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Synopsis

Digital alerting to improve sepsis detection and patient outcomes in NHS Trusts: a multi-methods study

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Published February 2026
DOI: 10.3310/GJCC0605
Volume 14 • Issue 5

Abstract

Background: Identifying clinical deterioration is a global health priority. Sepsis is a leading cause of deterioration, responsible for around 46,000 deaths annually in the United Kingdom. Early warning scores based on patients' vital signs can be embedded into electronic patient records to digitally alert clinicians to those at risk. Rapid identification and treatment – particularly with targeted intravenous antibiotics – are critical to improving outcomes in sepsis patients.
Research question: This study aimed to evaluate the effectiveness of digital alerts in improving outcomes for patients with sepsis. Using routine electronic patient record data from four United Kingdom National Health Service acute trusts, we investigated how digital alert systems influence patient outcomes and explored mechanisms and mediators of their effectiveness.
Objectives:

1. Map the types of digital alerts currently in use across United Kingdom hospitals for identifying patients at risk of sepsis (Workstream 1).
2. Evaluate the impact of digital alerts on patient outcomes (Workstream 2).
3. Examine how the implementation process affects alert performance, guided by the consolidated framework for implementation research (Workstream 3).
4. Provide recommendations on alert effectiveness and implementation strategies using systems modelling and mediation analysis (Workstream 4).

Methods: A mixed-methods approach was employed. A national survey assessed the use of digital sepsis alerts in English National Health Survey hospitals (Workstream 1). Qualitative interviews and focus groups explored the implementation process and its influence on alert performance (Workstream 3). A natural experiment with multilevel interrupted time series analysis examined the impact of sepsis screening tools and digital alerts on outcomes, primarily

in-hospital mortality (Workstream 2). Routinely collected clinical data were processed following National Institute for Health Research-Health Information Collaborative standards. Combining quantitative and qualitative data enabled us to link implementation processes with patient outcomes.
Results: All four trusts experienced reduced mortality rates among patients with serious infections following the introduction of digital sepsis screening tools. After adjustment for patient case-mix, admission patterns and pre-existing trends, one trust showed a statistically significant decrease in mortality linked to digital alert implementation. In two trusts, older patients experienced greater mortality reduction than younger ones following alert introduction. Qualitative findings highlighted factors contributing to more effective use of digital alerts: deployment in general wards rather than intensive care units; use by clinicians familiar with similar technologies; availability of 24/7 emergency outreach teams; robust technological infrastructure and alerts that were user-friendly, non-intrusive and not part of multiple competing alert systems.
Conclusions: The effectiveness of digital sepsis screening tools varies and may depend on patient's age and care setting. Our findings suggest that digital alerts should leverage a wider range of electronic patient record data and be tailored to specific patient groups. Different trusts and patient populations may require distinct indicators, thresholds and treatment protocols. These findings align with healthcare practitioners' calls for more sophisticated, patient-centred sepsis screening tools targeted at relevant clinical teams.
Future work and limitations: The study involved four National Health Service Trusts with strong data collaboration, but noted limitations include reliance on simple algorithms and varied case-mix and implementation processes. Future research should focus on robust evaluation methods, leveraging granular electronic patient record data and establishing a public registry of digital alert tools.
Funding: This synopsis presents independent research funded by the National Institute for Health and Care Research (NIHR) Health and Social Care Delivery Research programme as award number NIHR129082.
A plain language summary of this synopsis is available on the NIHR Journals Library Website https://doi.org/10.3310/GJCC0605.

Introduction

Rationale for research

Sepsis is a worldwide public health problem, with a recent report estimating a 11-million global death toll in 1 year alone. Early diagnosis and management are crucial to improve patient outcomes,[3,4] with inconsistent recognition and management of sepsis being repeatedly highlighted as a safety concern in hospital service/quality-of-care audits.[5]

These related issues currently make early sepsis recognition more challenging: interindividual heterogeneity in the underlying aetiology and clinical phenotype; inconsistency in the implementation of a consensus clinical definition; and most critically, the lack of a reliable test for sepsis.[6]

Screening for sepsis is widely implemented across countries and is essential for prompt treatment and optimal outcomes.[7] Latest international guidelines recommend that all hospitals and healthcare systems adopt sepsis performance improvement programmes, which include the use of screening tools to promptly identify sepsis.[3,8] However, compliance with these guidelines is not universal, and implementation is an ongoing challenge.[9]

Currently, hospitals in England are required to screen both emergency department (ED) patients and inpatients for sepsis 'where appropriate' and there have been associated financial incentives towards this.[10] Recent guidelines are summarised in *Appendix 1*, *Figure 1*. To date, none of these guidelines consider the use of electronic tools to aid screening, or their potential advantages and disadvantages. Despite their absence from current guidelines, electronic screening tools for sepsis have been in use in English hospitals for over 5 years. Previous work from our group showed that the introduction of a digital sepsis screening tool and accompanying alert were associated with reduction in risk of mortality and an increase in timely treatment with antibiotics.[11] Individual trusts have identified improvements in patient outcomes, including reductions in septic shock in under 45-year-olds from 60% to 7.7%;[12] 70% increase in patients diagnosed with sepsis receiving antibiotics within the target time frame and 64 potential lives were saved in 1 year.[13] However, these claims have not been peer reviewed, or adjusted for underlying trends and case-mix.

Currently, most electronic screening tools for sepsis available in England are rule-based, track and trigger (T&T)

systems, that is, systems which rely on periodic observation of selected physiological signs with predetermined criteria for escalating care.[14] The most commonly available tools include systemic inflammatory response syndrome (SIRS) criteria, quick Sepsis-related Organ Failure Assessment (qSOFA), modified early warning scores and, in the UK, National Early Warning Score (NEWS2).[8] SIRS and qSOFA were initially developed as diagnostic tools for sepsis, but these are now commonly used for highlighting patients at risk of poor outcomes from sepsis (details are shown in *Appendix 1*, *Table 1*).[6] These tools often have high sensitivity, but low specificity[8] (see *Appendix 1*, *Figure 1*).

As the UK NHS seeks to become paperless and embraces digital technology, the incorporation of digital alerts embedded within the electronic patient record (EPR) is an attractive option to aid clinical decision-making and has the potential to increase the quality, efficiency and cost-effectiveness of sepsis care. However, little is known about the digital alerts currently in use or the rationale for their inclusion in healthcare systems, including healthcare professional views, or implementation approaches. In the case of sepsis, there is some emerging evidence of the effectiveness of these tools, but there are no validated digital tools available to NHS Trusts which have been shown to be effective in improving patient outcomes in a range of settings.

Objectives

The first objective was to map the digital alerts currently in use in multiple UK hospitals to identify patients at risk of having sepsis [Workstream 1 (WS1)]. Building on previous work, we then aimed to evaluate the impact of digital alerts on outcomes for patients at risk of sepsis (Workstream 2). In parallel and using qualitative methodology, we aimed to examine the impact of the implementation process on digital alert performance, guided by the consolidated framework for implementation research (Workstream 3). The overall objective was to merge quantitative and qualitative findings to make recommendations on the effectiveness of different digital alerts and the most effective method of implementation [Workstream 4 (WS4)].

Methods for section and analysis

The first objective was to map the digital alerts currently in use in multiple UK hospitals to identify patients at risk of having sepsis. We aimed to describe digital sepsis alerts (DSAs), based on English NHS Trusts' responses to Freedom of Information (FoI) request. Working with a group of close collaborators, across multiple NHS Trusts identified, we identified key aspects of algorithms in use in five NHS hospitals to inform our further work. We used an FoI request to survey all hospitals and used internet searching to gather additional information. The FoI request was submitted to all acute NHS hospital trusts in England that have an ED (with the exception of the five NHS hospitals in the pilot work) to collect information on EPRs; electronic sepsis screening tools and the underlying algorithms they use; the association between the underlying algorithm and the alerts to clinicians; the timing of introduction of the electronic screening tool in the hospital; and which staff groups see and respond to alerts. Descriptive statistics were used to summarise findings.

The second objective aimed to evaluate the impact of digital alerts on outcomes for patients at risk of sepsis. EPR data were provided by NHS Trusts. Data used in this study were routinely collected, processed by trusts to comply with NHS requirements for Secondary Uses Service. These data are quality-checked by individual trusts before being submitted to the NHS and are compiled into Hospital Episode Statistics which have been widely used for research in the UK. Data are stored by trusts and were made accessible to us via secure data environments, with appropriate data-sharing and access government arrangements. See *Appendix 2*, *Box 1* for additional information. No verbal or written informed consent from individual patients was required for data set generation. This study was approved by the Health Regulatory Authority (288328).

Data for all adult (18 +) inpatients admitted between 1 April 2010 and 31 January 2020 were initially eligible for inclusion in the study. We identified two cohorts of patients using *International Statistical Classification of Diseases and Related Health Problems*, Tenth Revision (ICD-10) codes in the patients' record:

Suspicion of Sepsis (SoS) cohort: Patients we expected to be impacted by the introduction of a sepsis screening tool. We used published ICD-10 codes associated with bacterial infections that can cause sepsis.[9] This group is thought to mitigate against bias introduced through changes in coding practices.

Control cohort: A comparator group of patients whose outcomes we did not expect to be impacted by the introduction of the sepsis screening tool. These patients had an upper gastro-intestinal bleed.[12] We excluded patients who had an ICD-10 code included in the SoS list.

Descriptive analyses were used to variation in the patient cohorts over time and between trusts. We assessed the impact of the introduction of DSAs on in-hospital mortality in the SoS cohort and separately on the control cohort using an interrupted time series (ITS) study design. The ITS was designed using binomial regression models. Each cohort had a separate model predicting log (odds) of a patients in-hospital mortality from simple patient and admission data, including an interruption on the day the sepsis alert was introduced. To reduce potential bias introduced by the pre and post intervention cohorts being different, we adjusted for patient case-mix, including age, ethnicity, gender and comorbidities, using the weighted Elixhauser score. In addition, we adjusted for the season of admission and time of admission. We used a graphical approach to identify two 'seasons' and four time periods which were associated with different patterns in mortality.

For objective 3, a qualitative, multisite study with semistructured interviews with healthcare professionals (HCPs) was designed, alongside unstructured observations of HCPs working in hospitals.

A combination of purposive and convenience sampling was used. Three NHS Trusts were selected as sites for this qualitative study from the six trusts involved in the Digital Alerts for Sepsis (DiAlS) study. The three sites were chosen with consideration of diversity in the electronic health records (EHRs), informed by the findings from WS1.

Semistructured interviews with HCPs were mostly conducted remotely using video-conferencing software [Microsoft Teams (Microsoft Corporation, Redmond, WA, USA)]. The topic guide was developed from the study objectives, with input from the wider research team and the study's patient and public involvement (PPI) representative. Questions were asked to HCPs about their experiences of identifying and managing patients with sepsis and about their views and experiences of using DSAs. Interviews were audio-recorded and were professionally transcribed verbatim and pseudonymised.

Unstructured observations sought to observe clinical practice to see how DSAs fitted into the workflows of HCPs in different roles. We sought to assess what impact they had on clinical decision-making and to identify whether they were used differently by HCPs in different roles. Two types of observation were done: observations of practice in EDs with occasional informal conversations and one-to-one shadowing of a HCP in outreach teams (OTs), with more frequent dialogue. The observations lasted between 2 and 4 hours. Paper-and-pencil notes were taken, pseudonymised and typed up.

Data analysis began concurrently during data collection and was supported by NVivo 12 (QSR International, Warrington, UK). Data from both interviews and observations were analysed together inductively using thematic analysis.[15,16] Similarities and differences between transcripts were assessed using a constant comparison approach.[17] Codes were compared with one another to create categories, grouping similar codes together. All categories were clearly named to ensure that only related data were included in that category. Thematic frameworks were developed to represent the whole data set, across the three sites.

Research summary

A FoI request surveyed acute NHS Trusts on their adoption of EPRs and DSAs. FoI of requests were sent to 120 Acute NHS Trusts which had EDs. Responses were received from 94 NHS Trusts. Additional information was gathered from the DiAlS clinical team and from five NHS Trusts participating in DiAlS (see *Appendix 1*, *Table 1*). Of the 99 trusts that responded, 84 (84%) trusts responded that they had an EPR. The most common single provider was Cerner (18 trusts, 21%). System C, Dedalus and Allscripts Sunrise were also relatively common (13%, 7% and 10%, respectively). Four trusts used Epic and two used in-house systems. Over one-fifth of trusts (22%) identified a mix of companies providing their EPRs, with EDs and inpatient wards sometimes using different systems, and some identifying various patient administration systems.

Digital sepsis alerts were reported to be in use in 59 of the 85 digital trusts (69%). Systems based on NEWS2 were the most used across all systems [46 trusts (78%)]. Of these, 29 used a combined approach, an aggregate score of 5 or above or a single parameter of 3 or above, compared with 21 which either specified that they use a score of 5 or above or did not specify. Within trusts which use NEWS2, 24 (52%) use an additional screening tool; these include Red Flag Sepsis and qSOFA.[6] A further eight NEWS2 Trusts use an additional screening tool, such as asking for an indication of infection, and one uses SIRS criteria. Some trusts indicated that their digital system (DS) prompts a question or a series of questions about the possibility of sepsis, but there was no evidence that the responses to these were precompleted by the electronic system despite some of this information being available within the EPR. Eight trusts responded that they used Red Flag criteria as a stand-alone assessment, while three used qSOFA and two SIRS. Five trusts did not give sufficient information to determine the algorithm behind the sepsis alert. An additional four were unwilling to provide information on the algorithm, and three trusts use bespoke systems which were a modification of NEWS2 or Red Flag Sepsis. The EPR provider for all trusts which use a combination of NEWS2 and qSOFA is System C, and for those that use a SIRS-based system, it is Cerner. Cerner was also a common provider for trusts using Red Flag Sepsis alone or in combination with NEWS2.

We found no evidence that trusts were using EPRs to introduce data-driven algorithms or DSAs able to include, for example, pre-existing conditions that may be known to increase risk. The NHS 'move to digital' through the incorporation of EPR systems facilitates this translation of paper-based screening tools into DSs, including DSAs. In summary, we found that to improve care for patients with sepsis, comply with national financial incentive programmes and make best use of the introduction of EPR, hospitals in England have introduced DSAs. A variety of algorithms have been used, with different workflows and different implementation strategies.

Digital alerts have generally been introduced across hospitals without randomisation or in a phased approach which would support rigorous evaluation of their impact. The second project objective aimed to quantify the impact of the introduction of sepsis screening tools across multiple NHS Trusts, each of which uses different algorithms for early detection of sepsis. We also included a trust which uses a paper-based screening tool to enable us to explore the impact of digital and paper-based interventions. The aim of this study was to determine the effect of the introduction of a DSA on inpatient 30-day mortality.

In total, we examined mortality patterns in 607,980 SoS patients across three trusts (see *Appendix 2*, *Table 2*). In Trust A, we included 156,387 patients who were admitted over 119 months, in Trust B, 248,301 patients over 85 months, and in Trust C, 203,212 patients over 118 months. All trusts had a significantly lower mortality after the introduction of the sepsis screening tool before adjustment for patient case-mix or pre-existing trends (see *Appendix 2*, *Figures 2* and *3*). After adjusting for pre-existing trends, there was a significant reduction in mortality in Trusts A and C. There were significant differences in patient characteristics, including gender and ethnicity and admission patterns, between trusts. In all trusts, there were more females in the SoS cohort than males, there were a high proportion of patients aged ≥ 65 years and the majority of patients had at least one comorbidity.

In Trust A, crude analysis indicated that there was reduction in mortality following introduction of the screening tool (see *Appendix 2*, *Figures 2* and *3*). After adjusting for time and season of admission, and patient case-mix, the screening tool showed no evidence of impact on mortality. We investigated whether the alert had differential impacts on specific patient groups by fitting a priori-specified interaction terms. This suggested that the introduction of the screening tool was significantly associated with a reduction in mortality in older patients, but not younger patients. There was no evidence of a different impact on patients with higher comorbidities.

In Trust B, prior to the introduction of a DSA, there was a decreasing trend in mortality in patients in the SoS cohort, and the association of the introduction of the alert with mortality is not significant in both crude and adjusted analyses. However, the interaction between age and the introduction of the alert is significant, suggesting that the alert had as significant impact on reducing mortality in older patients, but not in younger patients.

In Trust C, there was an increasing trend in mortality prior to the introduction of a DSA, an increase in odds of mortality of 2.6% [95% confidence interval (CI): 1.2% to 4.0%]. The introduction of the alert is associated with a decrease in odds of mortality of 14% (21% to 5%). In addition, after the introduction of the alert, the trend in mortality rate changes to a decreasing mortality rate (see *Appendix 2*, *Table 3*). In addition, there is no significant interaction between the introduction of the alert and age, suggesting the alert does not have a differential impact in patients of different ages.

In summary, results from the quantitative analyses support our previous work, which indicated a lower risk of mortality following introduction of DSAs in NHS Trusts, and confirms these results, across multiple NHS Trusts. Based on different age-related effects, our results suggest that alerts could be tailored to specific patient groups through inclusion of additional readily available EPR data.

Contextualising the quantitative findings is important, and objective 3 aimed to qualitatively explore the views and experiences of HCPs on the use of DSAs and to identify barriers and facilitators to the implementation and use of DSAs in NHS hospitals. Twenty-two HCPs were interviewed across the three NHS Trusts: 8 from Site 1, and 7 from each of the other two sites (see *Appendix 3*, *Table 4*). In Sites 1 and 2, 12 observation sessions were also undertaken: 5 in the EDs, and 7 sessions involved shadowing professionals, 3 of whom completed an interview (see *Appendix 3*, *Table 5*). Thematic analyses yielded three themes about HCPs' views and use of their DSA and a higher-level domain, capturing the complexity of how the hospital environment affected DSA use across the three sites.

Theme 1. Sepsis/deterioration digital alerts nested within electronic health records support decision-making

All participants liked that DSAs were nested within the DS of the EHRs shared across a trust. Having patient data all in one place, including clinical history, trends during their hospital stay, pre-conditions, comorbidities, test results and various digital alerts/scores, was described as useful to more quickly and safely build a picture of the patients who are flagged by the DSA. This was regarded as enabling better decision-making and quality care.

All participants underlined that the DSAs in the patients' EHRs were supporting, and by no means substituting, clinical decision-makers, whose knowledge and experience were of paramount importance in sepsis identification and management. DSAs were seen as 'a piece of the puzzle', neither intended for, nor leading to, the formulation of a diagnosis or clinical decision in isolation.

Theme 2. Sepsis/deterioration digital alerts are reminders that lead to context-dependent actions

Participants viewed DSAs as useful to remind and prompt HCPs of a number of actions, from reviewing a patient's information in the EHRs to visiting them in person. In general, participants reported that DSAs' utility decreased with increasing staff training and experience with sepsis cases; and with the higher senior HCPs/patient ratio of certain units, such as acute or intensive care. More junior HCPs said that DSAs afforded them with greater confidence to further investigate and interpret why DSAs triggered, which could lead them to follow the sepsis protocol and to escalate to senior decision-makers.

Theme 3. Improving sepsis/deterioration digital alerts and their implementation

Most participants expressed the importance of DSAs being easy to use and accessible; some participants underlined that a user-friendly DSA was important so that new staff could be trained more easily and quickly in its correct use. In this respect, several participants, especially from the OTs, envisioned DSAs embedded into portable devices so that HCPs could be reached when they are on the move. Other features of more advanced DSAs that participants suggested included: DSAs being adjusted to the patient, factoring in their baseline parameters, comorbidities and previous conditions, or addressing relevant HCPs team; DSAs processing more information regarding the patient, transparently showing why they triggered and allowing for greater interaction with users. Many participants wished to have a DSA embedded in a DS shared beyond the trust and across the community, ambulance service and primary care. Participants felt that a widely integrated DSA would reduce ED waiting, triaging and handover times.

In summary, four interconnected levels of factors appeared paramount. First, there are elements pertaining to individual HCPs. As reported in Theme 2, HCPs' seniority and clinical specialty affect the use of DSAs. On occasion, personal circumstances (e.g. childcare duties and other non-professional commitments) can play a role in their decision-making. A second level of factors relate to the hospital unit or department; these will have HPCs with specific training and specialty caring for certain types of patients, and this influences the use of DSAs in these patient populations. For example, in intensive units, such as ED resuscitation and intensive care unit (ICU), sepsis cases are seen more frequently and more senior staff look after more severely ill patients, so observations are taken more frequently. Participants reported that these aspects make the DSA less relevant.

The third set of factors is that of the trust. The workload/staffing ratio, along with the presence of senior decision-makers per patient, are specific to the hospital unit and also dependent on the overall management and resources of the trust. Several participants, from Sites 2 and 3, raised the issue of delayed actioning of the DSA due to heavy workload, and to the retrospective uploading of patients' observations or clinical actions performed, resulting in lower performance towards meeting targets (e.g. antibiotics within 1 hour) at time of auditing. As highlighted in Theme 3, the trust plays a role by investing in staff education/training about sepsis/DSA; in the implementation of quality improvement; and in technological equipment – spanning from the number of computers available to introducing useful and accessible software programmes. The fourth set of factors is that of the digital tool itself, its features and functionalities, which correlate with optimal use of DSAs, as Theme 3 encapsulated. Some aspects inherent to the DSA are closely related to other factors, such as how ergonomic and accessible an alert is, which are linked to both trust and individual factors.

Research papers that are being synthesised in the synopsis

1. Honeyford K, Nwosu AP, Lazzarino R, Kinderlerer A, Welch J, Brent AJ, *et al*. Prevalence of electronic screening for sepsis in National Health Service acute hospitals in England. *BMJ Health Care Inform* 2023;**30**:e100743.
2. Honeyford K, Timney A, Lazzarino R, Welch J, Brent AJ, Kinderlerer A, *et al*. Digital innovation in healthcare: quantifying the impact of digital sepsis screening tools on patient outcomes – a multi-site natural experiment. *BMJ Health Care Inform* 2025;**32**:e101141.

3. Lazzarino R, Borek AJ, Honeyford K, Welch J, Brent AJ, Kinderlerer A, *et al*. Views and uses of sepsis digital alerts in National Health Service Trusts in England: qualitative study with health care professionals. *JMIR Hum Factors* 2024;**11**:e56949.

Discussion/interpretation

Digital tools currently in use in acute hospitals in England use simple algorithms, based on paper-based T&T systems and are not taking advantage of the granular data available in the EPR. While the majority of NHS Trusts in England are using NEWS2, as required in the National Standard Contract, this was not designed as a digital tool nor developed within data-rich environments. Many trusts are using alternative algorithms, often in combination with NEWS2, which do not have a strong evidence base. Studies which compare these approaches are vital to inform on the most effective practice.

As EPRs become universal, there is enormous potential in harnessing granular data to improve the performance of digital tools to support care of deteriorating patients. However, we need a strong methodological evaluation approach, and clinicians and hospital leaders have a responsibility to understand the digital tools in use in their hospitals. In our study, all trusts had a lower mortality rate in patients with a serious infection, identified by the SoS code list, after the introduction of a sepsis screening tool. After adjusting for patient case-mix, admission patterns and pre-existing trends, the introduction of digital sepsis screening tools was significantly associated with a decrease in mortality in one trust. In two trusts, there was evidence that the introduction of a sepsis screening tool was associated with a reduction in mortality in older patients.

We have previously shown that patients for whom a DSA was active had a lower risk of mortality than for those who had a similar profile. These results confirm that this lower risk is seen even when previous trends are considered. We found evidence that the introduction of a paper-based screening tool impacted on older patients; previously, paper-based screening tools have been shown to be associated with a reduced risk of mortality.[18] We have not found previous research which has looked at the differential impact of the sepsis screening tools on different groups of patients. The literature on the effectiveness of digital sepsis screening tools shows that our findings, with different impacts in different healthcare organisations, are consistent. Evidence is unclear and the rationale for different impact in different settings is not well understood. The alert at Trust C includes blood test results, which may be more useful, or it may be that the alert introduced in at Trust C was the right alert for the patient population at the right time for the healthcare organisation, and this is why a clear impact was seen. Crude changes in mortality rates may show that sepsis screening tools reduce mortality, and many NHS Trusts have highlighted the impact of new tools. We have shown that the picture is more complex, and after adjusting for patient mix and pre-existing trends, the impact of sepsis screening tools may not be clear cut; and more work is needed to determine if the tools are effective and also if they are equally effective on all patients.

Across England, digital screening tools in use in NHS hospitals are based on paper-based screening tools which are embedded in EHRs;[11] generally, they do not exploit the extensive data held in EHRs or use machine learning algorithms to personalise alerts. The picture with digital screening tools is complex, for example, evaluations of the Epic Sepsis Model have suggested a reduced risk of mortality,[19] with some suggesting possible harm due to its poor diagnostic performance.[20] Digital screening tools embedded in EHRs have advantages when compared to paper-based screening systems; they can be linked directly to treatment plans, which has been shown to improve adherence.[21]

The difference in effectiveness between the two DSAs may be due to the underlying trend in mortality prior to the introduction of the DSA. Additionally, in Trust C, the algorithm includes blood test results in addition to clinical observations. A recent study in a national data set suggested that people of White ethnicity had the highest risk of mortality from sepsis.[22] We found different risks of mortality for different ethnic groups between the three trusts. This suggests that there may be different impacts of ethnicity in different NHS Trusts, which are not apparent when using national databases. It also shows us the dangers of generalising from single sites. We retained 'not stated' and 'missing' as different ethnic groups and saw different odds of mortality in different trusts; this suggests that different trusts may use these codes differently.[23] We found that there had been an increase in the use of 'not known', 'not stated' or 'other' – a systematic bias in data quality. The groups in use may also not best describe the ethnic groups in different areas of England and may not be comparable internationally.[24] In the main analysis, we did not include deprivation, but we were able to explore deprivation in two trusts; in contrast to Zhang *et al*.,[22] we did not find poorer outcomes for more patients for more deprived areas, but we did find having no Index of Multiple Deprivation score was associated with poorer outcomes. This group may be more likely to have no permanent residence and therefore be representative of the most vulnerable patient.

Limitations with quantitative analysis

As with many studies on sepsis, we are limited by the challenges of identifying the patients who are diagnosed with sepsis from EHRs. We used the diagnosis list suggested by Inada-Kim *et al.*[25], which includes a wide range of diagnoses indicative of patients with a bacterial infection and therefore at risk of developing sepsis. This list has been shown to be less sensitive to changes in coding brought about by changes in national policy and coding changes linked to DSAs. Changes in sepsis incidence when measured using ICD-10 codes were seen to increase in all trusts, with a dramatic increase in spring 2017. This is unlikely to be due to an actual increase in sepsis incidence. Coding for sepsis is an international challenge, with studies suggesting the ICD-10 codes not only underestimating true sepsis incidence[26–28] but also susceptible to financial incentives.[29] The SoS list of codes we have utilised has been used in other studies[27] but has not yet been accepted by international surveillance groups.

Despite using a recommended method for determining causal inference, we cannot determine that the sepsis screening tools are solely responsible for identified reductions in mortality. We carried sensitivity analysis to determine if any changes in the mortality risk in SoS patients were also seen in patients with a non-related condition, and we found no evidence of an associated reduction in mortality risk. In addition, we have shown that there the introduction of an EPR was associated with changes in mortality.

Qualitative interviews found that participants generally viewed DSAs positively, but they emphasised that DSAs cannot substitute the HCP's knowledge and experience in the identification and management of sepsis. DSAs are only a 'piece of the puzzle' in a patient's presentation as well as in the complex, multimodal and multidisciplinary clinical practice. Participants considered DSAs as useful, context-specific reminders prompting HCPs to take a range of actions, from reviewing to escalating a patient.

Participants identified features of better DSAs, such as accessibility and user-friendliness. More sophisticated DSAs should be more specific, patient-based, target HCP teams, be portable and remotely accessible and integrate community, ambulance and primary care with secondary care to accelerate ED triaging.

Factors pertaining to the individual HCP, the hospital unit, the trust and the digital tool itself differently combine and were seen to affect the use of DSAs in the three trusts in this study. The combination of factors leading to the more optimal use of a DSA include: a general, non-ICU with a lower senior decision-maker/patient ratio; HCP's previous experience with the DSA; presence of a 24/7 emergency OT; DSAs' quality improvement initiatives and continuous sepsis training; strong technological resources in the trust; good staffing and teamwork; digital tool's ease of use; digital tools that are not numerous and intrusive.

Strengths and limitations

We included three trusts in this study to explore the differences in relation to the EHRs' DS and the DSA, the implementation optimisation strategies and the approach and training in relation to sepsis. We obtained a varied sample of professionals in relation to job role, medical specialty and hospital unit. The multisite design and the varied professional profiles afforded meaningful comparisons towards a clearer identification of factors affecting the use of the DSA. Observations provided insights on how the DSA fitted with workflows, which were richer than the self-reported descriptions of DSAs in the interviews. Lastly, two researchers (RL and AB) with different disciplinary backgrounds conducted interviews and observations in one of the sites. This added rigour to the process of data collection and analysis.

All three sites in this study are large, high-resourced and urban university hospitals, and the analysis could have benefited from including a trust with different characteristics. Including HCPs from other hospital wards and unit could have offered a contrasting example to further understand how DSAs are viewed and used, but this was beyond the resources available for this study. Finally, the study recruitment strategy resulted in sampling and non-response biases, which contributed also to the fact that certain professional categories, such as junior doctors, were absent. The possibility of conducting more observations might have provided richer data.

Comparison with prior work

The current understanding of how human factors affect the implementation and use of DSAs in NHS hospitals is minimal. The introduction of DSAs rests on the evidence of the challenges to optimally identify and manage sepsis in hospitals, in particular in EDs, where HCPs have been found to need more confidence and time to assess and escalate septic patients.[30,31] Our study found that DSAs support HCPs in identifying and making quicker decisions about deteriorating patients, which might be particularly important and helpful to new and less experienced HCPs in ED and in the general wards. The DSA is an additional element that HCPs factor in their practice; it is not a substitute for their judgement. Similarly, in a USA study, participants were more inclined to accept the machine learning-based system for sepsis if they perceived as a partner supporting their autonomy and workflow, and not a surrogate of their clinical judgement.[32] Literature on clinical decision support systems' (CDSS) implementation supports this finding: a study across four Italian hospitals concluded that the perception that an advanced CDSS could reduce HCPs' autonomy was the most significant barrier to implementation.[33]

Users' attitudes and perceptions about the ease of use and usefulness have been at the centre of established technology acceptance theories.[34,35] Trust in the DSA and its uptake were found to be affected by individual factors, such as previous experience with the DS – as two recent systematic reviews on the implementation of a CDSS[36] and of an EHR's DS have corroborated.[37] Although our participants did not directly discuss trust in the DSA, its importance can be inferred from other aspects they raised, especially when thinking about better DSAs. Participants would welcome more sophisticated and reliable DSAs, which would be more accurate and transparent – as previous work observed.[38,39] At the same time, perceived usefulness in the DSAs depended on the HCPs' professional experience and specialty training, our study revealed. More senior and emergency HCPs as well as intensivists tended to take less advantage from the DSA. Similarly, previous scholarship has demonstrated that HCPs can disregard the evidence underpinning CDSS for fear that their critical reasoning and, again, their professional autonomy are challenged[34] and also because the evidence embedded in the digital tool may be seen as jeopardising hierarchical, power relations based on medical specialty and seniority.[40]

Concomitantly, features and functionalities of the tool appear to influence the use of the DSA. A study highlighted that easy-to-use tablet applications as part of the DS for sepsis were important mediators facilitating implementation.[39] We also found that accessible, mobile phone applications and functions, such as the chat of the EHRs DS in Site 1, appear to support better use of the DSA. The usability of the digital tool has been a focal aspect in theories of ergonomics and human–technology interaction.[41,42] Work on the uptake of CDSS found that scarcity of available computers, unfriendly user interface and excessive number of intrusive alerts lead to disengagement and fatigue.[34,41–43] Our study corroborates the importance of factors inherent to the design of the DSA and the EHRs DS; both Sites 1 and 3 made the deliberate choice of keeping minimal or reducing soft-stop digital alerts.

Previous work has shown the importance of functional teamworking; this should be based on high standards of co-ordination and communication to ensure the smooth journey of the septic patient and improve clinical outcomes.[38,44] Our results indicate that the DSAs contribute to prompter patients' referral, escalation and treatment. However, participants felt that lack in communication among staff could hamper the proper use of the DSA as some participants in Site 2 raised. This resonates with the findings of the aforementioned study in the paediatric ED, where professionals' acknowledgment of the DSA was based on factors specific to the ED environment.[45] Significantly, another study found that a discontinuous flow of communication and teamwork among clinicians was a barrier to the integration of a machine learning sepsis early warning system in ED.[39]

Organisational factors were identified as a significant obstacle to recognising and responding to patients with sepsis in ED.[31] Significantly, our study corroborated how trust-level factors – such as good level of staffing, staff training and involvement in the DSA's optimisation, and appropriate technological resources – linked with more optimal use of DSA. In line with our results, other work concluded that organisational factors affected HCPs' trust in the sepsis alert; this connection was facilitated by engagement and education activities fostering DSAs' understanding and acceptance.[38] The importance of the context in affecting individual HCPs' decisions and practices related to CDSS has been demonstrated in studies employing the Normalisation Process Theory.[46–48] Accordingly, organisational and practice theories applied to the introduction of technology in the complex healthcare environment maintain that implementation processes are connected with the interaction between the technology, on the one hand, and HCPs' practices, teamwork relationships, organisation's policies and priorities, on the other hand.[48,49] The uniqueness of the hospital context makes it difficult to compare the effectiveness of a DSA in isolation.

Patient and public involvement

We have recruited two PPI members – one who is a coinvestigator (PG) and another who is a member of the Steering Group. As the project progressed, we recruited additional PPI members through individual NHS Trusts and the UK Sepsis Trusts.

The PPI group led on the following tasks:

1. Engagement in the synthesis of quantitative and qualitative findings in WS4. This work is ongoing and is being led by the UK Sepsis Trust. Animated videos of results (*n* = 2; 1 academic; 1 lay) are in progress,

and the UK Sepsis patient group have led with the production of the animation aimed at dissemination to the public.

2. Co-authoring papers. Pippa Goodman is a co-author on all papers and has commented on drafts.
3. Engagement with public, practitioners and policy-makers (including conference presentations).
4. Participation in the study steering group meetings. PPI members (led by PPI co-applicant PG) have attended all steering group meetings. These PPI members have been recruited via post discharge groups at Chelwest (n = 1) and Oxford (n = 1).

Imperial PERC informally evaluated patient experience of participating in DiAlS.

Implications for decision-makers

Results from our research indicate that the introduction of DSAs necessitates a multileveled approach[34,48] that includes understanding and actions at four levels: the HCP, the hospital unit, the trust and the digital tool.

An a priori analysis of the organisational environment to assess the trust readiness and unique feasibility for the introduction of the DSA is recommended. Mapping areas demanding change in the trust, and planning resources and actions for their improvement mitigate the risk that DSAs fail to offer the intended benefits. In addition to more structural factors, such as resources, staffing, sepsis training and a successful leadership–teamwork dynamic, it is also advisable that organisational cultural factors are factored in. Cultural factors that trusts should consider assessing include: the trust's prioritisation of sepsis or of deterioration and acuity; staff retention trends and sociodemographic profile; attitudes and readiness towards technological innovations; and the more impalpable norms regulating hierarchies and power among staff.

Hospital trusts should aim to plan ongoing implementation optimisation initiatives in the pilot and rollout phases. These initiatives should be flat-hierarchical and multidisciplinary so that HCPs with different job roles and training, based in different hospital units, can voice their unique perspective and support needs which they expect to be met by the DSA. The trust should ensure the continuous involvement of information technology developers[50] and that staff feedback is appropriately collected and analysed so that it materialises into context-based modifications of the tool. The engagement of staff should go hand-in-hand with education and training to aim at the maximisation of behaviour changes towards improved patient care. These activities should be reinforced by the establishment of champions and other strategic communication and educational campaigns, whereby staff can easily and remotely access information about the DSA. It would be useful if trusts established dedicated advisory groups monitoring and managing all the actions necessary for a more successful post go-live.[50]

Design, content and technical aspects can act as barriers or facilitators to changing the clinical behaviour towards better patient care in technology-based interventions.[49] Further multidisciplinary research should inform the development of DSAs which are easy to use, but that, at the same time, are more sophisticated, able to target specific HCPs and hospital units and simultaneously become more patient-specific, transparent and interactive. DSAs should also be more effectively linked to guidance on sepsis protocols, escalation practice and antibiotics prescribing. Researchers and developers should work in conjunction with HCPs and policy-makers to refine technology-based behaviour change techniques that *effectively* support HCPs' decision-making, care practice and improve patients' outcomes as a result.

Research recommendations

Our work utilised data from four large NHS Trusts involving the collaboration and co-operation between trusts. With support from the National Institute for Health Research-Health Informatics Collaborative, we were able to secure data-sharing agreements between trusts. We worked with clinicians and health informatics specialists to develop an agreed data dictionary, which is enabling a wide range of research projects. NHS Trusts with secured data environments enable the effective sharing of data for research, with tight data protection, to ensure research for improvements in the health care which will improve patient outcomes. This research shows that it is key that we design screening tools and digital alerts with a strong evidence base, including the indicators within the screening tool, and also in terms of the patient groups we are targeting. As indicated by the quantitative findings from this research, different patient groups within different trusts may need different indicators different thresholds for action and/or different actions and treatments. This supports calls from the HCPs themselves who, in the qualitative component, advise that more sophisticated sepsis screening tools should be more specific, patient-based, target HCP teams, be portable and remotely accessible and integrate with EPR. A key advantage of EPRs and embedded digital tools is that screening and treatment can be readily personalised without expecting healthcare professionals to look up specific guidance.

Wong *et al.*[20] have highlighted that, in the USA, 'the ease of integration within the EPR and loose federal regulations' means that hospitals adopt algorithms with ease without a detailed knowledge of real-world performance. This is also the case in England; however, the Medical Health Regulatory Authority is now recommending that software as a medical device should undergo proper scrutiny that 'commensurate with risk'. There is a need for a strong methodological library for evaluating digital tools, including determining risk. Digital tools currently in use in acute hospitals in England use simple algorithms based on paper-based T&T systems and are not taking advantage of granular data available in the EPR. While the majority of NHS Trusts in England are using NEWS2, as required in the National Standard Contract, this was not designed as a digital tool nor developed within data-rich environments. Many trusts are using alternative algorithms, often in combination with NEWS2, which do not have a strong evidence base. Studies which compare these approaches are vital to inform on the most effective practice.

As EPRs become universal, there is enormous potential in harnessing granular data to improve the performance of digital tools to support care of deteriorating patients. However, we need a strong methodological evaluation approach, and clinicians and hospital leaders have a responsibility to understand the digital tools in use in their hospitals. We would go further and suggest that there should be a publicly accessible registry of digital alerting tools in use in hospitals, including DSAs.

Conclusions

Current DSAs nested within the EHR are introduced to support the identification and management of sepsis/deterioration and improve patient outcomes. Current DSAs fulfil their purpose but not entirely and not equally in all hospitals; an organic, multilevel framework to enhance tailored implementation of DSAs is needed, along with the simultaneous validation of their effect on patient outcomes. No technological innovation in the healthcare setting can be a solo driver of change, and DSAs are not magic wands able to dissipate issues that instead become important barriers to their optimal use in the rollout phase. DSAs implemented in trusts with good levels of staffing, resources and functional teamwork are likely to be taken up more optimally and become good partners for HCPs. Equally, where the rollout of DSAs is accompanied by multidisciplinary quality optimisation initiatives, and by training, education and other sepsis awareness actions that continually engage staff, HCPs are more likely to accept and embed the DSA in their practice. Trust implementation of DSAs requires changes on multiple levels and at all phases of the intervention, starting from a pre-go-live analysis assessing and addressing organisational needs and readiness. Advancements towards minimally disruptive and smart DSAs – which are more accurate and specific, but at the same time, scalable and accessible – have to see policy changes and investments in multidisciplinary research agendas.

Equality, diversity and inclusion

This DiAIS study was committed to promoting equality, diversity and inclusion (EDI) throughout all stages. We ensured equal opportunities for all participants and researchers regardless of race, ethnicity, gender, age, disability, sexual orientation, religion or socioeconomic status. We actively promoted diversity within the research teams and participant recruitment, ensuring a broad range of perspectives. We also provided an inclusive environment, making necessary adjustments to support participants with specific needs and ensuring accessibility for all. By prioritising EDI, we enhanced the quality and relevance of our research and contributed to more equitable health and care solutions. We continuously monitored and improved our EDI practices throughout the project.

Additional information

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Other contribution

Pippa Goodman: Patient representative.

Patient data statement

This work uses data provided by patients and collected by the NHS as part of their care and support. Using patient data is vital to improve health and care for everyone. There is huge potential to make better use of information from people's patient records, to understand more about disease, develop new treatments, monitor safety and plan NHS services. Patient data should be kept safe and secure, to protect everyone's privacy, and it is important that there are safeguards to make sure that they are stored and used responsibly. Everyone should be able to find out about how patient data are used. #datasaveslives You can find out more about the background to this citation here: https://understandingpatientdata.org.uk/data-citation.

Data-sharing statement

Some of the outputs are generated from a qualitative study and therefore the data generated are not suitable for sharing beyond that contained within the manuscript. Further information can be obtained from the corresponding author. Requests for access to data should be addressed to the corresponding author.

Ethics statement

The project has ethical approval from the Health Regulatory Authority (Project ID – 288328, approved 20 February 2020). The qualitative study is registered on ClinicalTrials.gov and the registration identifier for this study is NCT05741801; the protocol ID is 16347.

Information governance statement

Imperial College London is committed to handling all personal information in line with the UK Data Protection Act (2018) and the General Data Protection Regulation (EU GDPR) 2016/679. Under Data Protection legislation NIHR is the Data Processor; the Department for Health and Social Care (DHSC) is the Data Controller, and we process personal data in accordance with their instructions. You can find out more about how we handle personal data, including how to exercise your individual rights and the contact details for DHSC's Data Protection Officer here: www.nihr.ac.uk/nihr-privacy-policy.

Disclosure of interests

Full disclosure of interests: Completed ICMJE forms for all authors, including all related interests, are available in the toolkit on the NIHR Journals Library report publication page at https://doi.org/10.3310/GJCC0605.

Primary conflicts of interest: We endeavour to obtain ICMJE disclosure of interests forms for all named authors. In this case, we have been unable to obtain these forms for every author. Please contact the corresponding author if you have any queries.

Department of Health and Social Care disclaimer

This publication presents independent research commissioned by the National Institute for Health and Care Research (NIHR). The views and opinions expressed by authors in this publication are those of the authors and do not necessarily reflect those of the NHS, the NIHR, MRC, NIHR Coordinating Centre, the Health and Social Care Delivery Research programme or the Department of Health and Social Care.

This synopsis was published based on current knowledge at the time and date of publication. NIHR is committed to being inclusive and will continually monitor best practice and guidance in relation to terminology and language to ensure that we remain relevant to our stakeholders.

Funding

This synopsis presents independent research funded by the National Institute for Health and Care Research (NIHR) Health and Social Care Delivery Research programme as award number NIHR129082.

Award publications

This synopsis provided an overview of the research award *Digital alerting to improve sepsis detection and patient outcomes in NHS Trusts*. Other articles published as part of this thread are:

Honeyford K, Nwosu AP, Lazzarino R, Kinderlerer A, Welch J, Brent AJ, *et al*. Prevalence of electronic screening for sepsis in National Health Service acute hospitals in England. *BMJ Health Care Inform* 2023;**30**:e100743. https://doi.org/10.1136/bmjhci-2023-100743

Honeyford K, Timney A, Lazzarino R, Welch J, Brent AJ, Kinderlerer A, *et al*. Digital innovation in healthcare: quantifying the impact of digital sepsis screening tools on patient outcomes – a multisite natural experiment. *BMJ Health Care Inform* 2025;**32**:e101141. https://doi.org/10.1136/bmjhci-2024-101141

Lazzarino R, Borek AJ, Honeyford K, Welch J, Brent AJ, Kinderlerer A, *et al*. Views and uses of sepsis digital alerts in National Health Service Trusts in England: qualitative study with health care professionals. *JMIR Hum Factors* 2024;**11**:e56949. https://doi.org/10.2196/56949

For more information about this research please view the award page (www.fundingawards.nihr.ac.uk/award/NIHR129082).

About this synopsis

The contractual start date for this research was in September 2020. This article began editorial review in July 2024 and was accepted for publication in June 2025. The authors have been wholly responsible for all data collection, analysis and interpretation, and for writing up their work. The Health and Social Care Delivery Research editors and publisher have tried to ensure the accuracy of the authors' article and would like to thank the reviewers for their constructive comments on the draft document. However, they do not accept liability for damages or losses arising from material published in this article.

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List of abbreviations

CDSS	clinical decision support system
DiAIS	Digital Alerts for Sepsis
DS	digital system
DSA	digital sepsis alert
ED	emergency department
EDI	equality, diversity and inclusion
EHR	electronic health record
EPR	electronic patient record
FoI	Freedom of Information
HCP	healthcare professional
ICD-10	*International Statistical Classification of Diseases and Related Health Problems*, Tenth Revision
ICU	intensive care unit
ITS	interrupted time series
NEWS2	National Early Warning Score
OT	outreach team
PPI	patient and public involvement
qSOFA	quick Sepsis-related Organ Failure Assessment
SIRS	systemic inflammatory response syndrome
SoS	Suspicion of Sepsis
T&T	track and trigger
WS1	Workstream 1
WS4	Workstream 4

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Appendix 1

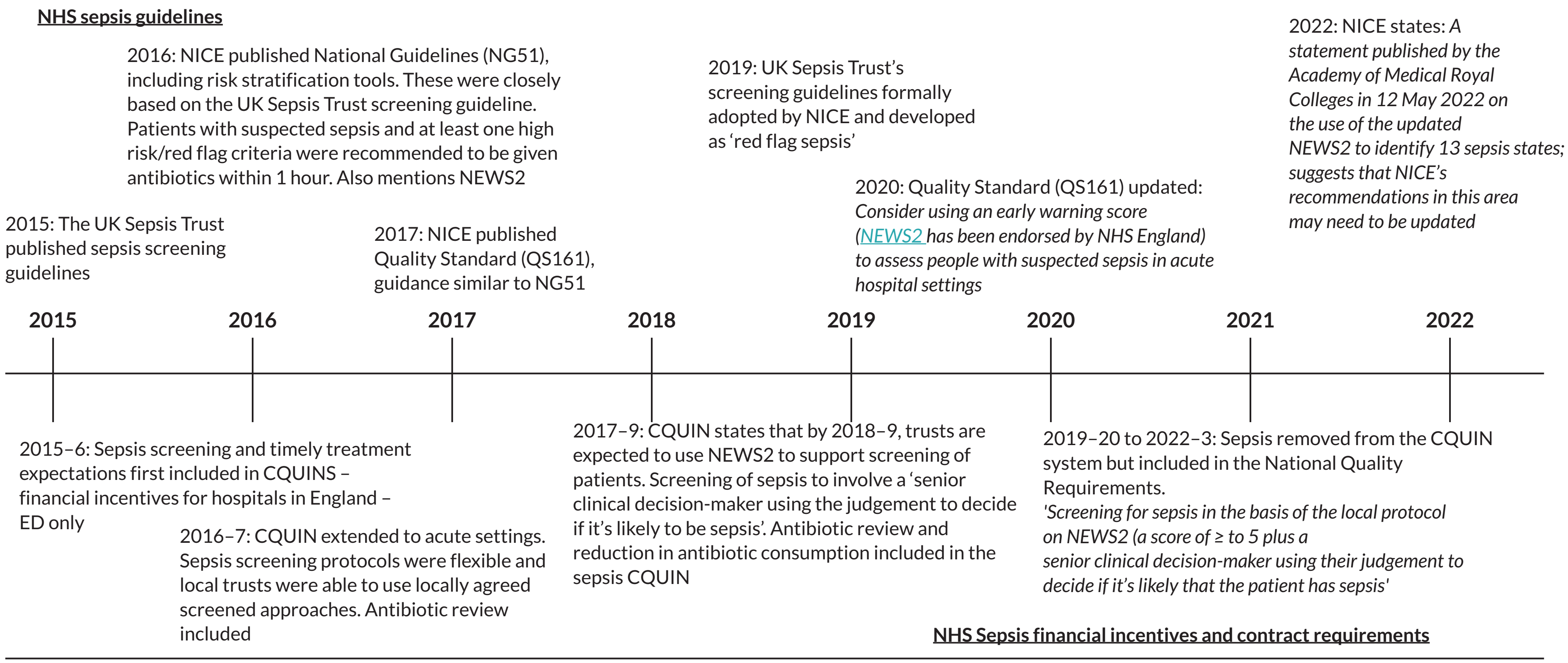

FIGURE 1 Timeline showing the development of sepsis guidelines and incentives in the NHS in England. CQUIN, Commissioning for Quality and Innovation; NICE, National Institute for Health and Care Excellence. Reproduced with permission from Honeyford *et al.*[1] This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 4.0) licence, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. See: https://creativecommons.org/licenses/by/4.0/. The figure includes minor additions and formatting changes to the original text.

This synopsis should be referenced as follows:
Honeyford K, Cooke G, Kinderler A, Welch J, Brent A, Glampson B, *et al.* Digital alerting to improve sepsis detection and patient outcomes in NHS Trusts: a multi-methods study. *Health Soc Care Deliv Res* 2026;**14**(5). https://doi.org/10.3310/GJCC0605

DOI: 10.3310/GJCC0605

TABLE 1 Electronic patient record providers, DSAs and associated algorithms in use in England NHS

	All EPRs	Sepsis alerts	Alone	& qSOFA	& Red Flag	& sepsis screen	& SIRS	qSOFA alone	Red Flag alone	SIRS alone
Total	84	59	22	9	6	8	1	3	8	2
Mix	19 (23%)	14 (24%)	4	3	2	3			2	
Cerner	18 (21%)	15 (27%)	6		2		1		4	2
System C	11 (13%)	8 (14%)	1	5				1		
Allscripts sunrise	6 (7%)	3 (5%)	1			1		1	1	
Dedalus	8 (10%)	3 (5%)	1		1	1				
In-house	2 (5%)	1 (2%)	–			1				
Epic	4 (5%)	3 (5%)	2			1				
Other	14 (17%)	8 (15%)	5	1	1			1	1	
Missing	2 (2%)	–	1			1				

Note
% are column percentages, showing the proportion of each algorithm associated with each of the main EPR provider.

Source

Appendix 2

TABLE 2 Summary of patients admitted with the SoS before and after the introduction of a sepsis screening tool

	Trust A		Trust B		Trust C		Trust D	
	Before	After	Before	After	Before	After	Before	After
No. of patients admitted	79,527	76,860	66,419	181,882	116,404	86,888	43,046	14,466
Gender								
Male	34,495 (43.4)	33,709 (43.9)	31,257 (47.1)	86,356 (47.6)	52,033 (44.7)	39,002 (44.9)	19,903 (46.2)	6836 (47.3)
Female	45,032 (56.6)	43,151 (56.1)	35,162 (52.9)	95,526 (52.4)	64,371 (55.3)	47,886 (55.1)	23,143 (53.8)	7630 (52.7)
Ethnicity								
White British and Irish	34,409 (43.3)	31,053 (40.4)	53,296 (80.2)	136,944 (75.3)	51,324 (44.1)	30,006 (34.5)	19,081 (44.3)	6720 (46.5)
Asian[a]	10,217 (12.8)	11,253 (14.6)	2313 (3.5)	6219 (3.4)	12,540 (10.8)	9298 (10.7)	3615 (8.4)	1498 (10.4)
Black[b]	4160 (5.2)	3554 (4.6)	880 (1.3)	2462 (1.4)	13,354 (11.5)	9641 (11.1)	3401 (7.9)	1444 (10)
Any other ethnicity	17,108 (21.5)	16,582 (21.6)	2741 (4.1)	9998 (5.5)	27,813 (23.9)	21,707 (25.0)	8482 (19.7)	3536 (24.4)
Not stated	9662 (12.5)	12,913 (16.8)	6920 (10.3)	24,861 (13.6)	5309 (4.6)	10,584 (12.2)	3791 (44.3)	864 (46.5)
Not known or missing	3971 (5.0)	1505 (2.0)	269 (0.4)	1443 (0.7)	6064 (5.2)	5652 (6.5)		
Age[c]	49 (27–64)	61 (37–77)	55 (30–70)	52 (29–66)	55 (33–70)	49 (27–64)		
Elixhauser score[c]	5 (0–12)	3 (0–8)	3 (0–8)	4 (0–10)	4 (0–10)	5 (0–12)		
Season of admission								
Winter (December–March)	32,720 (37.7)	26,767 (34.8)	24,852 (37.4)	60,158 (33.1)	37,442 (32.2)	32,720 (37.7)		
Spring, summer, autumn (April–November)	51,377 (62.3)	50,093 (65.2)	41,567 (62.6)	121,724 (66.9)	78,962 (67.8)	51,377 (62.3)		
Time of admission								
Morning (07.00–09.00)	10,941 (12.6)	8182 (10.6)	9414 (14.2)	31,682 (17.4)	14,018 (12.0)	10,941 (12.6)		
Mid-day (10.00–13.00)	16,905 (19.5)	13,761 (17.9)	14,385 (21.7)	43,711 (24.0)	19,099 (16.4)	16,905 (19.5)		
Afternoon (14.00–19.00)	28,146 (32.4)	24,997 (32.5)	23,606 (35.5)	59,811 (32.9)	39,434 (33.9)	28,146 (32.4)		
Night (20.00–06.00)	30,869 (35.6)	29,920 (38.9)	19,014 (28.6)	46,678 (25.7)	43,853 (37.7)	30,869 (35.6)		
Patients who died	4200 (4.8)	3017 (3.9)	3979 (6.0)	9429 (5.2)	5834 (5.0)	4200 (4.8)		

a Asian, Asian British and Mixed Asian.
b Black, Black British and Mixed Black.
c Median and interquartile range.

Note
Counts and % of all admissions in brackets.

Source
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DOI: 10.3310/GJCC0605

TABLE 3 Interrupted time series analysis of the impact of sepsis screening tools on mortality outcomes for SoS patients in three NHS Trusts in England

	Trust A		Trust B		Trust C	
Variable	**OR (95% CI)**	***p*-value**	**OR (95% CI)**	***p*-value**	**OR (95% CI)**	***p*-value**
Alert introduction	0.931 (0.822 to 1.054)	0.261	0.961 (0.877 to 1.053)	0.391	0.826 (0.749 to 0.911)	0.0001
Time in days since the start of the study period (gradient)	1.000 (1.000 to 1.000)	0.003	1.000 (1.000 to 1.000)	0.041	1.000 (1.000 to 1.000)	0.0003
Time in **years** since the start of the study period	1.044 (1.020 to 1.068)	0.003	0.963 (0.929 to 0.998)	0.041	1.025 (1.012 to 1.039)	0.0003
Change in gradient[a]	1.000 (1.000 to 1.000)	0.133	1.000 (1.000 to 1.000)	0.968	1.000 (1.000 to 1.000)	< 0.0001
Season of admission (reference is February–October), winter admission	1.174 (1.103 to 1.250)	< 0.0001	1.112 (1.061 to 1.166)	< 0.0001	1.097 (1.046 to 1.151)	0.0001
Time of admission (reference is morning)						
Afternoon	1.526 (1.318 to 1.767)	< 0.0001	1.735 (1.583 to 1.901)	< 0.0001	1.446 (1.313 to 1.593)	< 0.0001
Mid-day	1.380 (1.178 to 1.618)	0.0001	1.630 (1.479 to 1.796)	< 0.0001	1.324 (1.190 to 1.473)	< 0.0001
Night	1.562 (1.351 to 1.807)	< 0.0001	1.856 (1.692 to 2.037)	< 0.0001	1.565 (1.422 to 1.722)	< 0.0001
Ethnicity (references are White British and Irish)						
Ethnicity – any other	0.658 (0.592 to 0.732)	< 0.0001	0.968 (0.832 to 1.126)	0.675	1.042 (0.982 to 1.106)	0.1771
Asian[b]	1.203 (1.096 to 1.321)	0.0001	0.707 (0.578 to 0.866)	0.0008	0.949 (0.875 to 1.029)	0.2071
Black[c]	0.550 (0.430 to 0.703)	< 0.0001	0.952 (0.712 to 1.273)	0.741	0.820 (0.753 to 0.894)	< 0.0001
Not known or missing	1.011 (0.883 to 1.157)	0.877	2.765 (2.064 to 3.704)	< 0.0001	0.905 (0.802 to 1.023)	0.1103
Not stated	0.878 (0.800 to 0.964)	0.006	1.426 (1.325 to 1.534)	< 0.0001	1.309 (1.196 to 1.433)	< 0.0001
Age (in years)	1.051 (1.048 to 1.053)	< 0.0001	1.046 (1.044 to 1.047)	< 0.0001	1.040 (1.039 to 1.042)	< 0.0001
Gender (male is reference) Female	0.878 (0.826 to 0.933)	< 0.0001	0.892 (0.852 to 0.934)	< 0.0001	0.932 (0.890 to 0.975)	0.0024
Elixhauser score	1.112 (1.108 to 1.116)	< 0.0001	1.114 (1.111 to 1.118)	< 0.0001	1.111 (1.108 to 1.114)	< 0.0001

a Interaction between time in days since the start of the study period and the introduction of the alert.
b Asian, Asian British and mixed Asian.
c Black, Black British and mixed Black.

Note
The ITS data are presented as odds ratios (OR; 95% CI), except where specified. Values are given to three decimal places.

Source

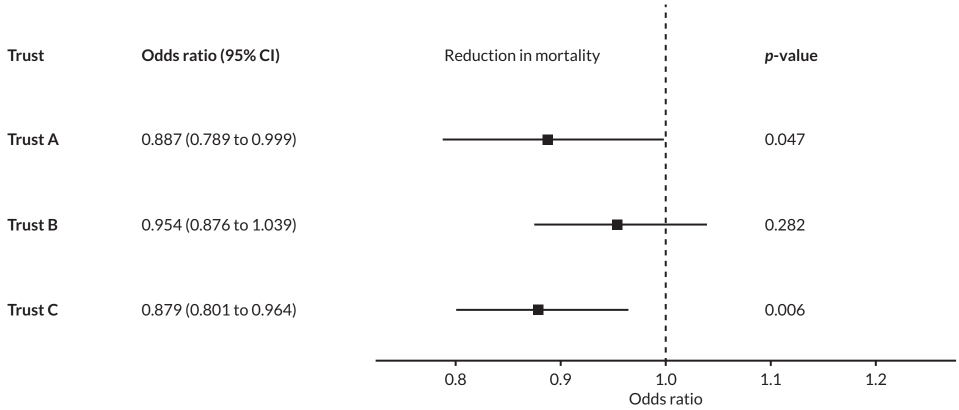

FIGURE 2 Odds ratios for impact of the introduction of a sepsis screening tool, adjusted for pre-existing trend. Reproduced with permission from Honeyford *et al.*[2] This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 4.0) licence, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. See: https://creativecommons.org/licenses/by/4.0/. The figure includes minor additions and formatting changes to the original text.

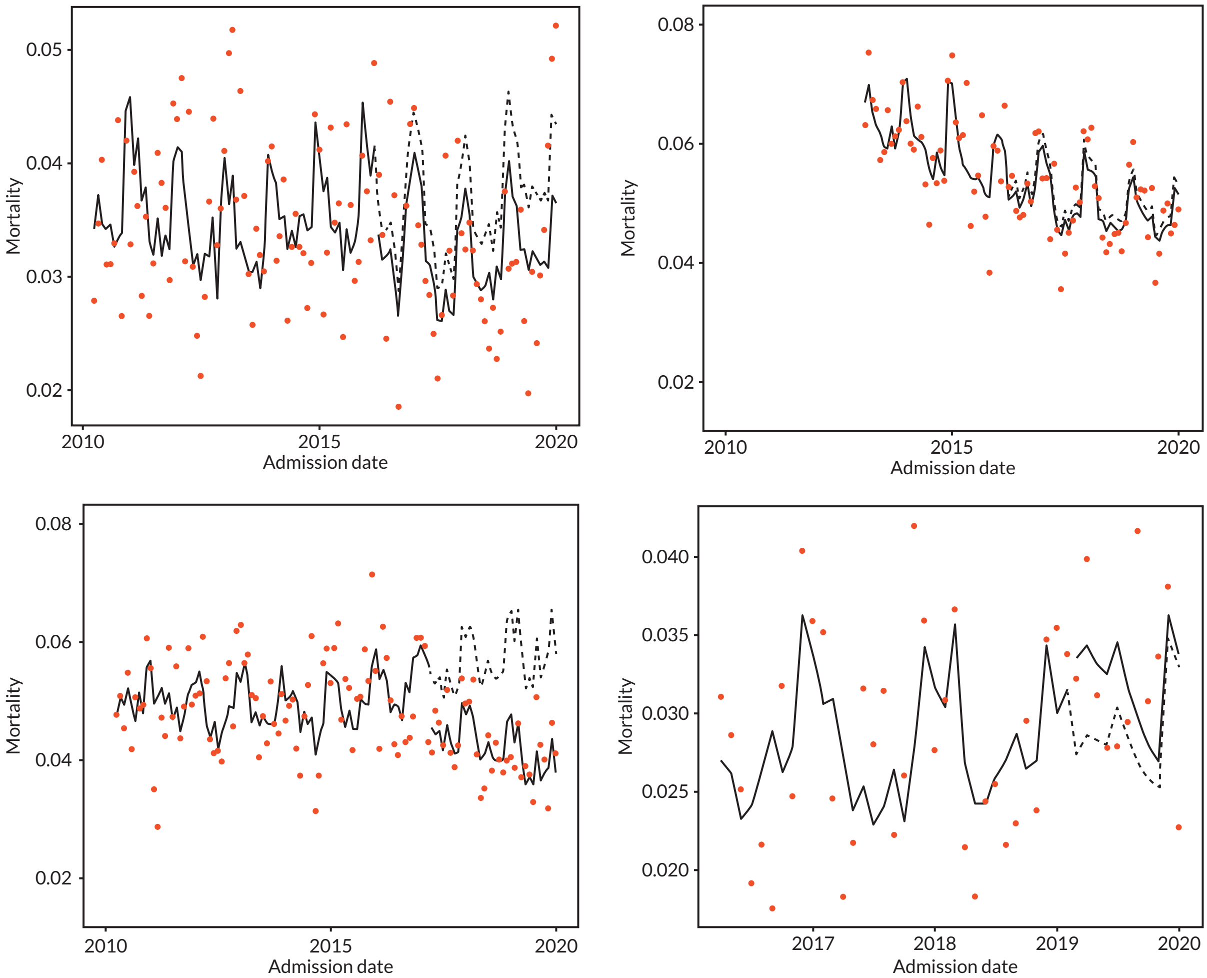

FIGURE 3 Interrupted time series of impact of introduction of sepsis alert on mortality. Reproduced with permission from Honeyford *et al.*[2] This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 4.0) licence, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. See: https://creativecommons.org/licenses/by/4.0/. The figure includes minor additions and formatting changes to the original text.

AQ3 **BOX 1** Data-sharing

A key strength of this study was the collaboration between four NHS Trusts providing data in sharing, analysing and interpreting data. The NIHR-Health Informatics Collaborative facilitated data-sharing agreements between the NHS Trusts. We worked with clinicians and health informatics specialists to develop a data dictionary enabling a wide range of research projects. Health Informatics managers at each NHS Trust quality-checked and processed the data according to the data dictionary before subsequent transfer to either Imperial College Healthcare NHS Trust and Imperial College London (iCARE) research facility and Secure Data Environment or NIHR Biomedical research centre (BRC) Informatics Digital Environment (BRIDgE) secure data environment.

Appendix 3

TABLE 4 Main characteristics of NHS Trusts' research sites

	Site 1	Site 2	Site 3
The EHRs' DS	DS introduced in 2019	DS introduced in 2015	DS (same as Site 2) progressively introduced from 2013
	DS interface is user-friendly and uniform across the site's units and job roles	DS interface is not very straightforward, with numerous top and side tabs and colours	
		Intensive care has a different DS	DS differentiates between the log in of a nurse and a doctor, who access different information
	There are other alerts in use, mainly passive, especially for ED triaging	There are other soft-stop digital alerts, as well as passive ones, such NEWS2, and for ED triaging	
	DS has several functions, for example a chat, and can be used as a phone app, linked to other apps and to the tablets used for patients' observations		Other software and applications are in use, for example on sepsis management and antibiotics administration
The SDDA	SDDA introduced with the DS in 2019	SDDA introduced in 2016	SDDA progressively introduced from 2016
	SDDA is NEW2 and sepsis is suspected with a score of 5+ and a confirmed/suspected infection	SDDA is based on an in-house adaptation of Sepsis Red Flag screening tool	SDDA is in-built in the DS, based on St John Sepsis Algorithm SDDA is informed by a binary alarm paradigm, generating two alerts: (1) for potential sepsis and (2) for potential severe sepsis
	SDDA is a passive icon which changes colour according to the score	SDDA is both soft-stop and passive	
		Prescribers and non-prescribers can respond differently to the SDDA	
	On the wards, professionals have to open the EHR to see the SDDA	On the wards, the alert box pops up when an EHR is opened and closed, until appropriately actioned	
	In ED, SDDA is appearing on the list of patients visible on digital dashboard	In ED, SDDA is also a passive icon visible on the patients' digital dashboard which changes colour according to the clinical actions (e.g. sepsis is confirmed, treated and dismissed)	

continued

TABLE 4 Main characteristics of NHS Trusts' research sites (*continued*)

	Site 1	Site 2	Site 3
Trust actions on sepsis, DS/SDDA	Deterioration and acuity are the priority over sepsis per se	Sepsis has been among the trust's priorities up until COVID-19	
		The trust implemented initiatives for sepsis awareness raising and education, including in relation to the 'Gold hour target' (e.g. sites' performance competitions, videos and information on the intranet, sepsis trolleys and champions)	
	ED led on the introduction and adaptation of SDDA/DS to the trust, with some consultations with other units		Weekly flat-hierarchy, multidisciplinary meetings on sepsis awareness and SDDA's optimisation This initiative ceased due to COVID-19
	Deliberate choice to keep minimal the number of soft-stop digital alerts		Deliberate choice to reduce the number of soft-stop digital alerts
	The trust has a NEWS2-based, nurse-led, 24/7 OT	There is a team dedicated to sepsis awareness and training and to monitor SDDAs and support hospital units The team works in normal office hours; its visibility declined to staff changes, but is due to expand capacity	The trust has a NEWS2-based, nurse-led, 24/7 OT

SDDA, sepsis/deterioration digital alert.

Source

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TABLE 5 Characteristics of participants

	Participants (*n*)	Declared gender (*n* = female)	Age in years; mean (range)	Job title/hospital unit (*n*)	Years of experience; mean (range)	Years of use of digital alerts; mean (range)
Site 1	8	3	43.5 (34–55)	Nurses/OT, *n* = 3 Nurse/ED, *n* = 1 Consultants/ICU, *n* = 3 Consultant/ED, *n* = 1	10 (7–18)	6 (4–10)
Site 2	7	5	36 (29–42)	Nurse/OT, *n* = 2 Nurse/ED, *n* = 1 Nurse/AMU, *n* = 1 Consultant/OT, *n* = 1 Consultant/ED, *n* = 1 Consultant/ICU, *n* = 1	6 (3–8)	5 (1–7)
Site 3	7	7	43 (30–54)	Nurses/OT, *n* = 3 Nurse/ED, *n* = 1 Nurse/AMU, *n* = 1 Consultants/ED, *n* = 2	9 (1–20)	7 (5–10)
	N = 22	*N* = 15	*M* = 41	Nurses, *n* = 13 Consultants, *n* = 9 OT, *n* = 9 ED, *n* = 7 AMU, *n* = 2 ICU, *n* = 4	*M* = 11	*M* = 6

AMU, acute medical unit.

Source

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