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Reach, Effectiveness, Adoption, and Maintenance of Mobile Electronic Clinical Decision Support Tools Deployed as Part of National Quality Improvement Projects

Ellen K. Kerns
University of Nebraska Medical Center

Reach, Effectiveness, Adoption, and Maintenance of Mobile Electronic Clinical Decision Support Tools Deployed as Part of National Quality Improvement Projects

by

Ellen Kerns

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Supervisory Committee:

Bethany Lowndes, Ph.D.

Martina Clarke, Ph.D.

James McClay, M.D.

Hongying Dai, Ph.D.

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Reach, Effectiveness, Adoption, and Maintenance of Mobile Electronic Clinical Decision Support (mECDS) Tools Deployed as Part of National Quality Improvement Projects

Ellen Kerns, Ph.D.

Supervisor: Russell McCulloh, M.D.

Electronic clinical decision support (ECDS) tools are often developed within quality improvement (QI) projects to increase adherence with the latest clinical practice guidelines. However, the potential reach and maintenance of ECDS use beyond the time and location of their associated project are very limited. Deploying ECDS using a mobile app (mECDS) has shown the potential to be a viable method of overcoming these limitations. However, it is unclear what pattern the reach and adoption of such a tool might follow and what effect this use has on clinical practice. Our team developed an app which contained two different mECDS tools released as part of two national quality improvement projects. By connecting the patient care collected by these projects to the usage of their corresponding mECDS tools, we aimed to investigate the effect of mECDS tool usage on clinical practice within both projects and determine long term mECDS use patterns within (reach and adoption) and beyond (maintenance) the projects. We quantified mECDS utilization using cumulative project metric-related screen views over the study period in the area in which each participating site was located. We determined associations between mECDS utilization and project metrics using mixed-effect generalized linear models, adjusted for time, site characteristics (project 1) and additionally for site-level QI project engagement, and patient characteristics (project 2). Weekly mECDS utilization was further examined for trends within and for 2 years after the first project's intervention period. Despite limitations in directly linking usage and practice data, a clear association between area-level tool use and an increase in that site's adherence to national practice standards was found. Additionally, project 1's tool use was found to increase, both temporally and geographically, beyond the project period. Further research is needed to determine the factors driving use, whether this continued use has an impact on clinical practice and patient outcomes and linking clinicians' mECDS usage more directly to their behavior.

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LIST OF ABBREVIATIONS

AAP	American Academy of Pediatrics
app	application
CDS	clinical decision support
DMA	designated marketing area
ECDS	electronic clinical decision support
EHR	electronic health record
listservs	electronic mailing lists
ED	emergency department
mECDS	Mobile device-based electronic clinical decision support
MetricHits	page views of quality metric-related content
PIPA	Pathway for Improving Asthma Care
QI	Quality Improvement
QIC	Quality Improvement Collaborative
QIDA	Quality Improvement Data Aggregator
REVISE	Reducing Variation in Inpatient Sepsis Evaluation
VIP	Value in Inpatient Pediatrics

INTRODUCTION

New medical evidence takes an average of 17 years to enter into widespread clinical practice (1). Although healthcare institutions try to expedite the dissemination and implementation of evidence-based practices through the production of electronic clinical decision support (ECDS) tools (i.e. information systems designed to improve clinical decision making), ECDS development is resource-intensive, with limited portability across institutions (2). Despite this, ECDS tools are often created and implemented within Quality Improvement (QI) projects to increase adherence with guidelines. The development of ECDS is often labor-intensive, and the resulting tool faces considerable barriers to reach users beyond the original QI project sites given the variety of electronic health record (EHR) system standards in place (2). Even simple decision support available in most EHR systems, such as order sets, face many barriers and delays to implementation within the initial target health system and especially when attempting to scale to other systems (3).

Mobile device-based electronic clinical decision support (mECDS) tools are one potential method of overcoming such barriers to reach and maintenance of ECDS (4). mECDS tools, when deployed through a freely downloadable app, have the potential to be an effective and scalable (beyond both the initial project location) resource for improving quality of care and health outcomes (5). These tools also have been shown to integrate well into clinical workflow and reduce provider cognitive demand, improve medication dosing accuracy, aid with symptom recognition, and increase diagnostic and triage accuracy (6). Researchers have also studied the perceived usability and acceptability of such applications by healthcare providers as well as these end-users' perceptions of the patient care based on their level of mECDS tool usage (7,8).

While mECDS tools have the potential to broadly and efficiently improve care quality, studies to date have left important knowledge gaps related to validating their effectiveness in day

to day practice and how this varies by the level of actual use. Most studies assessing the impacts of mECDS deployment on clinical practice have been conducted in simulated settings without validating the results in situ. The few studies that have assessed mECDS impacts on real-world practice have consisted of simple pre-post analyses, which are subject to confounding biases from overall trends in healthcare delivery and changes in patient severity/case-mix over time (9). Prior randomized controlled trials of mECDS have not quantified the cumulative effects of mECDS utilization on clinician practice or explored the effects of mECDS at the hospital/facility level (6).

Additional challenges remain in the scaling the reach and maintaining the use of ECDS tools beyond the location and intervention period of the initial project (10). In the prior studies evaluating use post-QI project, ECDS tool utilization either dropped off rapidly or plateaued after the project was completed (11,12). It is also unclear what pattern the reach and adoption of such a tool might follow when freely available. Only two prior studies have evaluated usage trends of clinical decision support deployed as a freely downloadable app (13,14). Q'Reilly-Shah et al. looked at when, where, and how a free anesthesia calculator app was used in the first 10 months post release. They found that app use peaked in the early morning hours, occurred more often in low-income countries, and primarily involved content regarding pediatric patients (13). Wright et al. examined the first 6 months of usage patterns of an app containing electronic versions of Médecins Sans Frontières' common condition guidelines, and found use occurred in 150 countries with initial rapid growth in userbase in the first 2 months and sustained levels of use thereafter (14). The particular content accessed varied significantly between countries. Neither study evaluated use or reach beyond the first year or geographic variation in use at geographic levels smaller than country. Given the substantial time and financial investment that goes into developing ECDS, long-term data on reach and adoption are critical for determining whether these high costs are offset by maintained gains in adoption and reach. Having a better understanding of the geographic and temporal usage patterns of mECDS tools will help determine

the potential reach, effectiveness, adoption, and maintenance of such a tool deployed freely and without continued promotion.

Our team developed an app which contained two different mECDS tools released as part of two national quality improvement projects: Reducing Variation in Inpatient Sepsis Evaluation (REVISE) and Pathway for Improving Asthma Care (PIPA). These projects were run through the American Academy of Pediatrics' (AAP) Value in Inpatient Pediatrics (VIP) network which is made up of over 270 hospitals and whose mission is to improve inpatient pediatric care through reducing overutilization clinical resources by implementing the latest guidelines (15). The VIP Network projects focus on common pediatric illnesses resulting in ED visit and/or hospitalization (e.g. bronchiolitis, CAP and asthma) using a quality improvement collaborative (QIC) approach. This QIC approach involves developing and deploying a set of change package materials based on the latest evidence-based guidelines. Site leads work to implement the change package locally and enter case data to track adherence over time. Change package materials offered in VIP projects include: standardized order sets, academic detailing, prospective audit with feedback, peer coaching, and educational webinars.

In this manuscript, we employ the Reach, Effectiveness, Adoption, Implementation, and Maintenance (RE-AIM) framework to evaluate the mECDS tools added to the change package used in the PIPA and REVISE VIP projects. The RE-AIM framework is a widely-used tool in implementation science to assist with translating research to practice and estimating the impact of programs and interventions(16,17). We measure reach in terms of geographic areas with use, effectiveness in terms of association between area-use and embedded site performance, adoption in terms of cumulative project metric-related use within an area, and maintenance in terms of ongoing trends in both use and areas with use. No implementation measures were evaluated. By connecting the patient care collected through these projects to the temporal and geographical usage patterns of their corresponding mECDS tools, we aimed to investigate: a) the reach and

adoption of the REVISE mECDS tool within the project period and the effect of REVISE mECDS tool use on febrile infant management in the emergency department (ED), b) the reach and adoption of the PIPA mECDS tool within the project period and the effect of PIPA mECDS tool use on pediatric asthma care quality in the ED and inpatient setting controlling for overall project engagement, and c) determine long term (maintenance) REVISE mECDS tool use patterns within and beyond the project, spread to additional areas (reach), and how these patterns varied geographically. We hypothesize that sites in areas with higher usage levels of the corresponding project tool will have practice patterns more aligned with project metrics. We also hypothesize that both tools will be highly utilized in areas with a site during the project and that this use will be maintained beyond the project period. The PIPA and REVISE studies were approved by the AAP institutional review board. Teams at each participating site of both projects obtained local institutional review board approvals, as necessary. The analyses within this manuscript were deemed non-human subjects research by the University of Nebraska Medical Center Institutional Review Board.

CHAPTER 1: REACH AND ADOPTION OF THE REVISE mECDS TOOL AND ITS EFFECT ON FEBRILE INFANT MANAGEMENT[1]

1. **The content of this chapter has been published in the article: Kerns, E. K., Staggs, V. S., Fouquet, S. D., & McCulloh, R. J. (2019). Estimating the impact of deploying an electronic clinical decision support tool as part of a national practice improvement project. Journal of the American Medical Informatics Association, 26(7), 630-636.**

Objective

Our group developed a mECDS tool (called Febrile Infant) embedded within an app (entitled PedsGuide) and released it as part of the REVISE change package to provide stepwise guidance to clinicians. The development, initial distribution, and usage patterns of PedsGuide have been previously described (4). Releasing this application (app) as part of a national quality improvement project provided our team with a unique opportunity to assess not only the

distribution and use of the app, but also to pair such data with large-scale clinical practice and health outcomes data. Thus, the objective of this study was to investigate the reach and adoption of the REVISE mECDS tool within the project period and the effect of REVISE mECDS tool use on febrile infant management in the emergency department (ED)

Conditions of Focus

Infants <60 days of age with fever pose a significant challenge to clinicians as they are at risk (albeit low) of harboring a serious bacterial infection which, if left untreated, could lead to severe illness or death. Multiple risk stratification tools and institutional clinical practice guidelines exist to guide the management of these infants (18,19). Despite the existence of these resources to guide care, inconsistencies in guidelines and usage paired with an inability to identify with high accuracy infants likely to have a bacterial infection, has resulted in clinical practices that vary widely across healthcare institutions (20).

QI Project Description

To address this variation in care on a national level, the American Academy of Pediatrics' Value in Inpatient Pediatrics (VIP) Network conducted a clinical practice standardization project focused on the care of febrile infants 7-60 days of age (21). This project, entitled Reducing Excessive Variation in Infant Sepsis Evaluation (REVISE), deployed a change package of materials to the participating hospitals across the United States that was aimed to disseminate evidence-based recommendations for the appropriate use of diagnostic tests, hospitalization, and antibiotics for young infants with fever. The REVISE project was conducted at 133 hospitals across the US from September 2016 to January 2018. Healthcare provider teams at hospitals ranged from small, community-based institutions to free-standing university-affiliated children’s hospitals.

mECDS Development

Our interprofessional development team (which included clinical experts, human factors practitioners, health outcomes researchers, and a member of the REVISE project leadership team) developed and deployed Febrile Infant within PedsGuide with the specific intent of aligning app content with the REVISE core compliance metrics. Deployment of the app was one component of the change package provided to all REVISE participants. The complete change package included paper order sets, standard educational presentations, academic detailing (e.g. posters, handouts, etc.), and the PedsGuide app. The free app was available globally for download from the Apple App Store and GooglePlay on November 9, 2016 and was introduced via webinar to REVISE participants in December 2016. The app was also promoted through the REVISE project's email list-serve. Feedback on content and usability post-release was obtained both formally via survey and informally from end-users.

mECDS User Analytics

App usage data were collected from December 2016-November 2017. App usage data were collected using Google Analytics (22). Google Analytics records app usage in terms of the number of devices that the app has been opened on (users), the number of times the app has been opened or used (sessions), how long the app was used for each session (duration), and the number of times each button or screen within the app was touched (events). For our analysis, eligible users were restricted to those who had ever touched a Febrile Infant-specific app page within PedsGuide, and all session-related variables were restricted to those app uses that involved touching the Febrile Infant home screen within PedsGuide. All possible user events within the Febrile Infant portion of the PedsGuide app were classified as to whether they led to the user viewing content related to one of the five core compliance metrics (metric-related screen views). Some events involved the selection of check boxes that determine what portion of the app that the

user will be sent to next. Since these events did not lead to independent screens, but rather options within a screen, they were excluded from the event variables. Instead, these interactions were reported as their own variable (user decision selected) indicating the total number of times in which one of these selections was made.

Geocoding of User Analytics and Project Sites

Google Analytics captures the latitude and longitude of the cell tower or WiFi hotspot that the device is receiving data from or is registered to. This location data, while linked to a specific device, is completely de-identified and can be aggregated at various regional levels. Thus, we were able to capture a general location of where each use of the app was occurring. For the purposes of this analysis, all Google Analytics variables were aggregated by the designated marketing area (DMA) in which the device was being used, based on prior evidence of this geographic level's use in measuring behavior across regions.[12] Usage data were further stratified by month. The mapping software ArcGIS 10.1 (Esri, Redlands, CA) was used to produce a map shaded according to the number of metric-related screen views that occurred in the study period within each DMA. The DMA of each REVISE site was then determined by geocoding each site's address and performing a spatial join with a map of the DMA boundaries. All sites that fell within a DMA's boundary were assigned to that DMA.

Site-Reported Data Collection

Participating site characteristics such as the average annual number of febrile infants seen and presence of a university affiliation were collected at project initiation via survey. Clinical practice data, including adherence to the REVISE core compliance metrics, were collected via site chart reviews. These compliance metrics were developed with the assistance of nationally-recognized experts in febrile infant management. Data were entered into a secure, web-based electronic database (Quality Improvement Data Aggregator [QIDA]) maintained by the AAP.

Sites collected 12 monthly cycles of retrospective baseline data from September 2015 to August 2016. They then collected 12 monthly cycles of implementation data from December 2016 to November 2017. A 3-month window from September 2016 to November 2016 where data collection was optional was created to allow time for sites to obtain appropriate approvals and allocate sufficient resources to undertake implementation of the change package. Clinical practice data collected on the five core compliance metrics (appropriate hospitalization, appropriate length of stay, urinalysis obtainment, inappropriate chest X-ray, and appropriate antibiotic use) were analyzed for each hospital from its monthly data (Table 1).

Primary Predictor

Two measures of app usage were derived to examine as correlates of outcome metrics. The first was "metric hits per case," computed for each DMA-month combination by dividing the total number of metric-related screen views during the month by the total number of febrile infant cases reported by the sites within the DMA for the month. This measure serves as a very rough estimate of the monthly app usage "density" for the DMA. The second measure was "cumulative prior metric hits per site," designed to reflect accumulated knowledge gained by use of the app over time. We computed this measure by summing metric-related screen views by users in the DMA across months, from the DMA's first month of usage data through the month immediately preceding the index month, and then dividing by the number of sites in the DMA. For example, the value for March was computed by summing the DMA's metric hits through February and dividing by its number of sites. The measure was set to zero for the first study month (December 2016).

Table 1: Implementation Metrics and Balancing Metric for the REVISE National Collaborative

Metric	Definition	Target	Integrated into PedsGuide?
Appropriate Admission	Infant had an appropriate evaluation [a] that indicated non-low risk [b]	90% of hospitalized infants	Yes
Appropriate length of stay (LOS)	<30h for low risk [b] <42h for non-low risk [b]	80% of hospitalized infants	Yes
Urinalysis Utilization	Infant had a UA performed by any method on the first day of encounter.	95% of infant evaluations	Yes
Inappropriate Chest X-Ray	Infant without documented respiratory symptoms received a chest x-ray either 24 hours prior to, or after, presentation.	≤10% of infants without respiratory symptoms	Yes
Appropriate Antibiotic Use	Infant received recommended empiric antibiotic regimens within 24 hours of presentation.	90% of antibiotics prescribed	Yes
Missed Serious Bacterial Infection (SBI)	Infant returned to the ED or was readmitted for a new diagnosis of meningitis, bacteremia or UTI within 7 days of discharge from the ED or inpatient setting.	<2% of evaluated infants discharged home	No

a. An evaluation was deemed appropriate if it included at least a urinalysis and a marker of inflammation or infection (e.g. white blood cell count, c-reactive protein, procalcitonin).
b. "non-low risk" defined as having had a relevant prior medical history or requiring admission for social reasons.

Statistical Analyses

To examine associations between app usage and metric change, mixed logistic regression models were fit (1 per metric) using the GLIMMIX Procedure in SAS 9.4. Given clustering of months within sites within DMAs, random site and DMA intercepts were included in each model, and a first-order autoregressive error structure was specified. Explanatory variables included the

two app usage measures (metric hits per case and cumulative prior metric hits) and the site characteristic variables.

Results

Of the 133 initially selected sites, 7 dropped out of the project or did not provide data. Three additional sites did not submit complete pre- and/or post-intervention data and were excluded from analysis. Thus, the sample comprised data from 123 sites in 64 DMAs. A total of 19,320 febrile infant evaluations were reported (11,871 in the pre-intervention period, 7,449 post-intervention). Site demographics are shown in Table 2. All but 3 sites reported at least 12 months of clinical data, 89% reported data for at least 18 months, and 45% of sites reported data for all 24 months.

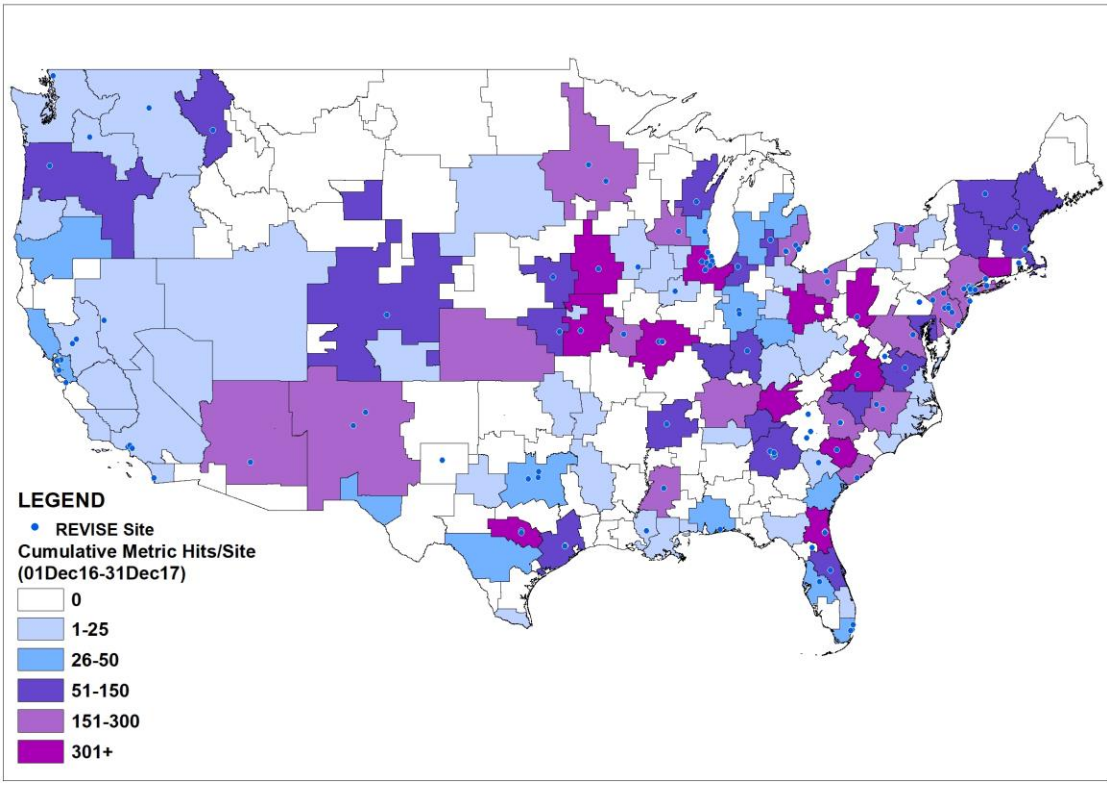
Table 2: REVISE Site Characteristics

Variable	Level	Number (%)
Non-ICU pediatric beds	≤50	56 (46%)
	>50	67 (54%)
Annual cases	≤100	53 (43%)
	>100	70 (57%)
University-affiliated	No	49 (40%)
	Yes	74 (60%
Pediatric emergency medicine physicians	No	24 (20%)
	Yes	99 (80%)
Census region	Midwest	38 (31%)
	Northeast	27 (22%)
	South	40 (33%)
	West	18 (15%)

A total of 10,883 use sessions occurred during the study period. These sessions consisted of 60,377 screen views of which 33,134 (55%) were metric-related. There were 88,543 user decisions made for an average of 6 screen views and 8 user decisions per session. Most (42; 66%) DMAs contained a single site; 19 (30%) contained 2-4 sites, and 3 (5%) contained 7 or more. Median (IQR) DMA population was 1.9 (0.9, 4.2) million. The number of metric hits per site

accumulated during the study varied widely by DMA, ranging from 0 to 2185 with median (IQR) 140 (61, 292) (see Figure 1).

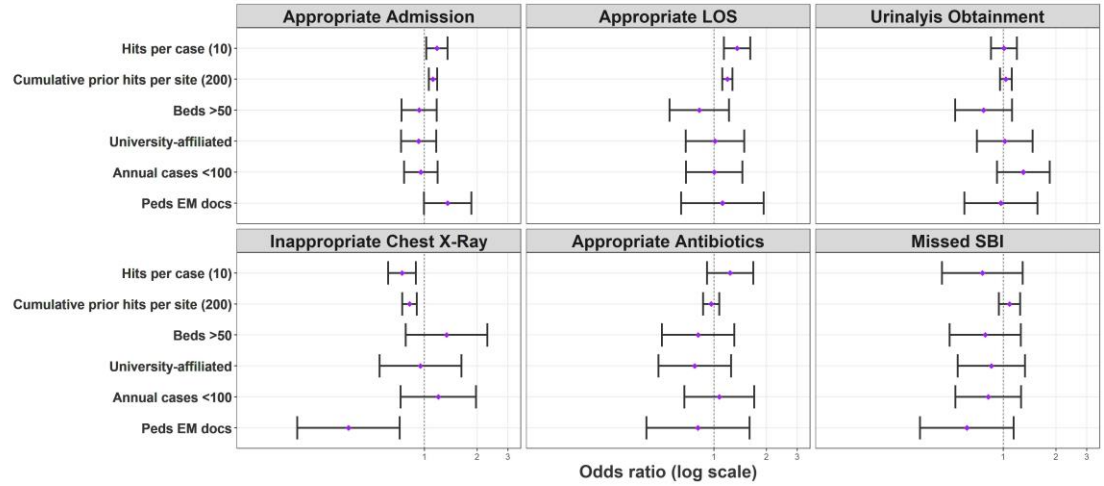
Figure 1: Cumulative REVISE mECDS Tool Metric Hits Per Site by U.S. DMA (Dec16-Dec17)



The number of accumulated metric hits in a DMA per site was a statistically significant predictor of site performance in the following month for four metrics (Figure 2). According to model estimates, an increase of 200 cumulative hits per site (a level achieved in 33% of DMAs) was associated with a 12% increase in odds of appropriate admission, a 20% increase in odds of appropriate length of stay, and an 18% decrease in odds of chest X-ray. In terms of change from the baseline rates for the three metrics, these numbers would imply respective increases of 2.0 and 2.8 percentage points in rates of appropriate admission and appropriate length of stay, and a 2.8 percentage point decrease in the rate of chest X-ray.

Number of metric hits per febrile infant case was a statistically significant predictor of these same three metrics. Ten additional metric hits per case was associated with 18% higher

Figure 2: REVISE Metric Logistic Regression Results: Odds Ratio Estimates with 95% Confidence Limits



odds of appropriate admission (implying an increase of 3.0 percentage points from the baseline rate; 95% CI: 1.02, 1.36), 36% higher odds of appropriate length of stay (95% CI: 1.14, 1.62; 5.0 percentage point increase from baseline), and 26% lower odds of chest X-ray (95% CI: 0.62, 0.89; 4.0 percentage point reduction from baseline). These effects were scaled for visualization and are not large when considered in terms of change associated with an increase of a single metric hit per case. Associations between app use and the balancing metric of missed serious bacterial infection were not statistically significant. Of the site characteristics, only census region and the presence of pediatric emergency physicians were predictive of change in any metric.

CHAPTER 2: REACH AND ADOPTION OF THE REVISE mECDS TOOL AND ITS EFFECT ON ASTHMA CARE QUALITY[2]

2. **The content of this chapter has been published in the article: Ellen Kerns, Russell McCulloh, Sarah Fouquet, Corrie McDaniel, Lynda Ken, Peony Liu, Sunitha Kaiser, Utilization and effects of mobile electronic clinical decision support on pediatric asthma care quality in the emergency department and inpatient setting, JAMIA Open, Volume 4, Issue 2, April 2021, ooab019, https://doi.org/10.1093/jamiaopen/ooab019**

Objective

Our team developed and launched a mECDS tool as part of Pathways for Improving Pediatric Asthma Care (PIPA), a multi-dimensional QI project. The mECDS tool provided

evidence-based decision support for both inpatient and ED management of asthma exacerbations in children. The PIPA project collected data on site-level project engagement (other QI/implementation activities) and pediatric asthma care quality monthly. Our team used these data to achieve our objective– to investigate the reach and adoption of the PIPA mECDS tool within the project period and the effect of PIPA mECDS tool use on pediatric asthma care quality in the ED and inpatient setting controlling for overall project engagement.

Condition of Focus

Childhood asthma is a leading cause of emergency visits, hospitalizations, missed school days, and missed work days for caregivers, with total estimated direct costs of approximately $6 billion annually in the United States (23–25). In 2018, VIP launched a new national QI project entitled PIPA. The project supported clinical pathway implementation with the global aim of "improving the value of care delivered to children with asthma"(26,27). PIPA included a diverse sample of EDs and inpatient wards across the country.

QI Project Description

We conducted a longitudinal, observational study using data from the PIPA project. Recruitment of PIPA sites occurred via 3 e-mails to VIP electronic mailing lists (listservs). These listservs include clinicians from over 250 EDs and hospitals in the United States that range widely in size, type (e.g., free-standing children's hospitals, community hospitals), ownership model (e.g., private, non-profit), and location (e.g., rural, urban). To adequately support the QI project, VIP had PIPA sites initiate the QI project in 2 waves, with half starting improvement activities in January 2018 and half starting in April 2018 (completing in December 2018 and March 2019, respectively). Core elements of this multi-dimensional QI project were designed using existing QI and implementation frameworks (the Institute for Healthcare Improvement's Model for Improvement and the Consolidated Framework for Implementation Research) (3,28).

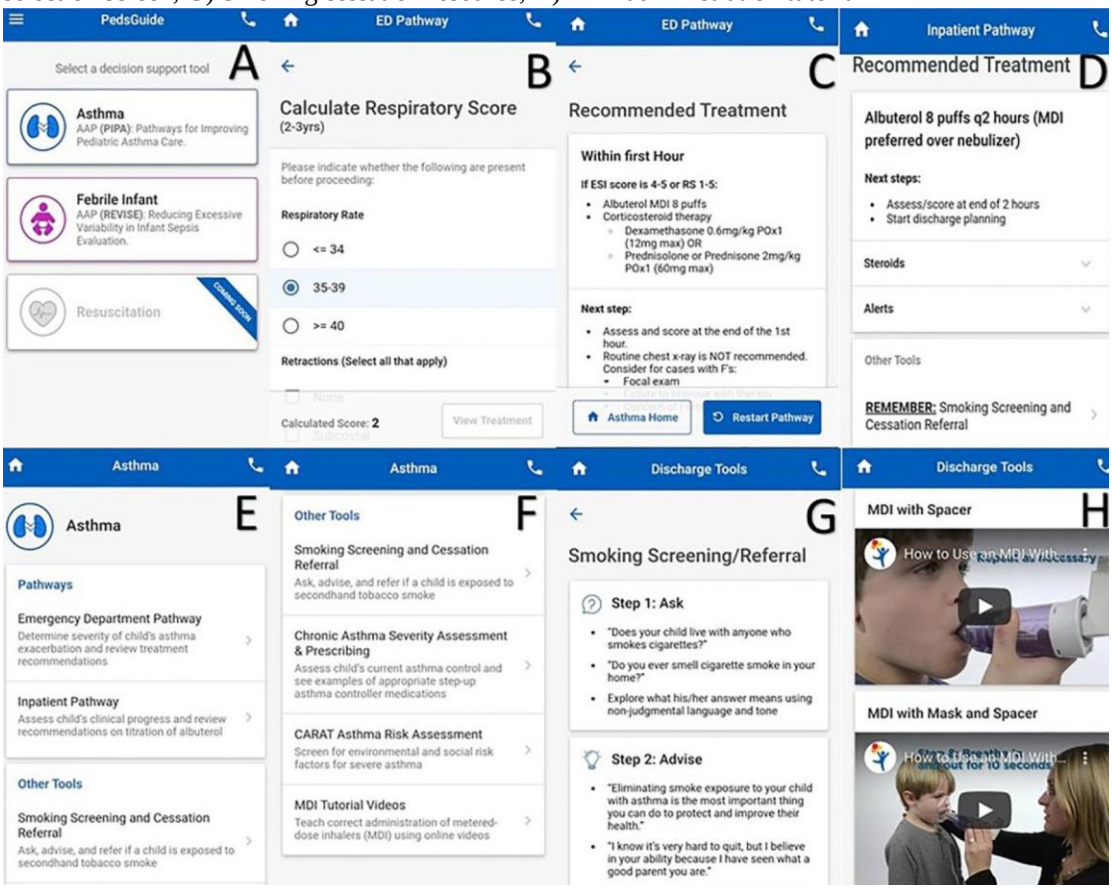
Participating EDs and hospitals were provided a pediatric asthma pathway implementation toolkit, which included sample evidence-based pathways and sample order sets based on pathway content. Each site designated a local physician implementation leader. These leaders recruited and then worked with local multidisciplinary teams to tailor and implement the pathways to fit local needs and context. Sites were provided several additional resources for implementation support: external practice facilitators, QI training, monthly audit and feedback, and educational seminars (e.g., evidence-based asthma care).

mECDS Tool Description

The PIPA mECDS tool (Figure 3A) was developed using the human factors methods including heuristic analysis and iterative usability testing (4). The tool consisted of ED and inpatient pediatric asthma pathways (Figure 3E) that calculated a patient's severity score based on clinical parameters (e.g., respiratory rate, wheezing, breath sounds, etc.) specified by the user at the time of assessment (Figure 3B). The pathways then provided evidence-based management recommendations based on the calculated severity score. The ED pathway provided criteria for ordering chest radiography and reminders to promptly administer steroids as indicated (Figure 3C). The inpatient pathway included guidance on MDI dosing and administration as well as reminders and tools for screening for secondhand tobacco exposure (Figure 3D). The mECDS tool also provided a selection of other tools that reinforced clinician adherence to the selected

quality measures (Figure 3F) including links to smoking cessation resources (Figure 3G) and MDI administration tutorials (Figure 3H).

Figure 3: PIPA mECDS Pathways and Other Tools
A) mECDS within the overall app PedsGuide; B) Severity Score Calculator; C) Example ED pathway end screen; D) Example Inpatient Pathway End Screen; E) Pathway selection screen; F) Other resource selection screen; G) Smoking cessation resource; H) MDI administration tutorial



Deployment of the mECDS Tool within PIPA

The tool was released in August 2018 as an available update to the pre-existing PedsGuide app. The PedsGuide app was released in 2015 for use in a prior VIP project (REVISE). The app is free to download from both the iOS and Android app stores and requires no registration to begin using. The free mECDS tool release was announced to PIPA sites both via videoconference and email during project launch. However, there was then a 6-month delay before the tool was released leaving uptake of the tool to be largely driven by passive deployment

methods including word of mouth and users having already downloaded the app for the prior VIP project.

mECDS Tool User Analytics

mECDS tool utilization data were collected from release (August 23, 2018) to the end of the study period (March 31, 2019) using Google Analytics. Google Analytics automatically records mECDS utilization in terms of distinct devices on which the overall app has been opened (users), number of times the tool has been used (sessions), and what pages were viewed/buttons were clicked within the tool (events) (22). Time stamps of the hour and geolocation of each session by city are also recorded. City-level usage data was linked by study site location for comparisons across sites. There were no cities with more than one site. For this analysis, we analyzed users, sessions, and events related to the newly-developed asthma mECDS tool within the app used in REVISE (PedsGuide). Events were dichotomized according to whether they led the user to view quality metric-related content (MetricHits).

Site-Reported Data Collection

Participating site characteristics such as hospital size and location (rural vs urban) were collected at project initiation via electronic survey. Site project engagement (QI activities) was assessed monthly via electronic survey of each site's physician implementation leader. Surveys collected data on QI/implementation activities, specifically the state of implementation of key clinical pathway elements (e.g., criteria for ordering chest radiography) (29). Responses were converted into binary indicator variables that indicated whether each pathway element was implemented and in-use during the respective intervention month. Clinical practice data, including patient characteristics, adherence to performance metrics, and balancing metrics, were collected via chart review. A trained clinician from each site entered the chart review data on each ED visit/hospital admission into a secure, web-based electronic database (REDCap)

maintained by the University of California, San Francisco. Sites collected chart review data on ED visits/admissions that occurred from January 2017 to March 2019. Most fields used in this analysis were required for chart submission by sites. Less than 2% of charts had missing data for the few non-required fields, and these were excluded from the analysis.

Project Metrics

Study performance and balancing metrics were selected through a consensus process among the national expert panel assembled for this study by the AAP. Performance metrics in the ED setting included decreasing the utilization of chest radiography (Chest X-Ray); increasing the use of severity assessment at ED triage (Triage Assessment); and decreasing the time from ED arrival to systemic corticosteroids administration (Time to Steroids). The balancing metric for the ED was not increasing ED length of stay (ED LOS). In the inpatient setting, the performance metrics were decreasing length of hospital stay (Inpatient LOS); increasing early administration of metered dose inhalers (MDI, early defined as MDI at admission or first ordered at 1-2hr frequency); increasing documented screening for secondhand tobacco smoke exposure (Smoke Screening); and, when positive, increasing referral of caregivers to smoking cessation resources (Smoke Referral). The balancing metric was not increasing hospital readmission within 7 days of discharge (7-Day Readmit).

Primary Predictor

In the prior REVISE study, we found cumulative mECDS utilization was associated with care quality for infants with fever. Cumulative utilization may reflect accumulated knowledge gained by use of the tool over time; thus, this cumulative utilization was used as the primary predictor in this study (“Cumulative Metric Hits”). We determined “Cumulative Metric Hits” by summing metric-related screen views by all asthma mECDS tool users in each city to date, from the city’s first month of usage data through the month immediately preceding the index month.

For example, the value for October was computed by summing the city's metric hits from mECDS release through September. The measure was set to zero for the first release month (August 2018).

Statistical Analyses

We analyzed the relationship between patient characteristics and cumulative metric hits in the city-month in which they were seen using an ANOVA Test for patient age and Chi-squared tests for all others. The relationship between site characteristics and cumulative metric hits in each site's city in the final intervention month was analyzed using Fischer's Exact tests. Crude case adherence to each metric was tested using chi-squared tests for binary metrics and Mann-Whitney U-Tests for continuous metrics.

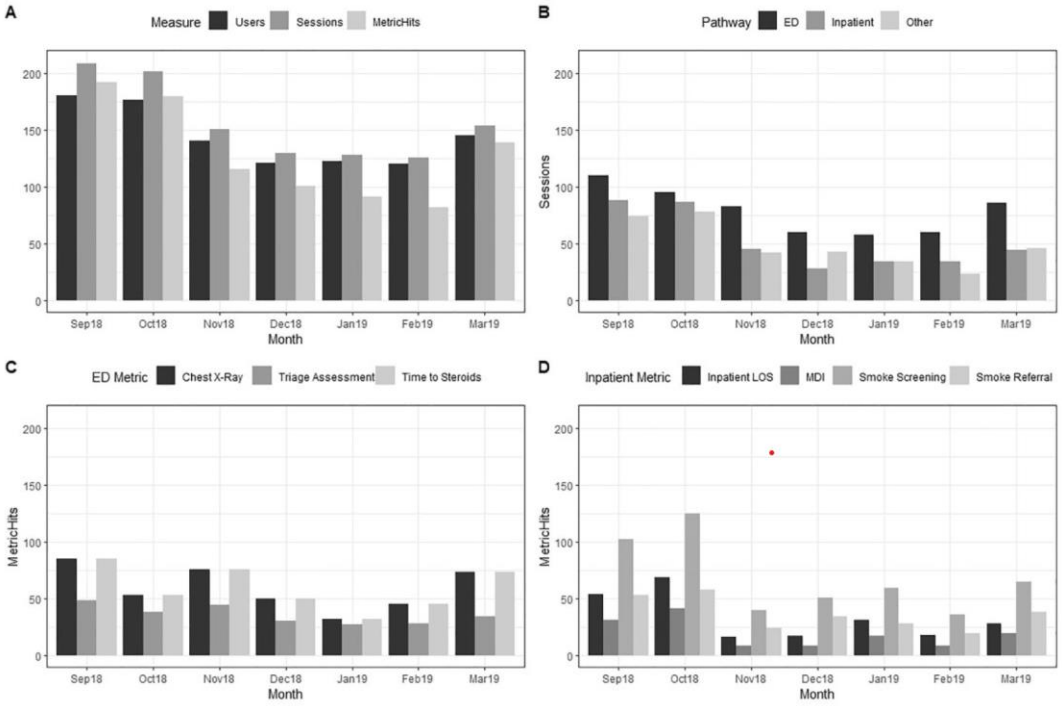
To determine associations between cumulative metric hits and quality metrics, we used generalized mixed effect linear models (1 per outcome/quality metric) using the R package lme4. The cut-off to derive odds ratios of case adherence by city-month cumulative metric hits was determined empirically by using the upper quartile of city-site use (5+ cumulative metric hits). A binomial distribution was used for binary metrics and a Gaussian distribution was used for continuous metrics. A log-link was used to compute ORs for continuous metrics (e.g., odds of longer/prolonged LOS between kids seen in cities and months with 5+ cumulative metric hits versus <5 cumulative metric hits). Given clustering of encounters within sites, a random site intercept was included in each model. To account for potential confounders including secular trends/time, patient case-mix, and overall QI engagement, we included the following explanatory variables: cumulative metric hits, study month, site characteristic variables (e.g., location, teaching status), site project engagement variables (e.g., implementation of QI interventions), and patient characteristics (insurance type, sex, age, and prior use of inhaled corticosteroids). All analyses were conducted using R v. 3.4.1 (Vienna, Austria) and p-values <0.05 were considered significant.

Results

A total of 89 sites were recruited for the PIPA study and 75 sites completed the study. Reasons for not completing included lack of support from hospital leadership/administrators, difficulty obtaining local institutional review board (IRB) approval, difficulty obtaining chart review data, staff turnover, difficulty due to competing QI projects and very low patient volumes (29). In total, the tool was used on 286 devices, 335 times, incurring 4,191 events, of which 922 (22%) were page views of quality metric-related content (MetricHits).

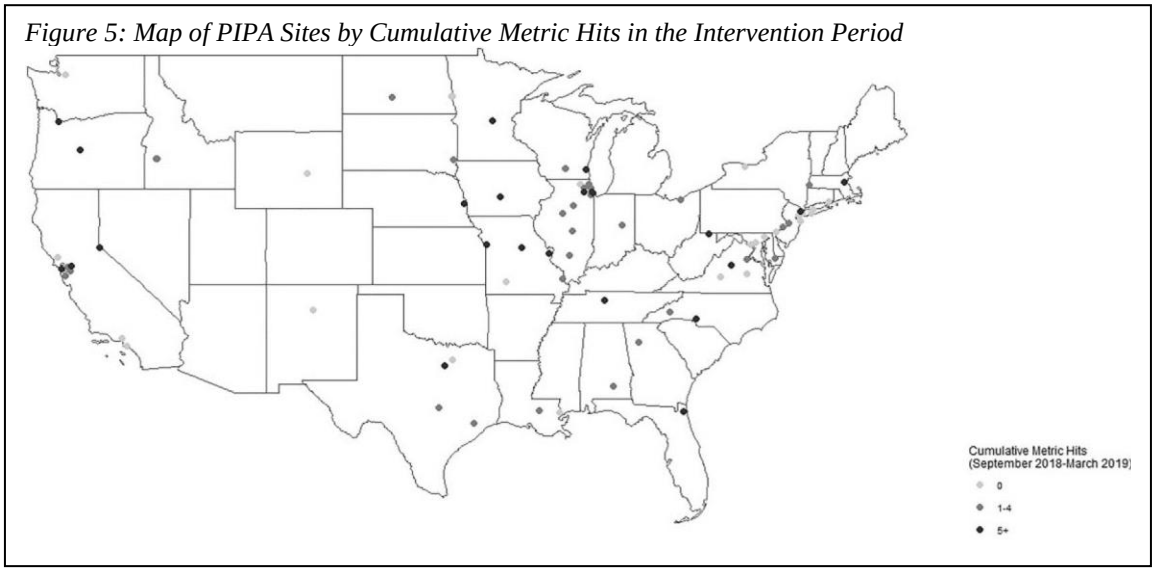
Usage trends from release until the end of the intervention are depicted in Figure 4.

Figure 4: Monthly mECDS Tool Utilization During the PIPA Project
A) Unique users (number of devices on which the tool was used), sessions (number of times the tool was used), and MetricHits (views of metric-related content) in each month; B) Number of sessions involving the ED pathway, inpatient pathway, and other tools in each month; C) Number of times content related to each ED metric was viewed in each month; D) Number of times content related to each Inpatient metric was viewed in each month



Users of the tool consistently engaged with it about once per month on average and had about 1 MetricHit per session. Overall, the inpatient pathway and ED pathway were used roughly the same number of times (205 vs. 190). The metric-related content most often viewed, particularly in early months, was secondhand tobacco smoke screening tools, followed by chest x-ray criteria. Guidance on ED management/timely steroid administration were second most viewed overall and surpassed smoke screening in some of the later months. Guidance on metered-dose inhaler dosing was consistently viewed least often. Site locations and city-level cumulative metric hits in the final month are depicted in Figure 5.

Figure 5: Map of PIPA Sites by Cumulative Metric Hits in the Intervention Period



Patient characteristics, care setting, and crude adherence to metric are depicted in Table 3 y the level of cumulative use in the city and month in which their encounter occurred. Higher levels of cumulative metric hits were associated with patient-level prior prescription of an inhaled corticosteroid, having a payor type of "other," and being seen in the inpatient setting.

Most cities with a study site (61%) had at least some use, but cities with free-standing children's hospitals had higher levels of use than those with community hospitals or non-freestanding children's hospitals (Table 4). Sites with higher QI project engagement had significantly higher mECDS utilization, specifically those that implemented the pathway elements MDI dosing guidance, bronchodilator protocol, and discharge criteria.

Table 3: Patient Characteristics and Metric Adherence by Cumulative Use in the City and Month of PIPA Encounter

		Total		Cumulative Metric Hits						p-value
				0		1-4		5+		
		#	%	#	%	#	%	#	%	
Total Patients		34,121		29,484	86%	2,216	6%	2,421	7%	
Age (years)*	**Mean (sd)**	7	4	7	4	7	4	7	4	<0.001
Sex**	**# (%)**									0.585
	Male	20,577	60%	17,804	60%	1,337	60%	1,436	59%	
	Female	13,544	40%	11,680	40%	879	40%	985	41%	
Insurance	**# (%)**									<0.001
Type**	**Public**	13,039	38%	11,242	38%	897	40%	900	37%	
	Private	5,512	16%	4,716	16%	432	19%	364	15%	
	Tricare	191	1%	168	1%	14	1%	9	0%	
	Other	1,857	5%	1,583	5%	85	4%	189	8%	
Prior Prescription	**# (%)**									<0.001
of Inhaled	**Yes**	15,724	46%	13,409	45%	1,042	47%	1,273	53%	
Corticosteroid**	**No**	18,397	54%	16,075	55%	1,174	53%	1,148	47%	
Setting**										
ED	**# (%)**	22,109	65%	19,198	65%	1,440	65%	1,471	61%	<0.001
Case Adherence										
Chest X-Ray**	**# (%)**	6,138	28%	5,410	28%	433	30%	295	20%	<0.001
Triage Assessment**	**# (%)**	19,866	90%	17,183	90%	1,395	97%	1,288	88%	<0.001
Time to Steroids (min)***	**Median (IQR)**	49	(30-81)	49	(30-82)	50	(32-81)	43	(28-69)	<0.001
Admission**	**# (%)**	4,219	19%	3,598	19%	359	25%	262	18%	<0.001
ED LOS (min)***	**Median (IQR)**	148	(102-208)	149	(102-209)	144	(103-199)	147	(103-207)	0.343
Inpatient	**# (%)**	12,012	35%	10,286	35%	776	35%	950	39%	
Case Adherence										
Inpatient LOS (hrs)***	**Median (IQR)**	29	(20-42)	29	(20-42)	31	(21-44)	28	(18-41)	<0.001
MDI**	**# (%)**	6,295	52%	5,161	50%	393	51%	741	78%	<0.001
Smoke Screening**	**# (%)**	9,755	81%	8,328	81%	659	85%	768	81%	0.024
Smoke Referral**	**# (%)**	1,323	11%	1,075	10%	113	15%	135	14%	<0.001
7 Day Readmit**	**# (%)**	276	2%	232	2%	12	2%	32	3%	0.032

*ANOVA Test; **Chi-Squared Test; *** Man-Whitney U Test

Most cities with a study site (61%) had at least some use, but cities with free-standing children's hospitals had higher levels of use than those with community hospitals or non-freestanding children's hospitals (Table 4). Sites with higher QI project engagement had significantly higher mECDS utilization, specifically those that implemented the pathway elements MDI dosing guidance, bronchodilator protocol, and discharge criteria.

Table 4: PIPA Hospital/ED Characteristics by Cumulative Metric Hits in the Final Intervention Month

	Total Sites		Cumulative Metric Hits						p-value*
			0		1-4		5+		
	#	%	#	%	#	%	#	%	
Site-Level Factors	75		29	39%	24	32%	22	29%	
Hospital Location									0.08
Urban	33	44%	10	34%	9	38%	14	64%	
Suburban	37	49%	17	59%	14	58%	6	27%	
Rural	5	7%	2	7%	1	4%	2	9%	
Hospital Type									0.07
Community	40	53%	21	72%	12	50%	7	32%	
Non-freestanding Children's	23	31%	6	21%	9	38%	8	36%	
Free-standing Children's	12	16%	2	7%	3	13%	7	32%	
Hospital Teaching Status									0.32
Yes	68	91%	27	93%	23	96%	18	82%	
No	7	9%	2	7%	1	4%	4	18%	
Hospital Bed Size									0.92
Large(>=250beds)	46	61%	19	66%	13	54%	14	64%	
Medium(100-249beds)	21	28%	7	24%	8	33%	6	27%	
Small(<100beds)	7	9%	2	7%	3	13%	2	9%	
QI Project Engagement (Pathway Elements Implemented): ED									
CXR Criteria	36	48%	13	45%	11	46%	12	55%	0.92
Severity Scoring Tool	51	68%	16	55%	16	67%	19	86%	0.16
Order Set for Corticosteroids	27	36%	8	28%	9	38%	10	45%	0.54
QI Project Engagement (Pathway Elements Implemented): Inpatient									
MDI Dosing Guidance	60	80%	17	59%	22	92%	21	95%	0.01
Bronchodilator Protocol	51	68%	14	48%	19	79%	18	82%	0.04
Discharge Criteria	57	76%	16	55%	21	88%	20	91%	0.01
Tobacco Screening Reminder	63	84%	20	69%	23	96%	20	91%	0.06
Cessation Tool Referral Reminder	62	83%	20	69%	23	96%	19	86%	0.06

*Fisher's Exact Test

City-level cumulative metric hits were associated with one ED quality metric (Figure 6). Children seen in a city and month with 5 additional cumulative metric hits were 5% less likely to be admitted to the hospital (OR: 0.95, 95% CI: 0.92-0.98). City-level cumulative metric hits were associated with 2 inpatient quality metrics (Figure 7). Children seen in a city and month with 5 additional cumulative metric hits had a reduction in odds of prolonged hospital length of stay cessation resources (OR: 1.08, 95% CI: 1.01-1.16).

Figure 7: Effects of 5 Additional Cumulative Metric Hits on PIPA ED Quality Metrics
Odds of case adherence to each ED metric in a given month and city with 5+ cumulative metric hits versus <5 cumulative metric hits (adjusted for site characteristics, site engagement, patient case mix, study month, and clustering by site)

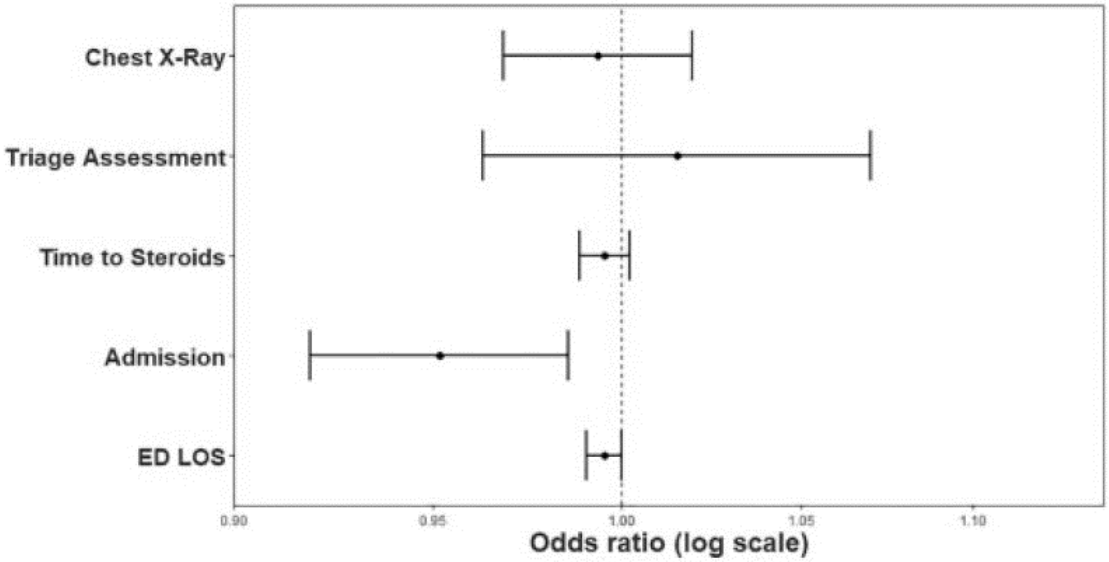
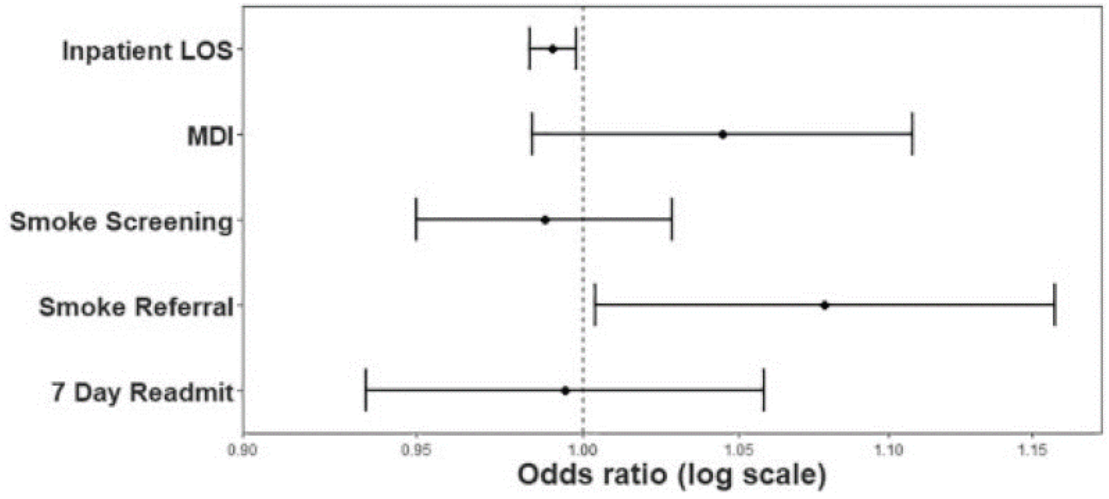


Figure 6: Effects of 5 Additional Cumulative Metric Hits on PIPA Inpatient Quality Metrics
Odds of case adherence to each inpatient metric in a given month and city with 5+ cumulative metric hits versus <5 cumulative metric hits (adjusted for site characteristics, site engagement, patient case mix, study month, and clustering by site)



CHAPTER 3: REACH AND MAINTENANCE OF mECDS TOOL USE AND SPREAD WITHIN AND BEYOND THE REVISE PROJECT

Objective

The mECDS tool used in REVISE was promoted to the sites via the project's introduction webinar, but the app it was published within (PedsGuide) was freely available for download from both Google Play and Apple's App Store. This availability allowed for the potential for use to occur well beyond both the site locations and the time period of the active REVISE project intervention. The aim of this study was to determine long term (maintenance) REVISE mECDS tool use patterns within and beyond the project, spread to additional areas (reach), and how these patterns varied geographically. We compared trends in tool use across three time periods (during the REVISE intervention, 1-year post intervention, 2-years post intervention) within designated market areas (DMAs) that contained a REVISE site and those that did not. Specifically we tested, during and post project (REVISE), whether mECDS tool use (1) increased over time, 2) spread to other DMAs, 3) differed between DMAs with and without REVISE sites, 4) was associated with other confounding factors at the DMA and temporal-level.

mECDS User Analytics

App usage data were collected from December 2016 to November 2019 using Google Analytics. Google Analytics records app usage at the individual device level in terms of the number of devices that the app has been opened on (users), the number of times the app has been opened or used (sessions), how long the app was used for each session (duration), and the number of times each button or screen within the app was touched (events) (22). Google Analytics also captures the latitude and longitude of the cell tower or WiFi hotspot that a device is receiving data

from or is registered to. These location data, tagged to a specific device, have been completely de-identified and aggregated at various geographic levels (from city to country). Thus, we performed a spatial analysis to capture the incidence of app usage across geographic regions at the time it occurred. For the purposes of this analysis, we chose to analyze the aggregated data at the designated market area (DMA) level because the coverage of DMA is most closely aligned with the catchment area of hospitals. We derived three weekly app usage statistics, including a measure of geographic reach entitled unique DMAs (total number of DMAs with app use within the week), a measure of usage activity volume entitled MetricHits (total number of project metric-related screen views occurring within the week), and a usage density measure entitled HitsPerDMA (MetricHits divided by Unique DMAs).

Covariate Derivation

Since the overarching target of REVISE was to increase febrile infant guideline adherence in ED settings with less experience in pediatric medicine, the relative concentration of children's hospitals (e.g. the hospital type least likely to need the app) was derived for each DMA. The geolocations (latitudes and longitudes) of all U.S. children's hospitals were obtained from the 2018 American Hospital Association Survey (30). Children's hospitals were aggregated as counts by DMA using an intersect spatial join with DMA boundaries obtained from the U.S. Census Bureau's repository of geographic shape files (31). Given the high potential that use would cluster in areas with a high proportion of REVISE sites, a density measure of REVISE sites per DMA using the same method was created. To account for the seasonal nature of febrile infant epidemiology, season of use was derived by binning the month based on the Northern Meteorological Seasons: Winter (December-February), Spring (March-May), Summer (June-August), and Fall (September-November) (32). Finally, to account for population density, DMA population was also obtained from the U.S. Census Bureau's DMA shapefile.

Statistical Analyses

In the univariate analysis, three app usage measures were compared separately by study period (REVISE [12/1/2016 to 11/30/2017], 1-year post [12/1/2017 to 11/30/2018], 2-years post [12/1/2018-11/30/2019]). To determine crude differences in weekly usage, median values were compared by the study period using Kruskal-Wallis tests. To determine how usage diffused over time, separate linear regression models were performed where the app usage measures (DMAs, MetricHits, and HitsPerDMA) were dependent variables and the study week (# of weeks since the study starting date of 12/1/2016) was the continuous explanatory variable for each study period. We analyzed the temporal data at a weekly basis because weekly data have less noise and better visual presentation than daily data, and because there was no significant variation pattern within a week. We further tested the interactions of study week × time period for each measure to assess heterogeneity in slopes of the weekly trends across the three time periods. Linear trends were reported because we did not identify significant quadratic or cubic trends in any models. To delineate the potential for uptake and sustainability in the absence of project participation, we divided DMAs into two strata by REVISE participation. Stratified analyses were conducted separately among DMAs that contained at least one REVISE site and among those that did not contain a REVISE site. Due to the correlation among the covariates (multicollinearity), we assessed the impact of confounding factors (explanatory variables) including seasonality, number of REVISE sites in the DMA, number of children's hospitals in the DMA, and DMA population separately on temporal trends in MetricHits among all DMAs. Data management, aggregation, visualization, and analyses were conducted using R version 3.6.4 (R Core Team, Vienna, Austria).

Results

Over the course of three years, usage of the mECDS tool occurred in 93% of U.S. DMAs (196/210) and accumulated 263,514 MetricHits. Total MetricHits in each DMA ranged from 0 to 41,888, with a median of 258. When use in all DMAs was compared across the study period, both median weekly MetricHits and unique DMAs with app use were found to be higher in each subsequent study period (p<0.001, Table 5). However, weekly HitsPerDMA was found to be significantly lower in the years after REVISE was completed than during the active QI intervention (p=0.003). When the analysis was restricted to just DMAs that contained a REVISE site, both MetricHits and unique DMAs were still found to increase over three study periods (p<0.0001) while HitsPerDMA remained relatively stable (p>0.05). In DMAs without a REVISE site, both MetricHits and unique DMAs were again found to increase over three study periods (p<0.001) while median weekly HitsPerDMA were found to be significantly lower in both years after the completion of REVISE (p<0.001). DMAs with a REVISE site accounted for the majority of MetricHits in all study periods (81% REVISE, 75% 1-year post, and 73% two years post), but only two-thirds of the DMAs during REVISE (65/156) and only half in the 2 years after (65/183 and 65/188 respectively).

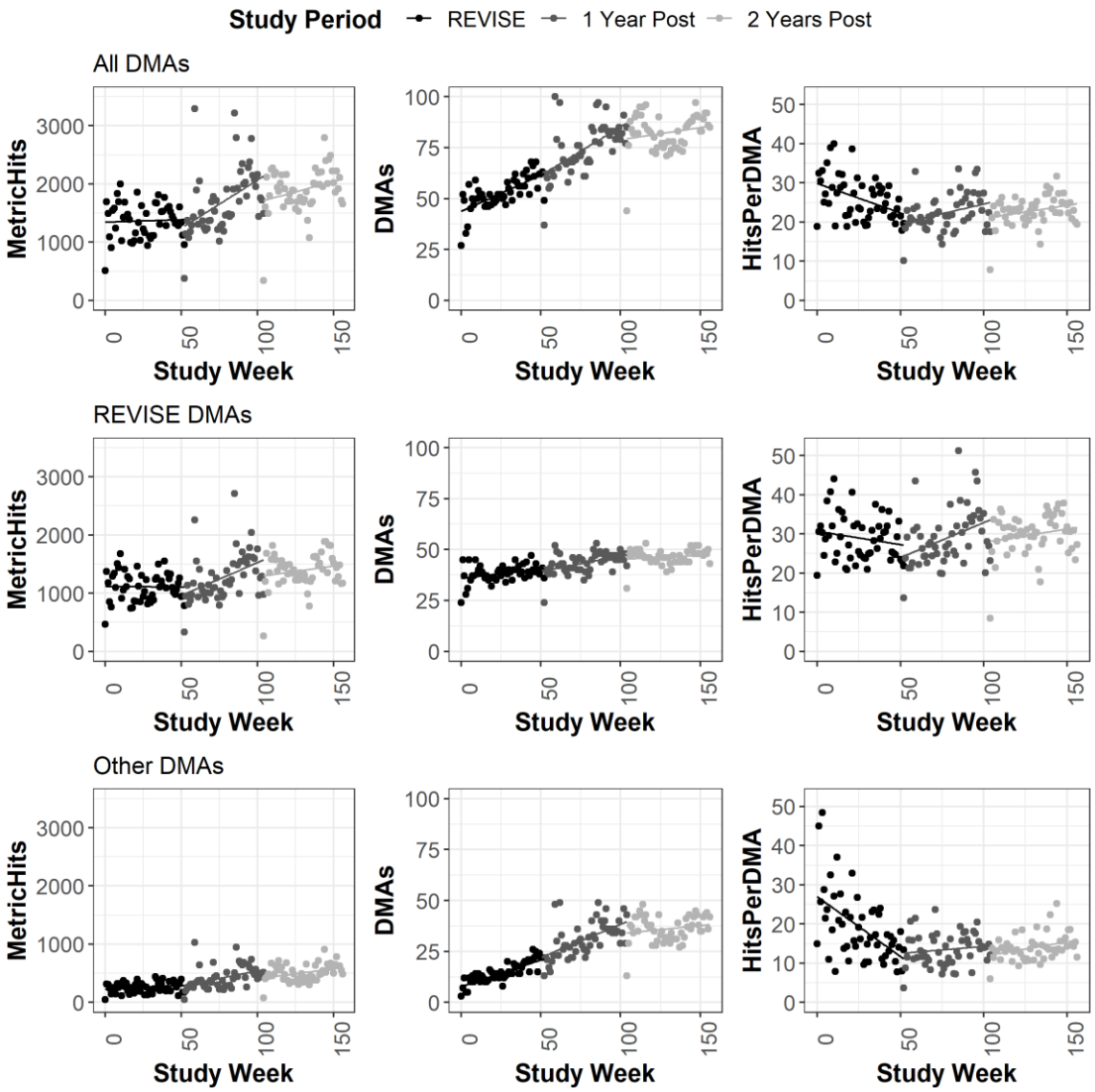
Table 5: Crude Rates of REVISE mECDS Tool Usage Measures By Study Period and DMA Subset

	MetricHits					UniqueDMAs					HitsPerDMA				
	Total	Weekly			Kruskal-Walis P-Value	Total	Weekly			Kruskal-Walis P-Value	Total	Weekly			Kruskal-Walis P-Value
		Median	IQR				Median	IQR				Median	IQR		
All DMAs					<0.001					<0.001					0.003
REVISE	72,360	1,387	1,117	1,584		156	52	49	58		3,650	25	22	29	
1 Year Post	90,386	1,534	1,310	2,002		183	76	68	83		3,107	22	20	25	
2 Years Post	100,768	1,917	1,700	2,159		188	83	77	89		3,132	23	21	25	
DMAs with a REVISE Site					<0.001					<0.001					0.161
REVISE	58,834	1,105	913	1,281		65	39	36	40		3,768	29	25	32	
1 Year Post	67,721	1,183	976	1,523		65	44	40	47		3,376	28	24	32	
2 Years Post	73,805	1,384	1,225	1,577		64	47	44	48		3,407	31	27	33	
DMAs without a REVISE Site					<0.001					<0.001					<0.001
REVISE	13,526	253	194	325		91	14	12	18		3,368	17	13	23	
1 Year Post	22,665	384	283	519		118	30	25	36		2,497	13	11	16	
2 Years Post	26,963	488	402	628		124	36	32	42		2,600	14	12	15	

[a]: Interquartile range.

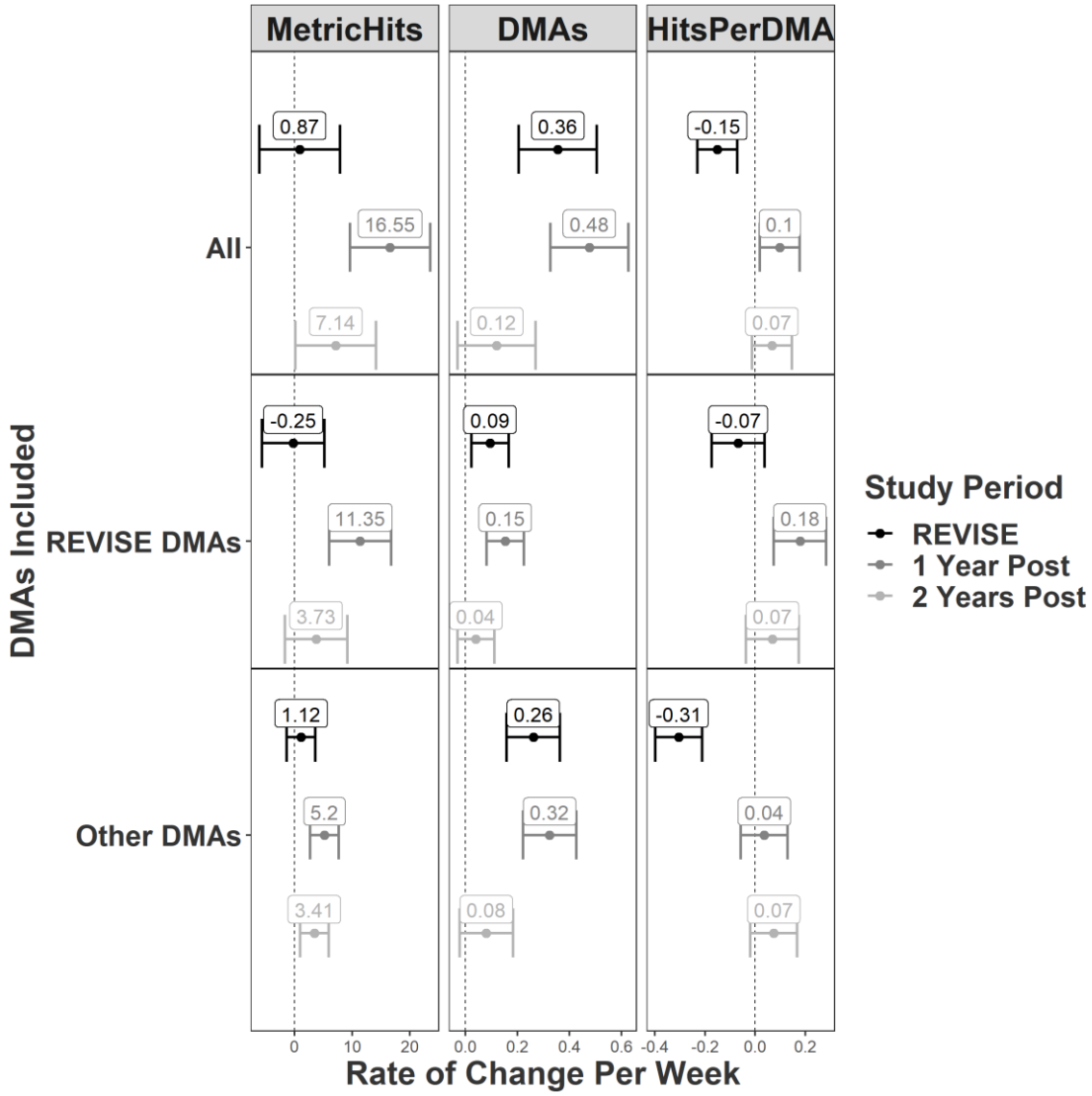
A linear regression analysis was performed to assess the rate of weekly change within each study period. When modeled over time, MetrcHits held stable in the REVISE period (weekly change: 0.87 95% CI [-6.1 to 7.8], p=0.81), grew at a rate of 17 per week 1-year post (95%CI [9.6 to 24], p<0.01), and grew at a reduced rate 2-years post (weekly change: 7.0 95% CI [0.2 to 14], p=0.21) [Figures 8-9, column 1].

Figure 8: Scatter Plots of Weekly REVISE mECDS Tool Usage Measures By Study Period and DMA Subset [a]



[a] Separate linear trends were fit during REVISE period, 1-year post, and 2-years post for each app usage measure.

Figure 9: Rate of Changes for REVISE mECDS Tool Usage Measures By Study Period and Include DMAs. [a]



[a]: Separate linear regression models were conducted with three mECDS usage measures (DMAs, MetricHits, and HitsPerDMA) as the dependent variable and time (week) as the independent variable. The regression coefficient (β) along with 95% confidence intervals were reported for the rate of change

The mECDS tool gained about one new unique DMA with use every 3 weeks in the REVISE period (weekly change: 0.36 95% CI [0.21 to 0.50], p<0.01), every two weeks 1-year post (weekly change: 0.48 95% CI [0.33 to 0.63], p=0.26) and then flattened out 2-years post (weekly change: 0.12 95% CI [-0.03 to 0.27], p=0.03) [Figures 8-9, column 2]. When MetricHits were divided by unique DMAs with use (HitsPerDMA), there was a significant downward trend in the REVISE period (weekly change: -0.15 95% CI [-0.23 to -0.07], p<0.01), an upward trend 1-year

post (weekly change: 0.10 95% CI [0.02-0.18], p<0.01), and no significant change during the 2-years post period (weekly change: 0.07 95% CI [-0.01 to 0.15], p<0.01) [Figures 8-9, column 3].

When the analysis was restricted to just DMAs with a REVISE site (Figures 1-2, row 2), the same trends in usage were found as the overall trend, except for the downward trend of HitsPerDMA in the REVISE period which no longer reached significance (weekly change: -0.07 95% CI [-0.17 to 0.04], p=0.20). Among DMAs without a REVISE site (Figures 1-2, row 3), MetricHits followed the same trends as in the model including all DMAs, but unique DMAs were only found to increase by one every four weeks in the REVISE period (weekly change: 0.26 95% CI [0.16 to 0.36], p<0.01) and were not found to increase at a significantly higher rate 1-year post (weekly change: 0.32 95% CI [0.22 to 0.43], p=0.39). HitsPerDMA had a downward trend in the REVISE period (weekly change: -0.31 95% CI [-0.40 to -0.21], p<0.01) and held stable in both the 1-year post (weekly change: 0.04 95% CI [-0.06 to 0.13], p<0.01) and 2-years post-period (weekly change: 0.07 95% CI [-0.02 to 0.17], p<0.01).

The analysis of confounding factors showed that MetricHits were higher in the summer than in the winter and increased with the number of REVISE sites, the number of Children's Hospitals, and the population of the DMA (Table 6). Independent adjustment for all covariates

Table 6: Association between Covariates and Weekly REVISE MetricHits Among All DMAs

	Increase in Weekly MetricHits[a]	Standard Error	p-value
Season[b]			
Winter	Reference	Reference	Reference
Spring	-0.45	0.27	0.09
Summer	0.65	0.32	0.04
Fall	-0.14	0.31	0.47
REVISE Sites[c]	1.44	0.03	<0.01
Children's Hospitals[d]	0.76	0.04	<0.01
DMA Population[e]	0.06	<0.01	<0.01

a. Due to the correlation among the covariates (multicollinearity), we performed separate regression analyses for each covariate (explanatory variable) on the MetricHits (dependant variable) by accounting for the temporal trends for study week among all DMAs across three periods. The model is expressed as MetricHits = StudyWeek + StudyPeriod + StudyWeek*StudyPeriod + Covariate.
b. Compared to Winter
c. Per every 1 additional REVISE Site in the DMA
d. Per every 1 additional Children's Hospital in the DMA
e. Per every 100,000 additional people in the DMA

reduced the effect estimates for the weekly rate of change in all study periods. The downward trend found during the active intervention was still significant with each adjustment, but the upward trend for 1-year post was found to be insignificant after adjusting for either seasonality or the number of children's hospitals. The upward trend found for 2-years post was not significant after adjustment for any of the covariates.

DISCUSSION

We employed the Reach, Effectiveness, Adoption, Implementation, and Maintenance (RE-AIM) framework to evaluate the mECDS tools added to two national quality improvement projects. We found both mECDS tools to be effective in that area-level use was associated with improved adherence to project metrics and the tool was used in most areas with a site (reach). Additionally, both tools led to hundreds of views of metric-related content during the project (adoption). Finally, the REVISE tool continued to gain use and areas with use in the 2 years beyond the project period (maintenance).

During the REVISE project, mECDS tool usage seemed to act in a cumulative manner in its impact on site adherence; cumulative metric hits per site was a statistically significant predictor of 3 out of 5 metrics. Hits per case, a rough measure of app "dose" per patient, was also a statistically significant predictor for 3 metrics, but the effect sizes were much smaller (Figure 2). There was insufficient evidence to conclude that either measure of app usage impacts appropriate antibiotic use or urinalysis, but adherence to this metric at baseline was already 97% and 90% on average respectively leaving little room for additional improvement. During the PIPA project, cumulative mECDS utilization was associated with improvements in the quality of asthma care for children, including reduced odds of hospital admission, reduced inpatient length of stay, and higher odds of referral of caretakers to smoking cessation resources (Figure 6 and 7). These findings suggest that the app facilitates learning over time, and as this learning increases

physicians would not require use of the app in every case, though its earlier use would remain an influence on future clinical decisions made. Cumulative use may also result in a ripple effect, changing the culture of practice as one clinician makes decisions using the app and others mimic the criteria used.

Reach, Effectiveness, and Adoption of the REVISE mECDS

Our results highlight several novel insights into estimating the impact of a mECDS tool on clinical practice. First with REVISE, by identifying a common unit of observation (the DMA), we were able to combine two disparate large-scale data sets. Roughly 20,000 febrile infant evaluations were analyzed against over 10,000 user sessions to assess for association. To our knowledge this report was the first of its kind linking clinical practice to mECDS use on such a large scale and outside of an EHR. Several studies have analyzed the usage patterns of their mECDS, but did not attempt to link this usage to measures of clinical practice or outcomes (33,34). A few studies attempted to determine impact on clinical practice, but none compared usage data and clinical practice data directly. One study looked at healthcare providers' perceptions related to the clinical care of patients based on their self-reported level of mECDS tool usage via a post implementation survey (7). Another study compared test scores of providers using an mECDS with those using a standard reference tool or memory alone (35). Most closely comparable is a study that evaluated the impact of introducing a mECDS into an ongoing anti-microbial stewardship program. However, this study only evaluated impact in terms of pre- and post-intervention rather than level of usage, and their intervention only involved 3 teaching hospitals in the same overall organization (36).

The change in metric adherence from baseline that can be attributed to cumulative app metric hits per site may seem small, but it has the potential for a large impact given the sheer number of infants with this presentation. Even a 2-3 percentage point improvement in an outcome like appropriate admission or length of stay, multiplied across tens of thousands of febrile infant

visits each year, translates into substantial cost savings to the healthcare system and avoidance of potentially traumatic events experienced by patients and families (37). It also must be kept in mind that this analysis only includes 12 months of usage. It would be expected that the app will continue to be used, leading to even further improvement in metric adherence over time, not only for providers at participating REVISE sites but for any provider who may use the app in the future.

The presence of physicians certified in pediatric emergency medicine (PEM) had a strong association with improvement in inappropriate chest x-ray obtainment and, though not statistically significant ($p = .056$), with improvement in appropriate admission. PEM physicians were already predisposed not to admit low risk infants when compared to those with only adult training, which may reflect a greater familiarity with this patient population based on prior training. Similarly, PEM physicians are less likely to order an unwarranted chest x-ray for a febrile infant, presumably because of greater understanding of common underlying diseases processes and likely diagnoses. An additional analysis conducted on the baseline chart review data revealed a similar increase in metric adherence among community hospitals that employed PEM physicians (data not shown). It is possible that these PEM physicians were empowered to influence other providers at their institution towards greater adherence when the VIP project was initiated at their site and they were made aware of the discrepancy in practice.

Reach, Effectiveness, and Adoption of the PIPA mECDS

With PIPA we were again able to leverage a geographic connection (hospital and use city), to determine variation in practice patterns by usage level. However, this analysis expanded on the model used during the REVISE analysis by adding in adjustment for site-level engagement and apply this linking method to another common pediatric condition (asthma) and a different care setting (inpatient). Additionally, we connected use more directly with the site by using city rather than DMA. We found that the mECDS tool was used in most cities with a project site and

that cumulative utilization of the mECDS tool was associated with improvements in 3 quality measures: hospital admission from the ED, inpatient length of stay, and referral of caretakers to smoking cessation resources. These findings align with those from REVISE and existing evidence from randomized controlled trials that mECDS tools can have positive impacts on clinicians' guideline adherence (6).

Guidelines recommend timely administration of bronchodilators and systemic corticosteroids for children with asthma exacerbations because timely administration decreases time to recovery and risk of hospital admission (38–40). Although we did not detect statistically significant changes in timely systemic corticosteroid administration, the mECDS tool may have supported other aspects of more timely care, such as severity assessment or administration of bronchodilators, thus driving our finding of lower hospital admission risk. It is also possible that use of the tool increased clinician recognition of moderate to severe patients speeding up the triage process and decreasing admission risk. Bronchodilator weaning protocols/pathways and standardized discharge criteria can also decrease hospital length of stay (41–43). Clinician use of these resources within the tool may have contributed to our findings of decreased length of inpatient stay. Lastly, we included a section within the mECDS tool that could be shared in real time with caretakers to provide smoking cessation resources, and this resource was highly utilized compared to others within the tool. This resource may have helped drive our findings of increased smoking cessation resource referral.

Unfortunately, usage overall was much lower than in REVISE which had about 11,000 uses (vs. 335) and 33,000 metric hits (vs. 900) in total and had an impact a smaller portion of the projects metrics (3/7 PIPA vs. 3/5 REVISE). However, in REVISE the mECDS tool was available for the full year-long intervention period and was promoted to all sites at project launch. The PIPA guideline was only available during the last 4 months of group 1 and 6 months of group 2's intervention period and was only promoted to group 2. Additionally, the PIPA pathways were

primarily a severity scoring tool and as such metric-related content was only presented on the end treatment screen while the febrile guideline was a stepwise style reference and thus had metric content more evenly distributed throughout. Further, usage was aggregated at the city-level rather than the designated market area (DMA) level which likely excluded some usage that occurred in the nearby area. Finally, REVISE had about 70% more sites than PIPA (133 vs. 80).

The overall effects of the PIPA mECDS tool were also small compared to prior studies of QI interventions, including the REVISE study. Recent pediatric asthma studies have shown larger magnitude improvements in rates of hospital admission from the ED (OR 0.53 [95% CI: 0.37-0.76] shown by Bekmezian et. al. (44), OR 0.63 [95% CI: 0.40-0.99] shown by Walls et. al. (45)); length of inpatient stay (decreases of approximately 8-9% (46,47)), and guideline adherence measures, such as referral of caretakers to smoking cessation resources (48). These findings underscore the importance of our analysis accounting for site project engagement with other elements of the change package/other QI and implementation activities. However, such QI activities, particularly those that involve implementation within the EHR, are labor intensive and not as easily disseminated across institutions as mECDS tools. Thus, mECDS tool may still play an important role in QI when adequate resources for QI interventions are not available, as well as a supplemental tool for increasing the effects of QI interventions.

Previous studies have shown that such project engagement is often unmeasured or only available via project leader self-report (49). The association found between self-reported project engagement/implementation and mECDS utilization indicates that mECDS utilization may be a good proxy for project engagement. This finding also supports the validity of self-reported project engagement. Sites had higher overall project engagement/implementation of key pathway elements in the inpatient versus ED setting (68-84% versus 36-68%). Although utilization was similar overall for the ED and inpatient pathways for the PIPA mECDS tool, the volume of patients seen in the ED was much higher (~22,000 in ED versus ~12,000 in the inpatient setting);

perhaps this indicates that the inpatient pathway had more uptake. This finding aligns with the greater impact of the tool on inpatient metrics. The final site-level factor associated with use was hospital type. Free standing children's hospitals are often repeat participants of VIP's QI projects; thus, clinicians at these sites may have already had had the app the tool was deployed within.

Maintenance of REVISE mECDS Tool Reach and Adoption

Development of electronic clinical decision support tools usually requires substantial resources, including thousands of hours invested in research, software development and physicians' engagement. However, the intervention period is often limited, therefore it is important that we evaluate their use long term. Deploying these tools using a app freely available in the Google Play and Apple app stores promotes the reach of such tools to extend beyond the intervention time period and location of the associated project. We extended our previous research to measure the usage of the REVISE mECDS tool 1 and 2-years post the intervention period. Our findings highlight several novel insights on the possible maintenance of reach and adoption of mECDS tools including: 1) spread to new areas and continued adoption within an area, 2) how these vary by the presence of an associated project, and 3) what area level factors impact these trends.

First, we found strong growth in the number of unique DMAs where the mECDS was used and the total metric-related screen views (MetricHits) during the period of 1-year post project (figure 8-9 row 1). Both MetricHits and unique DMAs with use continued to be relatively stable during the period of 2-years post project. Our findings demonstrated that the usage of the mECDS tool could be sustainable even with no continued interventions. This contrasts with findings from recent studies of non-mobile ECDS tool use after project completion. McCullagh et al. found that an electronic health record based rule implemented across primary care clinics in New York was used in over 80% of applicable encounters, but this usage fell to 45% by the end of the first year (11). Patel et al. found the improvement in screening rates for cardiovascular risk

factors among those clinicians given access to the tool compared to their counterpart controls(12). After their trial, Patel et. al. expanded access to the tool to all participants trial, and self-report assessments found consistent usage levels. Only one other study, to our knowledge, has assessed usage of mECDS over time. An assessment of a pediatric anesthesia tool found that usage of the mobile-based tool decreased over the course of the 1-year rotation of the cohort of students they focused on (35).

Second, we further stratified our analyses by DMAs with a REVISE site and those without. The results show that gains in the number of unique DMAs and usage (MetricHits) appear to be primarily driven by spread to new areas given our density measure (Figure 8-9 row 2 vs. 3). The growth in unique DMAs without a REVISE site was over two times that of DMAs with a REVISE site during year after the intervention period (labeled REVISE) .The results are promising given that there were no investments in dissemination after the intervention period and the mECDS tool continued to expand into other sites and gain usage, suggesting that the tool can make significant gains in reach for little additional burden beyond the initial development costs. Conversely, the density of use (HitsPerDMA) decreased over the course of the intervention year in DMAs without a REVISE site and then leveled off in the following years, but in DMAs with a REVISE site density was stable in the intervention year, increased 1-year post, and leveled off again 2-years post (Figures 8-9 rows 2-3; column 3). This finding suggests that tools released as freely available apps can spread to new areas on their own momentum, but they may need more targeted marketing (e.g. a corresponding project as with REVISE) to get established in each area.

Third, the reduction in the weekly change in MetricHits with adjustment for DMA population and number of children's hospitals in the DMA suggests that much of the increase in use 1 and 2-years post could be driven by uptake in children's hospitals often located in larger DMAs (Table 6). These institutions are relatively high resource settings in that they likely have their own clinical decision support infrastructure and/or the ability to incorporate things like

project order-sets into their EHR. This finding is contrary to what was found in the two studies looking at decision support use in aggregate over the first few months post release, which both found that usage was more likely to occur in lower resource countries (13,14). This finding may have been driven by the over-representation of children's hospitals in VIP projects given that 2% of all hospitals are children's hospitals (30) but children's hospitals comprised 13% of project-participating hospitals. It is also possible that clinicians working at children's hospitals were more likely to hear about the mECDS even when not participating in the project given that they are more likely to attend the pediatric focused conferences at which the overall results of REVISE and the impact of the mECDS were presented. Time trends in tool usage were also reduced when accounting for both the number of REVISE sites and season of use. The reduction based on the number of REVISE sites in the DMA makes sense for similar reasons as the number of children's hospitals. Clinicians at REVISE sites are more likely to hear of and begin using the tool given their hospital's participation in the project and thus account for some of the growth in usage over time. Higher usage in the summer than in the winter fits with the epidemiology of febrile infants as this presentation tends to peak in August (50). A slight upward trend at this time can be seen in each study year (Figure 8).

Strengths and Limitations

These studies had some considerable strengths. The app being paired with such a far-reaching national improvement projects allowed for both evaluations of association with app usage and good representation of hospitals as seen by the site characteristics in both projects. Usage at the DMA level in REVISE and city-level in PIPA varied significantly, which enhanced our ability to attribute differences in project metrics, including patient outcomes, to differences in aggregate mECDS tool usage. We were also able to account for several site factors that are known to be associated with adherence to evidence-based practices such as institution size, patient volume, and the presence of a university affiliation in REVISE and additionally project

engagement and monthly patient case mix in PIPA (51,52). Finally, the method of deployment of this tool allowed for complete and continuous tracking of when and where it was used well beyond the confines of its associated project.

Our studies had several limitations. First, we could only measure app usage at geographic intervals (DMA in REVISE and City in PIPA) and outcomes at the site level, making this analysis purely ecological in nature. We cannot assume that differences based on app usage at this level are representative of effects on individual clinical decision-making. However, we were able to evaluate the effectiveness of the REVISE mECDS by comparing clinical decisions made on simulated cases with the REVISE mECDS tool versus a standard reference tool among attending and resident physicians and found use of the REVISE mECDS tool to be associated with a large, statistically significant increase in adherence (53). We also cannot assume that app usage within a DMA/City was all occurring at one of the REVISE/PIPA sites during a patient assessment. It is quite likely that there is a contagion effect in app downloads, as evidenced by the observed usage of PedsGuide in DMAs without REVISE or PIPA sites. However, despite the unavoidable mismatches in linking measures of geographic aggregate app usage with clinical metrics at REVISE and PIPA sites, we found associations that were both statistically significant and clinically meaningful in both projects. To address the inability to identify app users who are also participants in the national project, future rollouts of mECDS tools through the app will include a registration screen which will have users select their site as applicable before proceeding to the tool itself.

Next, REVISE project guidelines capped case collection from each site at 20 per month. This means that for the larger sites with higher febrile infant volumes, our app usage density measure (metric hits per case) may have been inflated as it really measures metric hits per captured case rather than all cases seen by the site. It is also possible, particularly at teaching hospitals, that the metric screens are being seen by multiple providers as they evaluate one case

together which may bias this measure in the other direction. It is unclear what effect this may have on the association between usage and metric change, but the probability of multiple viewers per one instance of screen display at academic institutions may at least partially be accounted for by our inclusion of site university-affiliation in the model. Finally, we cannot rule out the possibility that increased adherence co-occurring with increased app usage was due simply to increased site engagement in general, but we were able to, at least in part, account for this in the PIPA analysis by including whether sites had implemented other change package elements in the models.

Interestingly, in a sub-analysis of DMAs with only one REVISE site, effects of mECDS tool use during the project use on the three metrics (Figure 2) for which we observed significant findings with the full sample were in the same direction but generally weaker (data not shown). When we followed this up by re-running the full sample analysis with models that included interaction terms to allow for app usage to have different effects for single- and multi-site DMAs, we generally observed stronger effects for multi-site DMAs, including a positive effect of accumulated metric hits per site on the urinalysis metric for multi-site, but not for single-site, DMAs (results not shown). DMAs with only a single site are more likely to have app use occurring at non-site hospitals as less of the DMA's total hospitals are participating which may have weakened the association with DMA-level use among these sites. Multi-site DMAs were disproportionately represented in the Northeast region, accounting for four of its six DMAs (67% as compared with 34% in the overall sample) and 93% of its sites (as compared with 66% sites in the overall sample). Thus, it is possible that regional differences are being reflected in the apparent differences between single- and multi-site DMAs, though with region being included as a model covariate this seems like a partial explanation at best.

Despite harnessing the same human factors methods (heuristic analysis, iterative usability testing) to develop the mECDS tool as in REVISE (4) and widely disseminating it, mECDS tool

uptake and usage was low during PIPA. This may have been due to delays in launching the tool (about 6 months after the launch of the QI intervention) or lack of explicit application of behavior change theory to mECDS implementation(though theory/frameworks were used in design of the overall QI intervention) (3,28). Our team did also conduct a mixed-methods study to better understand barriers to utilization of the QI interventions offered, including the mECDS tool (29). We found a potential barrier was lack of awareness. When asked why they did not use the mECDS tool, participants reported they did not know it was available. The combination of introducing the many QI interventions involved in the project change package (coaching, order-sets, etc.) in a relatively short time frame and then delaying the launch of the mECDS 6 months after introduction, may have contributed to this lack of awareness. The delayed launch also meant we were only able to track data for 6 months after launching the mECDS, so we did not evaluate sustainability of mECDS utilization. However, the eventual roll out of the mECDS tool reached a large, diverse sample of both EDs and inpatient wards from all regions of the country and strengthens the generalizability of our results.

The delay led to the PIPA mECDS tool use to only in the Fall and early Winter. Seasonal differences in disease trends and tool availability could have contributed to differences seen, as asthma cases overall are higher in the Fall and Winter. Also, since many of the sites were teaching hospitals, this could lead to practice differences given the release's correspondence with the beginning of the academic year with a new influx of staff and students. Unfortunately, we only had patient demographics that are correlates of patient severity and no direct measures of clinical severity, so we could not account for differing severity driven by season. However, models were adjusted for both time and teaching status, and we had comparison/control sites gathering outcome data at the same time/season (because of differing usage levels between sites).

Finally, the method of deployment did hinder our ability to detect impact on outcomes beyond the original project timeline. Project chart abstraction at associated sites, unlike use of the

tool, did not continue after project completion. Characteristics of those using the tool were also not able to be assessed as the tool required no registration and thus this information was not available.

Conclusion

Mobile electronic clinical decision support has the potential to overcome barriers to dissemination and improve quality of care and health outcomes across institutions. mECDS deployed via a freely available mobile app has the potential to achieve a sustained impact beyond the original implementation period, such as the QI intervention period in the REVISE and PIPA projects. mECDS tools are increasingly being developed and used in practice. Therefore, it is important that their impact on such practice is evaluated at individual institutions and beyond. To our knowledge this report is the first of its kind to attempt to link clinical practice to mECDS use on a national scale and outside of an EHR. It is also the first to do so in a way that controls for important potential confounders including case-mix differences and concomitant local QI efforts. Despite limitations in directly linking usage and practice data, a clear association between usage of the tool around a site's location and an increase in that site's adherence to national standards in practice was found. Additionally, use of the REVISE tool was found to increase, both temporally and geographically, beyond the original project. Further research is needed to determine the factors driving passive diffusion, whether such reach and uptake levels are replicable, whether this continued use has an impact on clinical practice and patient outcomes, linking clinicians' mECDS usage more directly to their behavior, and studying mECDS's impacts on other pediatric conditions.

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