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Review

Review

Novel displays of patient information in critical care settings: a systematic review

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ABSTRACT

Objective. Clinician information overload is prevalent in critical care settings. Improved visualization of patient information may help clinicians cope with information overload, increase efficiency, and improve quality. We compared the effect of information display interventions with usual care on patient care outcomes.

Materials and Methods. We conducted a systematic review including experimental and quasi-experimental studies of information display interventions conducted in critical care and anesthesiology settings. Citations from January 1990 to June 2018 were searched in PubMed and IEEE *Xplore*. Reviewers worked independently to screen articles, evaluate quality, and abstract primary outcomes and display features.

Results. Of 6742 studies identified, 22 studies evaluating 17 information displays met the study inclusion criteria. Information display categories included comprehensive integrated displays (3 displays), multipatient dashboards (7 displays), physiologic and laboratory monitoring (5 displays), and expert systems (2 displays). Significant improvement on primary outcomes over usual care was reported in 12 studies for 9 unique displays. Improvement was found mostly with comprehensive integrated displays (4 of 6 studies) and multipatient dashboards (5 of 7 studies). Only 1 of 5 randomized controlled trials had a positive effect in the primary outcome.

Conclusion. We found weak evidence suggesting comprehensive integrated displays improve provider efficiency and process outcomes, and multipatient dashboards improve compliance with care protocols and patient outcomes. Randomized controlled trials of physiologic and laboratory monitoring displays did not show improvement in primary outcomes, despite positive results in simulated settings. Important research translation gaps from laboratory to actual critical care settings exist.

Key words: data display, information display, clinical decision support systems, electronic medical record, health information systems, user-computer interface, critical care, review

INTRODUCTION

Critical care settings are complex environments with demanding care requirements.[1] On average, each intensive care unit (ICU) patient receives 178 care interventions daily.[2] This challenging care environment fosters human error, experienced by 16% of ICU patients, leading to increased stay or mortality.[3–5] Human error in critical care settings may be in part due to the lack of information displays that effectively help clinicians cope with information overload by improving situation awareness and supporting clinical decision making.[6]

Current displays of complex data in critical care are suboptimal and have been designed with little attention to human factors.[7] The majority of current information systems in critical care require clinicians to manually access and integrate data from multiple sources and devices, which requires substantial cognitive effort.[6] For example, providers aggregate patient data from disparate modules in the electronic health record (EHR) and bedside monitoring devices. These data are then manually integrated into information that is used to understand the patient's situation and make care decisions.[8] Critical care providers report frustration with locating, customizing, and prioritizing data.[8] Current EHR systems have not been designed to support clinicians' high-level cognitive processes[9] and work environment.[7]

Prior literature reviews outside critical care[10,11] and ad hoc reviews in critical care[12–14] show promising evidence that improved information display can decrease human error. However, none of the prior reviews systematically evaluated the effect of critical care information displays on patient care. To address this gap, we conducted a systematic review of critical care information displays to (1) identify the types of critical care information displays evaluated in clinical settings and (2) synthesize the evidence on the effect of these displays on process and patient outcomes.

MATERIALS AND METHODS

The study methodology followed the Institute of Medicine Standards for Systematic Reviews[15] and the Preferred Reporting Items for Systematic Reviews and Meta-Analysis systematic review guidelines.[16] Study procedures were based on formal processes and instruments defined a priori by the authors, and refined based on input from an expert review panel.

Data sources

We searched PubMed and the IEEE *Xplore* Digital Library from January 1990 to June 2018 to identify graphical user interfaces developed for critical care or anesthesiology. The search strategy for each database was developed iteratively with calibration against a set of known references (see Supplementary Material for search strategies). The final PubMed search was conducted on June 11, 2018 and the final IEEE *Xplore* search was conducted on June 15, 2018.

Study selection

We included quasi-experimental and experimental studies that compared the effect of the information displays vs usual care on efficiency, healthcare quality, and cost outcomes in critical care or anesthesiology settings. We excluded studies about displays that presented a single variable, displays of standalone monitoring devices, and studies not published in English. Title and abstract screening were done independently and in duplicate. Disagreements were resolved through consensus among all study authors. If the abstract had insufficient information to make a confident decision the article was selected for full-text review. A similar process was followed for articles selected for full-text screening. To adjust for the unbalanced article set, we used a bias and prevalence adjusted kappa to calculate inter-rater reliability.[17]

Data extraction

We extracted study design, population, setting, participants, intervention (display characteristics), study design, and outcomes. A primary reviewer extracted the information and a second reviewer checked for accuracy. Disagreements were reconciled through consensus. Quality was appraised using a modified Newcastle-Ottawa Scale[18] for cohort studies. Scale criteria included representativeness, selection of comparison group, randomization, comparability, outcome follow-up, and outcome assessment.[18] Data extracted about the display intervention included target users, purpose for the display, and types of data displayed; display features included the amount of information displayed, types of plots used, use of color or animation, communication of urgency or importance, and organization of the information.

Data synthesis

Information displays were iteratively grouped into categories of similar displays. Findings were narratively summarized according to each display category. Due to heterogeneity in study design and endpoints we were unable to perform a meta-analysis. We categorized studies according to the primary outcome as positive (ie, significant improvement in at least 1 primary outcome), mixed (ie, significant improvement in any secondary outcome, but not in any primary outcome), or neutral (ie, no significant improvement in primary or secondary outcomes) clinical effects. We found no studies with significant worsening in primary or secondary outcomes. Key display characteristics that had positive outcomes were compared, contrasted, and summarized.

RESULTS

Trial flow

We identified 6742 potentially eligible studies from the literature search. Of these studies, 22 met the inclusion criteria for review (Figure 1). Inter-rater agreement was 0.86 for title and abstract screening and 0.78 for full-text review.

Study characteristics

Table 1 summarizes the included manuscripts and study designs. The majority of articles were published since 2014. Seventeen studies were conducted in ICUs, 4 studies were carried out in operating rooms, and 1 study investigated response to critical care events in general hospital wards. Study designs included 14 pre-post studies,[19–32] 5 randomized controlled trials (RCTs),[33–37] and 3 cohort studies.[38–40] All studies compared an information display intervention to usual care. Study duration ranged from 2 to 48 months. Primary outcomes included user satisfaction,[26] provider efficiency (eg, time to complete tasks),[20,36–39] process outcomes,[20,21,25,27,30,32,36,40] patient outcomes,[23–25,28,29,31,33–35,38,39] and cost (Figure 2 and Table 3).[19,22]

Quality of studies

We reviewed the quality of all the included manuscripts (Table 2). Twenty of the studies selected a comparison group from the same community.[20,21,23–25,27–31,33–41] All but 1 study had high (≥75% of the participants) outcome follow-up.[19–21,23–25,27–41] Seventeen of the studies had truly or somewhat representative sample groups.[20,21,23–25,27–31,33–37,40,41] Fourteen of the studies assessed the outcome in an objective manner.[19–21,23–25,28,29,33,36,38–41] Comparability to control groups and randomization was generally low, with only 7[33–39] and 5[33–37] studies meeting quality criteria respectively.

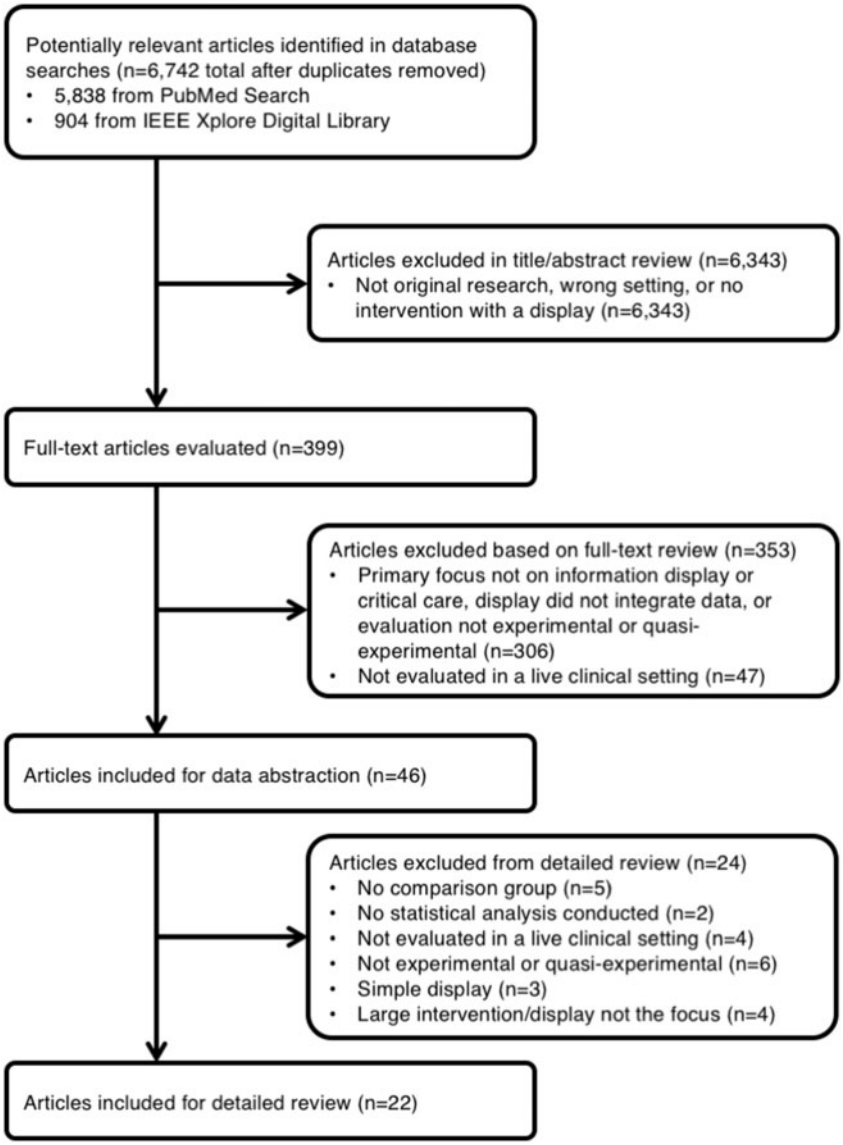

Figure 1. Trial flow.

Types of interventions

Information displays in the included studies were classified and analyzed according to 4 categories: comprehensive integrated displays,[26–30,37] multipatient dashboards,[20,21,23,25,31,32] physiologic and laboratory monitoring,[19,24,33–35,38,39] and expert systems (Figure 3 and Table 3).[36,41]

Comprehensive integrated displays combine information from different sources within EHRs (eg, medications, problems, vital signs, laboratory results) to support clinically meaningful grouping of related information. Rather than focusing on a specific disease or patient state, these displays provide a comprehensive view of a patient to improve situation awareness and communication (eg, information exchange in handoffs). Six studies evaluated 3 displays that organize information into clinically meaningful concept- and systems-based categories.[26–30,37]

Multipatient dashboards display multiple patients in a unit to improve compliance with standard care protocols, monitor progress toward treatment goals, and monitor critical care events. These displays were typically placed in a highly visible location, such as a wall next to the nursing station. Six studies evaluated multipatient dashboards to improve admission processes,[20] catheter care,[25] ventilator management,[23] glucose control,[21] and palliative care.[32] One study monitored patients' acuity scores for rapid response teams.[40]

Physiologic and laboratory monitoring displays included interventions that track parameters for a specific patient over time to help providers monitor trends, identify out-of-range values, and verify if certain parameters are within target goals. Unlike comprehensive integrated displays, physiologic and laboratory monitoring displays focus on specific disease states or body systems, such as "shock" or "cardiovascular." Examples include (1) a display that allows setting target goals and flags out-of-range values for cardiovascular monitoring[24]; (2) a graphical display of patient vital signs to achieve goal-directed therapy during anesthesia[33]; (3) a highly visible, shared display of cerebral perfusion for individual patients[34,35]; (4) a system that monitored anesthetic gas delivery and predicted drug concentration over time to support changes in anesthetic dosing[38,39]; and (5) a display of arterial blood gas results over time to reduce unnecessary arterial blood gas orders.[19]

Table 1. Characteristics of included studies

Type	Citation	Intervention	Participants	Location	Setting	Design	Duration (mo)
Comprehensive	Dziadzko et al, 2016[26]	AWARE—comprehensive viewer of ICU data organized by systems to support information management in the ICU	361 MD, NP, PA, RN, RT	AZ and FL, USA	ICU	Pre-post	14
	Pickering et al, 2015[37]		174 rounds	MN, USA	ICU	RCT	2
	Hoskote et al, 2017[27]		27 handoffs	MN, USA	ICU	Pre-post	Unknown
	Olchanski et al, 2017[28]		1839 patients	MN, USA	ICU	Pre-post	48
	Kheterpal et al, 2018[29]	AlertWatch OR—real-time data extraction from physiologic monitors and EHR displayed in schematic "live" view of organ systems	16 769 patients	MI, USA	OR	Pre-post	36
	Jiang et al, 2017[30]	Electronic handoff tool with organized free-text boxes	50 handoffs	NY, USA	ICU	Pre-post	5
Multipatient	Shaw et al, 2015[20]	Unit-wide dashboard of admission compliance to improve timeliness of compliance with quality and safety measures	450 patients	DC, USA	ICU	Pre-post	8
	Pageler et al, 2014[25]	Multipatient dashboard of CLABSI prevention measures to increase compliance with catheter care bundle and decrease CLABSIs	860 patients	CA, USA	ICU	Pre-post	39
	Lipton et al, 2011[21]	CDS for glucose control—current levels, trends, and protocols	667 patients	Netherlands	ICU	Pre-post	11
	Zaydfudim et al, 2009[23]	Multipatient dashboard of ventilator compliance to increase compliance with ventilator bundle and reduce VAP rates	11 216 ventilator d	TN, USA	ICU	Pre-post	42
	Bourdeaux et al, 2016[31]	Multipatient dashboard with visual cues when low tidal volume values are high	553 tidal volume time series	United Kingdom	ICU	Pre-post	48
	Cox et al, 2018[32]	Clinician and family-facing palliative care planner	78 patients, 67 family members, 10 clinicians	NC, USA	ICU	Pre-post	5
	Fletcher et al, 2018[40]	Multipatient dashboard with composite risk scores based on vital signs and laboratory results	6737 patient admissions	WA, USA	any hospital ward	N-Cohort	5
Physiologic and laboratory monitoring	Giuliano et al, 2012[24]	Horizon Trends—baseline target and range for any physiological parameter, and ST Map—highlights ST changes in ECG	74 patients	NH, USA	ICU	Pre-post	Unknown
	Sondergaard et al, 2012[33]	Display of patient cardiovascular data and trends in the context of target ranges to support anesthesia monitoring	27 patients undergoing major abdominal surgery	Sweden	OR	RCT	3
	Kennedy et al, 2010[39]	Predictive display of anesthetic gas concentration to support anesthetic delivery decision making	25 patients	New Zealand	OR	N-cohort	Unknown
	Kennedy et al, 2004[38]		15 patients, 13 anesthesiologists	New Zealand	OR	N-cohort	6
	Kirkness et al, 2008[35]	Highly visible CPP display to help clinicians quickly identify patients with low CPP	100 patients with cerebral aneurysm	WA, USA	ICU	RCT	22
	Kirkness et al, 2006[34]		157 patients with traumatic brain injury	WA, USA	ICU	RCT	22
	Bansal et al, 2001[19]	CDS for ABG ordering—ABG display over time	ABG lab tests ordered (average of 269/wk pre, 387/wk post)	TN, USA	ICU	Pre-post with parallel control	3
Expert system	Semler et al, 2015[36]	Integrated sepsis management tool	407 patients	TN, USA	ICU	RCT	4
	Evans et al, 1995[22]	HELP—CDS for antibiotic ordering	962 patients	UT, USA	ICU	Pre-post	20

ABG: arterial blood gas; AWARE: Ambient Warning And Response Evaluation; CDS: clinical decision support; CLABSI: central line-associated bloodstream infections; CPP: cerebral perfusion pressure; ECG: electrocardiogram; EHR: electronic health record; HELP: Health Evaluation through Logical Processing; ICU: intensive care unit; MD: medical doctor; NP: nurse practitioner; OR: operating room; PA: physician assistant; RCT: randomized controlled trial; RN: registered nurse; RT: respiratory therapist; VAP: ventilator-associated pneumonia.

Expert systems included interventions that use automated logic and patient parameters to recommend optimal decisions for specific conditions or care processes. Two studies evaluated expert systems to support care decisions for infectious diseases: an integrated sepsis management tool,[36] and a decision support tool for antibiotic ordering.[22] These systems integrate relevant information from various sources in the EHR and provide patient-specific treatment recommendations and optimal antibiotic therapy.

Effect of information displays on clinical care

Twelve of the 22 (55%) studies found significant improvement in at least 1 primary outcome (Table 3).[21,23,40,41,24–26,28,29,31,37,38] Information display types associated with significant improvement included comprehensive integrated displays (4 of 6 studies; 2 displays),[26,28,29,37] multipatient dashboards (5 of 7 studies; 5 displays),[21,23,25,31,40] physiologic and laboratory monitoring (2 of 7 studies; 2 displays),[24,38] and expert systems (1 of 2 studies; 1 display).[22]

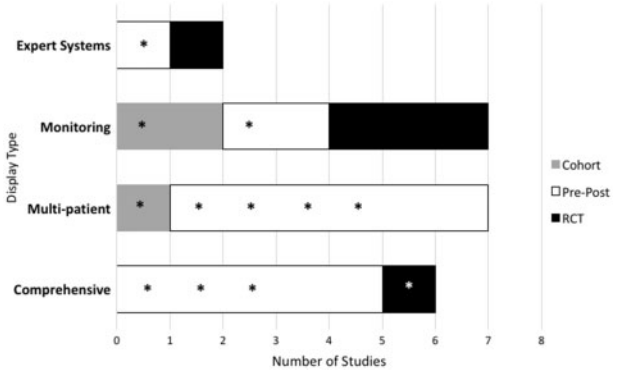

Figure 2. Summary of included manuscripts. Positive findings are marked by an asterisk. RCT: randomized controlled trial.

Overall, the strength of evidence on the effect of information displays on clinical care was low, with only 4 studies being RCTs.[33–37] Of the 4 RCTs, only Pickering et al,[37] 2015 found significant improvement. In this study, investigators designed a comprehensive integrated display that extracted high value from the EHR and organized by clinical concept. Additional information such as interventions, laboratory data, problem lists, and notes can be accessed on demand from the display. Participants who had access to the display significantly decreased preround data-gathering time from 12 to 9 minutes/patient ($P = .03$).[37] Most of the evidence supporting the benefits of information displays came from pre-post and N-cohort studies. Of the 14 pre-post 3 N-cohort studies, 11 (65%) found significant improvement.[21,23–26,28,29,31,38,40,41]

Kirkness et al[34] conducted an RCT with mixed results (ie, no difference in primary outcomes, but improved secondary outcomes). They investigated the effect of a multipatient dashboard of cerebral perfusion pressure over time on patient recovery 6 months after a traumatic brain injury episode.[34] There were no differences in primary outcomes related to patient recovery (Extended Glasgow Outcome Scale: 4.13 vs 4.37, $P = .389$; Functional Status Examination: 18.46 vs 19.02, $P = .749$). Yet, there was a significant improvement in odds of survival at discharge (3.82; $P = .03$).[34] Kirkness et al,[35] another RCT investigating the same display, assessed patient recovery 6 months after a cerebral aneurysm, and found no differences between the control and intervention groups (Extended Glasgow Outcome Scale: 4.16 vs 4.37, $P = .42$; Functional Status Examination: 19.78 vs 18.88, $P = .45$).

Table 2. Study quality

Type	Author, Year	Sampling	Comparison Group	Randomized	Comparability	Outcome Follow-Up	Outcome Assessment
Comprehensive	Dziadzko et al, 2016[26]	0	0	0	0	0	Subjective
	Pickering et al, 2015[37]	1	1	1	1	1	Subjective
	Hoskote et al, 2017[27]	1	1	0	0	1	Subjective
	Olchanski et al, 2017[28]	1	1	0	0	1	Objective
	Kheterpal et al, 2018[29]	1	1	0	0	1	Objective
	Jiang et al, 2017[30]	1	1	0	0	1	Subjective
Multipatient	Shaw et al, 2015[20]	1	1	0	0	1	Objective
	Pageler et al, 2014[25]	1	1	0	0	1	Objective
	Lipton et al, 2011[21]	1	1	0	0	1	Objective
	Zaydfudim et al, 2009[23]	1	1	0	0	1	Objective
	Bourdeaux et al, 2016[31]	1	1	0	0	1	Subjective
	Cox et al, 2018[32]	0	0	0	0	1	Subjective
	Fletcher et al, 2018[40]	1	1	0	0	1	Objective
Physiologic and laboratory monitoring	Giuliano et al, 2012[24]	1	1	0	0	1	Objective
	Sondergaard et al, 2012[33]	1	1	1	1	1	Objective
	Kennedy et al, 2010[39]	0	1	0	1	1	Objective
	Kennedy et al, 2004[38]	0	1	0	1	1	Objective
	Kirkness et al, 2008[35]	1	1	1	1	1	Subjective
	Kirkness et al, 2006[34]	1	1	1	1	1	Subjective
	Bansal et al, 2001[19]	0	0	0	0	1	Objective
Expert system	Semler et al, 2015[36]	1	1	1	1	1	Objective
	Evans et al, 1995[22]	1	1	0	0	1	Objective

Note: Studies were ranked 0 (poor) or 1 (high) for sampling (1 = representative), comparison group (1 = same community), randomization (1 = randomized), comparability (1 = matched cohorts, baseline data, or concealed allocation), and follow-up (1 = ¾ or more participants provided data). Studies were also classified as subjective or objective assessments.

Table 3. Key display features and study outcomes according to information display category

Type	Citation	Design	Key Features	Primary endpoint(s)	Result(s)	Effect
Comprehensive	Dziadzko et al, 2016[26]	Pre-post	High-value data, extracted from the EMR, are organized by clinical concept and displayed in patient-centered viewers; additional information including interventions, laboratory data, problem lists, and notes can be accessed; urgency of clinical problems displayed by color.	*Satisfaction*: User	Improved satisfaction in 13 of 15 questions compared with EHR functionality ($P<.05$).	Positive
	Pickering et al, 2015[37]	RCT		*Efficiency*: Time spent on pre-round data gathering per patient	Decreased time from 12 to 9 min ($P=.03$).	Positive
	Hoskote et al, 2017[27]	Pre-post		*Process*: Percentage agreement in tasks	No significant difference: 24.6% pre vs 31.3% post ($P=.1$).	Neutral
	Olchanski et al, 2017[28]	Pre-post		*Patient Outcome*: ICU mortality	No significant difference: 4.6% pre vs 3.4% post ($P=.33$).	Positive
				Patient Outcome: Length of stay in ICU	Decreased length of stay: 4.1 d pre vs 2.5 d post ($P<.0001$)	
	Kheterpal et al, 2018[29]	Pre-post	AlertWatch OR: real-time data extraction from physiologic monitors and EHR displayed in schematic "live" view of organ systems, color, text, and audible alerts.	*Patient Outcome*: Time MAP <55 mm Hg (hypotension)	Decreased: 2 min AlertWatch vs 1 min parallel control vs 1 min historical control ($P<.001$)	Positive
				Process Outcome: Inappropriate ventilation	Decreased: 28% AlertWatch vs 37% parallel control vs 57% historical control ($P<.001$)	
				Process Outcome: Median crystalloid infused (fluid resuscitation rate)	Decreased: 5.88 $mL \cdot kg^{-1} \cdot h^{-1}$ AlertWatch vs 6.17 $mL \cdot kg^{-1} \cdot h^{-1}$ parallel control vs 7.40 $mL \cdot kg^{-1} \cdot h^{-1}$ historical control ($P<.001$)	
	Jiang et al, 2017[30]	Pre-post	Electronic handoff tool with labeled free-text boxes for data entry; printout version includes the Handoff Tool and EHR data, such as medication orders and laboratory results.	*Process*: Mean content overlap index	No difference: 0.06 pre vs 0.06 post ($P=.75$)	Neutral
				Process: Mean discrepancy rate per hands-off group	No significant difference: 0.76 pre vs 1.17 post ($P=.17$)	
Multipatient dashboards	Shaw et al, 2015[20]	Pre-post	Unit-wide dashboard displays noncompliant patients for a set of safety measures.	*Process*: Median time from ICU admission to treatment consent	No significant difference at preimplementation (393 min), 1 mo postimplementation (304 min), and 4 mo post implementation (202 min) ($P=.13$).	Neutral
	Pageler et al, 2014[25]	Pre-post	Patient-specific, EHR-enhanced checklists, educational information on bundle items, and a unit-wide safety and quality dashboard. Color used to indicate noncompliant.	*Process*: Compliance with CLABSI prevention bundle (5 elements)	Increased compliance with daily documentation of line necessity (from 30% to 73%; $P<.001$); dressing changes (from 87% to 90%; $P=.003$); cap changes (from 87% to 93%; $P<.001$); and port needle changes (from 69% to 95%; $P<.001$). Decreased compliance with insertion bundle documentation (from 67% to 62%; $P=.001$).	Positive
				Patient outcome: Rate of CLABSI	Decreased rates from 2.6 to 0.7 per 1000 line-days ($P=.03$).	

(continued)

Table 3. continued

Type	Citation	Design	Key Features	Primary endpoint(s)	Result(s)	Effect
	Lipton et al, 2011[21]	Pre-post	Current glucose levels and trends for multiple patients along with protocol advice for insulin dosage.	*Process*: Compliance with glucose measurement time	Increased compliance from 40% to 52% ($P < .001$)	Positive
	Zaydfudim et al, 2009[23]	Pre-post	Multipatient dashboard of ventilator bundle compliance, ventilator status, deep venous thrombosis, and stress ulcer prophylaxis. Color used to indicate noncompliant.	*Patient outcome*: Rate of VAP	Reduced rates from 15.2 to 9.3 per 1000 ventilator d ($P = .01$).	Positive
	Bourdeaux et al, 2016[31]	Pre-post	Dashboard with visual cues for high TVes; multipatient display screens (mounted on the wall at either end of the ICU) showed red when TVe >8 and yellow when TVe >6.	*Process outcome*: Time it takes the TVe values to drop below threshold	Decreased time: 4.2 h pre, 1.4 h post year 1, 0.95 h post year 2, 0.66 h post year 3	Positive
	Cox et al, 2018[32]	Pre-post	Clinicians can access a dashboard that allows them to view a list of patients meeting automated palliative care triggers, approve a palliative care consult for any patient on the list, and review family-completed palliative care needs assessments adapted from the needs of the social nature, existential concerns, symptoms, and therapeutic interaction (NEST) scale.	*Process*: Mean ICU days before palliative care consult *Process*: Mean ICU days after palliative care consult *Process*: Mechanical ventilation days after palliative care consult *Secondary outcome*: NEST total unmet needs score	No difference: 3.6 d Intervention vs 6.9 d Control A ($P = .21$) No difference: 4.4 d Intervention vs 5.1 d Control A ($P > .05$) No difference: 7 d Intervention vs 9 d Control A ($P > .05$) Improved: Decrease in Intervention of 12.7 units vs Increase in Control B of 3.4 units ($P = .002$)	Mixed
	Fletcher et al, 2018[40]	N-Cohort	Customizable list of patients showing risk of decompensation and composite calculations based on vital signs and laboratory results including (1) a rapid response score and (2) a modified early warning score; scores are color coded to show 3 levels of risk severity.	*Process*: Number of first rapid response team activations *Process*: Number of unexpected ICU transfers	Significant increase: 71.5 while the display was off vs 86.0 while the display was on per 1000 admissions (IRR, 1.20; $P = .04$) No difference: 117 while the display was off vs 145 while the display was on (IRR, 1.15; $P = .25$)	Positive
Physiologic and laboratory monitoring	Giuliano et al, 2012[24]	Pre-post	Horizon Trends displays baseline target and range for any physiological parameter. ST Map highlights ST changes in ECG	*Patient outcome*: Mean arterial pressure *Patient outcome*: % of time MAP levels were within target levels	Increased MAP from 63.7 to 68.1 mm Hg ($P = .004$) Increased from 72.8% to 76.3% ($P = .031$)	Positive
	Sondergaard et al, 2012[33]	RCT	Graphical and numeric display of patient parameters and targets	*Patient outcome*: Mean percentage time MAP and CO in target zone averaged standardized difference	No difference: 36.7 (95% CI, 24.2%-49.2%) vs 36.5% (95% CI, 24.0%-49.0%) No difference, 1.5 (range, 1.1–2.3) vs 1.6 (range, 1.2–2.6).	Neutral
	Kennedy et al, 2010[39]	N-cohort	Anesthetic uptake model that predicts end-tidal sevoflurane and isoflurane concentrations	*Patient outcome*: Time to change in C_{eff} levels of sevoflurane	No difference, 220 vs 227 s (95% CI for the difference, –51 s to 32 s)	Neutral
	Kennedy et al, 2004[38]	N-cohort		*Patient outcome*; Time to change in end-tidal sevoflurane	Changes made on average 1.5–2.3 times faster ($P < .05$).	Positive

(continued)

Table 3. continued

Type	Citation	Design	Key Features	Primary endpoint(s)	Result(s)	Effect
	Kirkness et al, 2008[35]	RCT	Bars of CPP trend in different colors based on a threshold of 70 mm Hg and numeric display of current CPP.	*Patient outcome*: GOSE exam 6 months after injury	No difference, 4.16 vs 4.37 ($P=.42$)	Neutral
				FSE 6 months after injury	No difference, 19.78 vs 18.88 ($P=.45$)	
	Kirkness et al, 2006[34]	RCT		*Patient outcome*: GOSE score 6 months after injury	No difference, 4.13 vs 3.82 ($P=.389$)	Mixed
				FSE score 6 months after injury	No difference, 18.46 vs 19.02 ($P=.749$)	
				Secondary outcome: improved odds of survival at discharge	Odds ratio, 3.82 (95% CI, 1.13–12.92; $P=.03$).	
	Bansal et al, 2001[19]	Pre-post, parallel control	Patient ABG results graphed over time; color shading indicated abnormally high or low values; order entry for ABG ordered to promote less ordering and includes a variety of timing/urgency options	*Cost*: Ratio of number of ABG tests processed between intervention and control units	Nonsignificant ratio after adjusting for temporal variation in linear regression model ($P=.55$)	Neutral
Expert system	Semler et al, 2015[36]	RCT	Integrated sepsis management tool	*Process outcome*: Time from enrollment to completion of all items on 6-hour sepsis resuscitation bundle	No difference: hazard ratio, 1.98 (95% CI, 0.75–5.20; $P=.159$)	Neutral
	Evans et al, 1995[22]	Pre-post	Integrated display of infection parameters and antibiotic use recommendations	*Cost*: Average antibiotic per patient	Decreased from $382.68 to $295.65 ($P<.04$)	Positive

Outcomes were rated positive if any primary outcome significantly improved, mixed if any secondary but not primary outcomes significantly improved, and neutral if no difference was observed—no studies found an overall negative impact.

ABG: arterial blood gas; C_{eff}: estimates of past and future effect site; CI: confidence interval; CLABSI: central line–associated blood stream infection; CO: cardiac output; CPP: cerebral perfusion pressure; ECG: electrocardiogram; EHR: electronic health record; FSE: Functional Status Examination; GOSE: Extended Glasgow Outcome Scale; ICU: intensive care unit; IRR: incidence rate ratio; MAP: mean arterial pressure; RCT: randomized controlled trial; TVe: tidal volume; VAP: ventilator-associated pneumonia.

The remaining 2 RCTs, Semler et al[36] and Sondergaard et al,[33] had neutral findings. Semler et al[36] found no difference in time from enrollment to completion of a 6-item sepsis resuscitation bundle using an expert system for sepsis management (hazard ratio, 1.98; $P=.159$). Sondergaard et al[33] investigated a display of cardiovascular data to support physiologic monitoring in anesthesia during major abdominal surgery and found no effect on the percentage of time mean arterial pressure (36.7% [95% confidence interval, 24.2%-49.2%] vs 36.5% [95% confidence interval, 24.0%-49.0%]) and cardiac output were in the target zone (1.5 [range, 1.1–2.3] vs 1.6 [range, 1.2–2.6]).

DISCUSSION

We systematically reviewed the literature on the clinical effect of electronic information display interventions in critical care and anesthesiology settings. Seventeen information displays were evaluated in 22 studies. Six studies evaluated comprehensive integrated displays, 7 studies evaluated multipatient dashboards, 7 studies evaluated physiologic and laboratory monitoring displays of individual patients, and 2 studies evaluated expert systems that provide decision support recommendations for specific conditions. Although over half (12 of 22) of the studies found significant impacts on primary outcomes such as health care patient outcomes, process outcomes, efficiency, and cost,[21,23–26,28,29,31,37,38,40,41] inferences on the efficacy of critical care information displays are limited by low to moderate study quality. Of the 4 RCTs, 4 found no difference in primary outcomes between novel information displays and usual care.[33–36] In the following sections, we discuss the findings related to each type of display and compare and contrast the present review findings with a systematic review on similar information displays evaluated in simulated settings.

Comprehensive integrated displays

Four of the 6 studies in this category found positive effects in primary outcomes, including improved clinician satisfaction, improved provider efficiency in preparing for patient rounds, and decreased ICU length of stay. Since comprehensive integrated displays gather and present relevant data from multiple EHR sources in clinically meaningful structures, increased clinician efficiency and satisfaction is expected, possibly resulting from better support for high-level cognitive processing.

Multipatient dashboards

Five of the 7 studies in this category found improvement in process (eg, compliance with care protocols)[21,25,40] and patient outcomes

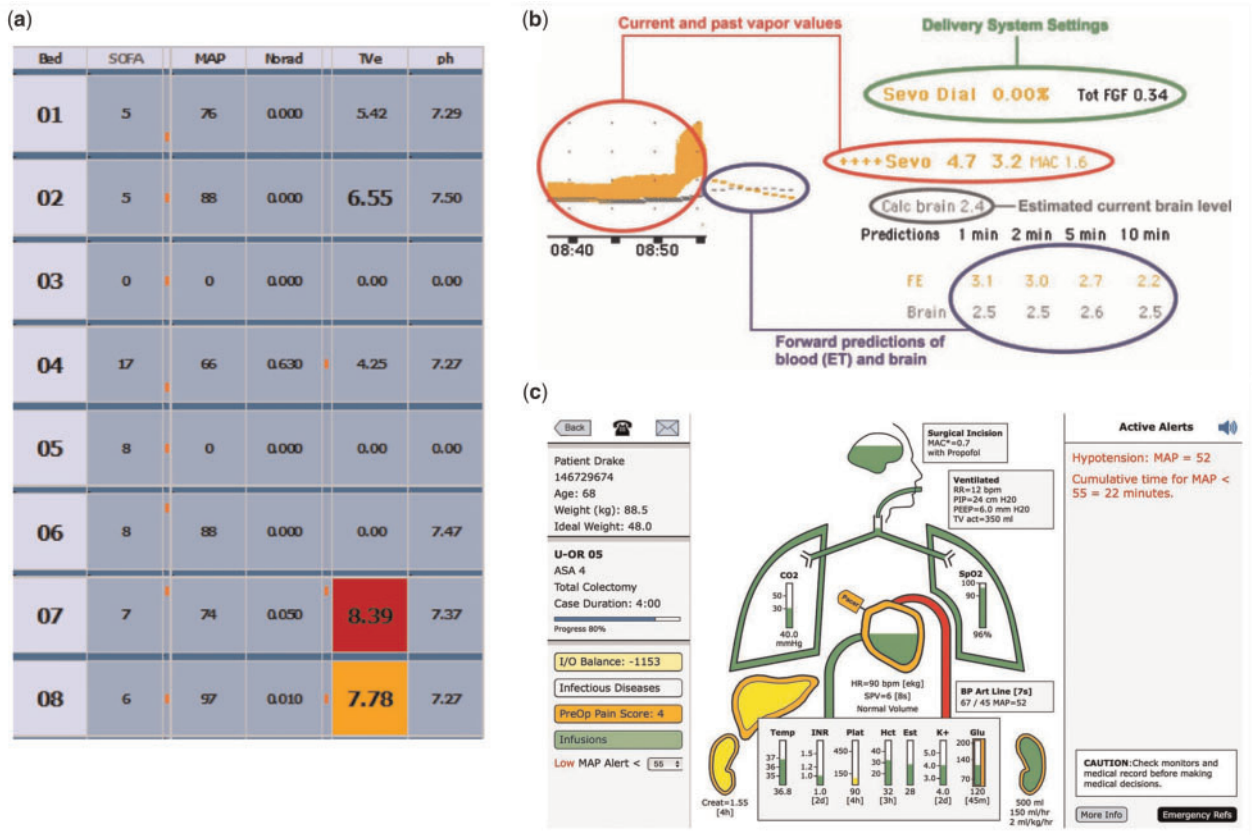

Figure 3. Example user interfaces: (A) multipatient,[31] (B) monitoring,[39] and (3) comprehensive.[29] Figures reprinted with permission.

(eg, reduced rate of hospital infections).[23,25,31] In light of distributed cognition theory,[42] multipatient dashboards may effectively help propagate the representational state of all patients in a unit regarding prespecified activities and goals. Although all 4 studies with positive outcomes used a pre-post or cohort design, the large effect sizes on important patient outcomes are compelling and warrant further investigation with stronger study designs.

Support for physiologic and laboratory monitoring

Two of the 7 studies in this category found improvements in surrogate quality outcomes, including increased percentage of time patients' mean arterial pressure was within target goals (72.8%-76.3%),[24] and decreased time to change in end-tidal sevoflurane (1.5–2.3 faster) in anesthesia settings.[38] Five studies, which included 4 RCTs and a pre-post with a parallel control, did not find significant changes in the primary outcome.[19,33–35,39]

Expert systems

Two studies investigated systems that provide automated, patient-specific treatment recommendations for specific conditions.[22,36] One pre-post study conducted in 1995 found cost reduction in antibiotic use (from $382.68 to $295.65 per patient) after introduction of an expert system that displays information relevant to infectious diseases and recommends most cost-effective antibiotic choices.[22] The other study (RCT design) found no difference in time from enrollment to completion of all items on a 6-hour sepsis resuscitation bundle.[36] With recent advances in machine learning and artificial intelligence, and emerging adoption of automated surveillance systems,[43–45] there may be an increasing and resurgent role for expert systems in critical care, perhaps as a component of comprehensive integrated displays and multipatient dashboards.

Comparison with studies in simulation settings

When comparing the evidence from studies conducted in clinical vs simulated settings, we found consistent findings in comprehensive integrated displays and translation gaps especially in physiologic and laboratory monitoring displays. Thirteen studies in simulated settings found benefits of comprehensive integrated displays in outcomes such as clinician efficiency, accuracy, and satisfaction (Wright MC, et al, unpublished data, 2018). On the other hand, despite simulation studies showing benefits of physiologic and laboratory monitoring displays using various trend representations, there was little similar evidence in clinical settings. Factors that may have contributed to the translation gaps above include lack of clinician adoption and technical implementation challenges. Authors of physiologic and laboratory monitoring display studies claim low clinician adoption may have compromised the observed effects.[34] Specific barriers included information availability lag time,[29] poor workflow integration,[36] availability of more familiar display options,[39,40] and insufficient experience with the new information displays. On the other hand, 2 studies attributed positive outcomes in part to workflow integration with established daily rounds.[30,32] Therefore, to be effective in clinical settings, it is possible that the various displays that support the monitoring of specific systems and disease states need to be integrated as a part of multipatient dashboards or comprehensive integrated displays. Interestingly, no studies on multipatient

dashboards were identified in simulated settings.[46] Research in simulated settings is needed to help design optimal displays, especially investigating more comprehensive dashboards that cover a larger set of care protocols.

Technical implementation challenges may have impeded the implementation of certain categories of information displays in real settings. Comprehensive integrated displays, in particular, require access to a variety of data from different sources in structured computable format, which is not easily accomplished in current closed-architecture EHR systems. The emerging adoption of more open architectures, based on standards such as SMART on Fast Healthcare Interoperability Resources, is creating opportunities to overcome implementation barriers.[46]

Strengths and limitations

To our knowledge, this is the first systematic review of information display interventions in critical care settings. We followed a standard systematic review process, which included a formal a priori protocol, systematic searching of multiple databases, independent article screening and abstraction by 2 raters, formal quality appraisal using a standard instrument, and integration with the findings of a systematic review focused on similar studies in simulation settings. Limitations include low to moderate quality of included studies, wide heterogeneity of information displays and study designs, which precluded a meta-analysis, and lack of assessment of publication bias, which could have partially contributed to the absence of negative results in the included manuscripts.

Implications for practice and future research

Future research should take measures to help close the gap between research done in laboratory and clinical settings. Implementation science frameworks may help ensure that potential barriers are identified and addressed early in the display design phase and through the implementation. In addition, investigators should take advantage of prevalent commercial EHR systems in U.S. academic medical centers to evaluate critical care information display innovations.[47] With the emerging adoption of interoperability standards that allow integration of external applications with EHR systems, information displays shown to be effective in laboratory settings can be integrated into providers' workflow and tested in multicenter experimental studies. With a much larger number of potential study sites, this EHR ecosystem can also help improve study quality, allowing randomized designs or at least long-term time series with parallel controls. Last, several innovations that have shown promising results in simulated settings still need to be evaluated in clinical settings.

CONCLUSIONS

We identified 22 studies that investigated information display interventions in critical care and anesthesiology settings. Display interventions included comprehensive integrated displays, multipatient dashboards, physiologic and laboratory monitoring, and expert systems. Although over half of the studies observed significant improvement in at least 1 primary outcome, only 1 of 4 RCTs showed significant improvement. Despite promising results both in laboratory and clinical settings, comprehensive integrated displays are relatively understudied. Multipatient dashboards seem to improve compliance to standard care protocols and achieve target treatment goals. Most studies on physiologic and laboratory monitoring displays did not produce positive effects, with low provider adoption raised as the most common explanatory factor. Limitations include overall low quality of the included studies and lack of a meta-analysis due to large heterogeneity in the information display interventions and study designs. Promising results found in a systematic review of information displays in simulated settings have largely not translated to clinical settings, possibly due to technical barriers. Investigators should leverage the evolving EHR landscape in U.S. medical centers to test novel information displays in clinical settings using well-designed study methodology.

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SUPPLEMENTARY MATERIAL

Supplementary material is available at *Journal of the American Medical Informatics Association* online.

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