Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

Project Title: Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

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Progress Report (4/1/2019-3/31/2020)

Abstract

Background: Blood cultures are overused in sepsis diagnosis, which result in additional laboratory tests, unnecessary antibiotic use, prolonged hospitalization, and increased healthcare costs. To optimize blood culture utilization and reduce its negative impacts on healthcare quality, safety, and efficiency, better clinical decision support (CDS) tools are needed.

Objective: The proposed project aims to (1) examine individual and team cognitive work associated with obtaining a blood culture; (2) develop an electronic CDS tool to reduce unnecessary blood culture use; and (3) implement the CDS tool and assess its use and impacts on blood culture use and patient outcomes.

Methods: We conducted critical decision method interviews with clinicians in the pediatric intensive care unit (PICU) at Johns Hopkins Hospital (JHH) to examine the cognitive work associated with obtaining a blood culture. In addition, we assessed the existing electronic health record (EHR) system (i.e., EPIC) to identify challenges to collecting key information required for blood culture decision-making and sepsis diagnosis. Based on findings from the critical decision method interviews and the review of the EHR, we collaborated with FastForward within the Johns Hopkins Technology Ventures and engaged clinicians in the PICU at JHH (e.g., attending physicians, fellow physicians, resident physicians, nurses) to iteratively develop the electronic CDS tool. We pilot tested the CDS tool on the PICU at JHH and have been continuously collecting data on the use of blood cultures and patient outcome.

Results: Based on the critical decision method interviews with 19 clinicians (2 attending physicians, 4 fellow physicians, 3 resident physicians, 4 nurse practitioners, 5 nurses, 1 nurse manager), we created a process map of the cognitive work associated with obtaining a blood culture and identified work system factors influencing blood culture decision-making. In addition, we reviewed 41 pieces of information that are critical to blood culture decision-making and sepsis diagnosis. For each item, we identified the related information, the sources of the information in the EHR system, and the challenges to collecting the information from each source. Based on these findings, we developed an electronic CDS tool, which incorporated four processes (i.e., trigger, think, treat, track) into a single workflow designed to optimize team performance of all tasks to diagnose and treat sepsis. The CDS tool was pilot tested on the PICU at JHH. Clinical data showed sustained reduction in blood culture use.

Key Words: Sepsis diagnosis and treatment, blood culture use, naturalistic clinical decision-making, clinical decision support, human factors

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Progress Report (4/1/2019-3/31/2020)

1. Background

Sepsis, a life-threatening complication of bloodstream infections, kills over 200,000 people a year in the US.[1,2] Early identification of sepsis and the use of blood cultures to guide antimicrobial therapy is essential.[3] In practice, because of the high mortality of sepsis, the risks of under-diagnosis and -treatment, and the concern about inappropriate antibiotic use, providers tend to order blood cultures liberally.[4] The overuse of blood cultures has been shown to result in additional laboratory tests, unnecessary antibiotic use, prolonged hospitalization, and increased healthcare costs.[5,6] To optimize blood culture utilization and reduce its negative impacts on healthcare quality, safety, and efficiency, better clinical decision support (CDS) tools are needed.

Appropriate use of blood cultures may be achieved through an analytic decision-making process, during which providers use cognition, metacognition, and discipline-specific knowledge to analyze patient information from various sources, predict the presence of bloodstream infections, and assess alternative diagnostic plans.[7] Usually, this process involves not only the cognitive work of individual providers, but also the teamwork or distributed cognitive work[8-10] of providers from different groups (e.g., physicians, nurses) and levels (e.g., resident and attending physicians).[11] In practice, however, providers rarely use a completely analytic strategy for decision-making because of time pressure and uncertainty. Instead, they search prior experience for patterns to recognize a situation (pattern matching) and evaluate potential actions one at a time to find a satisfactory one (mental simulation); this strategy is called naturalistic decision-making.[12-14]

While naturalistic decision-making allows providers to make rapid decisions, it can be risky when providers, especially those with less experience, rely solely on matching the situation to the patterns they have learned (e.g., obtaining blood cultures in febrile patients who are unlikely to have sepsis). Existing CDS tools for improving the use of laboratory tests focus either on low-level cognitive functions (e.g., reminding) or the use of statistical and mathematical models to support analytic decision-making.[15,16] These CDS tools cannot address naturalistic decision-making challenges and, therefore, may not get adopted by providers and improve decision quality.[17,18] To our knowledge, no CDS tool has been developed for naturalistic decision-making.[19] **To address this gap, we proposed this project to draw upon the strengths of both analytic and naturalistic decision-making and develop an electronic CDS tool to reduce unnecessary blood culture utilization.**

The electronic CDS tool is informed by a paper-based tool created for the Johns Hopkins Hospital (JHH) pediatric intensive care unit (PICU) to guide the evaluation of febrile patients. The paper-based tool has been shown to reduce the number of blood cultures collected by 46%.[20] In preparation to disseminate the paper-based tool at two hospitals, we interviewed various providers who recommended integrating it into the electronic health record (EHR) to support high-level cognitive functions (e.g., information gathering and synthesis).[11] Potential benefits of an electronic CDS tool include, but are not limited to (1) less need for additional provider data entry, (2) automatic provision of CDS as part of the workflow, and (3) integration with charting or order entry system to support workflow integration.[21]

2. Objectives

The proposed project has three specific aims:

1. To examine individual and team cognitive work associated with obtaining a blood culture;
2. To develop an electronic CDS tool to reduce unnecessary blood culture use;
3. To implement the CDS tool and assess its use and impacts on blood culture use and patient outcomes.

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

3. Methods

Aim 1: To examine individual and team cognitive work associated with obtaining a blood culture

To examine the cognitive work associated with obtaining a blood culture, we conducted critical decision method interviews[22] with clinicians in the PICU at JHH. We reviewed blood culture orders placed in the PICU on a weekly basis and identified cases where a patient had (1) a fever and a blood culture ordered, (2) a fever but no blood culture ordered, or (3) no fever but a blood culture ordered. Clinicians involved in identified cases were then purposively selected and invited to participate in individual face-to-face interviews. During each interview, the participant was asked to review 1 to 3 cases, describe the key decision points or major events in each case (e.g., recognizing a patient with change of status, ruling out causes for change of status), and provide detailed information related to each decision point/major event (e.g., people involved, information collected, tools used). To facilitate the interviews, a summary of each case was provided to the participant during the interview (Figure 1).

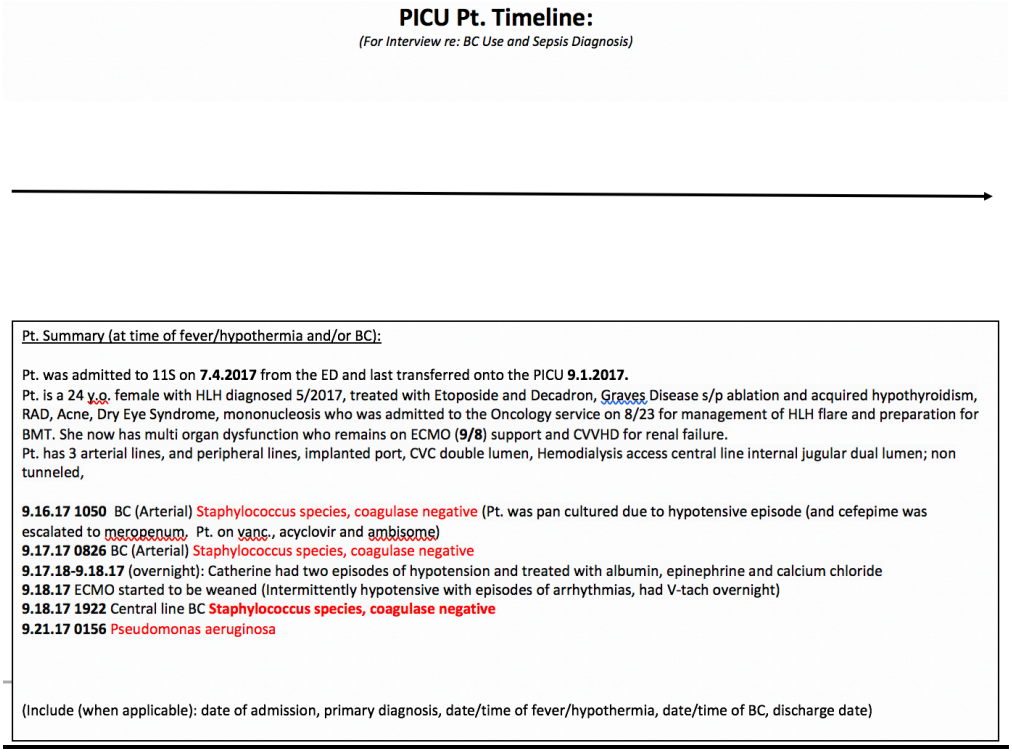

Figure 1 Example of case summary used to facilitate critical decision method interviews

Aim 2: To develop an electronic CDS tool to reduce unnecessary blood culture use

In addition to the critical decision method interviews, we assessed the existing EHR system (i.e., EPIC) to identify challenges to collecting key information required for blood culture decision-making and sepsis diagnosis. Specifically, we reviewed the paper-based tool that we developed to guide the evaluation of febrile patients. For each item listed on the paper-based tool, we identified all sources of the information in the EHR

system and the challenges to collecting the information from each source. Findings from both the critical decision method interviews and the review of the existing EHR system were used to inform the development of the electronic CDS tool.

Following the contextual design approach, we collaborated with FastForward within the Johns Hopkins Technology Ventures ((FastForward is a coordinated suite of resources designed to efficiently move technologies from startup to marketplace, https://ventures.jhu.edu/programs-services/fastforward/) and engaged clinicians in the PICU at JHH (e.g., attending physicians, fellow physicians, resident physicians, nurses) to develop the electronic CDS tool. We conducted a series of focus group design sessions to translate findings from the critical decision method interviews and the review of the existing EHR system into design requirements and to develop and refine prototypes of the electronic CDS tool. In between the focus groups, we continuously evaluated the usability of the prototypes with individual clinicians until we finalized the design of the electronic CDS tool.

Aim 3: To implement the CDS tool and assess its use and impacts on blood culture use and patient outcomes

We pilot tested the CDS tool on the PICU at JHH. Training including a didactic presentation and a hands-on exercise session was provided to all PICU physicians (e.g., attending, fellow and resident physicians). The didactic presentation provided a brief introduction to the overall research study and a detailed explanation of how the electronic CDS tool should be used. During the hands-on exercise session, physicians were given a few patient scenarios and asked to use the electronic CDS tool to determine whether to obtain a blood culture. In addition to the training, information sessions were held with other PICU clinicians (e.g., nurses) to inform them of the imminent implementation of the electronic CDS tool.

We have been continuously collecting data on the use of blood cultures (e.g., blood cultures rate per 100 patient-days in the PICU) and patient outcome (e.g., PICU length of stay, mortality rates, rates of hospital and PICU readmission within 7 days of discharge) to evaluate the impacts of the electronic CDS tool using a quasi-experimental interrupted-time series design. In addition, we are monitoring the use of the electronic CDS tool on the PICU at JHH and categorizing patient cases into 10 groups (Table 1). We purposively select patient cases from groups 2 to 9 and invited clinicians involved in selected cases to participate in post-implementation critical decision method interviews. Table 1 highlighted the foci of interviews regarding each group of patient case.

Table 1 Patient case groups after the implementation of the CDS tool

Patient case groups	Diagnostic accuracy	Foci of post-implementation interviews
1 Time →	CDS √ Clinician √	None
2 Time → t_S	CDS X Clinician X	(Safety concern) Why did both clinician and CDS tool fail to capture signs of sepsis?
3 Time → t_{CDS}	CDS X Clinician √	Why did CDS tool fire a false alarm?
4 Time → t_{CDS} t_S	CDS √ Clinician X	(Safety concern) What signs of sepsis did CDS tool capture that clinician failed to capture? Why did clinician not respond to CDS tool?

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

Patient case groups	Diagnostic accuracy	Foci of post-implementation interviews
5 Time → $t_{Clinician} \approx t_{BC+Rx}$	CDS ? Clinician ?	Did antibiotics result in no sepsis developed or did clinician misdiagnose sepsis?
6 Time → $t_{Clinician} \approx t_{BC+Rx}$ t_S	CDS X Clinician √	What signs of sepsis did clinician capture that CDS tool failed to capture? Why did sepsis develop after the administration of antibiotics?
7 Time → t_{CDS} $t_{Clinician} \approx t_{BC+Rx}$	CDS ? Clinician ?	(Ideal situation) Did antibiotics result in no sepsis developed or did CDS tool and clinician misdiagnose sepsis?
8 Time → t_{CDS} $t_{Clinician} \approx t_{BC+Rx}$ t_S	CDS √ Clinician √	(Ideal situation) Why did sepsis develop after the administration of antibiotics?
9 Time → $t_{Clinician} \approx t_{BC+Rx}$ t_{CDS}	CDS ? Clinician ?	What signs of sepsis did clinician capture before CDS tool and how? Did antibiotics result in no sepsis developed or did CDS tool and clinician misdiagnose sepsis?
10 Time → $t_{Clinician} \approx t_{BC+Rx}$ t_{CDS} t_S	CDS √ Clinician √	What signs of sepsis did clinician capture before CDS tool and how? Why did sepsis develop after the administration of antibiotics?

Notes: t_{CDS} – time when CDS tool alerts clinician about sepsis; $t_{Clinician}$ – time when clinician suspects sepsis; t_{BC+Rx} – time when clinician orders blood cultures and antibiotics; t_S – time when patient is diagnosed with sepsis

4. Results

Aim 1: To examine individual and team cognitive work associated with obtaining a blood culture

Cognitive work associated with obtaining a blood culture. We conducted critical decision method interviews with 19 clinicians (2 attending physicians, 4 fellow physicians, 3 resident physicians, 4 nurse practitioners, 5 nurses, 1 nurse manager) and reviewed a total of 37 cases (18 cases with fever and blood culture ordered, 17 cases with no fever but blood culture ordered, 2 cases with fever but no blood culture ordered). Based on the interview data, we created a process map describing the cognitive work associated with obtaining a blood culture. The process map includes 4 steps: (1) knowing patient history, (2) recognizing patient with change of status, (3) ruling out causes of change of status, and (4) making and validating decisions on blood culture ordering (Figure 2). Table 2 summarizes the main approaches, potential problems, and implications for CDS design related to each step.

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

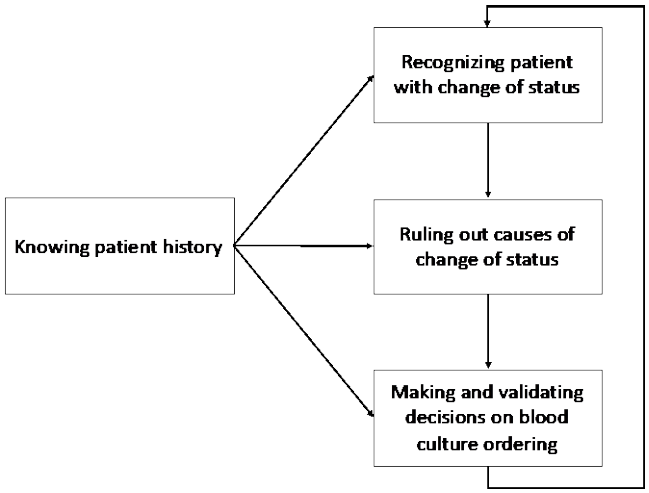

Figure 2 Cognitive process of blood culture ordering

Table 2 Summary of interview data

Cognitive steps	Main approaches	Potential problems	Implications for CDS design
Knowing patient history	• Long-term knowledge about a patient • Daily review of patient conditions	• New clinicians or clinicians who cover for others not having knowledge about a patient • Patient information scattered across different source	• Summarizing patient information that is available in EHR • Indicating other sources of patient information
Recognizing patient with change of status	• Monitoring change of clinical indicators (analytical) • Matching patient conditions with clinical patterns learned from past experience (intuitive)	• Focusing only on current status • Different patients having different signs/thresholds • Focusing only on clinical indicators • EHR not bringing abnormal status to attention	• Providing information on current status and trend • Learning and building a library of clinical patterns • Alerting clinicians about change of status
Ruling out causes of change of status	• Understanding entire condition of patient • Considering potential causes of change of status • Matching patient condition with typical clinical representations of each cause (analytical vs intuitive)	• Ordering blood cultures reflexively • Limited knowledge about potential causes and associated clinical representations • Limited time to collect information from different sources • Mismatch between patient condition and clinical representations because of incomplete information	• Indicating all potential causes • Indicating additional information needed and sources of the information
Making and validating decisions on blood culture ordering	• Running decisions by senior physicians • Running decisions by nurse/nurse verifying BC orders	• Junior physicians making decisions without senior physicians • Senior physicians not challenging decisions made by junior physicians because of mutual respect • Junior physicians not challenging decisions made by senior physicians because of hierarchy • Nurses not challenging decisions made by physicians	• Forcing function to get approval from senior physicians • Balancing “hard stop” and “clinical need”

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Progress Report (4/1/2019-3/31/2020)

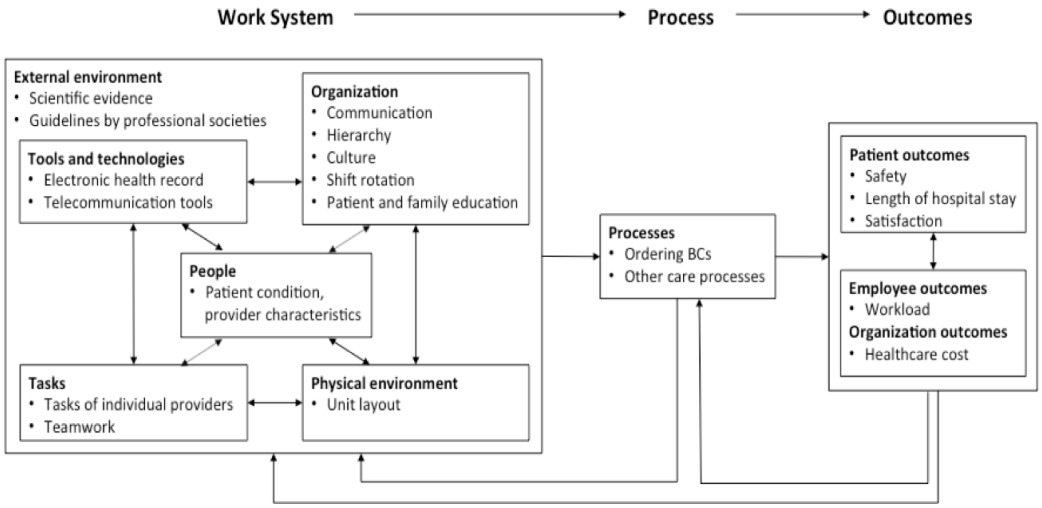


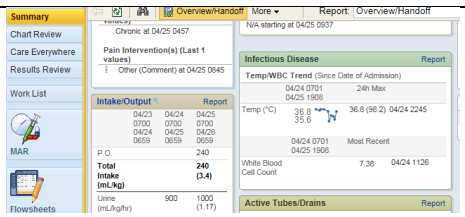
Figure 3 Work system factors influencing blood culture decision-making

Work system factors influencing blood culture decision-making. In addition to the cognitive process of blood culture ordering, we also used the Systems Engineering Initiative for Patient Safety (SEIPS) model[23] to identify work system factors influencing blood culture decision-making (Figure 3).[24]

Aim 2: To develop an electronic CDS tool to reduce unnecessary blood culture use

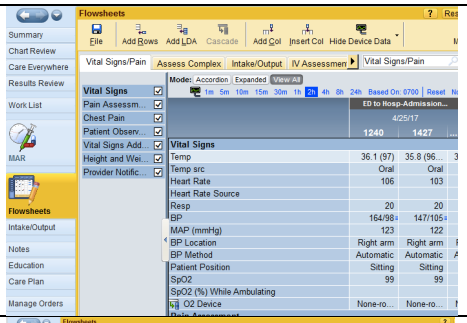
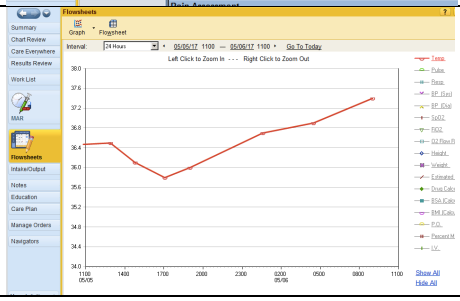
Challenges to collecting information from the existing EHR system. The paper-based tool consisted of 41 items that are critical to blood culture decision-making and sepsis diagnosis. These 41 items were grouped into four categories: (1) signs of systemic infection (e.g., temperature, rigors), (2) risk factors (e.g., host immune status, central line present and concerns), (3) other sources of infection (e.g., conjunctivitis, respiratory symptoms), and (4) non-infectious cause of symptoms (e.g., withdrawal, surgery within 24 hours). For each item, we identified the related information, the sources of the information in the EHR system, and the challenges to collecting the information from each source. Table 3 shows examples of findings from the review of the existing EHR system.

Table 3 Examples of challenges to collecting formation from existing EHR system

Items on paper-based tool	Related information	Sources of the information in EHR	Examples (screenshots)	Challenges
Signs of systemic infection				
Temperature: max min source? (Rectal temp is contraindicated in neutropenic pt.)	Vitals: Temp (high), Temp (low), source (rectal, temporal, oral)	Summary: Infectious Disease: Temp/WBC Trend		No information about "source", shows low and high but must go into flowsheets or graph to see trend

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

Items on paper-based tool	Related information	Sources of the information in EHR	Examples (screenshots)	Challenges
	Vitals: Temp (high), Temp (low), source (rectal, temporal, oral)	Flowsheets => Vital Signs/Pain		In order to determine trend, must scroll through
	Vitals: Temp (high), Temp (low), source (rectal, temporal, oral)	Flowsheets => Graph		Does not show source

Notes: Colon (:) indicates information within that view, no additional tabs to click; Arrow (=>) indicates the next tab to click to access information

Design of the electronic CDS tool. Informed by findings from the critical decision method interviews and the review of the paper-based tool and associated EHR information, we collaborated with FastForward within the Johns Hopkins Technology Ventures and engaged clinicians in the PICU at JHH (e.g., attending physicians, fellow physicians, resident physicians, nurses) to iteratively develop the electronic CDS tool. We conducted a total of 4 focus group design sessions. Table 4 summarizes the timeline, participants, and activities of the focus groups design sessions.

Table 4 Focus group design sessions

Focus groups	Timeline	Participants	Activities
1	07/2018	4 physicians, 2 nurses, 1 nurse manager, 3 researchers	- Review findings from critical decision method interviews and review of existing EHR system - Brainstorm design ideas for the electronic CDS tool
2	09/2018	3 physicians, 2 nurses, 3 researchers	- Develop prototypes of the electronic CDS tool (feature discovery and prioritization)
3	11/2018	4 physicians, 2 nurses, 3 researchers	- Develop prototypes of the electronic CDS tool (user interface design)
4	02/2019	4 physicians, 2 nurses, 3 researchers	- Develop prototypes of the electronic CDS tool (review and revision)

The electronic CDS tool. Figure 4 shows a high-level architecture of the CDS tool. EHR data is fed into a secure database via (as much as is possible) the emerging HL7 standard FHIR (Fast Healthcare Interoperability Resources). Data from bedside devices (including the physiological monitors) is aggregated in the same database. A SMART-like application programming interface (API) allows developers consistent access to the aggregated data. This architecture is expected to be extended to address other common conditions in the PICU, such venous thromboembolism, acute respiratory distress syndrome, traumatic brain injury, ventilator management, and central line associated blood stream infection.

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

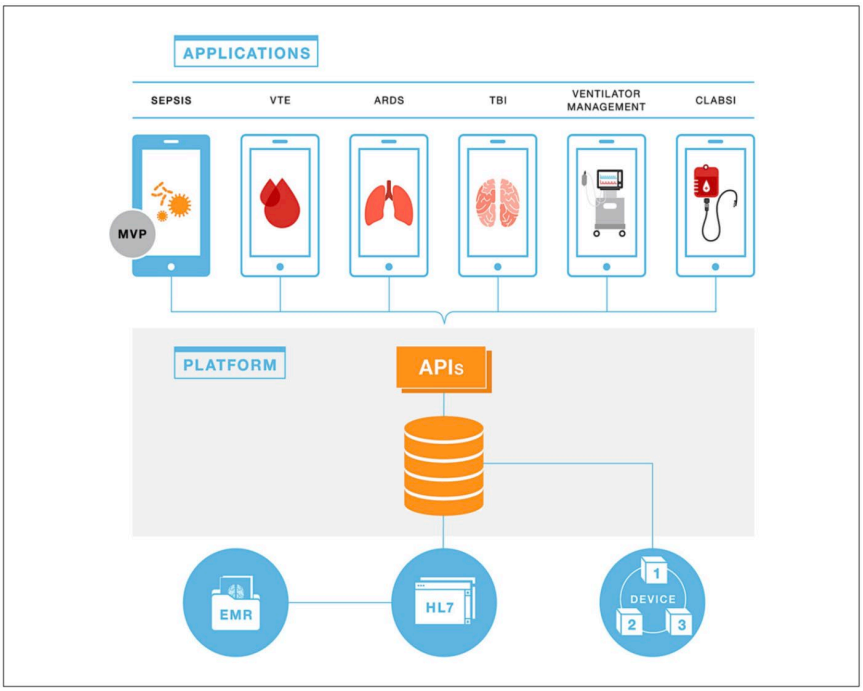


Figure 4 High-level architecture of the CDS tool

The final design of the CDS tool incorporates four processes (i.e., trigger, think, treat, track) into a single workflow designed to optimize team performance of all task to diagnose and treat sepsis (Table 5). Figure 5 shows the interface of the tracking tab. A detection algorithm triggers a sepsis watch and the bedside nurse completes the diagnostic support checklist. The physician team reviews the checklist with the other relevant clinical data and confirms that the trigger is clinically correct thus changing the patient's condition to sepsis warning. The sequence of tasks is presented in the timeline to the team with individualized messages to the correct clinician. The ICU Sepsis Steward is also on this message thread and supports and ensure the doses of antibiotics are delivered timely. We are continuously improving the design of the electronic CDS tool.

Table 5 Workflow of the CDS tool

Processes	Description
Trigger	Use real-time physiological and EHR data to identify children potentially with sepsis
Think	Use a diagnostic algorithm to gather clinician input to confirm the Trigger is correct
Treat	Suggests guideline-based therapies
Track	1. Provide feedback to the team – in real time – including a prioritized task list so the most critical tasks are addressed first; 2. Monitor both the therapies administered and the responses to those therapies (including post-ICU outcomes); 3. Report the data as real-world evidence

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

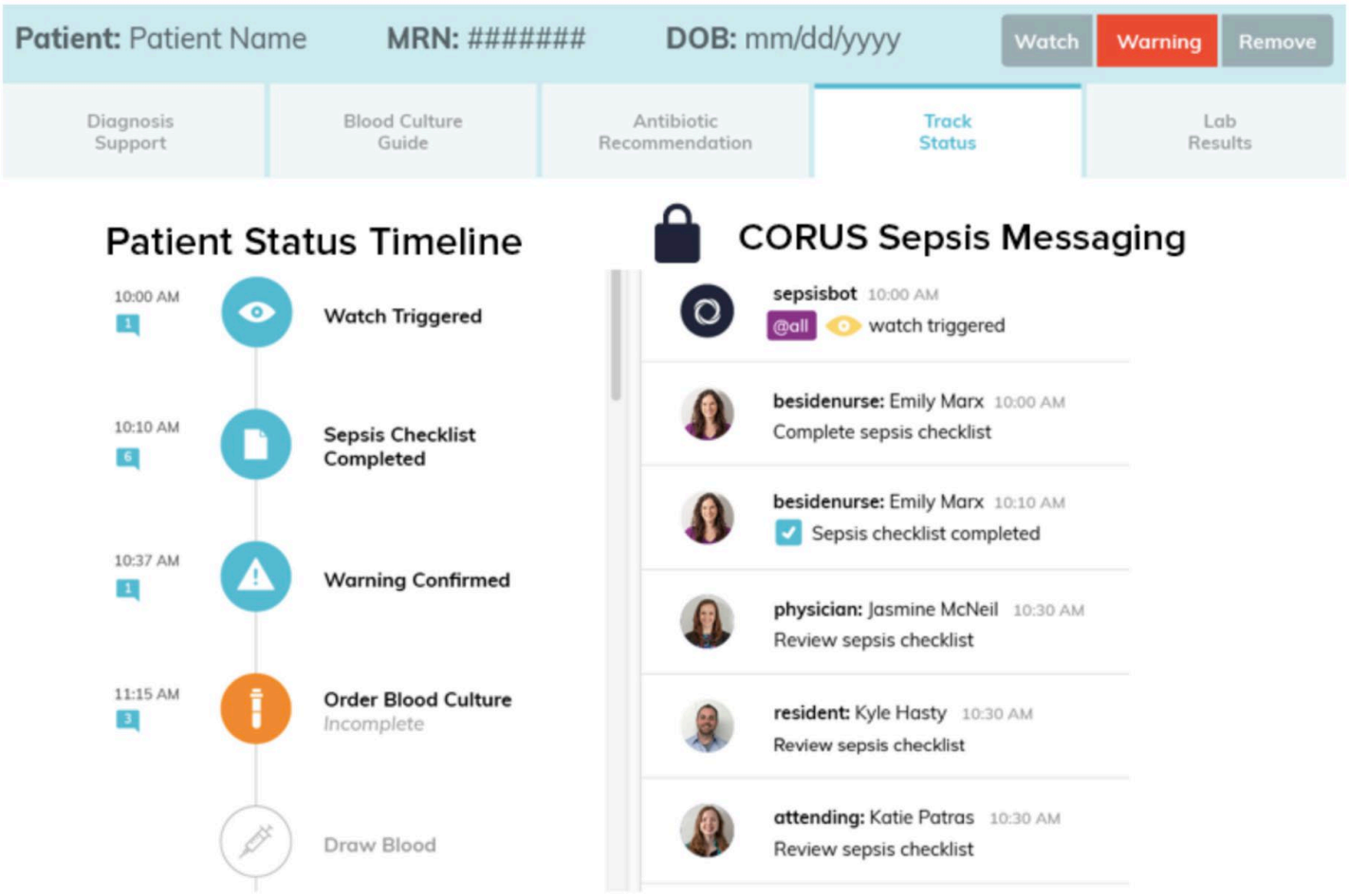


Figure 5 Interfaces of the current version of the electronic CDS tool

Aim 3: To implement the CDS tool and assess its use and impacts on blood culture use and patient outcomes

Data on blood culture use. We pilot tested the CDS tool on the PICU at JHH. A dashboard was created to continuously collect and update data on blood culture use and patient outcomes (e.g., PICU length of stay, mortality rates, rates of hospital and PICU readmission within 7 days of discharge) on a monthly basis. Figure 5 shows the blood culture use data from July 2016 to July 2020.

Development of a Clinical Decision Support Tool for Facilitating Naturalistic Decision-Making and Improving Blood Culture Utilization

Progress Report (4/1/2019-3/31/2020)

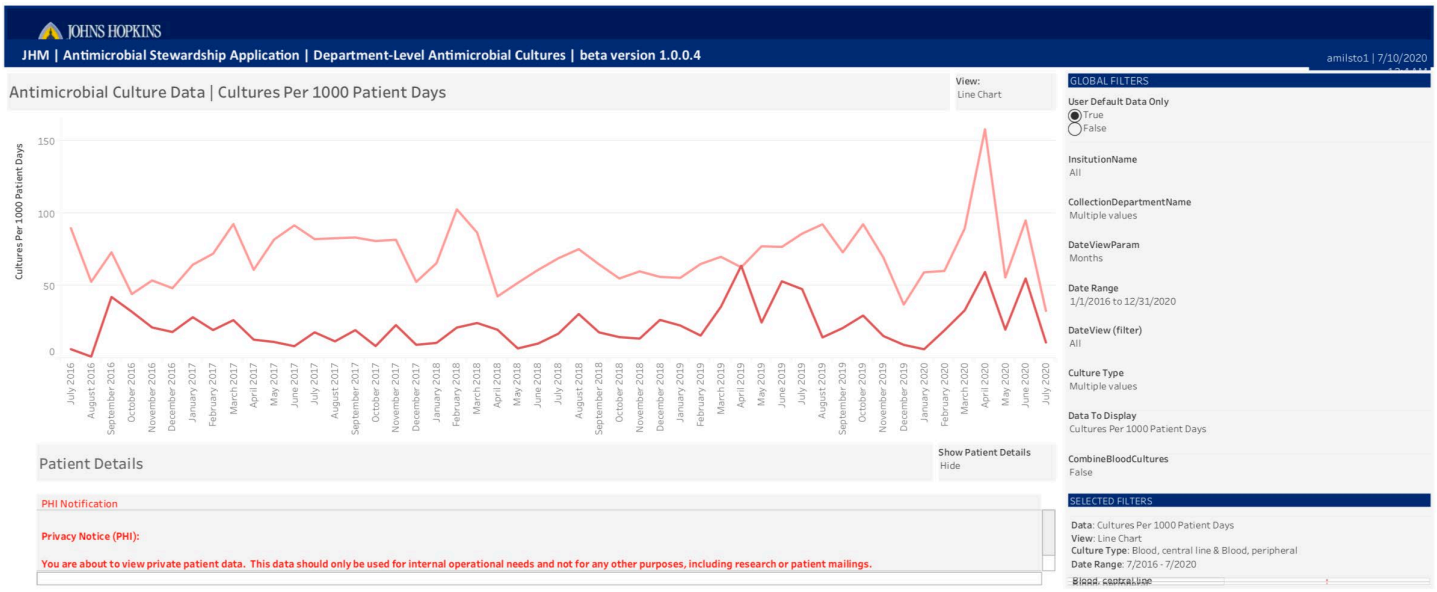


Figure 5 Blood culture use on the PICU at JHH (July 2016 – July 2020)

Data on the use of the electronic CDS tool. We are in the process of collecting and analyzing the post-implementation interview data and will report the findings in future manuscripts.

Next step

We are planning to submit an application for the NIH Small Business Innovation Research (SBIR) grant to commercialize and disseminate the electronic CDS tool for improving blood culture use and sepsis diagnosis in PICUs.

5. Publications

Journal papers

Xie, A., King, A. F., Koontz, D. W., Fackler, J. C., & Milstone, A. M. (to be submitted). Naturalistic clinical decision-making on blood culture use in pediatric sepsis diagnosis: implications for clinical decision support design. Journal of Cognitive Engineering and Decision Making.

Xie, A, Koontz, D. W., Voskertchian, A., Fackler, J. C., Milstone, A. M., & Woods-Hill, C. Z. (2020). Survey-based work system assessment to facilitate large-scale dissemination of healthcare quality improvement programs. Pediatric Quality & Safety, 5(2):e288.

Xie, A., Woods-Hill, C. Z., Berenholtz, S. M., & Milstone, A. M. (2019). Use of human factors and ergonomics to disseminate health care quality improvement programs. Quality Management in Healthcare, 28(2):117-118.

Xie, A., Woods-Hill, C. Z., King, A. F., Enos-Graves, H., Ascenzi, A., Gurses, A. P., Klaus, S. A., Fackler, J. C., & Milstone, A. M. (2019). Work system assessment to facilitate the dissemination of a quality improvement

program for optimizing blood culture use: a case study using a human factors engineering approach. Journal of the Pediatric Infectious Diseases Society, 8(1):39-45.

Conference presentations

Xie, A., King, A. F., Koontz, D. W., Fackler, J. C., Milstone, A. M., & Gurses, A. P. (2018). Understanding the cognitive work underlying blood culture use and sepsis diagnosis: implications for clinical decision support development. The 20th Congress of the International Ergonomics Association. Florence, Italy.

Xie, A., Woods-Hill, C. Z., Koontz, D. W., Fackler, J. C., & Milstone, A. M. (2020). Human factors and ergonomics-based work system assessment to facilitate quality improvement dissemination, Ergonomics & Human Factors 2020 / ODAM 2020, Virtual.

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