Developing Clinical Decision Support within a Commercial Electronic Health Record System to Improve Antimicrobial Prescribing in the Neonatal ICU

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Summary
Objective: To develop and implement a clinical decision support (CDS) tool to improve antibiotic prescribing in neonatal intensive care units (NICUs) and to evaluate user acceptance of the CDS tool.
Methods: Following sociotechnical analysis of NICU prescribing processes, a CDS tool for empiric and targeted antimicrobial therapy for healthcare-associated infections (HAIs) was developed and incorporated into a commercial electronic health record (EHR) in two NICUs. User logs were reviewed and NICU prescribers were surveyed for their perceptions of the CDS tool.
Results: The CDS tool aggregated selected laboratory results, including culture results, to make treatment recommendations for common clinical scenarios. From July 2010 to May 2012, 1,303 CDS activations for 452 patients occurred representing 22% of patients prescribed antibiotics during this period. While NICU clinicians viewed two culture results per tool activation, prescribing recommendations were viewed during only 15% of activations. Most (63%) survey respondents were aware of the CDS tool, but fewer (37%) used it during their most recent NICU rotation. Respondents considered the most useful features to be summarized culture results (43%) and antibiotic recommendations (48%).
Discussion: During the study period, the CDS tool functionality was hindered by EHR upgrades, implementation of a new laboratory information system, and changes to antimicrobial testing methodologies. Loss of functionality may have reduced viewing antibiotic recommendations. In contrast, viewing culture results was frequently performed, likely because this feature was perceived as useful and functionality was preserved.
Conclusion: To improve CDS tool visibility and usefulness, we recommend early user and information technology team involvement which would facilitate use and mitigate implementation challenges.

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1. Background

Infants in the neonatal intensive care unit (NICU) are at high risk of developing healthcare-associated infections (HAIs), including those caused by multidrug-resistant organisms [1]. Late onset sepsis, meningitis, and necrotizing enterocolitis are clinical scenarios common to all NICUs, but can be caused by pathogens with antimicrobial susceptibility patterns unique to local settings [2-4]. Thus, initiation of empiric broad-spectrum antimicrobial therapy, prior to availability of culture results, should be based on local epidemiology as well as the clinical history of individual infants. Optimizing empiric use of antibiotics and then adjusting to targeted therapy when informative culture results are available are recommended clinical practices [5-7]. However, as signs and symptoms of sepsis in infants are often non-specific, the practice of initiating and continuing broad-spectrum antibiotics despite negative cultures can lead to overuse of antibiotics with subsequent increases in toxicity, resistance, and healthcare expenditures [8, 9]. We have previously reported that approximately 25% of antibiotics used in the NICU may be inappropriate [8].

In 2007, the Infectious Diseases Society of America (IDSA) and the Society for Healthcare Epidemiology of America (SHEA) published evidence-based guidelines for antimicrobial stewardship programs for acute care settings. Antimicrobial stewardship seeks to optimize treatment and clinical outcomes while minimizing adverse consequences such as antimicrobial resistance and toxicity due to unnecessary antibiotic exposure [10]. In addition, these guidelines suggested that the use of electronic health records (EHRs), computerized provider order entry and clinical decision support (CDS) could facilitate antimicrobial stewardship [10]. Notably, CDS systems have been hypothesized as a means to improve quality, reduce costs, and decrease errors within healthcare [10-14].

To inform CDS tool design and increase user acceptability, our group previously conducted a sociotechnical analysis of four NICUs to assess antibiotic prescribing practices [15]. The analysis yielded the following common themes: (1) When faced with an infant with signs and symptoms of infection, clinicians will choose to provide broad-spectrum antibiotics as a potentially life-saving therapy, despite the potential of increasing overuse and antibiotic resistance in their NICU; (2) A hierarchy of decision making exists in the clinical environment wherein the clinician entering antibiotic orders (e.g., the pediatric resident or nurse practitioner) is frequently not the clinician ultimately responsible for making decisions (i.e., the attending physician); (3) NICU clinicians did want to decrease overall use of antibiotics and (4) use antimicrobial susceptibility results to guide appropriate antibiotic treatment of a specific pathogen. We used the results of the sociotechnical analysis to design, develop, and implement an antibiotic prescribing CDS tool within a commercial EHR. In this paper we describe (1) development of the decision logic, (2) design of the functional prototype, (3) patterns of use, and (4) user satisfaction. We also report the challenges encountered during implementation.

2. Methods

The CDS tool was developed as one of three interdisciplinary interventions designed to improve antibiotic prescribing in the NICU population. The larger multi-center prospective study, "Improving Antimicrobial Prescribing Practices in the Neonatal Intensive Care Unit" (5R01NR010821), was conducted in four academically affiliated NICUs to assess the impact of three interdisciplinary interventions recommended in the IDSA/SHEA antimicrobial stewardship guidelines [10] including education [16], CDS, and provider feedback [17].

2.1 Study Sites and Clinician Cohorts

Two of the four NICUs were randomly assigned to the same CDS tool. These two NICUs are affiliated with NewYork-Presbyterian Hospital and together have approximately 107 beds and 1,600 annual admissions. Study subjects were clinicians who prescribe antimicrobial agents including neonatal attending physicians, pediatric residents, neonatology fellows, house physicians, and nurse practitioners. Approval to conduct this study was received from the institutional review boards of Columbia University Medical Center and Weill Cornell Medical College.

2.2 CDS Development and Implementation

As mentioned above, we have reported the sociotechnical analysis of NICU antibiotic prescribing processes [15]. The next stages of the development of the CDS tool consisted of: (1) developing antimicrobial decision logic from July 2009 to January 2010; and (2) creating a prototype CDS tool from October 2009 to June 2010 which was incorporated into a commercial EHR, Allscripts Sunrise (Allscripts, Chicago, IL) in July 2010.

2.2.1 Decision logic for recommendations for antimicrobial selection

The study team conducted weekly sessions with a pediatric infectious disease specialist/ hospital epidemiologist [PG] to develop the initial decision logic algorithms for antimicrobial recommendations for common HAIs in the NICU population. The relative importance of the sources used to develop the algorithms is shown in ►Table 1. As so few practice guidelines or randomized clinical trials of antibiotic treatment for this population existed, we relied on local epidemiology, practices, and expertise to develop the algorithms. Incorporating local prescribing practices and local antimicrobial stewardship expertise have been shown to be important in CDS tool design and user acceptability [10, 18, 19].

The aggregated antimicrobial susceptibility patterns for the study NICUs, i.e. local antibiogram data, were not available in the EHR nor was there functionality to import these data into the CDS tool in real-time. Thus, common antimicrobial susceptibility patterns, based on the previous year's antibiogram data were incorporated into the fixed decision logic for empiric therapy *a priori*. The algorithms addressed empiric and targeted antimicrobial therapy for common pathogens as well as infections at different body sites (e.g., bloodstream infection versus meningitis). Algorithms for early onset sepsis were not developed. The decision logic algorithms were refined by integrating findings from previous studies using clinical vignettes developed by the study team [16, 17]. Next, attending neonatologists, additional pediatric infectious disease physicians, and hospital epidemiologists from the two NICUs reviewed the candidate algorithms and revised them to ensure they reflected local prescribing practices.

2.2.2 Creation and Implementation of the Antimicrobial Prescribing CDS Tool

The two NICUs randomized to receive CDS used the same commercial EHR system, Allscripts Sunrise (Allscripts, Chicago, IL). The vendor provided an application-programming interface (API), ObjectsPlus/XA™, for the system which allowed the development of custom modules using the Microsoft C# programming language with the Microsoft .NET Framework (Microsoft, Redmond, WA) [20]. The CDS tool was modular with the user interface, decision logic, and EHR database retrieval functions separated to maximize reuse and portability to other EHR systems. In addition to the antimicrobial prescribing recommendations provided by the CDS tool, NICU prescribers identified other components to facilitate antimicrobial prescribing. These components included selected patient demographics, simplified and summarized culture results, active antimicrobial orders and doses, and selected laboratory results as shown in ►Table 2.

A design team of pediatric infectious disease specialists, a neonatologist, a biomedical informatician and a programmer developed the initial tool. The user interface incorporated the clinical perspectives of the neonatologist and pediatric infectious disease specialists. The prototype CDS tool was presented to attending neonatologists from the two study NICUs. Based on their feedback, the user interface was redesigned as described below. Next, a convenience sample of five participants from each NICU was selected to perform user testing with constructed scenarios and real data was conducted within a test environment. The study team observed use to inform additional refinements. Software development was performed by three investigators (RSH, KC, DKV).

2.3 User Logs

To understand the patterns of use of the CDS tool, we implemented comprehensive audit logging that recorded the date and time of each user action, type of action, and user identifier. CDS tool activations, viewing of susceptibility reports for culture results and treatment recommendations were tallied.

2.4 User Survey

We developed an 18-item anonymous web-based survey to assess user awareness and acceptance of the CDS tool; ease of use compared with other available electronic data sources (e.g., EHR presentation of laboratory results); and recommendations for additional features. We administered the survey to all eligible NICU prescribers from July to September 2011, one year after initial implementation of the CDS tool. Response rates were based on the total number of respondents. Unanswered questions were considered to be negative responses.

3. Results

3.1 Study Sites and Clinician Cohorts

During the study, 2009 patients were prescribed antibiotics. The types of practitioners in the clinician cohort at the two sites are shown in ►Table 3. Fifty-six providers worked at Site 1 and 27 worked at Site 2. The distribution of the types of practitioners was similar at the two study NICUs.

3.2 CDS Development and Implementation

3.2.1 Decision logic for recommendations for antimicrobial selection

The final antimicrobial selection decision logic consisted of four different algorithms, which provided recommendations for empiric and targeted therapy for common Gram-positive and Gram-negative pathogens in the NICU population. The data incorporated into these recommendations are shown in ►Table 4 and a sample algorithm is shown in ►Figure 1. Since the type of infection influences the choice of antibiotics, each algorithm included the following clinical scenarios associated with HAIs: late onset sepsis, meningitis, and/or necrotizing enterocolitis. The algorithms did not provide specific antibiotic dosage or dosing interval recommendations as both sites used NeoFax® (a paper-based manual of drugs used in neonatal care) for these parameters. However, each algorithm incorporated a message about renal insufficiency as this can influence the dosing interval for many antimicrobial agents. Additionally, the algorithms were consistent with the educational interventions in the larger multicenter study.

Depending on the timing of CDS tool activation, culture results could be pending (no data available), preliminary ('no growth to date' or Gram stain result prior to species identification), or final ('no growth final' or the identification and antimicrobial susceptibility of the detected pathogen). For pending and preliminary results, the algorithms for empiric antibiotics considered the patient's previous cultures including antimicrobial susceptibility results to recommend the most appropriate antibiotics (►Table 4). If the final result yielded an organism with antimicrobial susceptibilities, the algorithms for targeted therapy were used. These included separate algorithms for each of the common Gram-positive pathogens (*Staphylococcus aureus*, coagulase-negative staphylococci, group B streptococcus, and enterococci) and a common algorithm for all Gram-negative pathogens. If the final culture result reflected no microbial growth, the message "Consider discontinuation of antibiotic treatment" was shown. If the culture results yielded an organism not included in the treatment algorithms (e.g., a rare Gram-positive pathogen or a pathogen resistant to all antibiotics), or if the selected clinical scenario was complex (e.g., meningitis with renal insufficiency), the algorithms recommended consultation with a pediatric infectious disease specialist.

3.2.2 Creation and Implementation of the Antimicrobial Prescribing CDS Tool

The initial user interface of the prototype CDS tool required redesign as the neonatologists at both study sites expressed safety concerns as the interface provided recommendations for all HAI clinical scenarios in a single view as shown in ►Figure 2a. The clinicians were concerned that different recommendations could be confused and infants could be prescribed inappropriate antibiotics. The subsequent re-design provided a single recommendation that could be modified if the user selected potential complications, e.g., renal insufficiency or meningitis on the main window of the CDS tool (►Figure 2b). Antimicrobial recommendations were then shown via a pop-up message window

(▶Figure 2c). This new design was well accepted by the neonatologists during further user testing. User testing also identified difficulty distinguishing positive and negative culture results. Thus, results of positive cultures were presented in bold font to facilitate recognition (▶Figure 2b and 2d). A screenshot of the multiple windows of the final CDS tool overlaid on the commercial EHR user interface is shown (▶Figure 2d). After implementation in the production system in June 2010, no further changes to the user interface were made.

Prescribers could manually add the CDS tool icon to their personal toolbar in the EHR to make the icon readily available or the tool could also be accessed via a drop-down "Tools" menu. The icon only had to be added once to the toolbar. The CDS tool was designed to be accessed independently of computerized physician order entry (CPOE). We chose to design the CDS tool in this way for the following reasons:

1. Our pre-implementation analysis showed that while the clinicians writing antibiotic orders were not necessarily the decision makers, they did often make suggestions for treatment based on culture information and laboratory results which could influence the decision makers;
2. Not all orders were written while the decision maker was immediately available;
3. We wanted the tool to be used for information aggregation to increase the awareness of antibiotic stewardship;
4. We did not know *a priori* which units would receive the CDS tool and the developers felt that separating the tool from CPOE would give the tool the most flexibility both from a workflow and a EHR implementation point of view; and
5. Since the tool was a part of a research project and not part of established hospital information technology (IT), we did not want errors in the tool to effect the operation of the EHR.

As a consequence, the CDS tool did not automatically activate as a result of a particular user action (i.e., order entry for antibiotics), but the user needed to actively select and activate the tool for use. Following activation, the CDS tool required the user to select a suspected clinical scenario and a specific culture prior to providing antibiotic recommendations. Users could obtain recommendations if the clinical scenarios changed or if additional culture results became available.

The tool was designed to be modular to promote reuse. ▶Figure 3 shows a component diagram of the CDS tool. There are four main components to the CDS tool. The first component is a data extraction component which used customized Structured Query Language (SQL) calls to pull the raw data (e.g., culture results including organisms and sensitivity results formatted as strings) from the commercial EHR database. The tool could use some data elements without additional transformation (i.e., age, date of birth, patient name and numerical laboratory results). However, the culture result data were stored as a set of strings which needed to be encoded into a computationally useful form. The encoder component used a series of regular expression matches to identify key organisms and their sensitivities from the strings of raw data. These results were subsequently used by the decision logic component to provide the tool user interface with the needed messages for antimicrobial recommendations. Excluding comments and empty lines, the tool user interface, decision logic component and encoder component contained 2199, 1202 and 1070 physical lines of code respectively. They contained no site specific code. The data extraction component code contained 2792 physical lines of code of which 72 lines (2.6%) were considered to be site-specific (calls to custom hospital code or custom SQL calls).

During the first year of deployment of the CDS tool, the study team encountered several challenges. Clinicians complained to a site investigator (Site 2) that antibiotic recommendations consistently defaulted to "consult pediatric infectious disease". Upon investigation of these complaints by the study team, it was found that both sites had loss of recommendations functionality and that an EHR upgrade was identified as the cause. Further challenges included: (1) a transition to a new vendor for the clinical microbiology laboratory information system, and (2) changes to antimicrobial testing methodologies. As a result of these unforeseen sequential changes, the tool was unable to provide accurate culture-based treatment recommendations, as modifications to the data extraction and encoder components needed to be made. The tool user interface and the decision logic component remained unchanged throughout the study. With each new modification, the tool was tested in a special test environment. When errors were found, they were corrected and the process was repeated. Each cycle took as long as two weeks to complete. Combined with a programming freeze

process around EHR upgrades, the CDS tool's antibiotic recommendations function defaulted to consultation with a pediatric infectious disease specialist for most clinical scenarios for approximately 8 of the first 12 months. During this 12-month period, the other features of the CDS tool functioned. Once the tool was functioning as initially designed, the study team re-educated prescribing clinicians about the tool.

3.3 User Logs

From July 2010 to May 2012, 1303 activations of the CDS tool occurred for 452 patients (representing 22% of all patients who were prescribed antibiotics). Pediatric residents and neonatology fellows, attending physicians, and nurse practitioners/ house physicians were responsible for 44%, 40%, and 10% of activations, respectively. Non-prescribing clinicians (e.g., bedside nurses, pharmacists, respiratory therapists and medical students) were responsible for 6% of activations. For patients for whom the CDS tool was used, users opened the tool a median of once per patient (IQR: 1 – 3) for a median duration of 28 seconds (IQR: 13 – 72). Users viewed the antibiotic sensitivity report for a median of 2 different cultures with each activation (IQR: 2–3). Users viewed antibiotic prescribing recommendations during 15% of tool openings although recommendations were sometimes viewed multiple times during a single activation. These patterns were consistent across the types of providers (data not shown). ►Figure 4a shows a graph of the number of tool activations per patient on antibiotics by site and by study month. ►Figure 4b shows a graph of the ratio of recommendation activations to tool activations by site and by study month. The patterns of use appear to be different at the two sites. Both sites had a rise then fall of tool activations before the period of time when the tool was not functioning properly. However, Site 1 continued to use the tool and the tool use slowly increased whereas in Site 2 use stopped until the last 5 months of the study (►Figure 4a). When the tool was opened, antibiotic recommendations were less frequently viewed at Site 1 than at Site 2 (►Figure 4b).

3.4 User Survey

Forty-six (28%) of 164 eligible respondents completed the survey, including 12 NICU attending physicians, 5 neonatology fellows, 18 residents, 2 house physicians, and 9 nurse practitioners. Twenty nine respondents (63%) were aware of the CDS tool. However, only 37% (17/46) of respondents had used the CDS tool during their most recent rotation in the NICU. The most useful features of the CDS tool perceived by respondents are shown in ►Table 5. Respondents at the two sites reported similar perceptions.

Twenty respondents (43%) reported that the CDS tool assisted in antibiotic decision-making and 19 (41%) reported it saved time compared to other available electronic resources. Respondents reported they used the CDS tool after rounds (32%), prior to rounds (9%), and during rounds (9%). The remaining respondents stated that they did not use the tool regularly (17%) or did not answer (33%). Respondents used the CDS tool to modify antibiotic treatment when culture results were available (37%); to assist with initial treatment (21%); to review culture results (20%); and to review current antibiotic orders (17%). Seven respondents were concerned that the prescribing recommendations "often said to consult ID rather than giving a recommendation". Replacing the tool icon on the toolbar after the EHR upgrade also proved to be an obstacle to use for three respondents. Respondents also suggested new features for the CDS tool including total duration of treatment (43%) and dosage recommendations (33%).

4. Discussion

Several CDS systems for antibiotic prescribing have been described that provide insights into the complexity of implementing such programs [14, 21-27]. Evans et al. [14] implemented a CDS system for antibiotic management at the Latter Day Saints Hospital (LDS) in Salt Lake City which took over a decade to develop, requiring sustained institutional commitment, clinical leadership, and medical staff acceptance. In an editorial accompanying this landmark paper, Garibaldi posits that while com-

puter installation is easy and IT expertise is widely available, the human components of computer-assisted programs are much more difficult to duplicate at other hospitals [28]. Mullet et al. implemented a similar CDS tool at the pediatric ICU at the primary children's teaching hospital in Salt Lake City which included logic for the NICU population [22]. The group noted that the outcome benefits seen in adult patients were not seen in the pediatric patients [14, 22]. Thus, different populations may influence the outcomes associated with CDS. The complexity of comparing studies is highlighted by Shebl et al. [25] and drawing generalizable conclusions about the impact of CDS tools may be difficult given the diversity of settings and measured outcomes. Finally, studies of CDS tools have not yet assessed the presumably complex reasons why prescribers may not follow CDS guidance; it is difficult to assess prescriber attitudes, level of expertise, and decision-making style [26].

We sought to design this tool to be portable to other NICUs. Our tool was implemented in a commercial EHR system and designed as an integral component of a larger antimicrobial stewardship program specifically developed for the NICU population. Our tool's user interface and decision logic component were the same for both sites. The tool's user interface could be easily ported to other systems as it used basic user interface components (available to most user interface APIs). Similarly, the decision logic component could be easily ported since it was designed as a set of rule based instructions. While there were some practice variations at the sites, we were able to unify them into a single set of recommendations for use at both sites. However, the data extraction component would need modifications, if ported to other systems, as vendor EHRs allow for database configurability to meet local needs. Furthermore, we suspect that few EHRs encode microbiology culture results, i.e., the specific organism or its antibiotic susceptibility, but rather store these results as strings. Thankfully, the names of organisms and the names of antibiotics are very similar in different systems and thus, the encoder component would need minimal changes to the regular expression matching system.

The clinicians used our tool to view culture results and their associated susceptibility reports. Although the commercial EMR had similar functionality, we hypothesize that the simplified CDS tool display contributed to the frequent viewing of cultures results. While recommendations for antibiotic prescribing were perceived as a useful feature by 48% of survey respondents, this feature was only used during 15% of tool activations. We hypothesize several possible explanations for this result:

1. There was decreased confidence in the prescribing recommendations due to the unanticipated and prolonged technical challenges to deployment of this function;
2. As the tool was being used to view culture results which may not change each day, it would not be expected that users would view antibiotic recommendations each time they opened the tool;
3. The tool was being used to collect data for individual infants for reasons other than antibiotic prescribing (e.g., following trends for blood count parameters).

We also observed that prescribing recommendations were sometimes viewed multiple times during one activation. Possible explanations include:

1. Users may have been interrupted during tool use due to competing demands inherent in the complex NICU environment;
2. Users were attempting to find other reasonable recommendations beyond "consultation of pediatric infectious disease"; and
3. Users may have been using the system for educational purposes.

Nonetheless, users reported the tool saved time and assisted with antibiotic decision-making, particularly the recommendations for modification of treatment when culture results were available. Furthermore, users made suggestions for new features including recommendations for treatment duration and dosing.

While we did not perform a sociotechnical analysis of our implementation, we hypothesize that individual-level, technological, group-level, organizational and external factors may have hindered user acceptance. At the individual provider level, we designed the tool to be used by all prescribers. It is possible that the tool only partially fulfilled the needs of each type of user and thus, the tool was not championed by any one group of users. User "buy-in" was further hampered by the design course; while end-users had early input, their subsequent input was only requested at the end of creation of the tool, rather than throughout the design phase. We further speculate this lack of owner-

ship may have impeded meaningful feedback during the production phase. As the tool was only used the NICU, pediatric residents may have developed work flow patterns to collect similar information during their other patient care rotations which made the CDS tool less relevant.

Technologic factors that may have hindered acceptance included the development of the CDS tool as part of a research project, rather than as part of established hospital IT operations. Our research team did not include IT personnel nor did the tool undergo formal hospital IT testing. Thus, we did not capitalize on local IT expertise nor were we alerted about upcoming system changes. Additionally, the IT help desk personnel were unaware of the CDS tool and could not assist the clinicians (e.g., restoring the tool icon to their toolbar when disruptions occurred after an EHR system upgrade).

Furthermore, acceptance may have been hindered by group-level factors. The tool was introduced using a single implementation strategy for providers at both study sites. However, the tool appeared to have different use patterns at each site as shown in ▶Figure 4a and ▶Figure 4b. Different use patterns suggest that unmeasured site differences in prescribers or patients may have played a role in our implementation. Organizationally, we had an ad hoc campaign to promote awareness and education. Our implementation would have been improved by a consistent and formal educational process repeated at set intervals.

External factors also may have hindered acceptance. As this was a research project, we had secured the appropriate support of institutional leadership in 2006. However, in 2009 with the passage of the HITECH portion of the American Recovery and Reinvestment Act, the Centers for Medicare and Medicaid Services started incentive programs ("meaningful use") for EHR certification, use and implementation [29, 30]. This meaningful use policy consumed many IT resources thereby limiting resources for smaller projects. We further speculate that the financial crisis that began in 2008 [31] may have further decreased IT resources.

Our study has several limitations. Our tool was only implemented in two academic NICUs that used a single EHR vendor product and thus, our findings may not be generalizable. Differences in workflow and clinician acceptance could arise in non-academically affiliated NICUs and technical difficulties could arise in porting the code to other EHR vendor products. Furthermore, we did not analyze our data with respect to different patient populations (e.g., surgical versus medical patients) which could impact tool use. We sought to evaluate our tool by reviewing user logs and administering a user survey. While we were able to observe the tool activations, recommendation activations, and culture result viewings through the user logs, due to the limitations of timestamp logs, we could not assess how frequently clinicians chose to view the selected laboratories and antimicrobial orders as they were displayed automatically. Furthermore, we do not know to what extent these elements assisted the clinicians in their antimicrobial prescribing activities. Interpretation of our survey results is limited by our low response rate and it is possible that the survey was completed by those clinicians with a vested interest in CDS or antibiotic prescribing. Lastly, while we hypothesized several possible mechanisms for implementation challenges, we did not pursue a formal sociotechnical analysis of our tool implementation.

5. Conclusions

We designed a CDS tool for NICU antibiotic prescribing within a commercial EHR and implemented it at two sites. Despite careful sociotechnical analysis of the NICU antibiotic prescribing practices, pre-production user feedback, and use-based testing, our implementation suffered from technical challenges, which limited the tool's functionality. Clinicians identified important shortcomings of our tool supporting the need for robust user feedback at all phases of a CDS tool project. We believe that even when rigorous design and usability methods are used, new discoveries are made during production that can inform developers about the design of CDS tools. We recommend early involvement of hospital IT personnel to help provide a robust user feedback and testing mechanisms. We also recommend that developers consider a pilot phase at a single site with a limited number users during which adequate resources can be deployed for aggressive collection of feedback by on-site study personnel and direct observations of how the system is being used in a real-world production setting. In this way, user concerns and requests for "value-added" functions can be

accurately identified, analyzed, and addressed with timely changes that promote patient safety, improve healthcare quality, and improve tool usefulness.

Clinical Relevance Statement

While many clinician decision support tools have been built in custom electronic health record systems, our clinical decision support tool was designed within a commercial electronic health record system to complement other antimicrobial stewardship interventions and to be used in the complex environment of two different neonatal intensive care units. Despite careful sociotechnical analysis of the neonatal intensive care unit antibiotic prescribing practices, pre-production user feedback and use-based user testing, our implementation suffered from technical challenges. Clinicians continued to use our tool for other functionality and were able to identify important shortcomings of our tool. Our experience highlights the need for robust user feedback and iterative design techniques to improve tool quality and usefulness.

Conflicts of Interest

The authors declare that they have no conflicts of interest in the research.

Protection of Human and Animal Subjects

Approval to conduct this study was received from the institutional review boards of Columbia University Medical Center and Weill Cornell Medical College.

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Contributor Statement

RSH participated in the design, implementation and maintenance of the tool and decision logic; analyzed the tool use; designed and analyzed the survey; drafted and revised the paper. He is the guarantor. KC participated in the design, implementation and maintenance of the tool as well as revised the draft paper. BS participated in the interviews for the decision logic and revised the draft paper. SP participated in the design and testing of the tool, design of the survey, revision of the decision logic, and revised the draft paper. JD participated in the design, testing of the tool, testing and revision of the decision logic, and revised the draft paper. PD participated in the testing of the tool, revision of the decision logic and revised the draft paper. YF participated in the design and analysis of the survey as well as revised the draft paper. PG participated in the design of the decision logic and revision of the draft paper. DKV participated in the implementation of the tool, maintained the user logs, and revised the draft paper. JP participated in the testing of the tool, revision of the decision logic and revised the draft paper. EL participated in the design of the study and revised of the draft paper. LS participated in the design of the study; design, revision, and testing of the decision logic; design and testing of the tool; design and analysis of survey; and revised the draft paper.

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If Culture Result and Sensitivities are Available Then
    Stop and Run Targeted Recommendations Algorithm Instead

Start with Empty Recommendations

If No History of Vancomycin Resistance Then
    If No History of Oxacillin Resistance Then
        Add "Oxacillin or Vancomycin" to Recommendations
    Else
        Add "Vancomycin" to Recommendations

    If Clinical Scenario has Meningitis Then
        Add "Meningitic Dosing and Vancomycin Level Targets Message" to Recommendations
    Else
        If No History of Linezolid Resistance Then
            Add "Linezolid" to Recommendations
        Else
            Stop and Show "Serious Resistance Problem and Consult Infectious Diseases" as
            Recommendations

If History of Piperacillin/Tazobactam Resistance or History of Cefotaxime Resistance Then
    If History of Meropenem Resistance Then
        Stop and Show "Serious Resistance Problem and Consult Infectious Diseases" as
        Recommendations
    Else
        Add "Meropenem" to Recommendations
Else
    If Clinical Scenario is Meningitis and NEC Then
        If History of Meropenem Resistance Then
            Stop and Show "Serious Resistance Problem and Consult Infectious Diseases" as
            Recommendations
        Else
            Add "Meropenem" to Recommendations

    If Clinical Scenario is Meningitis Only Then
        If History of Gentamicin Resistance Then
            If History of Meropenem Resistance Then
                Stop and Show "Serious Resistance Problem and Consult Infectious Diseases" as
                Recommendations
            Else
                Add "Meropenem" to Recommendations
        Else
            Add "Cefotaxime" to Recommendations

    If Clinical Scenario is Sepsis Only Then
        If History of Gentamicin Resistance or Clinical Scenario includes Renal Impairment Then
            Add "Piperacillin/Tazobactam" to Recommendations
        Else
            Add "Gentamicin" to Recommendations

    If Clinical Scenario is NEC Only Then
        Add "Piperacillin/Tazobactam" to Recommendations

If Clinical Scenario includes Renal Impairment Then
    Add "Renal Dosing Messages" to Recommendations

If Clinical Scenario includes Meningitis Then
    Add "Consult Infectious Diseases" to Recommendations

If Culture Result is No Growth and Final Then
    Add "Consider Discontinuing Antibiotics Message" to Recommendations

Show Recommendations
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Fig. 1 Empiric Recommendations Algorithm described in Pseudocode

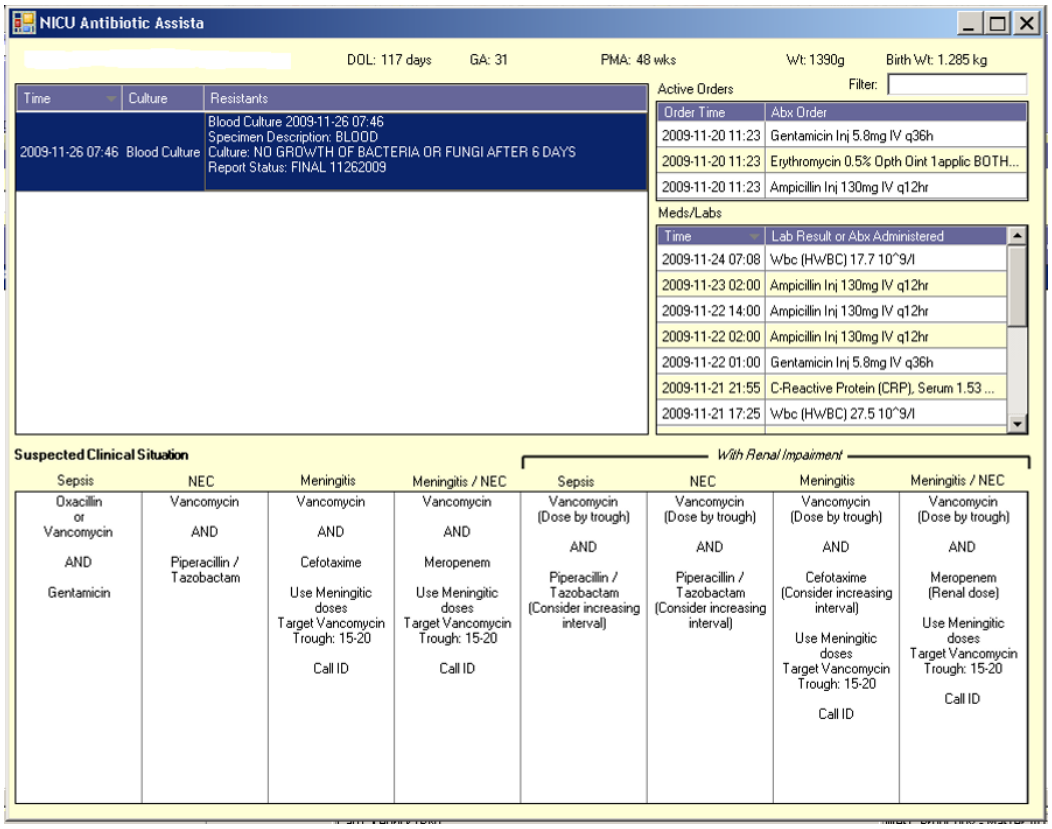

Fig. 2a Screenshot of the initial tool design which was deemed potentially unsafe by the neonatologists and subsequently revised in Figures 2b, 2c, and 2d.

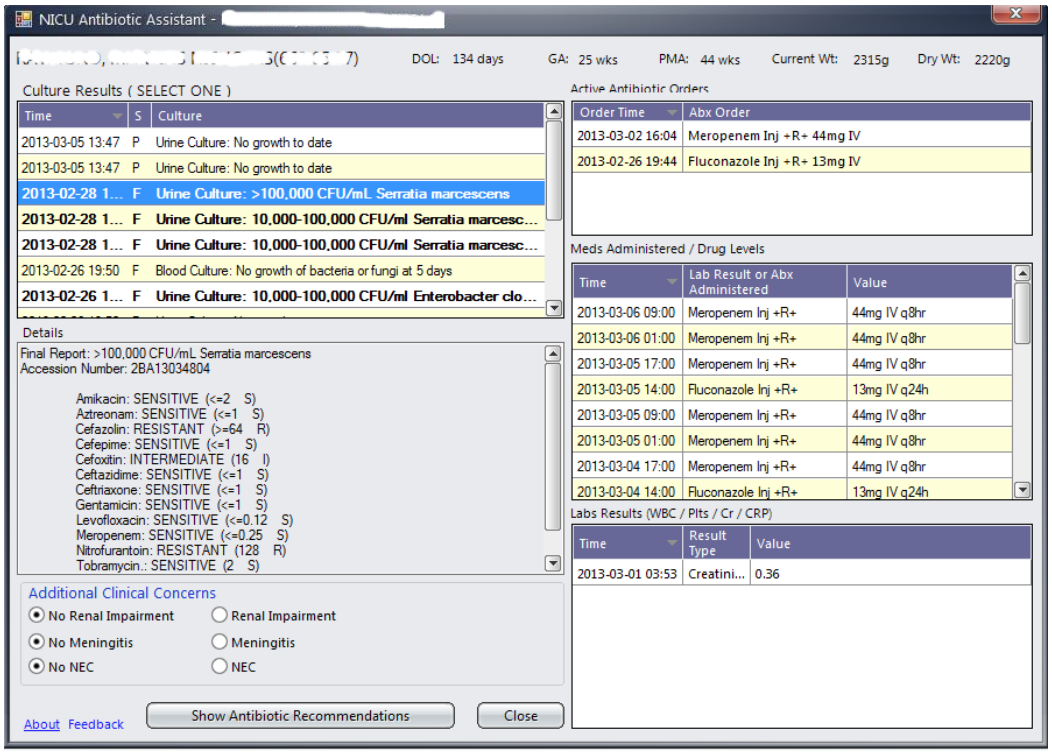

Fig. 2b Screenshot of the main screen of the final CDS tool

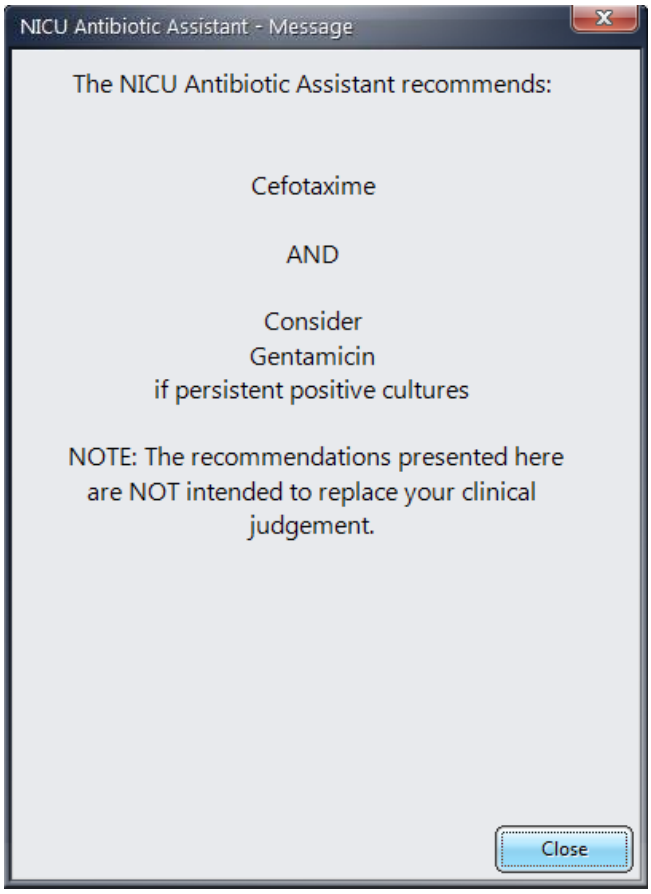

Fig. 2c
Screenshot of the message screen of the final CDS tool

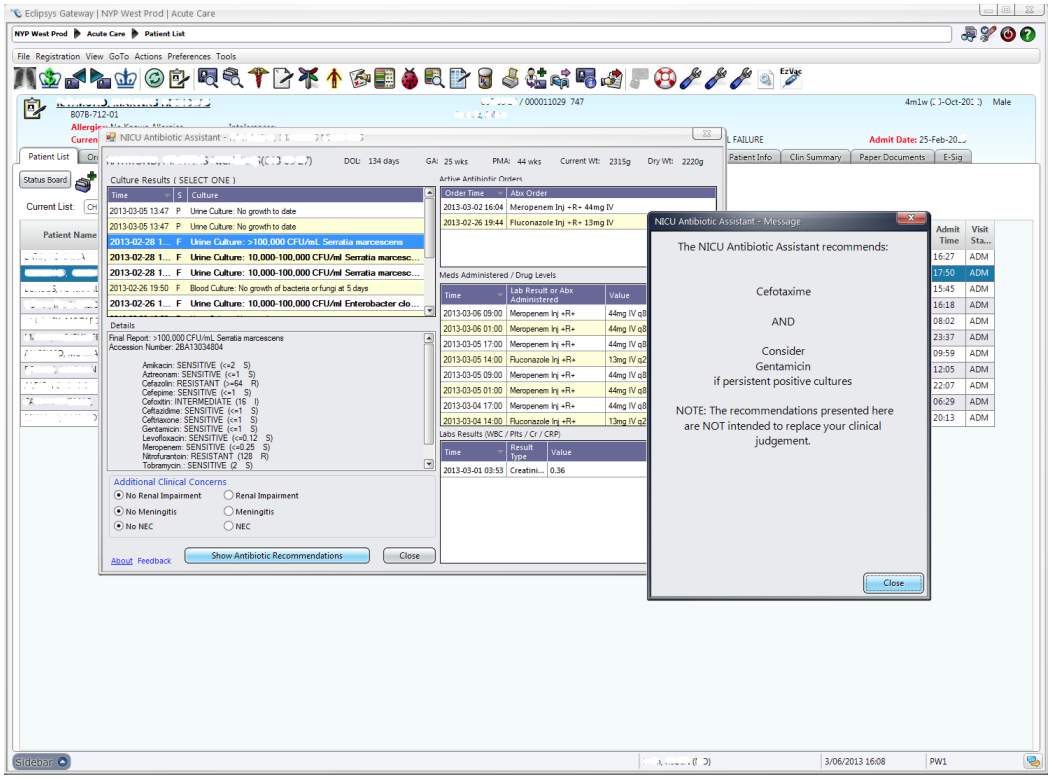

Fig. 2d Screenshot combining the EHR in the background and the two overlaid CDS windows (main and message).

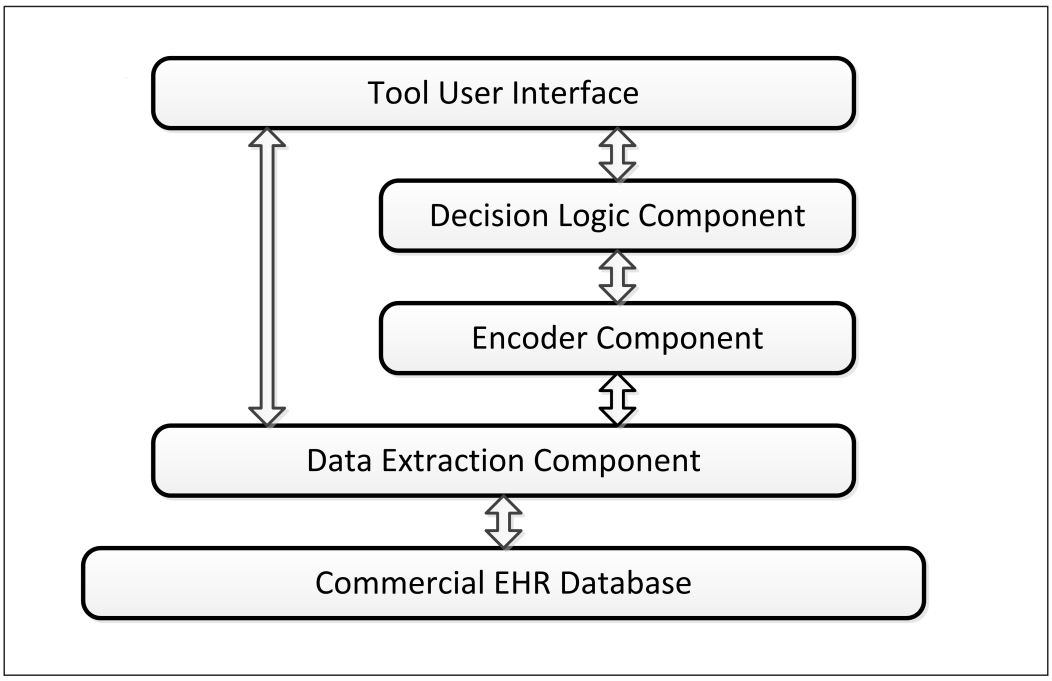

Fig. 3 Component diagram of the CDS tool.

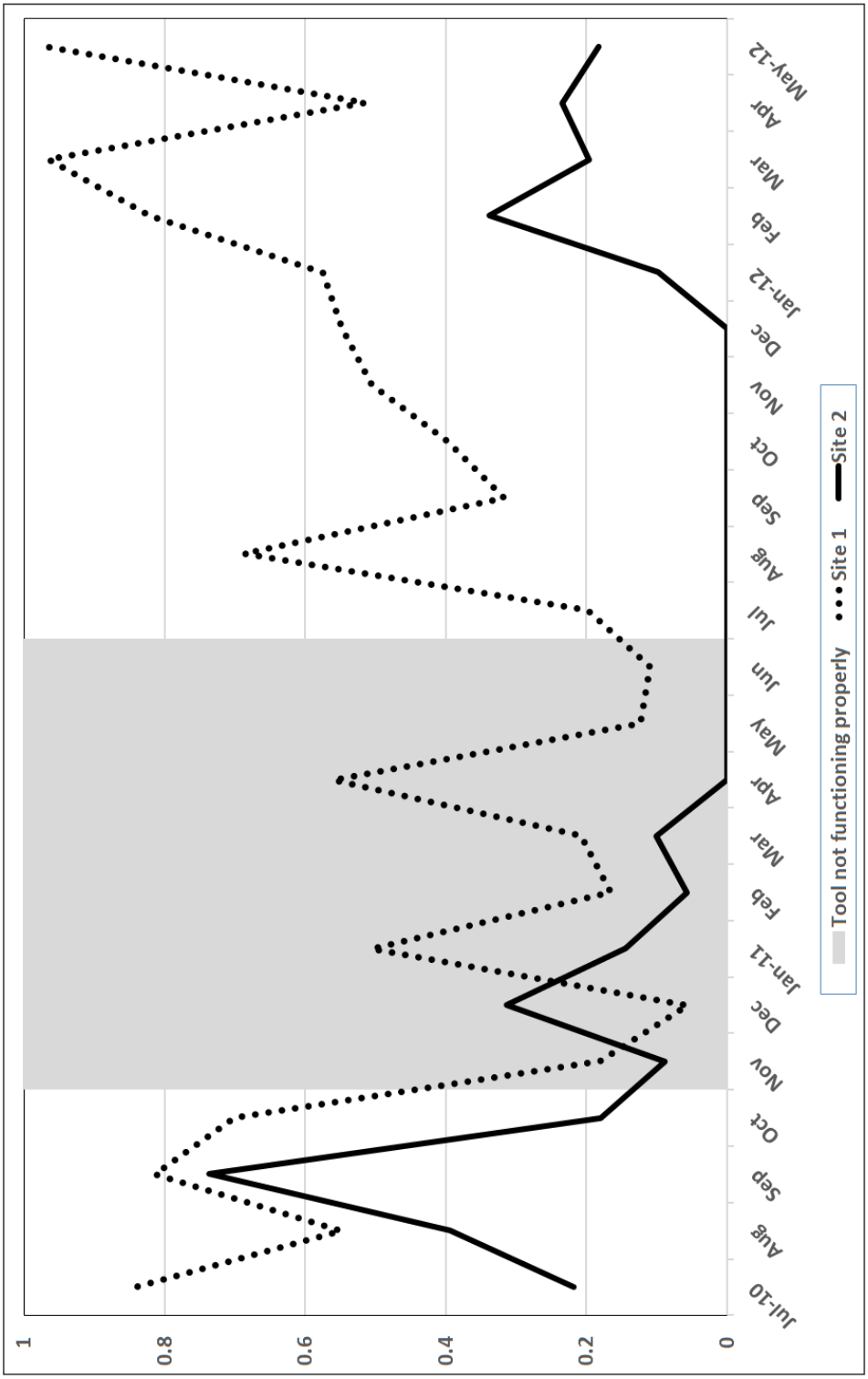

Fig. 4 Tool activations per patient on antibiotics by Site and by Study Month. The period of time where the tool did not function correctly is displayed by the shaded area.

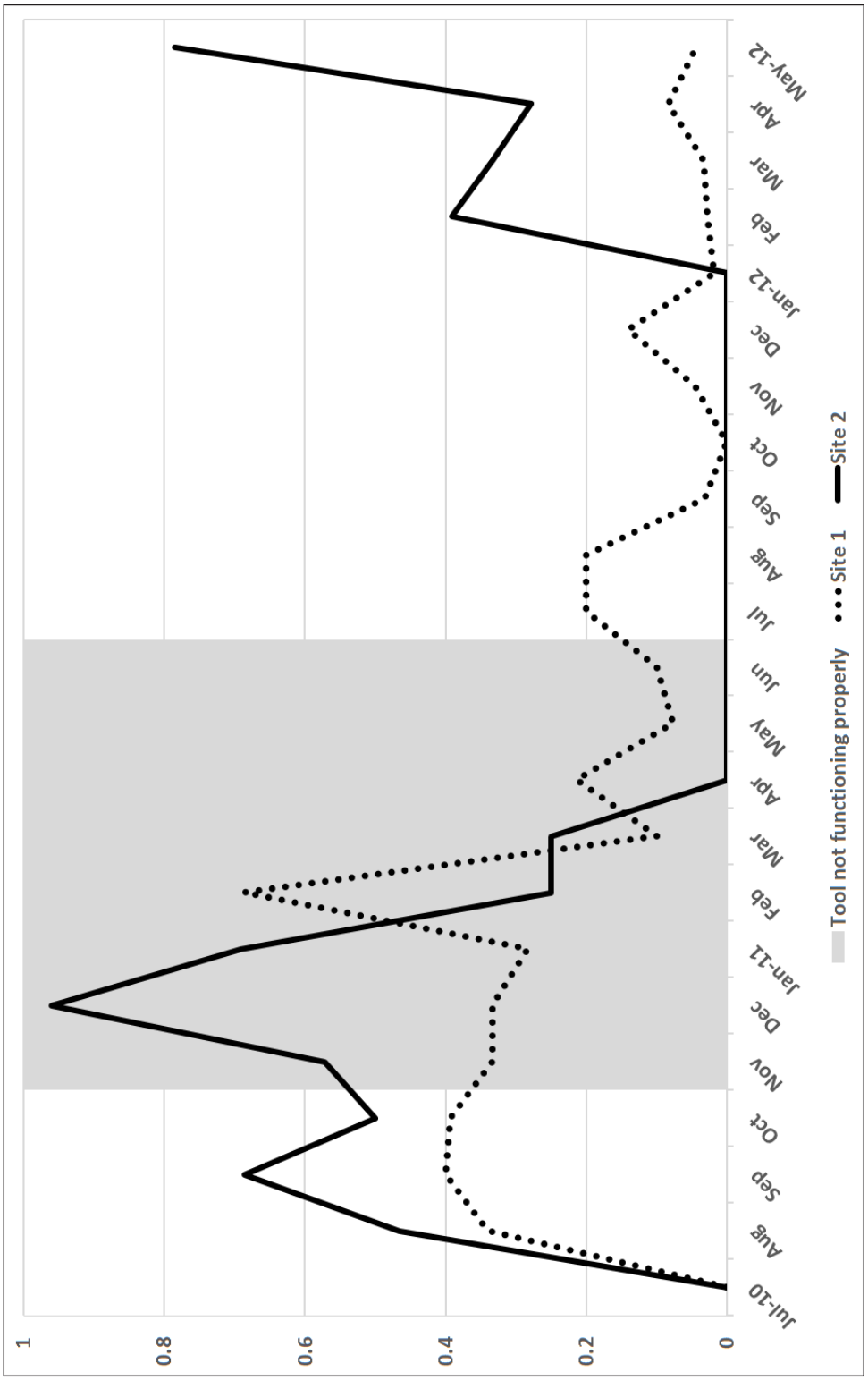

Fig. 4b Ratio of recommendation activations per tool activation by Site and by Study Month. The period of time where the tool did not function correctly is displayed by the shaded area.

Table 1 Sources Used to Development Antimicrobial Prescribing Algorithms

Parameters	Local Epidemiology	Local NICU Practices	Published Literature	Infectious Disease Expertise	Best Practice Guidelines
Common pathogens	+++	++	++	++	-
Antimicrobial agents	+++	++	++	++	+
Infections at different body sites	+	++	++	+++	-
Pharmacokinetic principles	-	-	++	++	+

+++principle source ++useful source +occasional source – not applicable or not useful

Table 2 Components of Computer Decision Support Tool to Facilitate Antimicrobial Prescribing in the NICU

Element	Description
Demographic characteristics	Birth weight Current weight Gestational age (in weeks) Post Menstrual age (in weeks) Chronological age (in days)
Clinical scenarios associated with HAIs	Late onset sepsis Meningitis Necrotizing enterocolitis Renal insufficiency
Culture results(selected by user)	Gram stain Species identification Susceptibility to individual antimicrobial agents
Selected laboratories	White blood cell count (including band count and immature to total ratio) Platelet count C-reactive protein Therapeutic drug monitoring for vancomycin and gentamicin Creatinine
Antimicrobial treatment	Active orders Active doses and dosing interval Recommended empiric and targeted agents

Table 3 Types of clinicians in the Study NICUs

Clinician type	Site 1	Site 2	p-value*
Attending neonatologists < 10 years of practice	4	4	0.43
Attending neonatologists ≥ 10 years of practice	15	3	0.16
Neonatology fellows	13	8	0.59
Neonatal nurse practitioners	19	12	0.46
House physicians	5	0	0.17
Total	**56**	**27**	
Pediatric residents work in the NICU?	**Yes/No**	**Yes/No**	
1st year residents	Yes	No	N/A
2nd year residents	Yes	Yes	N/A
3rd year residents	No	Yes	N/A

* by Fisher's Exact Test

Table 4 Data Used to Develop Empiric and Targeted Algorithms for Antimicrobial Recommendations

Electronic Health Record Data	Empiric Antimicrobial Recommendations	Targeted Antimicrobial Recommendations
Organisms	Staphylococcus aureus Coagulase negative staphylococci Enterococci group B streptococcus Gram-negative organisms	Results of current culture
Current culture results	Pending 'No growth to date' Gram stain only	Organism identified and susceptibility available
Previous susceptibility results	+	N/A
HAI clinical scenarios:		
Late onset sepsis Meningitis Necrotizing enterocolitis	+ + +	+ + +
Renal insufficiency	+	+

Table 5 Useful Features of the CDS Tool Elicited by Survey (n = 46 respondents)

Feature	Site 1 (n = 18)	Site 2 (n = 28)	p-value*
Summary of culture results	9 (50%)	11 (39%)	0.55
Antibiotic prescribing recommendations	8 (44%)	14 (50%)	0.77
Antibiotic orders	4 (22%)	7 (25%)	1.00
Therapeutic drug monitoring	2 (11%)	8 (28%)	0.27
Complete blood counts	1 (6%)	7 (25%)	0.12

* by Fisher's Exact Test

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