health record OR EHR	Title & abstract & full text	Keywords or synonyms searching
	17	Clinical decision support system*	Title & abstract & full text	Keywords or synonyms searching
	18	Decision support system, clinical/	Title & abstract & full text	Subject headings are indicated with "/"
	19	Clinical practice guideline	Title & abstract & full text	Keywords or synonyms searching
	20	Scoring system	Title & abstract & full text	Keywords or synonyms searching
	21	Telehealth	Title & abstract & full text	Keywords or synonyms searching
	22	Telemedicine/	Title & abstract & full text	Subject headings are indicated with "/"
	23	13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19 OR 20 OR 21 OR 22		OR will retrieve all articles from 13 to 22
	24	12 AND 23		AND will combine all research results
Third Concept	25	Emergency Departments OR ED OR Casualty OR ER OR Emergency Room	Title & abstract & full text	Keywords or synonyms searching
	26	Accident and Emergency	Title & abstract & full text	Keywords or synonyms searching
	27	Critical Care	Title & abstract & full text	Keywords or synonyms searching
	28	Intensive Care Unit OR ICU	Title & abstract & full text	Keywords or synonyms searching
	29	High dependency unit OR HDU OR High therapy unit	Title & abstract & full text	Keywords or synonyms searching
	30	Coronary care units OR CCU OR Cardiac Care	Title & abstract & full text	Keywords or synonyms searching
	31	25 OR 26 OR 27 OR 28 OR 29 OR 30		OR will retrieve all articles from 25 to 31
	32	11 AND 24 AND 31		AND will combine all research results
	33	Limit 21 to (English language and yr= "2004–2024" and "all adult (19 plus years)")		The research further limited regarding the patients' age, the year and language of publications

Note. CCU = Coronary Care Units; ED = Emergency Department; HER = Electronic Health Record; EMR = Electronic Medical Record; ER = Emergency Room; HDU = High Dependency Unit; ICU = Intensive Care Unit; yr = year

Quality assessment

Following full-text screening, the quality and validity of each included paper was critically and independently evaluated by two reviewers (QS, and either RW or JM) using the JBI critical appraisal tools [21]. The JBI critical appraisal tools consist of 13 checklists covering all experimental, quasi-experimental, observational and qualitative methods. Any conflicts were resolved by discussion among the reviewers.

To minimise the risk of bias, the authors identified 'mandatory items' for each of the JBI quality appraisal tools [23]. When conducting a quality assessment, the mandated items had to be recorded as 'yes' to pass the quality assessment [23]. The mandatory items were agreed to by each reviewer prior to commencing the evaluation process, as critical to ensuring quality in each design. There were two reasons for identifying 'mandatory items' for quality assessment in this systematic review. One reason was to critically examine the risk of bias, including selection bias, performance bias, detection bias and attrition bias, in order to decide whether the study utilised a trusted methodology to ensure reliable outcomes [24]. Another reason was to assess the characteristics of the study population, contexts and intervention to determine if the results could be generalised. By doing this, the possibility of including biased or misleading findings was reduced [24].

Data extraction

Following full text review and quality appraisal, data were extracted using a standardised data extraction form. Extracted data included: author, country the research was conducted in, study aim, setting (i.e., unit type), study design or method, participants, interventions and outcomes. Where exact p values were reported, these have been utilised. The data extraction form was completed independently by two authors, and no errors were identified.

Data analysis

Data were expected to be heterogenic, and therefore the research team were unable to conduct meta-analysis [25]. Therefore, the researchers planned to use synthesis without meta-analysis (SWiM) methods to analyse the data and describe findings [25].

Results

Study selection

As demonstrated in Fig. 1, the original search was conducted on 24/03/2024 and database searching identified 2,277 articles from five databases. There were no trials registered or grey literature identified that were relevant to the review question. Five hundred duplicates were removed, and 1,777 studies were eligible for title and abstract screening. Following title and abstract review, the full-text of 52 studies were assessed against the inclusion and exclusion criteria. The updated search was conducted on 19/10/2024 as illustrated in Fig. 2 and retrieved total 768 articles from the same five databases. No registered trials or grey literature were identified to answer the review question. There were 203 duplicates that were removed and 565 studies were eligible for title and abstract screening. After the title and abstract screening, the full-text of 23 articles were assessed using the same inclusion and exclusion criteria. 133 papers were sought for full-text review, and 58 papers were not available in full-text. Efforts were made to contact the corresponding authors to retrieve these, however this was unsuccessful. Reasons for excluded papers are summarised in both Figs. 1 and Fig. 2. Ultimately, total 27 studies were included for quality assessment.

Quality of studies

Four types of research designs were identified within the 27 studies reviewed for quality appraisal, including Randomised Control Trials (RCTs), Quasi-Experimental studies, Cohort studies and Cross-sectional studies. The mandatory items for each of the JBI quality appraisal tools were identified with a justification supporting each decision in Tables 2.1, 2.2, 2.3 and 2.4.

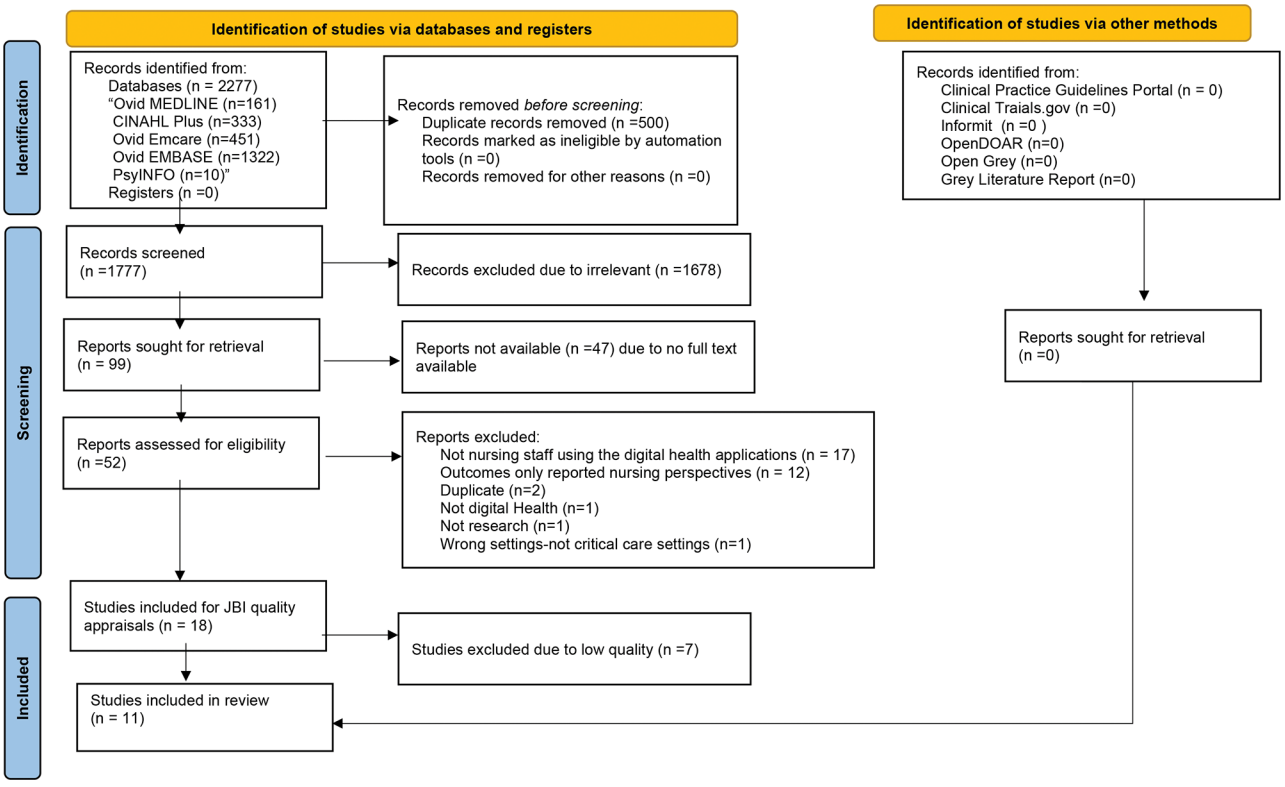

Fig. 1 Preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 flow chart for study selection for original systematic review on 24/03/2021 [26]

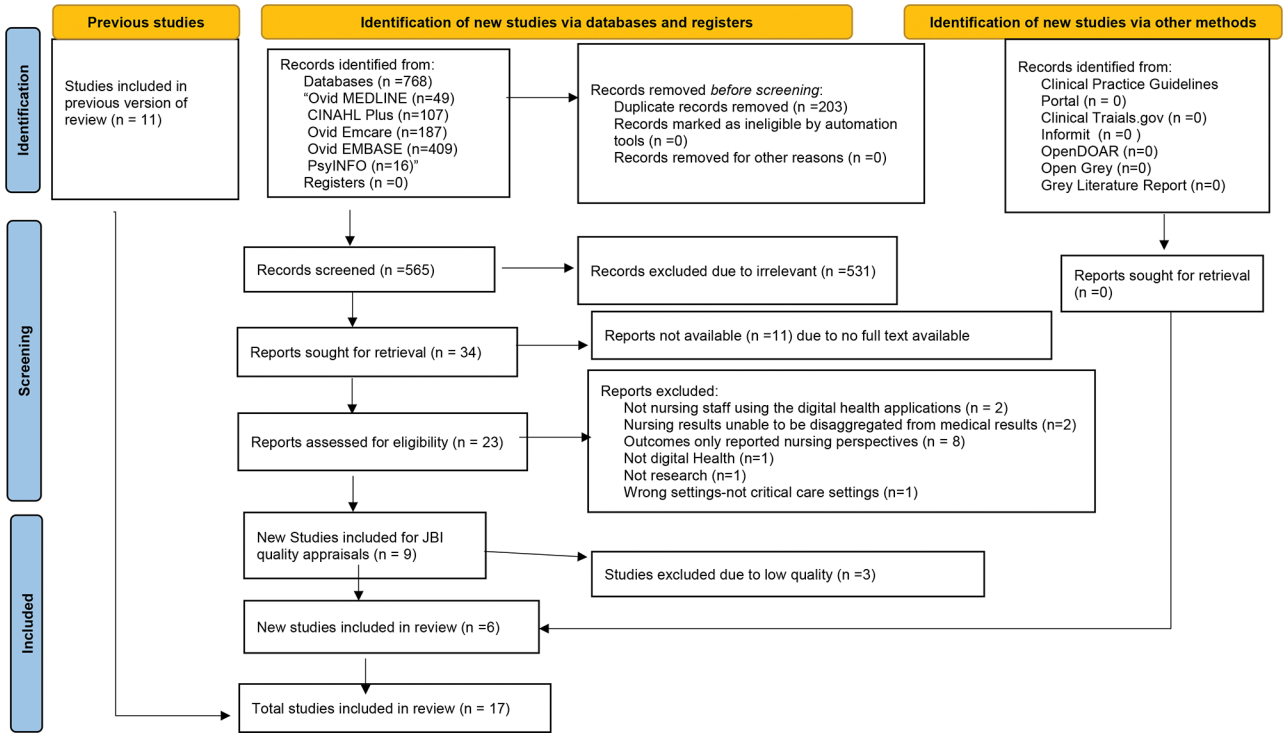

Fig. 2 Preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 flow chart for study selection for updated systematic review on 19/10/2024 [26]

Table 2.1 Summaries of JBI quality appraisal assessments-randomized controlled trial: quality assessment [21]

	Behrendt et al., 2014	Hanneman et al., 2015	Linton et al., 2021	Mann et al., 2011
Q1. Was true randomization used for assignment of participants to treatment groups?	X	✓	✓	✓
Q2. Was allocation to treatment groups concealed?	X	X	X	✓
Q3. Were treatment groups similar at the baseline? (Rationale: to minimise selection bias)	✓	✓	NA	✓
Q4. Were participants blind to treatment assignment?	✓	✓	X	✓
Q5. Were those delivering treatment blind to treatment assignment?	X	X	X	X
Q6. Were outcomes assessors blind to treatment assignment?	U	✓	X	X
Q7. Were treatment groups treated identically other than the intervention of interest? (Rationale: to minimise performance bias)	✓	✓	✓	✓
Q8. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	NA	NA	✓	✓
Q9. Were participants analyzed in the groups to which they were randomized?	✓	✓	✓	✓
Q10. Were outcomes measured in the same way for treatment groups? (Rationale: to minimise detection bias)	✓	✓	✓	✓
Q11. Were outcomes measured in a reliable way? (Rationale: to minimise risks of weakening the validity of inferences about the statistical relationships between 'cause' and 'effect'.)	✓	X	✓	✓
Q12. Was appropriate statistical analysis used? (Rationale: to minimise errors of statistical inference.)	✓	✓	✓	✓
Q13. Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?	✓	✓	✓	✓
Overall appraisal	I	E	E	I

Note. Items 3, 7, 10, 11, 12 were required for inclusion in this systematic review

NA = not applicable, U = unclear, I = Include, E = Exclude

Table 2.2 Summaries of JBI quality appraisal assessments-quasi-experimental studies: quality assessment (21)

	✓	✓
Q1. Is it clear in the study what is the 'cause' and what is the 'effect' (i.e. there is no confusion about which variable comes first)?	✓	✓
Q2. Were the participants included in any comparisons similar? (Rationale: to minimise selection and allocation bias)	✓	✓
Q3. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	✓	✓
Q4. Was there a control group?	✓	✓
Q5. Were there multiple measurements of the outcome both pre and post the intervention/exposure?	X	X
Q6. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	U	✓
Q7. Were the outcomes of participants included in any comparisons measured in the same way? (Rationale: to minimise detection bias)	✓	✓
Q8. Were outcomes measured in a reliable way? (Rationale: to minimise the measurement of the outcome bias)	X	✓
Q9. Was appropriate statistical analysis used? (Rationale: to minimise errors of statistical inference.)	X	✓
Overall appraisal	E	I

Note. Items 2, 7, 8, 9 were required for inclusion in this systematic review

U = unclear, I = Include, E = Exclude

Table 2.3 Summaries of JBI quality appraisal assessments-analytical cross-section study: quality assessment [21]

	Ludwig-Beymer et al., 2012
Q1. Were the criteria for inclusion in the sample clearly defined? (Rationale: to minimise selection bias)	X
Q2. Were the study subjects and the setting described in detail?	✓
Q3. Was the exposure measured in a valid and reliable way? (Rationale: to make sure that measurements of exposures are appropriate and can be repeated)	✓
Q4. Were objective, standard criteria used for measurement of the condition?	✓
Q5. Were confounding factors identified?	X
Q6. Were strategies to deal with confounding factors stated?	X
Q7. Were the outcomes measured in a valid and reliable way? (Rationale: To minimise risks of weakening the validity and reliability of inferences about the statistical relationships between 'cause' and 'effect'.)	✓
Q8. Was appropriate statistical analysis used? (Rationale: to minimise errors of statistical inference.)	✓
Overall appraisal	E

Note. Items 1, 3, 7, 8 were required for inclusion in this systematic review

E = Exclude

In total, 17 studies were included in this systematic review after 10 studies were excluded for being deemed to be low quality. These ten low quality studies had at least one mandatory item recorded as 'No' or 'Unclear' [27–36]. All quality appraisal assessments have been summarised in the Tables 2.1, 2.2, 2.3 and 2.4.

Study characteristics and designs

Among the 17 included studies, fourteen utilised a cohort study design [11, 14, 37–48]. One was a randomised controlled study [49], one was a non-randomised experimental study [13] and one was quasi-experimental study [50]. All participants were adult patients who presented or were admitted to the critical care setting, including seven in EDs and ten in ICUs. The studies were conducted in United States ($n = 8$), France ($n = 2$), Canada ($n = 2$), Greece ($n = 1$), Belgium ($n = 1$), Australia ($n = 1$), Switzerland ($n = 1$) and China ($n = 1$).

There were varied nursing informatics interventions used. Armstrong [47], Curtis et al. [38], Legambi et al. [46], Levesque et al. [40] and Zikos et al. [45] used electronic health information record system in their studies. Two studies examined the effects of telehealth [42, 44]. One additional paper [39] examined the implementation of both the electronic health information system and telehealth in the ICU. The utilization of both electronic health information record system and CDSSs have been assessed in one study [50]. Five studies utilised CDSS to guide care [11, 41, 43, 48, 49]. One study assessed the impact of an ADDS [37], one study examined the effects of CGM devices in ICUs [14] and another analysed the CBPM system in ICUs [13].

Various patient safety outcomes, patient safety outcome measures and processes of care were reported in the included studies and these are summarised in Table 3. All extracted data have been summarised in Table 4. Due to the heterogenic quantitative data recorded from all 17 included studies, the results have been discussed in detail below using SWiM approach based on patient safety outcomes [25].

Patient safety

Incidence of pressure ulcers

Behrendt et al. [13] utilised the CBPM to assess the incidence of pressure ulcers in the ICU. The CBPM contained a pressure-sensing mat and a control unit that illustrated pressure imaging at the bedside, intended to help nurses recognise high-pressure areas early and then off-load pressure accordingly [13]. All participants' pressure ulcer risks were assessed using a standard Braden scale which involved sensory perception, moisture, activity, mobility, nutrition, and friction and shear forces [13]. After the 2-month study period, the results showed there was a significant decrease of development of stage II pressure

Table 2.4 Summaries of JBI quality appraisal assessments- cohort study: quality assessment (21)

	Ang et al., 2024	Ackrivo et al., 2016	Armstrong, 2023	Berger et al., 2006	Chapuis et al., 2010	Curtis et al., 2020	Feral-Pierssens et al. 2024	Feral-Pierssens et al., 2022	Legmbi et al., 2021	Levesque et al., 2015	Kahn et al., 2014	McLeod et al., 2020	Meer et al., 2012	Meyfroidt et al., 2011	Ruesch et al., 2012	Slain et al., 2014	Vogelzang et al., 2005	Williams et al., 2019	Zhang et al., 2024	Zikos et al., 2014
Q1. Were the two groups similar and recruited from the same population? (Rationale: to minimise selection bias)	✓	✓	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	✓	✓
Q2. Were the exposures measured similarly to assign people to both exposed and unexposed groups?	✓	X	✓	✓	✓	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓	U	X	X	✓	✓
Q3. Was the exposure measured in a valid and reliable way? (Rationale: to make sure that measurements of exposures are appropriate and can be repeated)	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Q4. Were confounding factors identified?	X	X	X	✓	X	✓	U	X	✓	X	✓	X	✓	✓	X	✓	X	X	X	X
Q5. Were strategies to deal with confounding factors stated?	NA	X	NA	✓	X	X	X	NA	X	X	✓	X	X	✓	X	X	X	X	NA	X
Q6, Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)?	✓	NA	✓	NA	NA	NA	NA	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA
Q7. Were the outcomes measured in a valid and reliable way? (Rationale: to minimise risks of weakening the validity and reliability of inferences about the statistical relationships between 'cause' and 'effect'.)	✓	X	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Q8. Was the follow up time reported and sufficient to be long enough for outcomes to occur?	✓	NA	✓	NA	NA	NA	✓	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA
Q9. Was follow up complete, and if not, were the reasons to loss to follow up described and explored?	✓	✓	X	✓	✓	✓	✓	X	✓	✓	✓	✓	X	✓	✓	X	✓	✓	✓	✓
Q10.Were strategies to address incomplete follow up utilized?	NA	NA	U	X	NA	NA	✓	✓	NA	NA	✓	NA	X	NA	NA	X	NA	NA	NA	NA
Q11. Was appropriate statistical analysis used? (Rationale: to minimise errors of statistical inference.)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Overall appraisal	I	E	I	E	I	I	E	I	I	I	I	I	I	I	I	E	E	E	I	I

Note. Items 1, 3, 7, 11 were required for inclusion in this systematic review
NA=not applicable, U=unclear, I=Include, E=Exclude

ulcers between the control group and the CBPM group ($p = 0.02$) [13].

Armstrong [47] implemented the electronic health information record system to emphasise the standardised and correct reporting system to detect and to monitor HAPIs for ICU patients. Once the HAPIs were reported via the electronic health information record system, general root causes for those pressure injuries were analysed and discussed among nursing staff in ICU [47]. Relevant education, intervention and prevention activities were initiated to help pressure injury management [47]. After the standardized reporting system was implemented, the total HAPIs decreased from 1031 cases to 631 cases, about 38.8% reduction in the first year [47]. In the second year, there was a further 33% decrease in HAPIs, reducing from 631 cases to 423 cases [47].

The frequency of medication errors

Chapuis et al. [37] examined the effects of an automated drug dispensing system (ADDS) on the frequency of medication errors with regard to picking, preparation, and administration processes in a medical ICU. In Phase I, both control and study groups used a classic medication cabinet to dispense medications [37]. In the Phase II, 4-month study period, an ADDS was placed in one ICU (study group) and the control group continued to use the classic medication cabinet [37]. Outcomes reported on the percentage of total opportunities of error (%TOE) and the percentage of detailed opportunities of error (%DOE) [37].

After the introduction of ADDS (Phase II), the overall error rate was significantly reduced from 18.6% TOE in the control group, to 13.5% TOE in the study group ($p < 0.05$) [37]. Also, the %TOE was reduced dramatically

Table 3 Summary of patient safety outcomes, patient safety outcome measures, and processes of care in included studies

Patient safety	Author, Date,	Patient safety outcomes	Patient safety outcome measures	Processes of care
Incidence of Pressure ulcers	Armstrong, 2023	Frequency of hospital-acquired pressure injuries (HAPIs) development	HAPIs assessing tools	Standardised reporting system via the electronic health information record system used to detect and o monitor HAPIs for ICU patients
	Behrendt et al., 2014.	Frequency of stage II pressure ulcer development	HAPIs staging tool	Intervention group: Pressure Ulcer Systems (CBPM) informed repositioning of patients to off-load high pressure areas. Control group: patients repositioned based on protocol.
Incidence of medication errors	Chapuis et al., 2010.	Frequency of medication errors.	Audit tool to identify picking, preparation, and administration related medication errors	Intervention group: Medication Administration Systems (ADDS) used to prepare, dispense and administer medications. Control group: classic medication cabinet used to prepare, dispense and administer medications.
Glucose control in critical care settings	Ang et al., 2024	Time spent within targeted blood glucose range Blood glucose levels via CGM devices compared with point-of-care blood glucose levels	Audit tool capturing time patients spent in target range Audit tool capturing glucose levels Blood glucose levels	CGM device used to monitor glucose levels for postoperative patients with hyperglycemia and requiring intravenous insulin infusions in ICUs
	Mann et al., 2011.	Time spent within normal blood glucose range; Rates of hypoglycaemia.	Audit tool capturing time patients spent in target normoglycaemic range; Audit tool capturing incidence of hypoglycaemia.	Intervention group: CDSSs used to send alert messages to nurses to facilitate regular blood glucose management and insulin therapy. Control group: standard care protocol used to facilitate regular blood glucose measurements and appropriate managements.
	Meyfroidt et al., 2011.	Mean blood glucose level in normal range; Incidence of GPI and HGI and episodes of hypoglycaemia.	Audit tool capturing mean blood glucose levels; Audit tool capturing Glycaemic penalty index (GPI); Audit tool capturing Hyperglycaemic index (HGI); Audit tool capturing episodes of hypoglycaemia.	CDSSs used to send alert messages to nurses to facilitate regular blood glucose measurements and appropriate management.
Compliance with care bundles in Intensive Care Units	Kahn et al., 2014.	Nursing staff compliance with ICU care bundle;	Audit tools to measuring the compliance rates with ventilator care bundles;	Nurse-led EHR model used to support nurses to adhere to evidence-based practice and provide regular ventilator bundle care
	Zhang et al., 2024	Percentage of inaccurate vital signs documentations; Percentage of missed medication administrations; Percentage of incomplete nursing assessments	Medical records capturing the number of inaccurate vital signs, missed medication administrations and incomplete nursing assessment documentations	CDSSs working as quality control purpose used to send alerts to nurses to identify any inaccurate vital signs, missed medication administrations and incomplete mandatory nursing assessments
Incidence of ICU-acquired complications.	Kahn et al., 2014.	Ventilator-associated pneumonia rates;	Audit tools capturing incidence of ventilator-associated pneumonia rates;	Nurse-led EHR model used to support nurses to adhere to evidence-based practice and provide regular ventilator bundle care
	Ruesch et al., 2012.	Nursing staff compliance with VAP bundles, the deep vein thrombosis and peptic ulcer diseases bundles; Incidence of ventilator-associated pneumonia;	Audit tool capturing nursing compliance with ventilator-associated pneumonia bundles, deep vein thrombosis bundles and peptic ulcer disease bundles; Audit tool capturing rates of ventilator-associated pneumonia;	tele-ICU staffing models used to prompt nurses to adhere to evidence-based practice.

Table 3 (continued)

Patient safety	Author, Date,	Patient safety outcomes	Patient safety outcome measures	Processes of care
Compliance with screening for risks in Emergency Departments	Curtis et al., 2020	Compliance with risk assessments in EDs.	Completion rates of risk assessments (falls, pressure ulcers and substance use) in EDs.	Electronic health information record system used to prompt nurses to complete risk assessments.
	Legambi et al., 2021	Compliance with risk assessments for agitation in EDs	Completion rates of the behavioural activity rating scale (BARS)	The electronic health information record system used to facilitate the completion of risk assessments for agitation
	Lowenstein et al., 2023	Compliance with risk assessments for opioid misuse in EDs	Completion rates of the clinical opioid withdrawal scale (COWS) assessments	Electronic health information record system and CDSSs used to improve the completion rates of risk assessments for patients with opioid use disorders
Triage accuracy and interrater reliability	McLeod et al., 2020.	Triage interrater reliability.	Audit tool capturing Triage interrater reliability	eCTAS used to inform triage decisions
	Meer et al., 2012.	Triage interrater reliability.	Audit tool capturing triage interrater reliability	telehealth used to inform triage decisions
Safety of triage redirection process	Feral-Piers-sens et al., 2022	Safety of the redirection process	Medical records capturing the number of patients returned back to EDs unexpectedly within 48 h and within 7 days post redirection process	CDSS used for redirection process in triage for low-acuity patients in EDs
Length of stay and re-admission rates in critical care settings and hospitals	Levesque et al., 2015.	Length of ICU and hospital stay ; ICU & hospital readmission rates;	Medical record capturing ICU & hospital length of stay; Audit tool capturing ICU readmission rates ;	Electronic health information record system used to improve the information processing and workflow in ICUs
	Kahn et al., 2014.	length of ICU and hospital stay;	Medical record capturing ICU & hospital length of stay	Nurse-led EHR model used to support nurses to adhere to evidence-based practice and provide regular ventilator bundle care
	Ruesch et al., 2012.	ICU length of stay;	Medical record capturing ICU length of stay	tele-ICU staffing models used to prompt nurses to adhere to evidence-based practice.
	Zikos et al., 2014.	length of ED stay.	Medical record capturing ED length of stay	electronic health information record system used to improve information processing and workflow.
Mortality rates in critical care settings	Levesque et al., 2015.	ICU mortality rate.	Audit tool capturing ICU mortality rate	Electronic health information record system used to improve the information processing and workflow in ICUs
	Ruesch et al., 2012.	ICU mortality rate.	Audit tool capturing ICU mortality rate.	tele-ICU staffing models used to prompt nurses to adhere to evidence-based practice.

Note. ADDS = automated drug dispensing system; BARS = behavioural activity rating scale; CBPM = continuous bedside pressure mapping; CDSSs = clinical decision support systems; CGM = continuous glucose monitoring; COWS = clinical opioid withdrawal scale; ED = emergency department; eCTAS = electronic Canadian triage and acuity scale; EHR = electronic health record; GPI = glycaemic penalty index; HAPIs = hospital-acquired pressure injuries; HGI = hyperglycaemic index; ICU = intensive care unit; VAP = ventilator-associated pneumonia

Table 4 Summary of study characteristics

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
Ang et al., 2024 United States	Evaluate the accuracy of CGM devices compared with point-of-care blood glucose testing	Cohort study	CGM devices	In one of adult ICU	59 postoperative patients with hyperglycaemia and requiring intravenous insulin infusion	Post-intervention: 99.7% of the paired CGM glucose levels and point-of-care blood glucose testing fell within the Zone A and Zone B of the Clarke Error Grid which indicated a high accuracy CGM measurements for postoperative patients in ICUs 90% of time spent within the glucose targeted range by using the CGM devices
Armstrong, 2023 United States	Assess the impacts of standardised reporting system via the electronic health information record system on the development of HAPIs	Cohort study	Standardised reporting system via the electronic health information record system	In cardiothoracic ICU and neurologic ICU	Total 619 patients were analysed for HAPIs for 2 years	Pre-intervention period: from May 2018 to April 2019: total 1235 HAPIs were identified and from April 2019 to May 2020, total 1031 HAPIs were identified. Post-intervention period: From May 2020 to April 2021, there was total 631 HAPIs which was reduced by 38.8%. From May 2021 to April 2022, there was total 423 HAPIs identified which was reduced by 33%.
Behrendt et al., 2014. United States	Hypothesis: CBPM would improve efficiency of patients' repositioning, reducing HAPIs	Non-randomised experimental study	Pressure Ulcer Systems-CBPM	Medical ICU in a tertiary-care hospital.	422 patients (CBPM $n=213$; control $n=209$).	Significant reduction in development of Stage II pressure ulcers: CBPM group $n=2$ patients (0.9%); control group $n=10$ patients (4.8%); $p=0.02$.
Chapuis et al., 2010. France	Assess the impact of an ADDS on the incidence of medication errors related to picking, preparation, and administration.	Cohort study	Medication Administration Systems-ADDS	Two MICUs in a 2,000-bed university hospital. Both units (8 and 10 beds) had comparable activities and shared the same staff	68 nurses were observed. 1,476 medications were picked, prepared and administered.	No difference in % Total Opportunities for Error (TOE) identified between control and study units prior to ADDS implementation (19.3% TOE and 20.4% TOE respectively)).A Significant difference was observed in %TOE post ADDS implementation (18.6% and13.5% TOE, respectively; $p<0.05$). %TOE significantly decreased in the study unit pre and post ADDS (20.4% TOE pre-ADDS (Phase I) to 13.5% TOE post-ADDS (Phase II), $p<0.01$). Preparation dose errors decreased from 3.8–0.5% Detailed Opportunities for Error (DOE) ($p=0.017$) in the study unit. No reduction in picking or administration errors. Storage errors reduced post-ADDS (study unit pre $n=51$, 27.7%, post $n=2$, 0.7%; control unit pre $n=65$, 34.9%, post $n=27$, 14.4%; $p<0.01$). Most errors ($n=244$, 84%) caused no harm. ADDS implementation did not change the % of medication errors causing harm (Control = 0.6% DOE, study group = 0.7% DOE).

Table 4 (continued)

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
Curtis et al., 2020 Australia	Examine the impact of a consolidated electronic checklist on risk screening rates for falls, pressure ulcers and substance use.	Cohort study	Electronic health information record system	Four EDs in a regional health service, between November 2016 and February 2019.	A total of 33,561 ED presentations were analysed for the pre group and 35,807 for the post group	The proportion of patients who had all three screens completed increased from 1.3–5.5% ($p < 0.001$). Substance use screening increased from 1.7–12.4% ($p < 0.001$). Pressure ulcer risk screening increased from 38.6–41.7% ($p < 0.001$). When only patients aged 65 years and above were examined, the completion rate of pressure ulcer risk screening increased from 46.6% (pre) to 53.1% (post) ($p < 0.001$). In contrast, falls screening decreased from 38.0–32.6% ($p < 0.001$).
Feral-Pierssens et al.,, 2022 Canada	Assess the safety of a redirection process by triage nurses using CDSSs for low-acuity patients	Cohort study	CDSSs	A level 1 academic trauma centre	642 low-acuity patients redirected to nearby clinics	Post-implementation, among a total of 642 redirected low-acuity patients, there were 2.8% of the patients ($n = 18$) and 4.8% of the patients ($n = 31$) returned back to the ED unexpectedly within 48 h and within 7 days, respectively. There were no hospital admissions or deaths identified within 7 days among those redirected low-acuity patients.
Kahn et al., 2014. United States	Examine ICU care delivery and outcomes following nurse-led EHR use	Cohort study	Electronic health information record system	8 subspecialty ICUs in an Academic Medical Centre of a University Hospital	13,227 patients were included in the study. 4,339 (32.8%) in preintervention period, 8,938 (67.6%) in postintervention period.	Post EHR intervention, daily sedation interruptions increased (IRR, 1.57; 95% CI, 1.45–1.71; $p < 0.001$), daily spontaneous breathing trials increased (IRR, 1.24; 95% CI, 1.20–1.29, $p < 0.001$), mean ICU length of stay reduced (pre = 4.1 ± 5.4 days, post = 3.9 ± 5.0 days; $p = 0.005$) and hospital length of stay reduced (pre = 11.9 ± 12.5 days, post = 10.8 ± 11.2 days; $p < 0.001$). no difference found in Catheter-associated urinary tract infection (1.58 before, 1.77 after, IRR 1.12; 95%CI 1.20–1.29; $p = 0.63$), central catheter-associated bloodstream infection (0.72 before, 0.77 after, IRR 1.06, 95%CI, 0.58–1.94; $p = 0.84$), ventilator-associated pneumonia rates (3.24 before, 2.67 after, IRR 0.82 (95%CI, 0.57–1.19, $p = 0.30$), or hospital mortality (0.96 95%CI (0.84–1.09) $p = 0.54$).

Table 4 (continued)

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
Legambi et al., 2021 United States	Assess the impacts of an electronic behavioural activity rating scale (BARS) on risk assessments rates for agitation	Cohort study	Electronic health information record system	Beltimore Emergency department	Total 780 patients with behavioural and medical health presentations	Post-BARS implementation: of total 780 patients with behavioural and medical health presentations, nearly 65.77% patients ($n=513$) had BARS documented every 2 h. Agitation was also detected and documented for 206 patients ($n=26.41\%$) which indicated their BARS score 5 or 6 out of 7. Among those agitated patients, about 68% ($n=140$) of agitated patients' behaviours were reduced by nonrestraint interventions, including medications, de-escalation techniques and diversional activities. Total 18 episodes of restraint were used post-BARS implementation comparing to 20 episodes of restraint use pre-BARS implementation. Although there was no statistical significance regarding the incidence of restraint use post-BARS implementation, 75% of reduction was documented for patients who stayed with restraint more than one day in EDs post-BARS implementation ($n=8$ patients pre-BARS; $n=2$ patients post -BARS).
Levesque et al., 2015. France	Evaluate the effects of ICIS on the outcome of critically ill patients.	Cohort study	Electronic health information record system	15-bed Liver ICU of a University Hospital	1,397adult patients (BEFORE, $n=662$ and AFTER $n=735$)	Implementation of ICIS decreased the ICU length of stay (pre = 8.5 ± 15.2 days, post = 6.8 ± 12.9 days; $p=0.048$). No significant change to length of hospital stay (pre = 27.7± 34.6 days, post = 28.6±33.3 days; $p=0.79$), ICU readmission rate (pre = 4.4%, post = 4.2%; $p=0.86$), or mortality rate (pre = 11.2%, post-= 9.6%; $p=0.35$). However, observed mortality was significantly lower than predicted by SAPS II post ICIS (SMR 0.75; $p<0.001$).

Table 4 (continued)

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
Lowenstein et al., 2023 United States	Examine the impacts of an electronic clinical opioid withdrawal scale (COWS) on risk assessments rates for opioid misuse	Quasi-experimental study	Electronic health information record system and CDSSs	5 EDs including 3 intervention EDs and 2 control EDs under the same health systems	In the intervention group: total presentations were 2462. There were 1258 presentations pre-intervention period and 1204 post-intervention period. In the control group: total presentations were 731. There were 459 presentations pre-intervention period and 272 post-intervention period.	In the intervention EDs, the completion rates of COWS have been increased by 21.5% from 26% ($n=332$) in the pre-implementation periods to 48% ($n=577$) in the post-implantation periods in the intervention EDs (95% CI: 17.7 to 25.3). However, there were no statistically significant changes in the control EDs (9.6% ($n=44$) COWS completion rates pre-implementation; 14.3% ($n=39$) COWS completion rates post-implementation; 95% CI: -0.5 to 10).
Mann et al., 2011. United States	To determine the safety and efficacy of Clinical Decision Support Systems (CDSSs) to control serum glucose concentration in a burns intensive care unit	Randomised controlled trial	CDSSs	16-bed regional adult burn centre ICU responsible for the care of both military and civilian burn patients.	22 patients enrolled, but data reported on 18 patients as some did not complete the study.	Mean blood glucose levels in CDSS group were significantly lower than those in the paper protocol group (CDSS = 113 ± 10.2 mg/dL, paper = 119 ± 14 mg/dL; $p=0.02$). Time in BGL target range was significantly longer in the CDSS cohort (CDSS = 47 ± 17% time, paper protocol = 41 ± 16.6% time; $p<0.05$). Time over target range was not significantly reduced in the CDSS group (CDSS group: 49 ± 17.8% vs. Paper group: 54 ± 17.1%; $p=0.08$); and time less than 80 mg/dl was similar between groups (CDSS: 4.5 ± 2.8% vs. Paper protocol: 4.8 ± 3.3%; $p=0.8$). A total of four events of hypoglycaemia (< 40 mg/dl) occurred, two events in each study arm. No adverse clinical events were noted for any episode of low blood glucose level.

Table 4 (continued)

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
McLeod et al., 2020. Canada	To determine the interrater agreement of triage score pre- and post-implementation of eCTAS. Determine the triage time and accuracy pre- and post-implementation of eCTAS.	Cohort study	CDSSs	7 hospital EDs across Ontario, Canada.	A total of 1,491 individual patient triage assessments (752 pre-eCTAS, 739 post-implementation) were audited	Improvements in accuracy were observed across all triage categories post-eCTAS implementation. eCTAS significantly reduced the number of patients over-triaged (pre = 12.0%, post = 5.1%; 95% CI 4.0 to 9.7,) and under-triaged (pre = 12.6%, post = 2.2%; 95% CI 7.9 to 13.2), and this was consistent across all participating sites. Interrater agreement was higher post eCTAS. Aggregate unweighted κ pre-eCTAS = 0.63 (95% CI 0.58 to 0.68), post-eCTAS = 0.89 (95% CI 0.86 to 0.92); quadratic-weighted κ pre-eCTAS = 0.79; post-eCTAS = 0.93. Triage time was captured for 3,808 patients pre-eCTAS and for 3,489 post-eCTAS. Median triage time increased post eCTAS implementation (pre-eCTAS = 312 s, post e-CTAS = 347 s; 95% CI 29 to 40 s).
Meyfroidt et al., 2011. Belgium	Assess the impact of a computer-generated blood glucose alert, generated by a Patient Data Management System and superimposed on a paper-based guideline, on tight glycaemic control in the ICU.	Cohort study	CDSSs	56-bed, predominantly surgical ICU of a 1900-bed tertiary University Hospital.	Pre-alert cohort $n = 729$ adults admitted to ICU between 31/1/2007 and 31/7/2007, and alert cohort $n = 644$ adults admitted to ICU between 31/8/2007 and 6/2/2008.	CDSS significantly reduced mean blood glucose value per patient (pre-alert = 112 (105–122) mg/dl, post alert 110 (104–119) mg/dl; $p = 0.002$), and mean Glycaemic Penalty Index (GPI) (pre-alert = 20 (14–28), post-alert = 19 (13–26); $p = 0.029$). HGI also significantly reduced, pre-alert = 10 (5–17) mg/dl, post-alert = 9 (4–15); $p = 0.004$). The percentage of patients who experienced an episode of hypoglycaemia significantly declined from 6.5% ($n = 47$) pre-alert system to 4.0% ($n = 26$) post-alert system (ρ =0.043). The introduction of the alert did not result in a reduction in the HoGI (0.5 mg/dl in both groups).
Meer et al., 2012. Switzerland	Investigate the safety of computer-assisted telephone triage for walk-in patients with non-life-threatening medical conditions in an ED	Cohort study	Telehealth	Interdisciplinary Adult Emergency Centre of a University Hospital.	208 patients	The unweighted κ was 0.092 and the weighted κ was 0.115 between hospital physicians versus call centre nurses. The unweighted κ was 0.080 and weighted κ was 0.159 between primary care physicians and call centre nurses.

Table 4 (continued)

Author, Date, Country setting	Study objectives	Design/ Methods	Interventions	Setting	Participants	Key Findings
Ruesch et al., 2012. United States	Examine the impact of a nurse-implemented tele-ICU staffing model on patient complications and outcomes.	Cohort study	Telehealth	Adult Critical Care Unit	1308 patients	Overall ICU length of stay significantly decreased on a per day basis from 4.1 to 3.5 days ($p \leq 0.05$). Severity-adjusted mortality decreased the actual mortality compared with predicted mortality, indicating 22 lives saved. The incidence of VAP decreased by 13% related to a change in the median VAP from 2.99 in 2008 to 2.6 in 2009. Staff compliance with VAP bundle significantly increased, from 87.2–93.3% ($p = 0.02$). Compliance with patient deep vein thrombosis and peptic ulcer disease bundles demonstrated continuous improvement of 1%and 0.5%, respectively. These results were not statistically significant.
Zhang et al., 2024 China	Explore the impacts of the electronic health information record quality control system on the real-time data collection and quality control for nursing assessments and medication administrations	Cohort study	CDSSs working as quality control purpose	in one of the ICUs in China	Total 600 patients' cases were analysed	Post-intervention, the results demonstrated the significant improvements in the percentages of inaccurate vital signs documentations (decreasing from 9% pre-implementation to 1.33% post implementation, $p < 0.001$). The incidence of incomplete mediation administrations was reduced by 1.66% dropping from 3.33% pre-implementation to 1.67% post-implementation ($p < 0.001$). The prevalence of missed nursing assessments dropped down from 8% pre-implementation to 1.33% post-implementation ($p < 0.001$).
Zikos et al., 2014. Greece	Investigate the effect of an electronic trauma documentation system on ED length of stay	Cohort study	Electronic health information record system	Emergency department of a university hospital with a capacity of 950 beds	Control group paper-based documentation ($n = 99$) (Year 1), intervention group electronic documentation ($n = 101$) (Year 2).	Time between admission and completion of planned care was significantly lower in the intervention group (100 ± 92 min) than the control group (149 ± 29 min) ($p < 0.001$). A similar effect was found on the total ED length of stay (intervention group = 127 ± 93 min, control group = 206 ± 41 min in the control group; $p < 0.001$). Time between completion of care and discharge from the ED also significantly reduced (intervention 26 ± 10 min, control 57 ± 23 min; $p < 0.001$)

Note. ADDS = automated drug dispensing system; BARS = behavioural activity rating scale; CBPM = continuous bedside pressure mapping; CDSSs = clinical decision support systems; CI = Confidence Interval; CGM = continuous glucose monitoring; COWS = clinical opioid withdrawal scale; %DOE = the percentage of detailed opportunities for error; ED = emergency department; eCTAS = electronic Canadian triage and acuity scale; EHR = electronic health record; EMR = electronic medical record; GPI = glycaemic penalty index; HAPIs = hospital-acquired pressure injuries; HGI = hyperglycaemic index; HoGI = hypoglycaemic index; ICU = intensive care unit; ICIS = intensive care information system; IRR = incidence rate ratio; MICU = medical intensive care unit; %TOE = the percentage of total opportunities for error; VAP = ventilator-associated pneumonia

from 20.4% TOE pre-ADDS (Phase I) to 13.5% TOE post-ADS (Phase II) ($p < 0.01$) [37].

In the study group, the number of preparation dose errors was significantly reduced by 3.3% DOE, from 3.8% DOE pre-ADDS to 0.5% DOE post-ADS ($p < 0.05$) [37]. For the storage errors, compared to the pre-ADDS storage errors (51 in the study group and 65 in the control group), the reduction was significant in both groups post ADS introduction (2 and 27 respectively, $p < 0.01$) [37]. However, there were no differences recognised before and after the implementation of ADDS among the picking and administration process; omission and extra dose errors [37]. As for the severity of medication errors, no impacts from ADDS introduction were identified [37].

Glucose control in critical care settings

Hyper- and hypo-glycaemia are related to adverse patient outcomes. Three studies explored the effects of nursing informatics on glycaemic control in ICU [14, 43, 49]. Two studies utilised the CDSSs to detect critical blood glucose levels and send alert messages to ICU nursing staff [43, 49]. One study used Continuous Glucose Monitoring (CCM) devices to measure real-time glucose levels for hyperglycemic patients in ICUs [14].

Meyfroidt et al. [43] examined the effects of CDSSs on glucose control in ICU by using the pre-and post-intervention method. In contrast, Mann et al. [49] used a crossover randomised control trial to assess the impacts of CDSSs on glycaemic control and insulin therapy in a burns ICU compared to a paper protocol. This research focused on the time ICU patients spent in target normoglycaemic range [49].

Both studies reported that mean blood glucose levels were closer to normal range following the implementation of the CDSS. Mean blood glucose levels statistically significantly reduced ($p = 0.002$) [43]. The Glycaemic penalty index (GPI) and Hyperglycaemic index (HGI) also decreased significantly after introduction of CDSSs ($p = 0.029$; $p = 0.004$, respectively) [43]. Mann et al. [49] reported that mean blood glucose levels in the CDSS group were significantly lower than those in the paper protocol group ($p = 0.02$). There was also a significant increase in the time spent within normal blood glucose range when using the CDSSs ($p < 0.05$) [49].

Additionally, the percentage of patients who experienced an episode of hypoglycaemia in ICU significantly declined post-alert system ($p = 0.043$) [43]. However, there was no significant impact on Hypoglycaemic index (HoGI) and blood glucose sampling numbers [43]. In Mann et al.'s [49] study, there was also no significant difference regarding the time over and under the normoglycemic range ($p = 0.08$; $p = 0.8$, respectively) nor the incidence of hypoglycaemia (two incidents of hypoglycaemia in each group) between the CDSSs group and the control group.

Ang et al. [14] placed the CGM devices on the abdomen of postoperative patients with hyperglycemia who required intravenous insulin infusions in ICUs. They assessed the CGM glucose accuracy by comparing the CGM values with point-of care blood glucose testing [14]. The results showed that 99.7% of the paired CGM glucose levels and point-of-care blood glucose testing fell within the Zone A and Zone B of the Clarke Error Grid which indicated a high accuracy CGM measurements for postoperative patients in ICUs [14]. Patients spent 90% of time within the glucose targeted range when using the CGM devices [14]. The target range was not reported in this paper.

Compliance with care bundles in intensive care units

Two studies analysed nurses' compliance with care bundles in ICU following the introduction of tele-ICU models. The tele-ICU models involved experienced critical care nurses remotely providing guidance to bedside nurses to ensure appropriate nursing care was delivered to patients [39, 44]. ICU care bundles describe a 'package' of evidence-based interventions that should be undertaken to reduce hospital acquired infections and improve patient safety and outcomes [51]. Following implementation of the tele-ICU model, Ruesch et al. [44] explored staff compliance with care bundles including ventilator-associated pneumonia (VAP) bundles, deep vein thrombosis bundles and peptic ulcer disease bundles. While raw numerical data were not reported, the authors reported that nursing staff compliance with VAP bundles increased significantly post-tele-ICU ($p = 0.02$) [44]. Both the deep vein thrombosis and peptic ulcer disease bundles' compliance increased by 1% and 0.5%, respectively, but were not statistically significant [44].

Kahn et al. [39] also assessed compliance with ventilator care bundles following the introduction of both a nurse-led tele-ICU model, and an electronic health information record system. Daily sedation interruptions and spontaneous breathing trials were the focus of the study. There were dramatic increases in the percentage of patients receiving daily sedation interruptions ($p < 0.001$) and daily spontaneous breathing trials $p < 0.001$) post implementation of the tele-ICU model and electronic health record system [39].

Zhang et al. [11] explored the use of the CDSS on quality control outcomes, focusing on real-time data collection and quality control for nursing assessment and medication administration in one of the ICUs in China. Such a CDSS was aimed at reminding nurses to correct any inaccurate vital signs values that were automatically collected by the electronic health information record system [11]. It also sent alerts to ICU nurses to identify any missed medication administration and mandatory nursing assessments [11]. The results demonstrated significant improvements in the percentages of inaccurate vital signs documentation (decreasing from 9% pre-implementation to 1.33% post implementation, $p < 0.001$) [11]. The incidence of incomplete mediation administration was reduced by 1.66% dropping from 3.33% pre-implementation to 1.67% post-implementation ($p < 0.001$) and the prevalence of missed nursing assessments dropped down from 8% pre-implementation to 1.33% post-implementation ($p < 0.001$) [11].

Incidence of ICU-acquired complications

There were contradictory findings demonstrated by two studies examining outcomes from tele-ICU models. Kahn et al. [39] concluded that there was no difference

in ventilator-associated pneumonia rates following the introduction of tele-ICU and an electronic health record system. However, the incidence of ventilator-associated pneumonia reduced by 13% utilising the tele-ICU model in Ruesch et al.'s [44] study. Kahn et al. [39] also reported no statistical difference on other ICU-acquired complications, including catheter-associated urinary tract infection and central catheter-associated bloodstream infection.

Compliance with screening for risks in emergency departments

There were several articles that discussed the impacts of nursing informatics on risk screening assessments in emergency departments. Curtis et al. [38] examined how the electronic health information record system impacted risk-screening completion rates for falls, pressure ulcers and substance use in EDs. The study utilised the Waterlow pressure ulcer tool, substance use tools and fall risk screening tools to conduct risk assessments for all ED patients [38]. The tools were incorporated into the electronic health information record system and were required as one of essential nursing assessments [38]. After a one-year intervention period, the percentage of patients who had all three screening assessments carried out, significantly increased post-intervention (from 1.3% increased to 5.5% $p < 0.001$) [38].

Legambi et al. [46] implemented a Behavioural Activity Rating Scale (BARS) in the electronic health information record system in the ED to facilitate early detection of agitated patients and provide nonrestraint interventions in a timely manner to reduce the incidence of restraint use and subsequent injuries. Post-BARS implementation, from a total of 780 patients with behavioural and medical presentations, nearly 65.77% patients ($n = 513$) had BARS documented every 2 h [46]. Agitation was also detected and documented for 206 patients ($n = 26.41\%$) which indicated their BARS score was 5 or 6 out of 7 [46]. Among those agitated patients, about 68% ($n = 140$) of agitated behaviours were reduced by nonrestraint interventions, including medications, de-escalation techniques and diversional activities [46]. There were a total of 18 episodes of restraint use post-BARS implementation compared with 20 episodes of restraint use pre-BARS implementation [46]. Although there was no statistical significance regarding the incidence of restraint use post-BARS implementation, there was a 75% reduction for patients who were restrained for more than 24 h in EDs post-BARS implementation ($n = 8$ patients pre-BARS; $n = 2$ patients post -BARS) [46].

Lowenstein et al. [50] established a quasi-experimental study in five EDs including three intervention EDs and two control EDs under the same health system to examine how the electronic health information record system and CDSSs affected the screening rates of Clinical Opioid Withdrawal Scale (COWS) assessments for patients with opioid use disorder. In the intervention EDs, nurses utilised the electronic health information record system to recognise patients with opioid use disorder at triage [50]. Once the patients with opioid use disorder had been identified, CDSSs would be activated to facilitate nurses to conduct COWS assessments and prompt clinicians to initiate medication treatments for those patients [50]. The results demonstrated the COWS completion rates increased by 21.5% from 26% in the pre-implementation period to 48% in the post-implantation period (95% CI: 17.7 to 25.3) [50]. However, there were no statistically significant changes in the control EDs (9.6% COWS completion rates pre-implementation; 14.3% COWS completion rates post-implementation; 95% CI: -0.5 to 10) [50].

Triage accuracy and interrater reliability

McLeod et al. [41] utilised the electronic Canadian Triage and Acuity Scale (eCTAS) tool to evaluate the interrater reliability of triage scores before and after the implementation of eCTAS, as a proxy patient safety measure. The eCTAS is a real-time electronic triage decision support system designed to help triage nurses standardize the triage process in order to improve triage accuracy and therefore patient safety [41]. The study was conducted in seven different EDs in Ontario, Canada [41]. Interrater reliability was used as a measure to assess the level of agreement between different triage nurses and an auditor; who independently assigned triage scores for the same ED presentations [41]. The results showed that interrater reliability was higher with eCTAS [41]. This was described as 'nearly perfect agreement' between triage nurses and the auditor when using the eCTAS [41].

In contrast, Meer et al. [42] concluded that when using computer-supported telephone triage, the interrater reliability was low among the call centre nurses, hospital physicians and primary care physicians, with poor agreement among their triage scores [42].

Safety of triage redirection process

Feral-Pierssens et al. [48] analysed the safety of a redirection process by triage nurses using CDSSs for low-acuity patients. The CDSSs were implemented in the EDs to prompt triage nurses to potentially redirect low-acuity patients to nearby clinics for management based on specific inclusion criteria [48]. Post-implementation, among a total of 642 redirected low-acuity patients, there were 2.8% of the patients ($n = 18$) unexpectedly returned to an ED within 48 h, and 4.8% of patients ($n = 31$) unexpectedly returned to an ED within 7 days [48]. There were no hospital admissions or deaths identified within 7 days among those redirected low-acuity patients [48].

Length of stay and re-admission rates in critical care settings and hospitals

Four studies explored the impact of nursing informatics on length of stay in the critical care unit and in hospital [39, 40, 44, 45]. Levesque et al. [40] examined the influence of an Intensive Care Information System (ICIS) on patient length of stay. The ICIS was designed to improve the information processing and workflow in ICUs by collecting and storing all nursing care data, bedside monitoring data, ventilator data, laboratory results, fluid balance, medication prescriptions and administration [40]. During the study period, no handwritten paper documentation was utilised [40]. The results showed a statistically significant reduction in the length of stay in ICU post ICIS implementation ($p = 0.048$) [40]. However, there was no statistically significant difference in length of hospital stay ($p = 0.79$) [40]. Similarly, there was no statistical difference regarding ICU re-admission rates pre-ICIS implementation and post-ICIS implementation ($p = 0.86$) [40].

Kahn et al. [39] and Ruesch et al. [44] analysed the effects of nurse-led tele-ICU models on patient ICU and hospital length of stay. Both studies showed a significantly reduced length of stay in ICU following the intervention. Ruesch et al.'s [44] results indicated overall ICU length of stay significantly declined ($p \leq 0.05$). Length of ICU and hospital stay also significantly reduced post intervention in the study by Kahn et al. [39] (length of ICU stay: pre = 4.1 ± 5.4 days, post = 3.9 ± 5.0 days, $p = 0.005$; length of hospital stay: pre = 11.9 ± 12.5 days, post = 10.8 ± 11.2 days, $p < 0.001$ respectively).

A study in Greece investigated the impacts of an electronic trauma documentation system on length of ED stay [45]. The data indicated a dramatic and significant decline in the time between admission and completion of planned care for trauma patients in the ED post using electronic documentation systems ($p < 0.001$) [45]. Similarly, the total ED length of stay and the time between completion of care and discharge from the ED decreased significantly in the electronic documentation group, compared to the control group ($p < 0.001$, $p < 0.001$, respectively) [45].

Mortality rates in critical care settings

Intensive Care Information Systems (ICIS) and nurse-led tele-ICU models have been described above. According to Levesque et al. [40], there was no statistical difference in the mortality rate between the pre-ICIS implementation in ICU and post-ICIS implementation ($p = 0.35$). Similarly, there was no statistical change in the mortality rate found in a US study between pre-and post-intervention groups by using both nurse-led tele ICU model and electronic health record system in the ICU ($p = 0.54$) [39].

However, Levesque et al. [40] did calculate the standardized mortality ratio (SMR) between the actual number of deaths in one study group and the number of predicted deaths based on the Simplified Acute Physiology Score II (SAPS II) [40]. Following the implementation of ICIS, the observed mortality rates were much lower than predicted by SAPS II ($p < 0.001$) [40]. Ruesch et al. [44] also identified a decline in severity-adjusted mortality between expected and observed deaths, when using a nurse-led tele-ICU model, reporting a saving of 22 lives.

Discussion

This systematic review comprehensively explored the impacts of nursing informatics on patient safety in critical care settings. There were 17 high quality articles included in this review. Overall, patient safety results were positive. Nursing informatics were shown to facilitate nurses' adherence to evidence-based practice and improve the process of care, resulting in reduced errors and promoting patient safety outcomes. This included decreased incidence of pressure ulcers and medication errors; better controlled blood glucose levels; and reduced length of ICU stay [13, 14, 37, 39, 40, 43–45, 47, 49]. Patient safety outcome measures were also improved, including improved compliance with ICU care bundles and nursing assessments as well as overall screening completion rates for risks of pressure ulcers, falls, substance use and agitation in EDs [11, 39, 44, 46, 50].

Results are encouraging for reducing medication errors and HAPIs incidents. The benefits of an automated drug dispensing system (ADDS), continuous bedside pressure mapping (CBPM) systems and standardised reporting system via the electronic health information record system have been demonstrated in the studies [13, 37, 47]. Medication errors can result in serious harm, disability or death [52]. Patients in critical care settings are more vulnerable to serious harm arising from medication errors due to their complicated co-morbidities and limited physiological reserves [53].The ADDS has potential beneficial effects on reducing medication errors by enhancing the accuracy of medication preparation [37]. HAPIs are considered a preventable healthcare adverse event [54]. HAPIs can result in patients suffering unnecessary pain, potential infection, poor progress and decreased quality of life [55]. The CBPM system and standardised reporting system via the electronic health information record system can enable nurses to correctly identify and assess pressure injuries [13, 47]. Those systems could also provide regular pressure area care in critical care settings to dramatically reduce the incidence of HAPIs, subsequently reducing length of hospital stay, mortality rates and improving quality of life [13, 47]. The reduction in medication errors and HAPIs may decrease the financial burden on healthcare systems. Medication errors cost

approximately US$ 42 billion each year world-wide [52]. In Australia, approximately 2700 hospitalisations were associated with HAPIs in 2018 to 2019 and the estimated cost of those HAPIs was about AU$ 56,000 per admission [56]. The implementation of nursing informatics could potentially reduce those costly complications.

Glucose control has been enhanced by the CDSSs and CGM devices in ICU [14, 43, 49]. For critically ill patients, glucose control might be associated with a reduction in infection and mortality rates, and better clinical outcomes [49, 57]. By introducing the CDSSs and CGM devices, glucose control could be improved and well maintained [14, 43, 49].

The electronic health information record system, CDSSs and telehealth have been explored in multiple settings and shown to have significant impacts on length of stay, compliance with ICU care bundles and screening completion rates for risks of falls, pressure ulcers, substance use and agitations in critical care settings by improving the process of care and workflow [38–40, 44–46, 50]. Completion of screening assessments for falls, pressure ulcers, substance use and agitation in EDs are aimed at early detection of risk factors for specific complications, such as falls and withdrawal symptoms due to substance misuse [38, 46, 50]. Those complications could potentially prolong the length of ED stay which has been linked to increased 30-day all-cause mortality rates and delayed time to critical interventions [58]. ICU care bundles are considered as evidence-based practice that could prevent patients from hospital-acquired complications which could prolong the ICU length of stay [59]. The implementation of nursing informatics helped reduce the length of ED and ICU stays. With reduced ED and ICU length of stay, the patient flow of overcrowded EDs would be facilitated; financial costs, mortality rates and readmission rates could be lowered [58, 59].

Nursing informatics has changed the way we deliver healthcare. The electronic health information record system has made it easier for nurses to access patient information accurately and rapidly [45]. It also helped nurses prioritise their tasks and reduce time on documentation with more time spent on direct patient care [10]. The global nursing shortage, and specifically a shortage of skilled critical care staff increases the risk of negative patient outcomes including increased mortality rates and increased nosocomial infections [60]. With poor critical care nurse staffing levels, nurses might experience burnout and emotional exhaustion [60]. This phenomenon has been significantly aggravated during the Coronavirus (COVID-19) pandemic [60]. The use of nurse-led tele-ICU models could potentially address the real-time shortages of critical care nurses. The nurse-led tele-ICU model is a way of providing expert nursing support to a broader range of staff including both novice and advanced bedside nurses to facilitate adherence to evidence-based guidelines during patient care [39, 44]. Within the tele-ICU models, the remote teams could also monitor the patients haemodynamic conditions via the electronic health information record systems and prompt bedside nurses to provide relevant interventions to respond to patient deterioration, preventing complications [44]. The potential value of such a model should be realised and this nurse-led tele-ICU model should be implemented more widely.

However, the use of CDSSs for ED triage or redirection process of low-acuity patients was not clearly supported and is somewhat controversial. Although Feral-Pierssens [48] reported the rates of unexpected returns to any EDs within 48 h and within 7 days post implementation of redirection program, it was difficult to compare the results to other existing literature due to different redirection strategies. Interestingly, a very low interrater reliability was demonstrated by Meer et al. [42] among call centre nurses, hospital physicians and primary care physicians using telehealth triage. The decision-making process is complex and dynamic [61]. Rather than an emphasis on correct triage decisions, it is important to analyse the reasons behind inconsistent triage decisions between clinicians [61]. Further research in this area is necessary.

Limitations

This systematic review has limitations. There are confounders affecting the measurement of patient safety outcomes. For example, it is difficult to state categorically that nursing informatics were the *only* contributing factor to results such as length of stay, mortality rates and readmission rates. Other factors, such as other clinicians involved in healthcare delivery, can potentially reduce the adverse health problems and improve patient outcomes. There were 58 full-text papers that were unable to be retrieved. Although the authors attempted to contact the corresponding authors of those 58 papers, none were made available. This could cause potential selection bias. Also, only papers in English were retrieved in this systematic review, potentially missing key relevant work in other languages. The studies included in this systematic review involved various countries, reflecting different cultural contexts which might influence the impacts of nursing informatics on patient safety outcomes.

Conclusion

In this systematic review, the impacts of nursing informatics on patient safety in critical care settings were comprehensively analysed from high-quality papers. In critical care settings, nursing informatics has been associated with improved patient safety outcomes. Nursing informatics contributed to decreasing and preventing

adverse events in hospital which could reduce the financial burden on healthcare systems and redirect healthcare funding to promote patient safety. However, further research regarding the impacts of nursing informatics in various clinical settings should be considered, particularly involving more controlled clinical trials.

Abbreviations

ADDS	Automated Drug Dispensing System
BARS	Behavioural activity rating scale
CBPM	Continuous Bedside Pressure Mapping
CCU	Coronary Care Units
CDSSs	Clinical Decision Support Systems
CI	Continuous glucose monitoring
COWS	Clinical opioid withdrawal scale
%DOE	The percentage of Detailed Opportunities for Error
ED	Emergency Department;
Ectas	Electronic Canadian Triage and Acuity Scale
HER	Electronic Health Record
EMR	Electronic Medical Record
GPI	Glycaemic Penalty Index
HAPIs	Hospital-Acquired Pressure Injuries;
HDU	High Dependency Units;
HGI	Hyperglycaemic Index;
HoGI	Hypoglycaemic Index;
ICU	Intensive Care Unit;
ICIS	Intensive Care Information System;
IRR	Incidence Rate Ratio;
JBI	Joanna Briggs Institute;
MICU	Medical Intensive Care Unit;
RCTs	Randomised Control Trials;
SWiM	Synthesis Without Meta-analysis;
TIGER	Technology Informatics Guiding Education Reform;
%TOE	The percentage of Total Opportunities for Error
VAP	Ventilator-Associated Pneumonia

Supplementary Information

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Supplementary Material 1

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Declarations

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Author details
[1]Nursing & Midwifery, Monash University, Austin Health, Melbourne Room 2.32, Level 2, Building E, Peninsula Campus, 47 – 49 Moorooduc Highway, Frankston, Melbourne, VIC 3199, Australia
[2]Nursing & Midwifery, Monash University, Melbourne Room 2.63, Building E, Peninsula Campus, 47-49 Moorooduc Highway, Frankston, Melbourne, VIC 3199, Australia
[3]Nursing & Midwifery, Monash University, Melbourne Peninsula Campus, 47 – 49 Moorooduc Highway Frankston, Melbourne, VIC 3199, Australia

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