Appendices

Supplementary Table S1 Summary of RQ-1 findings (dashboard implementation challenges) from previous systematic reviews

Supplementary Table S2 Summary of RQ-2 findings (successful methods) from previous systematic reviews

Supplementary Table S3 Summary of RQ-3 findings, part A (dashboard assessment methods) from previous systematic reviews

Supplementary Table S4 Summary of RQ-3 findings, part B (dashboard impact) from previous systematic reviews

Supplementary Table S5 PRISMA 2020 Checklist

Supplementary Table S6 Search strategy for the present review, optimised in Embase

Supplementary Table S7 Quality Assessment for Studies with Diverse Designs (QATSDD)

Supplementary Table S8 Summary of RQ-1 findings (dashboard implementation challenges) for our review

Supplementary Table S9 Study Outcomes Summary

Supplementary Table S10a and 10b Summary of RQ-2 findings (successful methods) for our review

Supplementary Table 1: Summary of findings pertaining to RQ-1 (dashboard implementation challenges) from seven prior review studies, stratified by the four elements of the 3-horizons model (see Figure 1); i.e., people, process, information and technology. Each challenge is marked with a '*' in the horizon column (1, 2 or 3) that the challenge relates to.

	Horizon			
	1	2	3	
People			*	1. Unintended consequences: The introduction of a dashboard may lead to greater clinician workload/cognitive load or risks to care
			*	2. Dashboard bias: The way in which information is presented may afect the decisions clinicians make, e.g. biases
			*	3. Care prioritisation concerns: incentivizing certain behaviors or outcomes at the expense of others.
			*	4. Tunnel vision: Only focusing on the aspects of performance that are measured, while at the same time displacing other important but unmeasured aspects of performance
			*	5. Measurement fixation: where explicit or implicit targets are set, an emphasis on meeting the target rather than the overarching purpose of care
			*	6. Clinicians choosing not to use dashboards - Dowding D, Randell R et al. (2015)
		*		7. Time require to learn system
		*		8. Training time - West VL, Borland D, Hammond WE. (2015)
			*	9. Resistance to change by clinicians - Buttigieg SC, Pace A, Rathert C. (2017)
			*	10. Clinician anxiety about electronic surveillance of their performance
			*	11. Information overload
			*	12. Insufficient stuff skilled in data analytics - Wilbanks BA & Langford PA (2014)
Process			*	13. Ethical concerns: Particularly related to big data and patient consent. The real-time collection of clinical information from day-to-day patient care might blur the lines between clinical practice and research
		*		14. High financial and human resources required to implement - Buttigieg SC, Pace A, Rathert C. (2017); (also - Auliya RS, Aknuranda I & Tolle H (2018)
			*	15. Different work environments require different metrics
		*		16. Organisation culture has to value objective, data-driven decision making - Wilbanks BA & Langford PA (2014)
		*		17. Setting standards: these may not exist in national benchmarks or guidelines, and therefore must be derived first - Buttigieg SC, Pace A, Rathert C. (2017)
Information		*		18. Amount of data and its display: The more data there is the more difficult it is to display
		*		19. Size and complexity of EHR data: for example distinguishing variables and temporal events
		*		20. Uncertainty of data: understanding the many variables that can lead to uncertain data in EHRs
	*			21. Data quality: missing values and inaccuracies
		*		22. Normalisation scheme need for aggregated numerical data in some circumstances - West VL, Borland D, Hammond WE.
		*		23. Data collection: although data is often in the EHR, there may be manual additions, integration with other data sources or manual transfers to the dasbhoard. - Buttigieg SC, Pace A, Rathert C. (2017)
		*		24. Lack of standardzied terminology used in EHR and lack of standardized definitions in KPIs
		*		25. Data is not always aggregated in meaningful formats - Wilbanks BA & Langford PA (2014)
Technology		*		26. Ability to use temporal data in visualizing aggregate data: important to users, but hard to display in an easy to absorb format
		*		27. Single screen view: how to present a great deal of data onto a single screen
		*		28. Summary to detail: Users want to see summary data, but drill down to a patient record. Linking the two can be difficult -West VL, Borland D, Hammond WE. (2015)
		*		29. real-time vs latent information: Establishing real-time data feeds is difficult Buttigieg SC, Pace A, Rathert C. (2017)
		*		30. Reliability and connectivity:
		*		31. Heterogenous data: how to unify heterogeneous data from separate applications with separate platforms, with a separate format. - Auliya RS, Aknuranda I & Tolle H (2018)
		*		32. Real time dashboards require timely input of data by clinicians
		*		33. Outcome measures of patient care are often not entered into the EHR in easy-to-retrieve formats
		*		34. Dashboards are less efficaceous for small data sets or measuring rare events because of increased variability - so smaller organisations less likey to benefit - Wilbanks BA & Langford PA (2014)

Supplementary Table 2: Summary of findings pertaining to RQ-2 (successful methods) drawn from Khairat SS, Dukkipati A, Lauria HA, et al. (2018) (as the only review synthesizing information on best practice methods). Each method is marked with a '*' in the horizon number column (1, 2 or 3) and an 'O' in the horizon category column (people, process, information and technology) for which the method may apply.

	Horizon Category & number							
RQ	People	Info.	Process	Tech.	1	2	3	Contributions of prior reviews to Research Questions
RQ-2: What successful methods have been used by healthcare organisations to overcome these challenges								
	O			O		*		1. Human centred design approach for dashboard look and functionality
	O			O			*	2. Interdisciplinary approach to developing, testing and implementing solutions
	O			O		*		3. Interactive prototyping to avoid design pitfalls
			O			*		4. Using open source to overcome cost vs adapting 3rd party vendor EHR
		O					*	5. Incorporating evidence-based, clinical practice guidelines to the dashboard to improve convenience for clinicians
				O		*		6. Clinician controlled selection menus and provision of preference settings for users
				O		*		7. Improved display of trends in physiological signs may improve clinician responsiveness
		O					*	8. Classification of data by body system helped clinicians to follow a systematic approach to optimizing the patient's holistic health

Supplementary Table 3: Summary of findings pertaining to RQ-3, part A (dashboard assessment methods) drawn from seven prior review studies, cited in the table.

RQ	Contributions of prior reviews to Research Question	Source
RQ-3a: How has clinical dashboard implementation been assessed?		
	1. Use of predetermined criteria and desired characteristics 2. Field testing in real-world settings 3. Obtaining user feedback 4. Establishing the usefulness to evaluate the effectivenes of clinical interventions 5. Notes that methods used to evaluate dashboards are not standardized	Wilbanks BA & Langford PA (2014)
	6. Cluster randomized controlled trial, designed to evaluate the effect of introducing the dashboard on patient outcomes (1 study) 7. Interrupted time series design to monitor the effect of introducing the dashboard on outcomes over time (2 studies) 8. Before-after studies (2 studies) 9. Non-comparative evaluations (2 studies) 10. Questionnaire surveys of users of dashboards (2 studies) 11. Usability study (1 study) 12. With two exceptions, the dashboards were evaluated in one organization, where they had been developed and implemented	Dowding D, Randell R et al. (2015)
	13. Qualitative evaluation conducted by observation (1 study) 14. Qualitative evaluation conducted by surveys (1 study) 15. Quantitative evaluation is done by questionnaires that examine various aspects, including ease of use, acceptability, decisional conflict, usefulness, feasibility, and effectiveness (1 study) 16. Applying a dashboard in different cases and test its effectiveness (1 study) 17. Accuracy of information (1 study) 18. Instruments used in the evaluation are TAM, UTAUT and dan WebQual	Auliya RS, Aknuranda I & Tolle H (2018)
	19. Errors per provider & adverse event count 20. Decreased time to task completion 21. Workload scores (NASA-TLX) 22. Risk of missing patient information 23. Brooke's Standardized Usability Tool to evaluate usability 24. Clinical decision-making accuracy 25. Decision making speed 26. Qualitative discussion of potential positive impact 27. Mental demand 28. Compliance with an evidence-based care 29. Time spent gathering data 30. Clinician satisfaction	Khairat SS, Dukkipati A, Lauria HA, et al. (2018)

Supplementary Table 4: Summary of findings pertaining to RQ-3, part B (dashboard impact) drawn from seven prior review studies, cited in the table.

RQ	Contributions of prior reviews to Research Question	Source
RQ-3b: How effective has their implementation been for healthcare organisations?		
	1. Minimise adverse events (8 studies)	Wilbanks BA & Langford PA
	2. Improve efficiency and quality (8 studies)	
	3. Dashboards designed to provide information to clinicians regarding prescription of antibiotics for respiratory infections were found to have no overall effect on prescribing rates	Dowding D, Randell R et al. (2015)
	4. A significant increase in the prescription of on-time antibiotics by anesthetists	
	5. Increased compliance with the ventilator bundle	
	6. A possible associated decrease in ventilator associated pneumonia in ICU settings	
	7. Increased recording of smoking status and health screening for diabetes, cardiovascular risk, cervical and breast cancer	
	8. Improvements in the time taken for radiology reporting	
	9. Improve clinicians' ability to find information effectively	
	10. May assist pharmacists to monitor adverse events associated with certain drugs	
	11. Overall, in some contexts, the use of dashboards appears to be associated with improved care processes and outcomes for patients	
	12. Nurses task completion times were nearly halved with integrated displays	Khairat SS, Dukkipati A, Lauria HA, et al. (2018)
	13. Clinical decision-making accuracy was higher	
	14. Reduced mental demand for clinicians	
	15. The median time from PICU admission to obtaining treatment consent decreased by 49%.	
	16. Patients with catheter in place >96 hours decreased from 16 to 11	
	17. Increased compliance and decreased adverse events	

PRISMA 2020 Checklist – "Towards a learning healthcare system: a systematic review and evidence-based framework for near real-time clinical analytics in a digital hospital"

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Background & Significance
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Research Questions and Objective
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Table 2
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Methods – 4.1
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Supplementary Table X6
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Methods – 4.3
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Methods – 4.3
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Methods – 4.3 & Supplementary Table X9
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Methods – 4.2/4.3
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Methods – 4.4 Quality assessment
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Supplementary Table X9
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Methods – 4.3
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N/A
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	N/A
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	N/A

PRISMA 2020 Checklist – "Towards a learning healthcare system: a systematic review and evidence-based framework for near real-time clinical analytics in a digital hospital"

Section and Topic	Item #	Checklist item	Location where item is reported
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/A
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	N/A
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	N/A
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Figure 3
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Figure 3
Study characteristics	17	Cite each included study and present its characteristics.	Table 3
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Supplementary Table X7 Quality assessment
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Results – 5.3 & Supplementary Table X9
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Table 3, Supplementary Table X7
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Results – 5.3
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N/A
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/A
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Supplementary Table X7
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/A
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Analysis of Prior Work – 3 Discussion – 6.1, 6.2
	23b	Discuss any limitations of the evidence included in the review.	Discussion – 6.4 Supplementary Table X7

PRISMA 2020 Checklist – "Towards a learning healthcare system: a systematic review and evidence-based framework for near real-time clinical analytics in a digital hospital"

Section and Topic	Item #	Checklist item	Location where item is reported
	23c	Discuss any limitations of the review processes used.	Discussion – 6.4
	23d	Discuss implications of the results for practice, policy, and future research.	Discussion – 6.3
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	N/A
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	N/A
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	N/A
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Acknowledgements
Competing interests	26	Declare any competing interests of review authors.	Conflict of Interest
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	N/A

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

For more information, visit: http://www.prisma-statement.org/

#8	#1 AND #5 AND #6 AND #7
#7	analytic* OR data OR dashboard
#6	realtime OR 'real time'/exp OR 'real time'
#5	#2 OR #3 OR #4
#4	'electronic patient record*' OR 'computerized patient record*' OR 'computerised patient record*'
#3	'electronic health record'/exp OR 'electronic medical record system'/exp OR 'electronic patient record'/exp
#2	'computerized medical record*' OR 'computerised medical record*' OR 'electronic health record*' OR 'electronic medical record*' OR emr OR ehr
#1	'inpatient'/exp OR inpatient OR 'in patient'/exp OR 'in patient' OR 'in hospital' OR hospitalized OR hospitalised

NB/ Additional search conducted & reviewed for articles missed in above strategy	dashboard:ti AND (realtime OR 'real time'/exp OR 'real time')

Supplementary Table 6: Search strategy for the present review, optimised in Embase.

Supplementary Table 7: Quality Assessment for Studies with Diverse Designs (QATSDD)

Author	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14	Item 15	Item 16	Score	%
Mlaver et al	1	2	2	0	1	2	2	1	N/A	N/A	1	2	1	0	2	3	20/42	48%
Fletcher et al	1	2	3	3	2	2	1	3	2	2	N/A	3	2	N/A	1	3	30/42	71%
Cox et al	1	2	3	0	2	2	0	2	3	3	N/A	3	1	N/A	2	3	27/42	64%
Franklin et al	3	2	1	0	1	1	1	0	N/A	N/A	1	1	0	0	1	2	14/42	33%
Ye et al	2	3	3	2	2	3	3	3	3	2	N/A	3	2	N/A	0	2	33/42	79%
Yoo et al	1	2	3	0	2	1	2	2	N/A	N/A	2	2	2	0	3	3	25/42	60%
Schall et al	1	2	2	2	1	3	3	1	0	1	2	2	2	1	3	3	29/48	60%
Fuller et al	1	2	3	2	1	3	1	2	2	2	2	2	3	3	2	3	34/48	71%
Merkel et al	0	1	2	0	0	0	0	0	0	0	N/A	0	0	N/A	0	0	3/42	7%
Kurtzman et al	2	2	3	0	1	3	1	2	2	1	2	1	1	2	0	2	25/48	52%
Staib et al	1	1	3	0	0	0	0	0	0	0	N/A	0	0	N/A	0	2	7/42	17%
Bersani et al	1	2	3	1	2	3	3	2	1	2	2	2	2	1	2	3	32/48	67%
Ibrahim et al	1	3	3	0	1	1	0	0	1	1	N/A	1	1	N/A	2	1	16/42	38%
Paulson et al	1	1	2	0	3	0	0	2	0	1	N/A	1	0	N/A	2	2	15/42	36%

Item 1: Explicit theoretical framework
Item 2: Statement of aims/objectives in main report
Item 3: Clear description of research setting

Item 4: Evidence of sample size considered in terms of analysis
Item 5: Representative sample of target group of a reasonable size
Item 6: Description of procedure for data collection
Item 7: Rationale for choice of data collection tool(s)
Item 8: Detailed recruitment data
Item 9: Statistical assessment of reliability and validity of measurement tool(s) (Quantitative studies only)
Item 10: Fit between research question and method of data collection (Quantitative studies only)
Item 11: Fit between research question and format and content of data collection tool e.g. interview schedule (Qualitative studies only)
Item 12: Fit between research question and method of analysis (Quantitative studies only)
Item 13: Good justification for analytic method selected
Item 14: Assessment of reliability of analytic process (Qualitative studies only)
Item 15: Evidence of user involvement in design
Item 16: Strengths and limitations critically discussed

Supplementary Table 8: Summary of findings pertaining to RQ-1, for our review

	Horizon 1	2	3	
People			*	1. Perception of dashboard as not an integral part of the rounds (clinical workflow) - Mlaver et al. 2017
			*	2. Determining actionable information to include in dashboard for real-time decision making to improve overall flow of dept (i.e not historical data e.g. LOS)
			*	3. Ability to integrate cognitive processes of staff with requirements of the work domain
			*	4. Use in unanticipated ways to gain insight before start of shift -- Franklin et al. 2017
		*		5. Physicians not having enough info in dashboard on pats they were rounding on
		*		6. RNs only wanted display of patients within their units -- Schall et al 2017.
		*		7. lack of awareness of all dashboard features/functionality -- Fuller et al. 2020
		*		8. Required IT sources -- Merkel et al. 2020
			*	9. Lack of time in resident schedule -- Kurtzman et al 2017
			*	2017
			*	11. Clinician Acceptance -- Paulson et al 2020
Process			*	12. Uncertainty on who should take responsibility for flagged items.
		*		13. Difficulty with providers buying into the tool at the beginning of the study due to accessing issues & bugs. Although many of these issues were addressed many providers were discouraged by their initial impressions.
			*	14. Persistent cultural issues about ownership of certain patient safety issues (e.g., physicians considering prevention of pressure ulcers as a nursing concern) deterred use.
		*		15. Changing implementation environment: there were different cultures, for example, rounds were conducted differently..., rounding structure and team size varied, and physician personnel varied month to month, leading to variation in use.
			*	16. Disagreements about what patient status necessitated a red/yellow/green/gray and these issues warranted discussions around our logic -- Bersani et al. 2020
		*		17. Time constraint. Collaboration across departments involves developing a shared mental model, which can involve a significant time investment. In the midst of an infectious disease outbreak that limited group meetings and physical interaction, it was difficult to assemble team of people to map and refine the requirements -- Ibrahim et al. 2020
			*	18. More frequent scanning would lead to increased numbers of patient rescues but at the expense of more alerts
			*	19. Counterintuitive nature of an alert based on the AAM score. Unlike other scores or code blues, which mandate an immediate response and in which the consequences of clinician actions are readily apparent, AAM was specifically calibrated to give 12 hours lead time. This means that when clinicians first see the patient it may appear that nothing is wrong, and when they intervene successfully it appears that nothing happened. Thus, paradoxically, successful detection and early intervention are not as evident as in those deteriorations in which the system did not issue an alert. -- Paulson et al. 2020
Information		*		20. EHR data recorded in diff applications/platforms/formats/locations with diff. data formatting (free-text, coded data, file formats)
		*		21. Need for bioinformatician to extensively code
Technology		*		22. Lag time loading dashboard (+ Franklin et al. 2017 + Fuller et al. 2020, Bersani et al. 2020)
		*		23. Dashboard is too "long" -- Mlaver et al. 2017
		*		24. Extraction of data in diff formats & conversion into common format for dashboard -- Cox et al, 2017
		*		25. Shifting time scales (goals for each stage may vary e.g. 10mins in triage vs 10h for inpatient bed) - dashboard can't be aligned on single shared time scale
		*		26. Understanding variability (design to emphasise binary adherence e.g. in or out of desired goal vs degrees of violation e.g. mins over threshold)
		*		27. Presenting diff types of data in readily-understandable format
		*		28. Interfaces need to accomodate diverse users/workflows/screen sizes/input devices
		*		29. Physical layout variation across facilities - dashboards not consistently accessible -- Franklin et al. 2017
		*		30. structural change to one site's ED (isolation room due to MERS outbreak) - needed reflecting in dashboard -- Yoo et al. 2018
		*		31. Making report dynamic enough for each user role
		*		32. Include additional quality indicators and patient warning 'flags'
		*		33. Touch screen preferred
		*		34. Display needs to be devoid of visual clutter -- Shall et al 2017
		*		35. Hard to assess dashboard use via logins, rather than sys. logins, where the user didn't use the dashboard -- Bersani et al. 2020
		*		36. EHR does not have radiology reading capability, which precludes the inclusion of important chest x-ray or CT scan results in calculating the severity score.
		*		37. Dashboard initially required manual updates that occurred every 2-3 hours during the daytime and physicians were not able to perform a display refresh when needed, which substantially limited its use, particularly after working hours -- Ibrahim et al. 2020

First author (year) & Country	Study Design	Health Care Settings	Target Population	Sample Size	Duration/Time	Target User	Intervention/s	Clinical Care Outcome Measures	Clinical Process Outcome Measures	Algorithm sensitivity/ specificity	Anecdotal evidence	Implementation	Main Findings
Mlaver et al (2017) USA	Cross-sectional	Tertiary academic hospital bed: 793	Inpatient	n=98 (patients) n=6 (participants)	pre (development) =16 months post (pilot)=1 week	The rounding team (nurse, residents, intern)	The PSLL Patient Safety Dashboard provided real-time alert/notification to the rounding team. When the patient's situation meets the safety logic criteria, the patient will be flagged on the dashboard with different colour coding.	N/A	Health-ITUES (Technology Usability Evaluation Scale) survey	N/A	N/A	Patient-level and unit-level dashboards integrated into EHR, fostering interdisciplinary bedside rounding.	The patient safety dashboard during the study hasn't been fully implemented into production. The dashboard was still in the production pilot stage when this paper was written. Hence, there was no measurement performed for the clinical outcome. Health-ITUES results: 'High perceived usability' – 3.9/5 'High ease of use' – 4.8/5 Lowest scoring item – 'dashboard is important part of rounding process' - 3.17/5
Fletcher et al (2018) USA	Repeated measures design	Acute Care ward of an academic medical centre bed: 413 annual admission: 19,000	Inpatients aged ≥18 years	n=6,736 (eligible admissions)	pre (pilot phase) =2 months post (assessment) =20 weeks	RRT (Rapid Response Team)	Provided the visibility to timely and accurate critical patient safety indicator information for multiple patients. Allowed clinician decision making and response to the RRT activations, unexpected ICU transfers, cardiopulmonary arrests. Dashboard visualised all hospital patients in real-time and ranked by the severity score.	Measured the reduction for unexpected ICU transfers, unexpected cardiopulmonary arrests and unexpected deaths. Incidence ratio of all RRT activations	N/A	N/A	N/A	User interface in the pre-existing EHR to provide real-time information.	The RRT dashboard is a tool to help providers recognise patient decompensation and may improve initial RRT notification. The dashboard minimised the alert fatigue by way of warnings on the dashboard to highlight the risk. A total of 774 RRT activations occurred, with 426 activations (122.1 per 1000 admissions) while the dashboard was on and 348 (107.2 per 1000 admissions) while the dashboard was off (incidence rate ratio (IRR) = 1.14, p = 0.07). Main findings include: 1. Significant increase of IRR for first RRT activations 2. No significant difference in IRR for overall/subsequent RRT activations 3. No difference to clinical care outcome (No significant differences in unexpected ICU transfers (IRR = 1.15, p = 0.25), cardiopulmonary arrests on general wards (IRR = 1.46, p = 0.43), or deaths on

													general wards (IRR = 0.96, p = 0.89).
Cox et al (2017) USA	Prospective Cohort Study	Tertiary academic hospital	Inpatient >=18 years and does not have history of cardiac transplantation, left ventricular assist device, or end-stage renal disease.	n=366 (patient - initial validation cohort study of individual identifiers), n=150 (random cohort patients - second validation cohort study of HF algorithm)	post (initial cohort) =6 months post (random cohort) =3 months	Heart failure providers (cardiologist, nurse practitioner, pharmacist)	The heart failure dashboard provided the list of patients with heart failure diseases and described their clinical profiles. Providers could review a patient's primary team, HF identification criteria, clinical variables and medical therapies using a colour-coded system. A longitudinal linking of patient metrics is provided.	N/A	N/A	Automatically identify the heart failure admissions & assess the characteristics of the disease and medical therapy in real time.	N/A	Dashboard created and directly linked within the EHR	The heart failure (HF) dashboard was previously implemented to Production before the study. The study evaluated the implementation of fully automated heart failure identification algorithm and clinical characterisation performance of the dashboard after 26 months of implementation. The algorithm demonstrated a high specificity (95%) yet limited sensitivity (56%).
Franklin et al (2017) USA	Cross-sectional	Training and academic hospitals, community hospitals, private hospitals	Emergency (ED) encounter	formative post n=19 (participants)	pre-design n=400 hours of observation (at least 75 hrs of observation per facility)	Clinicians, Medical directors, ED directors, charge nurses	The dashboard visualisations increased situation awareness and provided a snapshot of the department and individual stages of care in real-time.	N/A	N/A	N/A	Anecdotal evidence - formative assessments were undertaken prior to implementation, and limited post deployment outcome.	Prototype dashboards released in stages for evaluation	Presented to clinicians within 11 EDs. 19 participants provided feedback regarding to the usability of the dashboard and potential challenges in implementation (e.g. concerns regarding lag times). 172 interventions were implemented as the outcome of the evaluations. Results limited to log data, frequency of use, collected anecdotal evidence and eye tracking data.
Ye et al (2019) USA	Retrospective and prospective cohort	Two acute care Berkshire Health System hospitals	Inpatient	n=54,246 - retrospective cohort (n=42,484) - prospective cohort (n=11,762)	pre=2 years post=9 months	Clinicians	The Early Warning System (EWS) provided real-time alert/notification to clinicians when the patient's situation met with the predefined thresholds and risk scores. The algorithms provided real-time early warning of mortality risk in a health system with pre-existing EHR.	N/A	N/A	Evaluated the machine learning algorithms by identifying high risk patients; and alerting staff for patients with high risk of mortality	N/A	EWS embedded in existing EHR system	In the prospective validation, the EWS prospectively attained a c-statistic of 0.884, where 99 encounters were captured in the highest risk group, 69% (68/99) of whom died during the episodes. The possibility of death for the top 13.3% (34/255) of the patients were predicted at least 40.8 hours before death. The study had limited evidence to conclude whether the EWS had an effect on the reduction of patient mortality.

													There was limited discussion on visualisation/dashboard of the EWS.
Yoo et al (2018) Korea	Cross-sectional	Tertiary teaching hospital Annual Visit Volume: 79,000 Inpatient Bed: 2,000	Emergency Encounter	n=52 (participants)	pre=5 years post=41 days	Physicians, Nurses	The development and implementation of a dashboard which: 1. visualised the geographical layout of the department and patient location; and 2. visualised patient-level alert for workflow prioritisation; and 3. provided real-time summary data about ED performance/ state	N/A	Evaluation based on the throughput factors of a conceptual model of ED; Survey questionnaire include: 1. System Usability Scale (SUS) 2. Situational Awareness Index (SAI), composed based on Situation Awareness Rating Technique (SART)	N/A	N/A	A separate electronic dashboard outside EHR was developed and displayed on mounted monitors and PCs. A separate dashboard for patients and families was implemented using wall-mounted monitors, kiosks, and tablets.	The ED dashboard during the study hasn't been fully assessed for clinical outcomes and process effectiveness. The ED dashboard was in production for 5 years, but there was no obvious validated outcome of clinical and process effectiveness. The study was focused on the ED dashboard's usability and obtained a score of 67.6 points from physicians and nurses and indicated "marginally high acceptability" with "OK-to-Good usability." However, clinical staff found it distracting, taking attention away from the important tasks of the ED. The quality of the information provided by the dashboard was rated high; however, the quantity of information was rated relatively low.
Schall et al (2017) USA	Cross-sectional	Medical Centre (11 inpatient units)	Inpatient	n=7 (participants - 6 nurses & 1 physician)	N/A	Nurse and Physician	Dashboard providing visibility of critical patient safety indicator information for multiple patients	Task-based evaluation to assess differences of using dashboard versus conventional EHR display. Assessed differences in time to complete a task and percentage of tasks completed without error.	N/A	N/A	N/A	Dashboard embedded into pre-existing EHR	The findings showed the reduction of task completion time and error rates for 6 out of 8 quality indicators, yet the observed differences were not evaluated for statistical significance. Questionnaire surveys to evaluate system's usability = 'highly usable' 1. System Usability Scale (SUS) (mean 87.5 (SD, 9.6)) 2. Poststudy System Usability Questionnaire (PSSUQ) (mean 1.7 (SD 0.5)) Evaluation (of usability): 1. SUS score improved in comparison to prototype following preliminary review 2. There was good perceived learnability and usability

													(including readability despite colour blindness).
Fuller et al (2020) USA	Cross-sectional	Academic medical centre (30 inpatient units)	Inpatient	n=24 participants (clinicians including attending physicians, residents, physician assistants)	post=12 months	Physicians, Physician assistants	Real-time dashboard displaying opioid management, alerting clinicians to potential pain management issues and patient risks.	Task accuracy	1. Study usability by evaluating tasks undertaken using the EHR versus dashboard. Record audio comments of users undertaking tasks & computer screen activity using Morae 2. Survey questionnaire using NASA Raw Task Load Index (RTLX) to evaluate cognitive burden and work load	N/A	N/A	Dashboard application launches directly from a link within the EHR	The study has identified significant improvements when using the dashboard compared with the existing EHR: - reductions of 37% time on task (EHR = 323.96 secs vs. dashboard = 204.21 secs, p<0.001) - 87% fewer mouse clicks (EHR = 53 vs. dashboard = 12, p<0.001) - 68% less mouse movement (mean pixels travelled, EHR = 54,084 vs. dashboard = 17,315, p<0.001) The findings showed that the user accuracy and cognitive load (RTLX score) were not statistically changed: - users answered tasks correctly (EHR = 81% vs. dashboard = 90%, p=0.076) - difference in RTLX scores between dashboard and EHR = 2.7 points (p = 0.54)
Merkel et al (2020) USA	Case study	Acute care, and critical care State-wide	Emergency and Inpatient	N/A	pre (development) =19 days post=ongoing	Emergency operations committees (EOCs) Command Centre Operator	Provided visibility to critical resource information during COVID-19 pandemic, allowing each individual health system to track bed and ventilator capacity in real near time.	N/A	N/A	N/A	No outcome measure was reported	Near-time data populated to a web application independent of the EHR	The near real time bed and ventilator capacity tracking board allowed the hospital to manage and react to inpatient bed demands. The near real time capacity tracking allowed decision making for diverting ambulance to less crowded EDs within the state. The case study reported their implementation process, yet no assessment or results were published.
Bersani et al (2020) USA	Cluster-randomized stepped wedge trial	Academic, acute-care hospital	Inpatient	n=413 unique logins n=53 survey participants (nurses, prescribers)	post (random cohort) = 18 months	Prescribers, nurses, patients, and other care team members, including caregivers	Accessed directly within the EHR, the dashboard provides consolidated real-time EHR information. Dashboard displays critical patient safety indicator information for multiple patients using a colour-coding scheme.	N/A	1. Measure usability of the dashboard using the Health-ITUES survey 2. Weekly basic user	N/A	N/A	Real time data patient safety dashboard integrated into an EHR, with colour	53/180 providers responded to the Health-ITUES (response rate 29%). The overall ratings for the four measures were quality of work life (3.1+/-1.09), perceived usefulness (3.2+/-0.85), perceived ease of use (3.6 +/-0.95), and user control (3.4+/-

									reports on logins by day, total number of logins and top users			grading system	0.72), with variability by provider role and service. The dashboard was accessed by at least one provider on 70% of intervention days, for a total of 8,302 logins by 413 individual providers (184 nurses, 179 prescribers, 19 unit leadership staff, and another 6 users on other roles, 23 users are unidentified). High concentration of logins are between 5-8am, and large increase in logins during morning rounds (8:30-11:30am).
Ibrahim et al (2020) United Arab Emirates	Case study	Tertiary academic hospital (8000 admitted COVID patients)	Emergency and Inpatient	N/A	pre = 30 days post = 30 days	The rounding team (nurse, attending resident, resident, intern)	Dashboard created to demonstrate clinical severity of COVID-19 patients and patient location using up-to-date, colour coded displays on a single screen.	Percentage of patients requiring urgent intubation and cardiac resuscitation	N/A	N/A	N/A	A separate electronic dashboard external to the EHR	Comparing 30 days pre- and 30 days post-implementation, the percentage of patients who required urgent intubation or cardiac resuscitation on the general medical ward, rather than a critical care setting, declined by over 50% (8 out of 34, 33% vs. 7 out of 55, 13%; two-tailed $p < 0.05$ by Fisher's exact test; OR 3.43; CI 1.07 to 10.95).
Kurtzman et al (2017) USA	Mixed methods	University-owned teaching hospital	Inpatient	n=80 residents n=23 residents (focus group)	post = 6 months	Internal medicine residents/ trainees	Dashboard created to visualise rates of routine laboratory tests ordered.	N/A	Measured resident dashboard engagement using email read-receipts, a web-based tracking platform for dashboard access and calculated lab orders per doctor-patient day.	N/A	N/A	A separate electronic dashboard outside EHR developed to visualise routine laboratory tests.	No statistically significant difference in routine laboratory ordering by dashboard use. Residents who opened the email link to the dashboard ordered 0.26 fewer labs per doctor-patient-day than those who did not (95% confidence interval, −0.77 to 0.25; P= 0 .31).
Paulson et al (2020) USA	Cross-sectional	21 hospitals 3922 inpatient beds	Emergency and Inpatient	Not clear	Not clear	RRTs, Palliative Care teams, Virtual Quality Team (VQT) nurse	EWS and Advance Alert Monitor dashboard providing near real-time notification when patient meets predefined thresholds and risk scores.	N/A	System monitoring: Number of alerts triggered, percentage of patients resulting in call from VQT RN to RRT RN,	N/A	N/A	EWS and AAM dashboard embedded directly into the existing EHR.	Patients triggered an alert - 2018: 17,091, 2019 (10mths): 13,434. VQT RN contacted RRT RN - 2018: 75.6%, 2019 (10 months): 88.7%. Call placed within 1 hour – 2018 91.6%, 2019 (10 months): 94.2%

									percentage of those with nursing or physician documentation within EHR.				
Staib et al (2017) Australia	Case study	Tertiary hospital	Emergency and Inpatient	N/A	N/A	Physicians, Nurses	ED-inpatient interface (Edii) dashboard to manage patient transfers from ED to inpatient hospital services.	ED length of stay and mortality rates	N/A	N/A	N/A	A separate electronic dashboard accessed external to EHR and displayed on mounted monitors and PCs.	ED length of stay reduced from 7.2 to 3.3 hours Mortality rate reduced from 2.3% to 1.0%

Supplementary Table 9: Study Outcomes Summary

Supplementary Table 10a: Summary of findings pertaining to RQ-2, for our review

Contributions of prior reviews to Research Questions
RQ-2: What successful methods have been used by healthcare organisations to overcome these challenges
1. Regular meetings with medical/nursing leadership in specalised areas for feedback on prototype (e.g. adjust module for oncology, neurology depts) -- Mlaver et al. 2017
2. Non-interruptive alert (dashboard concept to reduce alert fatigue) 3. Dashboard supplements the already existing system (i.e. any concern RN can still activate RRT) 4. Employ full-time dedicated RN to monitor dashboard -- Fletcher et al. 2018
5. Validation pilot undertaken to determine ideal high freq. identifiers generated in EHR to include in algorithm 6. Combo of ICD-9 codes (history of HF) plus other identifiers to ID de novo HF pats (e.g. BNP >400) 7. Panel of high frequency providers to guide design/decision making re/ dashboard 8. Provide EMR repeated measurements over time (coding required to retrieve highest/lowest/most recent 9. To confirm validity of data - manual team EMR review 10. Dashboard needed full-time position dedicated to inpatient triage of resources/transistion of care 11. Improve admission order set utilisation (inc identifiers) or change ID methods for oustide hospital transfers (radio label button created on transfer admission form) -- Cox et al. 2017
12. Include functional info to ID patients approaching or over thresholds for a stage of care (enable real-time decision-making) 13. Ethnographic observations of clinicians and from workflows abstracted work domain ontology 14. Used frameworks of cognitive informatics to guide development 15. Prototype developed 16. Formative assessment (focus groups/single participant interviews)- adjustment of prototype 17. Dashboard suite released in stages 18. Live training provided, dashboard re-evaluated 2mths post go-live -- Franklin et al 2017
19. Happinovation team (multi-disciplinary team: hospital staff/ consultant / designers to see things from patient perspective) 20. Team developed 3 guiding principles for design & 3 design features 21. Prototype developed - updated over 5yr period 22. Change to overall colour coding of dashboard (to help ID bed status) 23. Icons next to patient - indicating acuity scale scores/cautions (to improve display of patietnt specific info) -- Yoo et al. 2018
24. Multidisciplinary focus group to ID dashboard design criteria and review improvements 25. Core quality metrics were evidence-based and using existing data (no additional input from clinicians required). Nat. stds 26. Ability to compile/view report prn (avoid alerts) 27. Program dashboard to display certain metrics from admission to discharge during single inpatient stay (to avoid overflow to subsequent admissions from charting omissions e.g. discontinuing catheter) 28. Add filter for attending physician 29. Icons and colour-coding to improve interpretation of threshold scores 30. Multifaceted implementation plan: promote use by demo'ing to ind and teams in clinical areas. Tip sheets. Local change agents to use during team huddles 31. Install more flat-screen monitors to improve access -- Schall et al 2017
32. User centred design principles (clinicians involved during iterative design/development) - Fuller et al. 2020
33. Collaborated to use command centre technology for statewide data to avoid siloed resource allocation 34. Close connection with state health authority for consistent message 35. Connect engineering teams from each hospital with IT teams from overarhcing group 36. Adaptive e.g. ability to add room attributes 37. Criticality of dashboard (due to covid): move quickly from design to implementation -- Merkel et al. 2020
38. User centred design 39. Colour coded alert boxes to aid decisions 40. Systematically trained most of the unit-based nurses (>80%), and engaged with physicians during weekly meetings. Study staff continued to provide “at-the-elbow” support and visited the units weekly to answer questions and promote user buy in. 41. Feedback from providers was collected early in the study to determine barriers to tool adoption and to develop approaches to increase use. 42. Competitive weekly user reports later replaced basic reports to encourage dashboard use, tapping into users’ internal motivation for mastery - these had a massive impact on uptake 43. Stronger implementation planning and increased engagement of stakeholders. 44. Advanced planning about how to engage stakeholders in order to have consistent and effective engagement—ensuring follow through on engagement – regular meetings or rounding to discuss issues that come up from clinicians 45. Bring in clinical users early. Clinical users who can pilot constantly. Clinical users who work on the floors all the time. 46. Better communication with leadership early so they have agency over the intervention and therefore have a little bit more excitement about it because they were part of the conception 47. When users saw the value of the tool, e.g., leading to actions that they might not otherwise have taken, then they generally continued to use it. This was indeed the intention of the tool’s designers for providers to see value in this tool and conclude that it saved time by consolidating information, or that the benefits of its use outweighed the cost of time taken to use it. 48. Applications should be pilot tested and iteratively refined to be as fast and bug free as possible before going live to avoid losing potential users who may not come back to it later, and any decrements in performance (such as loading time) need to be addressed immediately as they arise 49. Workflow and cultural issues need to be addressed upfront and continually during implementation; the most prominent issues will likely include the time pressure of rounds and the perception of different safety issues “belonging” to different provider types. 50. Rather than training different types of users separately, we plan to combine prescribers, nurses, and leadership in training sessions so that they can understand each other’s roles in using the Dashboard. -- Bersani et al. 2020

Supplementary Table 10b: Summary of findings pertaining to RQ-2, for our review

Contributions of prior reviews to Research Questions
RQ-2: What successful methods have been used by healthcare organisations to overcome these challenges
51. Alleviate concerns about punitive consequences -- Kurtzman et al. 2020
52. Two implementation strategies: afferent arm (standardization of early detection using remote monitoring), efferent arm (standardization of the clinical response and its infras-tructure) 53. (afferent arm) Alert fatigue is a known problem in medicine; It was not feasible to expect physicians or RRT RNs to access the inpatient EHR on an hourly basis to assess whether patients met the 8% risk threshold. Doing so would cause great dissatisfaction due to increased alert fatigue. Instead of direct data displays to frontline nurses and physicians, initial presentation of alerts would be transferred to an electronic dashboard and reviewed by experienced, specially trained RNs working from their homes. 54. Developed a workflow known as snoozing— deliberate nonreporting of an alert—to prevent and mitigate alert fatigue. Because physiologic values may remain abnormal even after treatment initiation, patients may trigger alerts repeatedly or soon after admission, which can be irritating to clinicians. Alerts issued immediately after admission may not need action, in that treatment may have already been initiated (that is, the alert simply reflects pre-existing physiology). 55. (efferent arm) It was critical to identify a consistent pathway for RRT RN escalation to the physician for patients identified by the AAM (early warning system). Developing a standard recommendation was challenging, given that each hospital had different resources available (e.g., residents, specialist physician availability 24/7, subspecialty services etc) and different departmental agreements across services for management of deteriorating patients. To standardize escalation pathways for the RRT RNs and patients, we partnered with the Hospitalists' Chief Group. This group endorsed a regional service agreement mandating that hospitalists would be the main point of contact for patients identified by AAM, independent of hospital service. 56. Due to the variation in hospital quality governance structures, we had to work with every hospital to develop a cohesive oversight structure. Each hospital now has an AAMlong-term oversight structure -- Paulson et al 2020
57. Clinician-IT collaboration 58. Throughout the development and implementation process, new ideas for elements and modifications of old elements continued to arise. A daily multidisciplinary clinical huddle was followed by a daily IT conference call that served to share feedback, discuss new protocols and approach challenges. These meetings also allowed us to quickly operationalize new guidelines by incorporating them into the EHR in almost real-time. 59. Incorporating feedback from the end-users as a means of continuous process improvement. -- Ibrahim et al, 2020
60. Utilised 25 clinical redesign interventions 61. The dashboard was developed in response to a clearly defined, important clinical problem; 62. The project was led by clinicians with operational roles that allowed the effective implementation and dissemination of the dashboard into everyday clinical practice across the organisation. The clinicians were able to utilise the expertly presented data to undertake health service improvement, which in turn was able to be tracked using the dashboard. 63. The dashboard was constructed in a way that encouraged easy replication in other facilities. It was designed as a local quality improvement tool and specifically not as a tool for benchmarking across sites. 64. The dashboard formed an integral part of a coordinated whole of hospital cultural change focusing on improving patient outcomes rather than process measures in isolation. -- Staib et al. 2017