Improving Head CT Scan Decisions for Pediatric Minor Head Trauma in General Emergency Departments: A Pragmatic Implementation Study

Andrew J. Knighton, PhD, CPA*; Doug Wolfe, MBA; Angelene Hunt, MSN; Allison Neeley, MBA; Neer Shrestha, MS; Steven Hess, BS; James Hellewell, MD, MS; Gregory Snow, PhD; Rajendu Srivastava, MD, MPH; Douglas Nelson, MD; Jeff E. Schunk, MD

*Corresponding Author. E-mail: Andrew.knighton@imail.org.

Study objective: To measure the effectiveness of a multimodal strategy, including simultaneous implementation of a clinical decision support system, to sustain adherence to a clinical pathway for care of children with minor head trauma treated in general emergency departments (EDs).

Methods: Prospective, type III hybrid effectiveness-implementation cohort study with a nonrandomized stepped-wedge design and monthly repeated site measures. The study population included pediatric minor head trauma encounters from July 2018 to December 2020 at 21 urban and rural general ED sites in an integrated health care system. Sites received the intervention in 1 of 2 steps, with each site providing control and intervention observations. Measures included guideline adherence, the computed tomography (CT) scan rate, and 72-hour readmissions with clinically important traumatic brain injury. Analysis was performed using multilevel hierarchical modeling with random intercepts for the site and physician.

Results: During the study, 12,670 pediatric minor head trauma encounters were cared for by 339 clinicians. The implementation of the clinical pathway resulted in higher odds of guideline adherence (adjusted odds ratio 1.12 [95% confidence interval 1.03 to 1.22]) and lower odds of a CT scan (adjusted odds ratio 0.96 [95% confidence interval 0.93 to 0.98]) in intervention versus control months. Absolute risk difference was observed in both guideline adherence (site median: +2.3% improvement) and the CT scan rate (site median: −6.6% reduction). No 72-hour readmissions with confirmed clinically important traumatic brain injury were identified.

Conclusion: Implementation of a minor head trauma clinical pathway using a multimodal approach, including a clinical decision support system, led to sustained improvements in adherence and a modest, yet safe, reduction in CT scans among generally low-risk patients in diverse general EDs. [Ann Emerg Med. 2022;■:1-12.]

Please see page XX for the Editor's Capsule Summary of this article.

0196-0644/$-see front matter

https://doi.org/10.1016/j.annemergmed.2022.04.030

SEE EDITORIAL, P. XX

INTRODUCTION

Background

Pediatric head trauma is a leading cause of emergency department (ED) visits for children, including major and mild traumatic brain injuries (TBIs) or concussions.[1,2] The risk of clinically important TBI (ciTBI) in pediatric patients with minor head trauma is less than 1%, yet, cranial computed tomography (CT) use remains a common practice.[3-9] Although CT scans in high-risk groups are a necessary diagnostic tool, CT scans in the low-risk groups yield little diagnostic benefit and expose children to unnecessary radiation.[10,11] In the United States, most children (69%) seeking emergency care are seen in EDs that see fewer than 15 pediatric patients per day with variable quality of pediatric care.[12-16] Translating evidence-based pediatric ED care to support pediatric readiness in general EDs is a priority of the American Academy of Pediatrics and the American College of Emergency Physicians.[17,18]

Primary Children's Hospital, an Intermountain Healthcare (Intermountain) children's hospital with a pediatric ED staffed by faculty from the University of Utah, was part of the original Pediatric Emergency Care Applied Research Network (PECARN) study that determined the risk stratification criteria for the diagnosis of ciTBI in children with minor head trauma.[19] Primary Children's Hospital subsequently developed clinical pathways for CT scan use based on PECARN study findings and observed improved adherence to the clinical pathway. However, these

Editor's Capsule Summary

What is already known on this topic

Despite available high-quality evidence, head CTs are frequently performed on children with minor blunt head trauma at low risk of clinically important injuries.

What question this study addressed

Does a multi-modal implementation of a clinical pathway that includes computerized decision support achieve sustained reductions in head CT utilization for children with minor blunt head trauma seen in general emergency departments (EDs)?

What this study adds to our knowledge

In this step-wedge implementation study conducted in 21 rural and general EDs, the intervention was associated with an increase in guideline adherence (aOR 1.12, 95% 1.03-1.22) and a decrease in head CT utilization (aOR 0.96, 95% 0.93-0.96).

How is this relevant to clinical practice

Multi-modal implementation strategies that include computerized decision support could improve pathway adherence and reduce head CT utilization in general EDs.

results did not translate to the other 21 Intermountain general EDs. The Intermountain system initially deployed an intranet-based lookup tool, a care pathway, and a mobile flashcard application across general EDs. Access to these tools required clinicians to navigate away from their usual clinical workflow. Unpublished preliminary field readiness assessments conducted with general emergency physicians at Intermountain revealed that emergency physicians perceived the retrieval of guideline information as cumbersome; the risk factors for pediatric TBIs are known, but elements may be misremembered; head CT scanning is expected by families and referring providers; and the CT scan provides significant reassurance to both the physician and family.

Importance

We hypothesized that the introduction of an information-rich alert near the CT scan decision point, coupled with periodic performance feedback, could better support emergency physicians assessing the risk of ciTBI. The alert provides key information, including the PECARN risk stratification criteria, to help clinicians reduce diagnostic uncertainty, improve guideline adherence, and reduce unnecessary CT scans.[20] Implementation studies have used a multimodal strategy including clinical decision support systems, but few have examined this strategy across a diverse range of nonacademic general EDs.[3,21] No prior studies have measured practice sustainment following a postimplementation period.

Goals of This Investigation

The aims of this study were as follows: (1) to measure the effectiveness of a multimodal implementation strategy designed to increase uptake and sustain adherence to a minor head trauma clinical pathway and decrease CT scans among patients with minor head trauma at low risk of ciTBI across general EDs at tertiary, community, and rural sites; and (2) to assess 72-hour readmissions for ciTBIs during both the uptake and sustainment study periods at study sites.

MATERIALS AND METHODS

Study Design and Setting

To evaluate the uptake of evidence-based practice, we conducted a prospective, type III hybrid effectiveness-implementation cohort study using a nonrandomized stepped-wedge implementation with 2 steps and monthly repeated site measures.[22-24] Hybrid effectiveness-implementation studies have a dual focus in assessing clinical effectiveness and implementation. The type III design focuses on the testing of an implementation strategy while assessing its effect on clinical outcomes.[22] The stepped-wedge study design is used to evaluate health service delivery interventions where simultaneous intervention at all sites is not possible, largely given resource constraints.[25] Each site contributes before and after observations, switching from control to intervention-exposed but not at the same time. Sites receiving the intervention at the same time are referred to as steps. The study was approved by the Intermountain Institutional Review Board (#1051764). We adhered to published best practices for reporting of observational studies (Strengthening the Reporting of Observational Studies in Epidemiology) and for presenting the results of multilevel data (Logical Explanations & Visualizations of Estimates in Linear mixed models).[26,27] Study participants and staff, the research team, and the analyst were not blinded to the intervention assignment.

The study was conducted in 21 general ED hospital sites at Intermountain, a not-for-profit, integrated, community-based health care system providing primary and secondary care to adult and pediatric patients in urban, rural, and frontier locations in Utah and surrounding states. The hospitals include tertiary (4), community (10), and rural (7) sites. The general EDs have approximately 400,000 ED visits annually, including 70,000 visits annually for patients less than 18 years of age (19%; general ED site range: 5% to 30%). These EDs have more than 5,400 pediatric minor head trauma encounters annually, representing 0.3% to 2.2% of all general ED encounters by site (5% to 11% with patients with minor head trauma who are less than 18 years of age; Table E1 [available at http://www.annemergmed.com]). Intermountain utilizes a shared electronic health record, Cerner, across all general ED sites.

Selection of Participants

The eligible study population included all pediatric patient encounters (unit of analysis) over a 30-month period from July 2018 to December 2020 who presented with minor head trauma (low, medium, or high risk of ciTBI) at 1 of the 21 general ED sites (unit of assignment). Patients were seen by physicians (MD, DO), certified physician assistants (PA-Cs), or nurse practitioners (hereafter, clinicians) who may treat patients at 1 or more sites. A patient could have more than one encounter during the study period. Patients less than 18 years of age seen at an Intermountain general ED with 1 or more of the following *International Classification of Diseases, Tenth Revision* codes specifically associated with minor head trauma (S01.01XA; S00.03XA; S06.0X0A; S06.9X1A; S06.9X9A; S09.8XXA; S09.90XA) were included, excluding those identified minor head trauma encounters where the ED chief complaint was abdominal pain—usually resulting from a traumatic event where a head injury was not the principal clinical concern (Table E2). We dichotomized age as either children less than 2 or 2 years and older, consistent with the Intermountain minor head trauma clinical pathways.

We identified eligible patient records using an automated search of the institutional data warehouse to identify general ED visits and abstracted patient, physician, and site-level data. Patients who underwent CT scanning were reviewed for PECARN risk factors, abstracted from the ED note. The experienced nurse abstractor (A.H.) received specific training for this study using a standardized data collection form on a preliminary set of patient records before study initiation. Variable definitions and abstraction guidelines were provided before data collection began. The data abstractor was not blinded to the study objective or outcomes. Periodic meetings between the data abstractor and the principal physician investigator (J.E.S.) were held to discuss the missing, conflicting, or ambiguous data or to review ciTBI risk classification on the minor head trauma encounters with a CT scan. There was no chart review of pediatric patients with minor head trauma who did not undergo head CT scanning.

Interventions

The main intervention was the deployment of existing evidence-based pediatric minor head trauma risk stratification criteria through a minor head trauma clinical pathway.[19] The clinical pathway stratification criteria specified that patients in the low-risk group should be observed for signs of ciTBI and not undergo CT scanning. For patients in the medium-risk group, the preferred diagnostic approach is neuromonitoring with CT scanning as the alternative for patients with multiple or worsening symptoms based on clinician judgment. Patients in the high-risk group should undergo CT scanning.

We classified the multimodal implementation strategies consistent with the implementation science literature.[28] An enterprise minor head trauma implementation team, led by 2 study authors (J.E.S. and D.W.), was responsible for systemwide deployment. The enterprise team developed education content and materials and deployed the clinical decision support system. A physician/nurse dyad was identified at each site to lead the local deployment and deliver site-level education. The enterprise team held quarterly reviews to assess the progress and develop remediation plans for low-performing sites.

The clinical decision support system included manual and automated feedback and education. First, the minor head trauma lead at each facility received monthly site-level feedback on performance. Feedback and education were also sent to individual physicians when a CT scan was obtained in a low-risk patient. Second, we embedded an easy-to-understand, information-rich graphic alert providing current PECARN risk stratification criteria and supporting evidence for classifying ciTBI, along with a risk assessment prompt linked to a head CT scan order or an "observation" order (Figure 1). This alert is referred to as the pediatric minor head trauma "pop-up." Within the pop-up, hovering over the underlined text activated expanded text specific to that symptom or note (Figure E1 (available at http://www.annemergmed.com)). The alert was designed to provide decision support ahead of clinical decisionmaking and was activated by specific "reason for visit" using the Cerner Power Note Emergency Department template-based documentation system. Given the goals of this effort to promote habit change in physicians and the nonspecific nature of minor head trauma coding in the reason for the visit, the pop-up

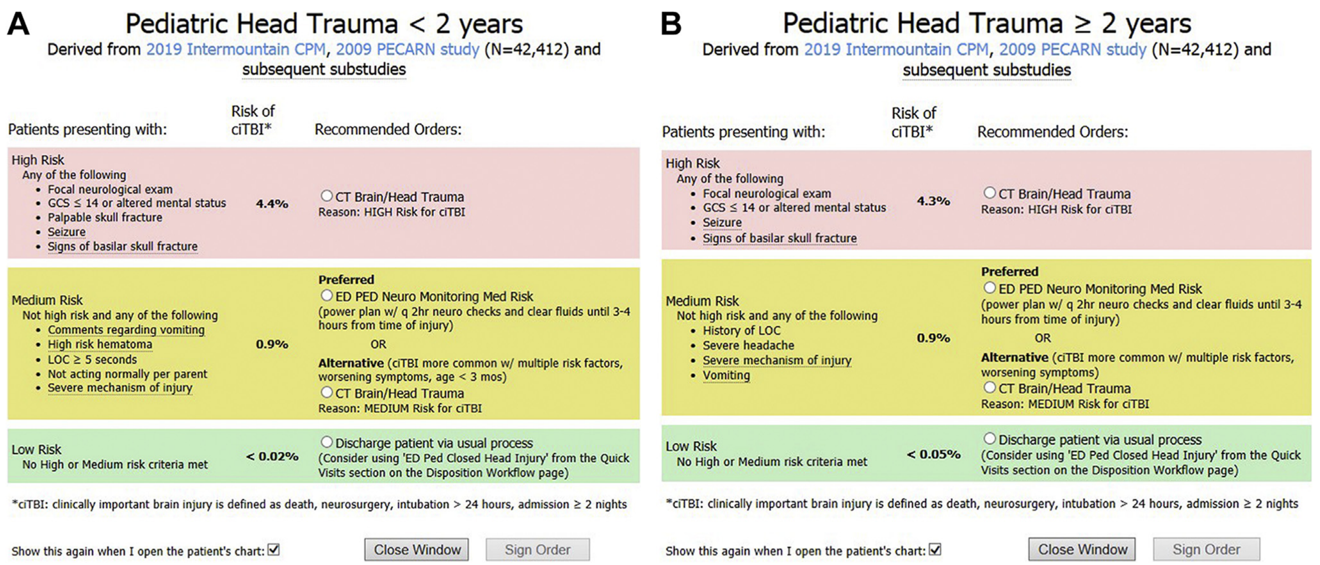

Figure 1. Pediatric head trauma *A,* less than 2 years; *B*, 2 or more years. Derived from 2019 Intermountain CPM, 2019 Pediatric Emergency Care Applied Research Network study (N=42,412) and subsequent substudies. ciTBI, clinically important traumatic brain injury (defined as death, neurosurgery, intubation > 24 hours, admission ≥ 2 nights); *CPM,* care process model; *CT,* computed tomography; *GCS,* Glasgow Coma scale/score; *LOC,* loss of consciousness; *PECARN*, Pediatric Emergency Care Applied Research Network; *PED,* pediatric ED.

automatically appeared when 1 of 4 specific Power Note Emergency Department codes were noted at triage: closed head injury with or without loss of consciousness and TBI with or without loss of consciousness. Reasons for the visit that were very common and would infrequently result in CT scan consideration (eg, scalp laceration or fall) did not activate the alert.

Sites were allocated nonrandomly to 1 of 2 steps based on size, geographic location, and operational readiness aligned with the sequential rollout of the intervention to the sites. Step 1 sites received the complete multimodal implementation intervention simultaneously beginning October 2018. Repeated site measures were taken monthly for the 9-month period at all sites. Beginning in July 2019, the step 2 sites received the complete multimodal implementation intervention. Repeated site measures were again taken monthly for the 9-month period at all sites. At this point in April 2020, all sites had adopted the intervention and contributed both control and intervention data. This also began the sustainment phase, where feedback and education to clinicians were no longer sent. The embedded alert and monthly site-level reporting to site leaders continued to operate at all sites, and physicians could retrieve the pop-up window at any time to review. Repeated site measures were again taken monthly for the 9-month sustainment/limited intervention period at all sites, with measurement completed on December 31, 2020 (Figure 2).

Methods of Measurement and Outcome Measures

Implementation and service outcomes were defined using standards for implementation research.[29] Implementation effectiveness, including the uptake of the intervention, was measured using a categoric (binary) measure of the overall adherence to the minor head trauma clinical pathway. Guideline adherence was defined as not performing a CT scan when the patient was low risk as determined by independent chart review. When a CT scan was performed in medium- or high-risk patients, it was deemed adherent to the guideline. We did not detail or abstract circumstances where an individual presented with medium- or high-risk symptoms and no CT scan was obtained. Clinicians have discretion in the guidelines whether or not to conduct a CT scan for intermediate cases, and, because the widespread overutilization of CT

Study population in each step and study period

Period	1	2	3	4
Period Start Date	7/1/2018	10/1/2018	7/1/2019	4/1/2020
Step 1	349	895	914	728
Step 2	1038	2874	3158	2714

Control
Full Intervention
Limited Intervention/ Sustainment

Figure 2. Study population in each step and study period.

Table 1. Site, physician, and admission characteristics for pediatric patients with minor head trauma.

Characteristics	Control Group Months	Full Intervention Group Months	Sustainment Months
ED site characteristics			
Patient admissions (n)	4,261	4,967	3,442
Site months (n)	234	207	189
Admissions per site month	18.2	24.0	18.2
Level I/II trauma center site encounters (n, %)	1,283 (30.1)	2,582 (51.9)	1,293 (37.6)
ED physician characteristics			
Unique physicians (n, %)*	281 (82.9)	290 (85.5)	273 (80.5)
Encounters per unique physician (mean, median)	15.2 (10)	17.1 (13)	12.6 (10)
ED admission characteristics			
Male (n, %)	2,516 (59.1)	2,992 (60.2)	2,088 (60.7)
<2 (n, %)	842 (19.8)	1,005 (20.2)	684 (19.9)
White (n, %)	3,792 (89.0)	4,266 (85.9)	2,985 (86.7)
Hispanic	718 (16.9)	969 (19.5)	612 (17.8)
Government/uninsured (n, %)	1,459 (34.2)	1,789 (36.0)	1,127 (32.7)
Admit/transfer (n, %)	177 (4.1)	202 (4.1)	230 (6.7)
Outcomes			
Guideline adherence	4,041 (94.8)	4,938 (99.4)	3,403 (98.9)
CT scan performed	1,644 (38.6)	1,478 (29.8)	1,220 (35.4)
Positive CT scan (% CT scans performed)	98 (6.0)	84 (5.7)	114 (9.3)
Positive with ciTBI (% positive CT scans)	9 (9.2)	13 (15.4)	38 (33.3)

ciTBI, Clinically important traumatic brain injury *CT,* computed tomography.
*A total of 339 unique clinicians had at least 1 minor head trauma encounter during the 30-month study period. Sixty-eight percent of clinicians had at least 1 encounter in all 3 study phases; 12% had at least 1 encounter in 2 of 3 phases, and 19% had an encounter in only 1 study phase.

scanning was a concern, we assumed that managing high-risk cases without a CT scan would be rare.

To measure service outcomes, an efficiency outcome was measured using a categoric (binary) measure of the CT scan rate. A safety outcome was measured by reviewing 72-hour readmissions to an ED within the health care system with the evidence of ciTBI. A positive CT scan included the presence of edema, hemorrhages, pneumocephalus, or a depressed skull fracture. Clinically important TBI was defined as any acute traumatic injury resulting in death, need for neurosurgery, intubation for more than 24 hours, and/or admission for head injury for 2 nights or more.[19]

Primary Data Analysis

We analyzed the primary outcomes using a stepped-wedge design and a 3-level, mixed-effects logistic regression model as outlined in Table E3. Because clinicians practice at more than 1 location, to reduce the risk of crossover effects, we nested sites into 14 distinct regions (level 3) for analysis and allowed for random effects due to regions and due to clinicians (level 2) within regions. We chose this approach because a 3-level hierarchical model allowed us to model differences between clinicians and between regions. The inclusion of the random effects provides a better estimate of the primary measures for clinicians and regions serving fewer patients with minor head trauma.

Principal analysis of fixed-effect dependent variables was performed at the patient encounter level. To address secular trends, we used a 2-way interaction effect, including time and treatment, and measured the effect of exposure to the implementation strategies over time (by month). Sustainment period months were compared to control months using a pre-post comparison. Dependent variables included evidence-based patient-level encounter characteristics (Level 1) associated with imaging use in EDs: age (less than 2 years, 2 years or more), race (White, non-White), ethnicity (Hispanic, non-Hispanic), insurance coverage (commercial, government [Medicare, Medicaid], or self-pay/uninsured), and discharge disposition (home, inpatient admission/facility transfer) as a proxy for patient severity.[30-33] To evaluate sustainment, we used a similar nested hierarchical model comparison between the preimplementation and sustainment periods.

Table 2. Univariate analysis by patient encounter characteristic (N=12,670).

Patient Encounter Characteristics	Proportion of Encounters Guideline Adherent %	Proportion of Encounters Guideline Adherent 95% CI	Proportion of Encounters With CT Scan %	Proportion of Encounters With CT Scan 95% CI
Encounter count	97.7%		34.3%	
Sex				
Female	97.7%	97.3-98.1	35.1%	33.8-36.4
Male	97.8%	97.3-98.0	33.7%	32.6-34.8
Age (y)				
<2	99.3%	98.9-99.6	24.0%	22.4-25.7
2-17	97.3%	97.0-97.6	36.8%	35.9-37.8
Race				
White	97.7%	97.4-98.0	34.6%	33.8-35.6
Other	97.8%	96.9-98.4	31.5%	29.2-33.8
Ethnicity				
Hispanic	98.0%	97.4-98.5	28.6%	26.8-30.5
Non-Hispanic	97.7%	97.3-97.9	35.5%	34.6-36.4
Insurance type				
Commercial	97.6%	97.2-97.9	37.8%	36.7-38.8
Government/self-pay	98.0%	97.6-98.4	27.4%	26.3-29.0
ED disposition				
Discharge home	97.7%	97.3-97.9	32.2%	31.3-33.0
Admit/transfer	99.2%	98.0-99.7	75.9%	72.3-79.0

CI, confidence interval.

All statistical analyses were performed using Stata, release 13 (StataCorp LP).

RESULTS

Characteristics of Study Subjects

Patient-level encounter characteristics for both groups are noted in Table 1. During the study period, 12,670 patient encounters (control: 4261; full intervention: 4967; and limited intervention/sustainment: 3442) involved 339 unique clinicians. Table E1 provides site-level characteristics. By design, the information-rich alert was presented to the clinician on 49% of intervention and sustainment encounters to minimize alert fatigue. Univariate analysis (Table 2) revealed that patient age was associated with the odds of guideline adherence. Patient age, race, ethnicity, patient insurance type, and general ED discharge disposition were independently associated with increased or decreased odds of CT scan use.

Main Results

Figure 3 presents unadjusted guideline adherence over time for step 1 and step 2 sites. The unadjusted proportion of guideline-adherent encounters increased from 94.8% in the control months to 99.4% in the full intervention months. Model results for guideline adherence are presented in Table 3**.** Model 0 presents results with random effects and secular trend fixed effects. Model 1 includes additional fixed-effect covariates. Adjusting for patient age and secular trends, the odds of an encounter being guideline-adherent was 1.12 (95% confidence interval [CI] 1.03 to 1.22) or about 10% higher during the intervention months versus the control months. The absolute risk difference in guideline adherence varied by site (median: +2.3%; range: −1.5% reduction to +11.6% improvement in adherence; Table E1). In a pre-post comparison between control and sustainment months, the sustainment months guideline adherence remained significantly above the control months (98.9% versus 94.7%; adjusted odds ratio [aOR] 5.33; 95% CI 3.75 to 7.59).

Figure 4 presents the unadjusted overall CT scan rate in patients with minor head trauma at step 1 and step 2 sites. The unadjusted proportion of encounters with a CT scan decreased from 38.6% in the control month to 29.8% in the full intervention months. Model results for the proportion of encounters with CT scan are presented in Table 4. Model 0 presents results with random effects and

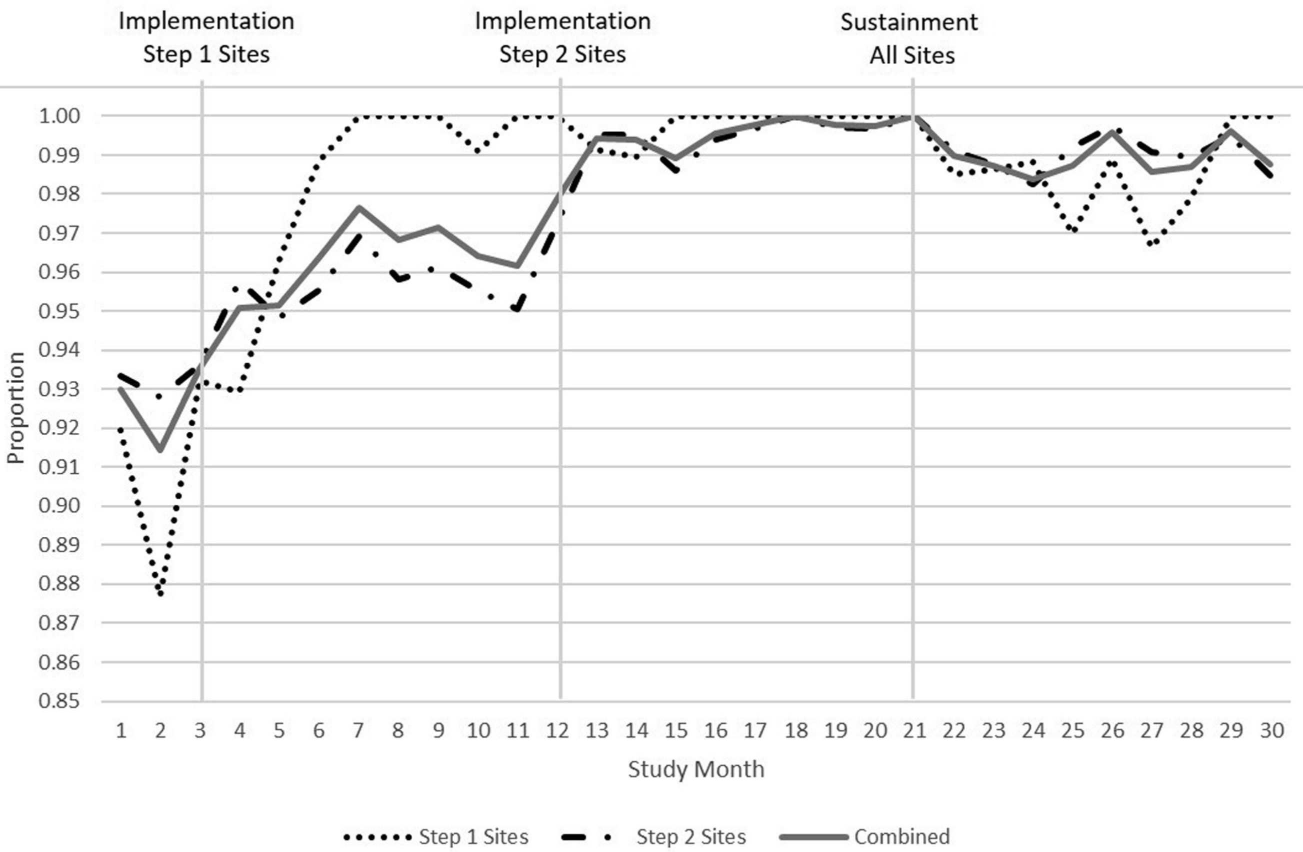

Figure 3. Unadjusted proportion of guideline adherence.

secular trend fixed effects. Model 1 includes additional fixed-effect covariates. Adjusting for covariates, the implementation of the clinical pathway led to a reduction in CT scans (aOR 0.96; 95% CI 0.93 to 0.98) or about 4% lower odds of ordering a CT scan during the intervention months versus the control months. The absolute risk difference in CT scans varied by site (median: −6.6%; range: −28.5% decrease to +12.8% increase; Table E1). In a pre-post comparison of control months with sustainment months, the sustainment months CT scan rate remained significantly below the control months (35.4% versus 38.6%; aOR 0.74; 95% CI 0.67 to 0.82). During all phases of the study, no 72-hour readmissions were identified with a confirmed ciTBI. Combined CT positivity rates increased from 6.0% during the control months to 9.3% during the sustainment months (aOR 1.45; 95% CI 1.00 to 2.08).

LIMITATIONS

The focus of this systemwide pragmatic implementation study was to decrease the use of a low-value imaging study among patients with minor head trauma at low risk of ciTBIs across a health care system with 21 general EDs. Nonrandom assignment may predispose the results to certain biases. The spillover of implementation tactics among sites is another limitation. This was minimized by significant geographic distance between sites and the distinct timing of the rollout of implementation strategies. Although some clinicians practice across multiple sites, this was limited to specific geographic regions with the health care system and addressed in the hierarchical modeling. Finally, any spillover would minimize the differences in the groups.

As cases with minor head trauma were identified using administrative data, some cases could have been missed or misclassified. However, given the standard coding and billing practices across Intermountain, the inclusion of cases with major head trauma or missing minor head trauma patient encounters would be randomly distributed across sites. A total of 18 cases (0.1%) involved level 1 trauma activation, and 430 (3.4%) involved level 2 trauma activation. A post hoc analysis removing these cases from the hierarchical analysis did not change the statistical conclusions.

This study did not specifically seek to uncover the physician rationale for either obtaining a CT scan or not or

Table 3. Results of 3-level mixed-effects logistic regression model measuring postimplementation change in the proportion of guideline-adherent encounters.

Models	Model 0 (N=9,228)	Model 1 (N=9,228)
Random effects (constant)*	**Variance (95% CI)**	**Variance (95% CI)**
Level 3-region	0.15 (0.04-0.69)	0.15 (0.04-0.67)
Level 2-physician	0.34 (0.16-0.74)	0.30 (0.13-0.70)
Residual intraclass correlation†		
Region	0.04 (0.01-0.16)	0.04 (0.01-0.16)
Physician in region	0.12 (0.07-0.23)	0.12 (0.06-0.22)
Level 1-encounter fixed effects	**Adjusted OR (95% CI)**	**Adjusted OR (95% CI)**
Secular trends/interaction		
Treatment	1.30 (0.48-3.52)	1.25 (0.46-3.43)
Month	1.08 (1.04-1.12)	1.08 (1.03-1.12)
Treatment/time	1.12 (1.03-1.22)	1.12 (1.03-1.22)
Age (y) (ref <2 y)		
2-17	N/A	0.16 (0.09-0.31)
Aikeke Information Criterion‡	2,026	1,974

N/A, not applicable; *OR,* odds ratio.
*The model random effects reflect variation that results from unobserved characteristics across regions and physicians nested within regions. Adjusting for unobserved characteristics associated with these random effects can eliminate some potential confounding in results.
†The residual intraclass correlation reflects the proportion of the variance in guideline adherence accounted for by the clustering by region or by physicians within regions. These effects appear modest in explaining the total variation in guideline adherence.
‡The reduction in the Aikeke Information Criterion when comparing model 0 and model 1 suggests that the addition of the fixed-effect covariate age contributes to improvements in the relative quality of the statistical model.

whether the clinical application of the risk category of low, medium, or high was correct. Similar to other stepped-wedge design studies, we did not conduct a power calculation a priori. The abstraction of the PECARN risk factors from the ED physician notes within the patient record was performed by a single unblinded nurse abstractor, possibly introducing bias and misclassification of cases with minor head trauma. To mitigate this, we conducted training and quality reviews, and all low-risk patient encounters for which a CT scan was ordered prompted an email to the ordering ED physician, creating an opportunity to clarify the reason. The number of encounters identified as misclassified through this process was very small. We did not examine the failure to order a CT scan in high-risk cases. We examined readmitted patients within 72 hours consistent with other studies but recognized that, rarely, serious head injury may present up to a week later. We may have also missed pediatric patients cared for during follow-up in other health care systems during the readmission window. However, most pediatric patients in Utah are cared for within a single health care system.

DISCUSSION

An information-rich text alert for risk classification of pediatric patients with minor head trauma as part of a systemwide clinical decision support system increased guideline adherence for CT scanning in children at low risk of ciTBI presenting to general EDs in a situation where historical broad dissemination strategies alone were not sufficient to change behavior. Improvements in guideline adherence were associated with a significant reduction in CT scan rates among a lower-risk population without increasing subsequent 72-hour readmissions for a ciTBI. Guideline adherence remained above and CT scan usage rate remained below the control group levels during the sustainment phase. The association between the use of implementation strategies and primary outcomes was strengthened through the stepped-wedge study design with an untreated control group and repeated measures accounting for secular trends. The use of a 3-level hierarchical model also adjusted for the random effects associated with clinician and site characteristics. The study was conducted at a single integrated health care delivery system using the same technologies and implementation strategies at each site, providing the strongest form of replication.[34]

Our overall results demonstrated a reduction in CT scan use, consistent with studies that found modest reductions in CT use following the implementation of a clinical decision support tool without increasing the risk of 72-hour

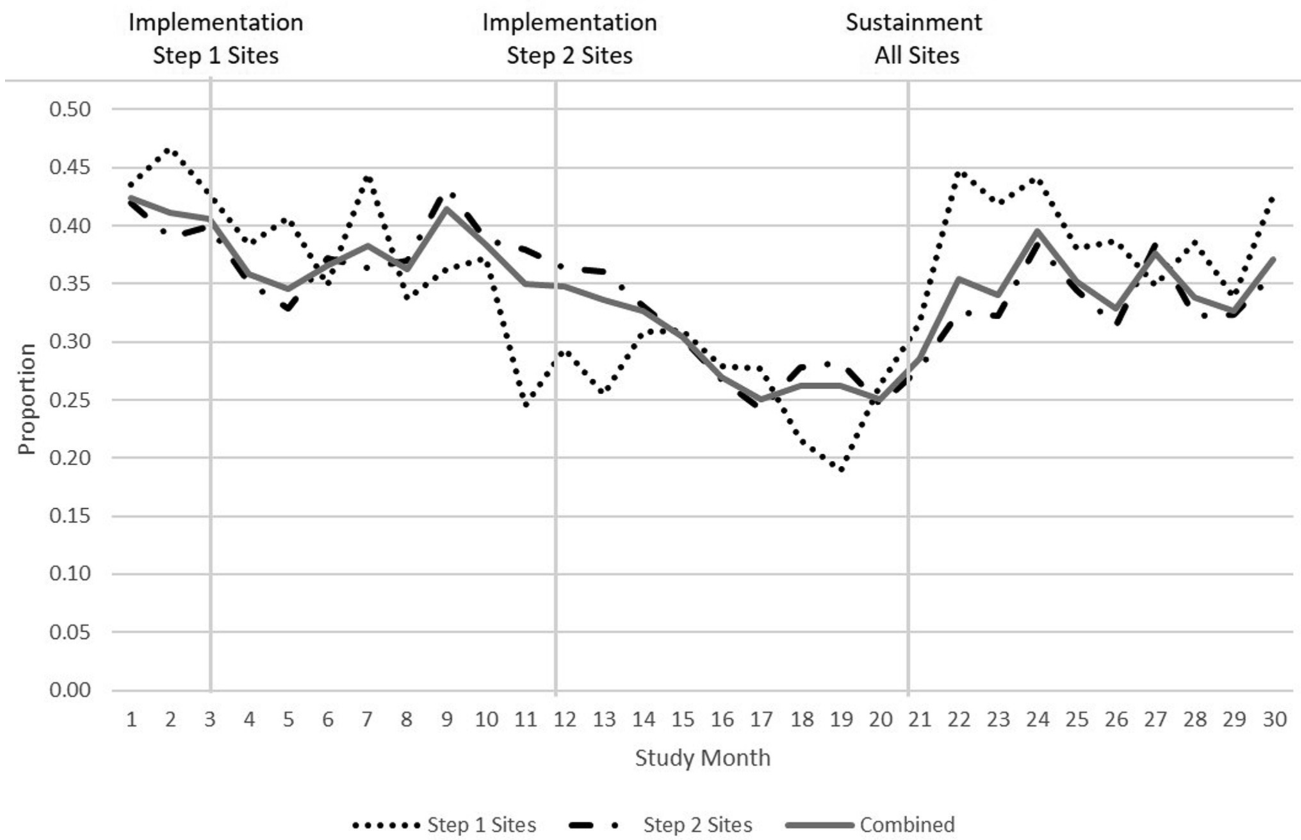

Figure 4. Unadjusted computed tomography scan rate. The sustainment period coincided with COVID-19 outbreak in 2020. Fewer people sought care during the COVID-19 pandemic, but when they did, it was for a more serious presentation (eg, persistence of symptoms or number of vomiting episodes).

readmission for ciTBIs in pediatric EDs. Nigrovic et al[35] noted a 6% absolute reduction in CT use for children with minor head trauma following guideline implementation at an academic pediatric level I urban trauma care center, whereas Atabaki et al[36] found a 7.9% absolute reduction in CT scan utilization rates (26.8% to 18.9%) in 2 pediatric EDs. In 3 other studies, there were absolute reductions: less than 5% or mixed results based on patient age or other confounding factors, including nonsignificant reductions in a single nonrandomized multicenter clinical trial and subsequent secondary analysis involving general EDs (4 intervention and 4 control general EDs).[3,21,37] This suggests that the deimplementation of conventional and established diagnostic practices, such as ordering CT scan for children with minor head trauma (but at very low risk for ciTBI), may require strategies that differ from traditional educational approaches or mere distribution of a clinical pathway. Decision support that occurs at the moment of the patient encounter should help physicians assess a patient's risk of ciTBI; properly identifying the most relevant diagnostic information could decrease diagnostic uncertainty and the associated cognitive burden.[38,39] The mean CT scan rate in this study during the control months (average: 38%; range: 19% to 62%; Table E1) was higher than those in these other studies, which generally ranged from 20% to 25%.[3,31,35-37] This higher rate and considerable variability across sites illustrate, among other things, a lack of unification of general ED practice across the Intermountain system, which includes a mix of both employed and multiple affiliated provider groups.

Risk stratification in emergency medicine is sometimes mitigated through scoring systems (eg, the pediatric appendicitis score) or by identifying high-risk criteria that lead to diagnostic study (eg, cervical spine injury, head injury). We suspect that clinicians may be less likely to stop a diagnostic practice that provides themselves and the family reassurance. Our study demonstrates that a bundled implementation strategy including the use of a periodic information-rich text alert provides a method for updating physicians on changes in evidence-based risk classification

Table 4. Results of 3-level mixed-effects logistic regression model measuring postimplementation change in the proportion of encounters with CT scan.

Models	Model 0 (N=9,228)	Model 1 (N=9,228)
Random effects (constant)*	**Variance (SE) (95% CI)**	**Variance (SE) (95% CI)**
Level 3-region	0.22 (0.13-0.37)	0.17 (0.09-0.32)
Level 2-physician	0.25 (0.19-0.34)	0.26 (0.20-0.32)
Residual intraclass correlation†		
Region	0.06 (0.04-0.09)	0.05 (0.02-0.08)
Physician in region	0.13 (0.10-0.16)	0.12 (0.09-0.15)
Level 1-encounter fixed effects	**Adjusted OR (95% CI)**	**Adjusted OR (95% CI)**
Secular trends/interaction		
Treatment	1.19 (0.89-1.58)	1.36 (1.01-1.82)
Month	0.99 (0.97-1.01)	0.99 (0.97-1.01)
Treatment/time	0.97 (0.94-0.99)	0.96 (0.93-0.98)
Sex		
Male	-	0.92 (0.84-1.01)
Age (y): [ref <2 y]		
2-17	-	1.88 (1.65-2.13)
Ethnicity: [ref: not Hispanic]		
Hispanic	-	0.85 (0.75-0.97)
Insurance type: [ref: commercial]		
Government	-	0.74 (0.67-0.83)
Disposition: [ref: discharge home]		
Hospital admit/transfer	-	9.75 (7.5-12.8)
Aikeke Information Criterion‡	11,288	10,767

OR, odds ratio; *SE,* standard error.
*The model random effects reflect variation that results from unobserved characteristics across regions and physicians nested within regions. Adjusting for unobserved characteristics associated with these random effects can eliminate some potential confounding in results.
†The residual intraclass correlation reflects the proportion of the variance in CT scan use accounted for by the clustering by region or by physicians within regions. These effects appear modest in explaining the total variation in CT scan use.
‡The reduction in the Aikeke Information Criterion when comparing model 0 and model 1 suggests that the addition of the fixed-effect covariates contribute to improvements in the relative quality of the statistical model.

criteria to facilitate the deimplementation of legacy clinical practices.

We attempted to deploy the information-rich text alert to optimize its effect as an education tool for general ED clinicians while minimizing the risk of false positive alerts. As a result, the alert was only evoked in about half the eligible encounters. Alert fatigue is a source of frustration for health care providers and decreases overall attention paid to alerts. Rather than viewing alert effectiveness as a transaction-level event to prompt immediate behavior change with each transaction, the information-rich graphic was meant to provide periodic education on risk classification criteria for minor head trauma. This study demonstrates that improved adherence can be achieved with less frequent alerts designed to augment traditional education/performance feedback implementation strategies. As the understanding and application of the clinical pathway is now largely routinized and clinician habits have developed across general EDs, we anticipate reducing alert frequency in favor of a clinician-initiated information retrieval strategy.

The COVID-19 pandemic with an associated marked decrease in ED volumes may have affected both guideline adherence and CT scan rates during the sustainment phase of this study. The effect of this ED volume change on our results is not fully understood. Although guideline adherence decreased during the sustainment period from the full intervention phase, it does not fully explain the increase in the CT scan rate during the same timeframe. Consistent with trends in general ED encounter volumes during the COVID-19 pandemic, Intermountain saw a 15.4% year-over-year reduction in patients presenting to

EDs with minor head trauma during the study sustainment period from April 2020 to December 2020. This minor head trauma volume reduction may be explained by statewide lockdown that lowered the underlying incidence of events associated with minor head trauma injuries (eg, school events, sports, motor vehicle travel). Concerns about exposure to infection may have reduced the number of people seeking health care following head trauma. Given these barriers to care, when care was sought, it was likely for more serious clinical presentations (eg, continued headache, multiple episodes of vomiting). This may be reflected in the unexpected increase in the CT scan rate from 30% to 35% from the full intervention to the sustainment period, the increase in the positivity rate in CT scans from 5.7% to 9.3%, and the number of positive CT scans including a ciTBI (from 13 to 38) as the average mixture of patients utilizing the ED shifted to more seriously injured patients. Guideline adherence for low-risk pediatric patients with minor head trauma remained very high during the sustainment phase (98.9%), suggesting that the implementation strategies were successful in sustaining the reduced use of CT in the lowest-risk patients.

Our study extends previous research by illustrating the success of a multimodal implementation strategy, including a clinical decision support system displaying minor head trauma education/risk stratification presented to the clinician during some minor head trauma visits, across a mixture of general EDs in tertiary, community, and rural hospital settings. This is particularly important given that most pediatric ED care in the United States is delivered in general ED settings. Similar strategies may successfully translate other evidence-based pediatric ED care to support pediatric readiness and management in general EDs.

The authors acknowledge the frontline clinical teams who work tirelessly to treat the patients and acknowledge the contributions of Jordan Albritton, PhD to the study design.

Supervising editor: Lise E. Nigrovic, MD, MPH. Specific detailed information about possible conflict of interest for individual editors is available at https://www.annemergmed.com/editors.

Author affiliations: From Intermountain Healthcare (Knighton, Wolfe, Hunt, Neeley, Shrestha, Hess, Hellewell, Snow, Srivastava, Nelson), Salt Lake City, UT; and the University of Utah School of Medicine (Srivastava, Nelson, Schunk), Salt Lake City, UT.

Author contributions: JES, AJK, RS, and DW conceived and designed the study and obtained internal funding. DN, JH, NS, and SH supervised technology intervention development and deployment. JES, DW, and AH supervised the conduct of the study and undertook recruitment of participating sites and data collection. AN managed the data, including data quality control. AJK and GS provided statistical advice on study design and analyzed the data. AJK drafted the manuscript, and all authors contributed substantially to its revision and approved the final submission. JES takes final responsibility for the paper as a whole.

All authors attest to meeting the four ICMJE.org authorship criteria: (1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (2) Drafting the work or revising it critically for important intellectual content; AND (3) Final approval of the version to be published; AND (4) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Funding and support: By *Annals* policy, all authors are required to disclose any and all commercial, financial, and other relationships in any way related to the subject of this article as per ICMJE conflict of interest guidelines (see www.icmje.org). Dr Knighton holds shares in a large publicly traded health care organization, recently completed work as a venous thromboembolism guideline development methodologist for the American College of Chest Physicians, and received additional support from the National Center for Advancing Translational Sciences of the National Institutes of Health (KL2TR002539). The funding body was not involved in the study and collection, analysis or interpretation of the data, or in writing the manuscript. Dr Srivastava is a physician founder of the IPASS Patient Safety Institute and his equity is owned by his employer, Intermountain Healthcare.

Funding and support: Funding for this research was provided by the operating funds of Intermountain Healthcare.

Publication dates: Received for publication November 8, 2021. Revisions received March 22, 2022, and April 13, 2022. Accepted for publication April 22, 2022.

Preliminary results presented at the Academy Health Annual Meeting, June 15, 2021 (Virtual).

REFERENCES

1. Report to Congress on mild traumatic brain injury in the United States: steps to prevent a serious public health problem. Centers for Disease Control and Prevention. Accessed October 1, 2021. cdc.gov/traumaticbraininjury/pdf/mtbireport-a.pdf
2. Faul M, Xu L, Wald MM, et al. Traumatic brain injury in the United States: emergency department visits, hospitalizations and deaths 2002-2006. Centers for Disease Control and Prevention. Accessed October 1, 2021. https://www.cdc.gov/traumaticbraininjury/pdf/blue_book.pdf
3. Dayan PS, Ballard DW, Tham E, et al. Use of traumatic brain injury prediction rules with clinical decision support. *Pediatrics*. 2017;139:e20162709.
4. Osmond MH, Klassen TP, Wells GA, et al. CATCH: a clinical decision rule for the use of computed tomography in children with minor head injury. *CMAJ*. 2010;182:341-348.
5. Lee S, Grant GA, Fisher PG, et al. R-SCAN: imaging for pediatric minor head trauma. *J Am Coll Radiol*. 2017;14:294-297.
6. Schunk JE, Rodgerson JD, Woodward GA. The utility of head computed tomographic scanning in pediatric patients with normal neurologic examination in the emergency department. *Pediatr Emerg Care*. 1996;12:160-165.

7. Dewan MC, Mummareddy N, Wellons JC, et al. Epidemiology of global pediatric traumatic brain injury: qualitative review. *World Neurosurg*. 2016;91:497-509.e1.
8. Burstein B, Upton JEM, Terra HF, et al. Use of CT for head trauma: 2007-2015. *Pediatrics*. 2018;142:e20180814.
9. Quayle KS, Powell EC, Mahajan P, et al. Epidemiology of blunt head trauma in children in U.S. emergency departments. *N Engl J Med*. 2014;371:1945-1947.
10. Miglioretti DL, Johnson E, Williams A, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr*. 2013;167:700-707.
11. Armao D, Smith JK. The health risks of ionizing radiation from computed tomography. *N C Med J*. 2014;75:126,128-131.
12. Gausche-Hill M, Ely M, Schmuhl P, et al. A national assessment of pediatric readiness of emergency departments. *JAMA Pediatr*. 2015;169:527-534.
13. Remick K, Gausche-Hill M, Joseph MM, et al. Pediatric readiness in the emergency department. *Pediatrics*. 2018;142:e20182459.
14. Shaw KN, Ruddy RM, Olsen CS, et al. Pediatric patient safety in emergency departments: unit characteristics and staff perceptions. *Pediatrics*. 2009;124:485-493.
15. Institute of Medicine, Board on Health Care Services. Committee on the Future of Emergency Care in the United States Health System. *Emergency Care for Children: Growing Pains*. The National Academies Press; 2006.
16. Stanley RM, Hoyle JD, Dayan PS, et al. Emergency department practice variation in computed tomography use for children with minor blunt head trauma. *J Pediatr*. 2014;165:1201-1206.e2.
17. American Academy of Pediatrics, Committee on Pediatric Emergency Medicine, American College of Emergency Physicians, et al. Joint policy statement—guidelines for care of children in the emergency department. *Pediatrics*. 2009;124:1233-1243.
18. Owusu-Ansah S, Moore B, Shah MI, et al. Pediatric readiness in emergency medical services systems. *Pediatrics*. 2020;145:e20193308.
19. Kuppermann N, Holmes JF, Dayan PS, et al. Identification of children at very low risk of clinically-important brain injuries after head trauma: a prospective cohort study. *Lancet*. 2009;374:1160-1170.
20. Bhise V, Rajan SS, Sittig DF, et al. Defining and measuring diagnostic uncertainty in medicine: a systematic review. *J Gen Intern Med*. 2018;33:103-115.
21. Ballard DW, Kuppermann N, Vinson DR, et al. Implementation of a clinical decision support system for children with minor blunt head trauma who are at nonnegligible risk for traumatic brain injuries. *Ann Emerg Med*. 2019;73:440-451.
22. Curran GM, Bauer M, Mittman B, et al. Effectiveness-implementation hybrid designs: combining elements of clinical effectiveness and implementation research to enhance public health impact. *Med Care*. 2012;50:217-226.
23. Harris AD, McGregor JC, Perencevich EN, et al. The use and interpretation of quasi-experimental studies in medical informatics. *J Am Med Inform Assoc*. 2006;13:16-23.
24. Shadish WR, Cook TD, Campbell DT. *Experiemental and Quasi-Experimental Designs for Generalized Causal Inference*. Houghton Mullfin; 2002.
25. Hemming K, Haines TP, Chilton PJ, et al. The stepped wedge cluster randomised trial: rationale, design, analysis, and reporting. *BMJ*. 2015;350:h391.
26. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet*. 2007;370:1453-1457.
27. Monsalves MJ, Bangdiwala AS, Thabane A, et al. LEVEL (Logical Explanations & Visualizations of Estimates in Linear mixed models): recommendations for reporting multilevel data and analyses. *BMC Med Res Methodol*. 2020;20:3.
28. Proctor EK, Powell BJ, McMillen JC. Implementation strategies: recommendations for specifying and reporting. *Implement Sci*. 2013;8:139.
29. Proctor E, Silmere H, Raghavan R, et al. Outcomes for implementation research: conceptual distinctions, measurement challenges, and research agenda. *Adm Policy Ment Health*. 2011;38:65-76.
30. Mannix R, Meehan WP, Monuteaux MC, et al. Computed tomography for minor head injury: variation and trends in major United States pediatric emergency departments. *J Pediatr*. 2012;160:136-139.e1.
31. Moser JW, Applegate KE. Imaging and insurance: do the uninsured get less imaging in emergency departments? *J Am Coll Radiol*. 2012;9:50-57.
32. Valtchinov VI, Ip IK, Khorasani R, et al. Use of imaging in the emergency department: do individual physicians contribute to variation? *AJR Am J Roentgenol*. 2019;213:637-643.
33. Marin JR, Weaver MD, Barnato AE, et al. Variation in emergency department head computed tomography use for pediatric head trauma. *Acad Emerg Med*. 2014;21:987-995.
34. Coiera E, Ammenwerth E, Georgiou A, et al. Does health informatics have a replication crisis? *J Am Med Inform Assoc*. 2018;25:963-968.
35. Nigrovic LE, Stack AM, Mannix RC, et al. Quality improvement effort to reduce cranial CTs for children with minor blunt head trauma. *Pediatrics*. 2015;136:e227-e233.
36. Atabaki SM, Jacobs BR, Brown KM, et al. Quality improvement in pediatric head trauma with PECARN rules implementation as computerized decision support. *Pediatr Qual Saf*. 2017;2:e019.
37. Sawaya RD, Wakil C, Wazir A, et al. Does implementation of the PECARN rules for minor head trauma improve patient-centered outcomes in a lower resource emergency department: a retrospective cohort study. *BMC Pediatr*. 2020;20:439.
38. Cabana MD, Rand CS, Powe NR, et al. Why don't physicians follow clinical practice guidelines? A framework for improvement. *JAMA*. 1999;282:1458-1465.
39. Grol R. Personal paper. Beliefs and evidence in changing clinical practice. *BMJ*. 1997;315:418-421.