BACKGROUND AND OBJECTIVE: Acute compartment syndrome (ACS) is a rare but serious complication of extremity injury that can cause permanent damage or death. ACS development is variable and unpredictable, and delay in recognition or treatment of ACS can lead to significant morbidity. Our objective was to create a reliable system for recognition of patients at risk and monitoring for ACS that could withstand frequent provider turnover.

METHODS: Using the Model for Improvement, we identified key drivers and failure modes for 2 processes: resident and nurse practitioner proper order entry and bedside nurse proper documentation of monitoring. Interventions were tested in frequent plan–do–study–act cycles. Effective interventions were used in combination to test for sustainability.

RESULTS: Proper order entry increased from 23% at baseline to 90%. Proper documentation for patients with correct orders increased from 15% to 70%. Individual interventions, including pocket card distribution, electronic medical record order set, and direct discussion by team leaders, were associated with improvement among residents but were not sustained with team turnover. Incorporating all 4 individual interventions into the on-boarding process for residents produced consistent success. Nursing documentation improved with education and maintenance of proper order entry.

CONCLUSIONS: We built a reliable, sustainable system to recognize and monitor patients at risk for ACS. Interventions designed to minimally disrupt existing workflows were individually associated with improvement. We achieved sustainability through staff turnover when we incorporated the interventions into routine orientation for new staff. Hospitals can use existing orders and protocols to sustain surveillance for ACS and other acute conditions. Pediatrics 2013;132:e1672–e1679

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ABBREVIATIONS ACS—acute compartment syndrome EMR—electronic medical record NP—nurse practitioner

Dr Schaffzin conceptualized and designed the project and measures, designed and executed interventions, reviewed and interpreted data, and drafted the initial manuscript and subsequent revisions; Ms Prichard conceptualized and designed the project and measures, designed and executed interventions, collected, reviewed, and interpreted data, and contributed to revision of the manuscript; Ms Bisig designed and executed interventions, reviewed and interpreted data, and contributed to initial and subsequent revisions; Ms Gainor designed and executed interventions, collected, reviewed, and interpreted data, and contributed to manuscript revision; Ms Wolfe and Dr Solan designed and executed interventions, reviewed and interpreted data, and contributed to initial drafting and revision of the manuscript; Ms Gainor designed and executed interventions, collected, reviewed, and interpreted data, and contributed to manuscript revision; Ms Webster designed the project and measures, designed interventions, reviewed and interpreted data, and contributed to revision of the manuscript; Dr McCarthy conceptualized the project, designed and executed interventions, reviewed and interpreted data, and contributed to initial drafting and revision of the manuscript; Ms Webster designed the project and measures, designed interventions, reviewed and interpreted data, and contributed to revision of the manuscript; and all authors approved the final manuscript as submitted.

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Acute compartment syndrome (ACS) is a rare but serious complication of patients with extremity injuries, specifically fractures.1-5 ACS development is variable and unpredictable, and delay in recognition or treatment of ACS can lead to significant disability including vascular compromise, tissue and muscle necrosis, limb loss, neurologic deficits, or death.1-9 The true incidence of ACS in children is uncertain. Currently evidence-based guidelines for screening in the pediatric population do not exist. Although a clinical pathway and an assessment tool have been developed, neither has been tested on a large scale.6,10 Traditional teaching describes the “5 Ps” (pain, paresthesias, pulselessness, pallor, and paralysis) as the common presenting symptoms indicating the development of ACS. However, the literature suggests that these symptoms are unreliable and often late findings, especially in children, where it is often more difficult to achieve cooperation and communication for accurate assessment.1,3,4,6,10

After a serious safety event involving a failure to diagnose ACS at our institution, we identified a lack of awareness about ACS among physicians and nurses and inconsistency with orders and monitoring of patients at greatest risk for developing ACS. This was thought to result in part from a high proportion of orthopedic surgery residents (who are the primary hospital providers for these patients) based at other institutions who rotate at our hospital. Maintaining a consistent approach to ACS is challenging because these residents change every few weeks or months. To counter these potential problems, we sought to standardize management of pediatric patients at greatest risk for ACS.

The aims of this study were to increase the percentage of correctly ordered neurovascular assessments for patients at risk for ACS from 23% to 90% and increase the percentage of correctly documented neurovascular assessments for patients at risk for ACS with proper orders from 15% to 95% within 11 months.

METHODS

Setting

Cincinnati Children’s Hospital Medical Center is a large free-standing academic pediatric facility in the midwestern United States with ~518 licensed inpatient beds. The orthopedic surgery service performed 2537 surgeries and admitted 603 patients during fiscal year 2011. During the study period, operative and inpatient care was provided by 13 attending surgeons, 44 residents, and 2 nurse practitioners (NPs). All inpatient and outpatient documentation and order entry are completed through an electronic medical record (EMR) system. Our project took place on a 27-bed medical–surgical nursing unit where most orthopedic patients are typically admitted. Multidisciplinary care of the patients on this unit involves bedside nurses and orthopedic residents and NPs, the latter of whom are supervised by pediatric orthopedic attending physicians. The resident team is composed of visiting orthopedic residents who rotate for 1- to 6-month periods covering the emergency department, operating room, inpatient units, outpatient clinics, and patient phone calls. During the project, rotating residents changed frequently in a staggered fashion, such that at least 1 member of the team changed every 2 to 6 weeks.

Planning the Intervention

A multidisciplinary improvement team led by a bedside nurse included 3 additional bedside nurses and a nursing-trained care coordinator, an orthopedic NP, and a hospital medicine fellow. The team was co-coached by the unit nursing director and a pediatric surgical hospitalist attending. The team used the Rapid Cycle Improvement Collaborative method, consisting of 7 group learning sessions over 4 months, with didactic presentations and structured group activities.11 The Model for Improvement was used, including process mapping, failure mode analysis, and key driver identification.12 Interventions were tested through a series of plan–do–study–act cycles.12 The process map, failure mode analysis, and key driver diagram were updated periodically at team meetings to incorporate learning from observations, feedback, and testing and to guide future work.

Operational Definitions

A patient at risk for ACS was defined as any patient with at least 1 of the following: tibia/fibula or supracondylar fracture, 2 fractures in 1 extremity, or forearm fracture with rods or reduction.1,3,4,12 Patients with other types of fractures and those admitted with the diagnosis of compartment syndrome were excluded. A correctly ordered neurovascular assessment was defined as an order for neurovascular assessment every 2 hours for an at-risk patient.14,15 A correctly documented neurovascular assessment was defined as a neurovascular assessment documented in the EMR every 2 hours for at-risk patients with correctly ordered neurovascular assessments (Supplemental Fig 5).

Improvement Activities

Given the rotating orthopedic surgery residents’ role in the diagnosis and management of ACS and the bedside nurses’ vital role in early identification of ACS, both groups were targeted as the intervention champions. Our smart aims were to increase the percentage of correctly ordered neurovascular assessments for patients at risk for ACS from 23% to 95% and increase the percentage of correctly documented neurovascular assessments for patients at risk for ACS with proper orders from...
15% to 95% within 11 months. Goals were set based on an expectation of $10^{-1}$ performance initially and revised to $10^{-2}$ performance ($\leq 5$ errors per 100 opportunities) as we incorporated more sophisticated failure prevention and basic failure identification and mitigation. Key drivers for proper resident order entry included consistent awareness of ACS, clear roles and responsibilities, and timely education, orientation, recognition of at-risk patients, and order entry; those for proper bedside nurse monitoring included consistent awareness of ACS, clear roles and responsibilities, nursing staff buy-in, timely recognition of at-risk patients, and accurate order entry and understanding of orders (Fig 1). We sought to increase early recognition of ACS in our pediatric patients through the following interventions: enhanced education to heighten awareness, identification and mitigation of failures, and standardization of computerized order entry.

**Education**

Orthopedic residents received a formal slide presentation as part of their lecture series from the division chair on ACS, including the monitoring project. Team members conducted frequent in-person reminders when discussing a patient or during a handoff by reviewing at-risk patient management. Additionally, as residents began their Cincinnati Children’s Hospital Medical Center rotation, the orthopedic NPs included instruction on the project and expected management of at-risk patients in their orientation slide presentation. The information included in these slides was similar to that on the reminder cards (Fig 2). Unit bedside nurses received informal education during multiple

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**FIGURE 1**

Key driver diagrams for (A) resident order entry and (B) nurse documentation.
unit morning huddles. At the outset, the division chair discussed the background, importance, and goals of the project. Later, directed conversations were initiated by charge nurses and team members to remind bedside nurses of the list of at-risk patients and the need to perform and document neurovascular checks every 2 hours. Additionally, charge nurses incorporated a similar conversation into routine bedside rounding (at least every 4 hours, charge nurses check in with all bedside nurses to discuss patient status and current and anticipated concerns and needs) for nurses caring for at-risk patients.

**Identification and Mitigation of Failures**

Resident order entry and bedside nurse monitoring failures were identified by chart review, typically within 24 hours. When a resident failure was identified, orthopedic NPs conducted one-on-one discussions with residents to make them aware and have them correct the orders. When a bedside nurse failure was identified, the nurse currently caring for the patient was notified, and proper monitoring was verified. Additionally, a team member contacted the bedside nurse responsible for the failure (typically not the current nurse) to notify him or her and review proper neurovascular assessment documentation.

![Compartment Syndrome In Epic](image)

**Compartment Syndrome Identification**

- **Patients at Risk**
  - Tib/Fib fractures
  - Supracondylar fractures
  - If patient is at risk for compartment syndrome DO NOT use valium
- **Questions/Issues?**
  - Ask Tiffanie or Krista

**Identification and Mitigation of Failures**

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![Compartment Syndrome Identification](image)

**FIGURE 2**

Pocket reminder cards distributed to orthopedic residents: A, front; B, back. ASAP, as soon as possible; Pre-Op, preoperative; Tib/Fib, tibia/fibula.
Reminders
Flyers targeting bedside nurses were posted throughout the unit (including in the bathroom, in the break room, in charting areas, and by the time clock) on 2 occasions. The first flyer contained the list of patients at risk for ACS and described the residents’ and the nurses’ role in screening for ACS. The second flyer contained a fun, catchy slogan (RUQ2) to remind nurses to assess and document neurovascular checks every 2 hours for at-risk patients. Each flyer was posted for 4 weeks and then removed to avoid message burnout. Resident pocket cards were developed that contained the list of at-risk patients, how to access and select the proper orders to be placed, and what actions to take if a patient was thought to be developing ACS (Fig 2).

Leveraging the EMR With Standardized Order Entry
Before project initiation, an admission order set existed in the EMR that residents used for all routine admissions. For proper ACS screening, residents needed to choose multiple orders in different areas of the order set. With the help of our institution’s Department of Information Systems, orders were consolidated into a single click, a list of at-risk patients was added, and a choice of neurovascular checks (at-risk versus routine patient monitoring) were required to increase reliability. The EMR was later modified to designate the choice of enhanced assessments with capital letters and red color (Fig 2A).

Data Collection and Analysis
All data were collected retrospectively from the EMR. Baseline data were collected for 16 weeks before project initiation in February 2011. Outcome measures included proper order entry for at-risk patients and proper documentation of monitoring of patients for whom orders were written. Two process control charts were maintained to assess the effect of interventions over time. The first documented orthopedic resident adherence to proper order entry for at-risk patients, defined as selection of the ACS orders for increased screening frequency. The second documented nurse execution of the order, defined as documentation of neurovascular checks every 2 hours for patients with proper orders during each nursing shift. Data were collected on all at-risk patients. Because of variation in frequency of patient admissions, run charts were organized in groups of 10 chronological patients. Data were analyzed by using statistical process control methods. A special cause was defined as a pattern of performance that was not part of the existing system as a result of a change in the system.\textsuperscript{12, 17}

RESULTS
Figure 3 illustrates the adherence rate for orthopedic residents entering proper orders for at-risk patients. Baseline mean adherence was 23%. Special cause was achieved after introduction of reminder cards. This was followed by an apparent decrease in adherence that coincided with resident team change, and again an increase to a mean of 71% after outreach by the orthopedic chair. Once all 4 interventions were incorporated into resident on-boarding, a mean of 90% was achieved and sustained through multiple team changes throughout a 5-month period.

Figure 4 illustrates the adherence rate for nurses documenting proper neurovascular checks for at-risk patients when ordered correctly. Baseline mean adherence was 15%. Special cause was achieved soon after project introduction, to a mean of 44%, and again with greater clarity of order entry to a sustained mean of 70%. During the 4 months before and 13 months after project initiation, 1 episode of ACS was identified \(\sim\) 1 month into the project.

DISCUSSION
We successfully developed a reliable system to identify and monitor patients at risk for ACS. Specifically, we increased ordering and documenting of neurovascular checks every 2 hours for at-risk patients to 90% of patients and 70% of shifts covering patients with correct orders, respectively. ACS is a true orthopedic emergency that in as little as 4 hours can lead to permanent damage including paralysis, numbness, pain, contractures, and limb loss.\textsuperscript{1–9} The proper timing of assessments for ACS, which typically include passive muscle motion, assessment of sensation, and pain assessment, is not clearly defined in practice. Our institutional practice was typically to assess patients every 4 hours, which is the default frequency in our EMR. However, because permanent damage may be present within 4 hours, patients may display signs of ischemia within 1 hour, and in animal studies loss of nerve conduction has been observed within 2 hours of initiation of ACS, we thought bedside nurse assessment should routinely be performed every 2 hours for at-risk patients.\textsuperscript{1, 9, 13–15}

Because delay in diagnosis may result in delayed intervention, increasing awareness and monitoring are key components of timely diagnosis of ACS and prevention of negative sequelae.\textsuperscript{2, 7} Cascio et al\textsuperscript{18} demonstrated that the combination of education with monitoring guided by a checklist was more effective than education alone in improving ACS documentation. We took this work a step further by developing a system that supports proper recognition and monitoring of at-risk patients reliably among resident, NP, and bedside nurse providers.

One challenge we faced was maintaining the system during turnover of resident providers. To overcome this obstacle, we used both low- and high-reliability
methods such as education, directed reminders from clinical supervisors, personal reminder cards, and timely feedback on successes and failures. We learned that an intervention that may work for 1 group may not for another. For example, we saw an initial improvement and midline shift after distribution of pocket reminder cards that quickly fell and nearly caused a reshift of the midline. Investigation of this event revealed that the residents on the team

**FIGURE 3**
Control chart (P-chart) for percentage of at-risk patients for whom proper orders were entered. The alternating shaded and unshaded areas denote time periods when resident team composition did not change. Patients are clustered in chronological groups of 10 because of inconsistent presentation of at-risk patients over time. A, formal resident education; B, pocket card distributed; C, EMR changes live; D, ACS in orientation presentation; E, division director directed conversation; F, EMR order set revised; G, 4 interventions combined.

**FIGURE 4**
Control chart (P-chart) for percentage of shifts in which proper neurovascular checks were documented for at-risk patients for whom proper orders were entered. Chronological clustering of nursing shifts per 10 at-risk patients with proper orders was done to match resident order entry tracking. A, informal nurse education; B, flyer posted on unit; C, bulletin board posted; D, division director at huddle; E, identify and mitigate; F, mandatory unit education; G, RUQ flyer posted; H, 1:1 nurse discussions.
in June did not find the cards useful. We also learned that repeating the set of 4 interventions with each change in team composition improved the reliability with which the proper intervention was used for the new team. It is possible that presenting 4 different actions at once in a learner-centered approach succeeded because it appealed to a variety of students’ internal motivations and experiences.19 By anticipating when new residents would arrive and implementing our set of interventions at the start of their rotation, we improved and sustained proper order entry through multiple changes in staff. Other studies have also found that scheduled personal reminders, such as during monthly resident orientation meetings, are effective in maintaining adherence to recommended actions.20,21

An important criterion we used to select interventions was to ensure that the overall structure of the work system surrounding recognition and monitoring of patients for ACS is not disrupted significantly. This criterion was developed based on feedback from bedside nurses at the outset of the project requesting that complete redesign of the work system not be undertaken for patients at risk for ACS alone because it would probably disrupt other important processes. This request is consistent with work system design theory, which posits that any modification to a single element in the system could lead to unanticipated and potentially negative effects elsewhere in the system.22 For this reason, rather than introducing new education on the assessment for ACS by using a published tool,6,10 we recognized that the neurovascular checks performed by bedside nurses already contained all the interventions in published tools, and we focused on increasing the frequency of the routine behavior. Similarly, we sought single steps within the process, the modification of which would affect events positively downstream. We hypothesized that proper order entry was such a step, based on a number of observations. First, rather than choosing from a long list in our EMR of orthopedic order sets specific for various diagnoses, residents tended to choose a generic preoperative admission order set when admitting at-risk patients. Second, nurses who failed to document proper monitoring reported confusion between what the proper monitoring frequency should be, because orders seemed to alternate regularly between every-2-hour and every-4-hour neurovascular assessments. Rather than creating a new ACS order set, we modified the monitoring orders within the generic order set to match the existing resident workflow. Improving resident order entry, coupled with educational efforts, improved correct monitoring more than fourfold and supported our hypothesis. We believe that the consistent ordering of proper monitoring by residents and NPs supported proper bedside nurse monitoring activities more efficiently than direct manipulation of the nursing system would have.

This study is subject to a number of limitations. The study was conducted at 1 health care facility with a small sample size; the results may not be generalizable to other systems or institutions. However, the phenomenon of frequent resident turnover and entrenched nursing processes exists in many health care settings, and the interventions we used could probably be replicated elsewhere, given their generic nature. Additionally, although it was sustained for 5 months, we did not reach our goal for proper documentation of monitoring by nurses. Future work will aim to improve nursing documentation and to spread the interventions to test their generalizability elsewhere in our facility. We were also unable to measure the effect of individual interventions to determine the most useful because we implemented interventions closely in time and worked simultaneously with nurses and residents. Furthermore, we determined that combining the 4 interventions did not cause undue stress once adopted. Future study to answer this question is being considered in the form of a factorial design study.23

Finally, we studied a process not linked directly to an observed clinical outcome. We originally designed the project to assess the rate of ACS among at-risk patients, but only 1 ACS event occurred during the first month of the study period. The case had successful order entry, and ACS was diagnosed incidentally in the operating room. The patient ultimately underwent 4 surgical procedures related directly to the ACS. Of note, we identified 1 near-miss event ~7 months before project initiation. The nurses and residents collaborated to monitor a patient closely and expedited the patient’s transfer to the operating room for fasciotomy. The patient ultimately had 2 directly and 2 indirectly related procedures. Although ACS was not prevented in either case, and each patient underwent multiple surgeries, a more serious outcome in each case was probably averted.

In each of the 3 years before project initiation, 3 cases of ACS were identified in orthopedic patients meeting our eligibility criteria; the majority of cases were symptomatic and underwent multiple surgeries as a result of their ACS. We cannot be certain the system prevented the development of ACS, although this is a possibility given the 66% reduction in cases seen in 2012. Anecdotally, we have observed greater provider awareness of ACS. Physicians and nurses who provide care on other units have asked why we do not follow the ACS protocol elsewhere, which is probably a sign of system readiness for
Spreading the intervention to other units will probably expand the pool of eligible patients and enable assessment of the true impact of the intervention on ACS.

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A Collaborative System to Improve Compartment Syndrome Recognition
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