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ORIGINAL RESEARCH ARTICLE

Preventability of Voluntarily Reported or Trigger Tool-Identified Medication Errors in a Pediatric Institution by Information Technology: A Retrospective Cohort Study

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Abstract

Introduction Information technology (IT) has the potential to prevent medication errors. While many studies have analyzed specific IT technologies and preventable adverse drug events, no studies have identified risk factors for errors still occurring that are not preventable by IT.

Objectives The objective of this study was to categorize reported or trigger tool-identified errors and adverse events (AEs) at a pediatric tertiary care institution. Also, we sought to identify medication errors preventable by IT, determine why IT-preventable errors occurred, and to identify risk factors for errors that were not preventable by IT.

Methods This was a retrospective analysis of voluntarily reported or trigger tool-identified errors and AEs occurring from 1 July 2011 to 30 June 2012. Medication errors reaching the patients were categorized based on the origin, severity, and location of the error, the month in which they occurred, and the age of the patient involved. Error characteristics were included in a multivariable logistic regression model to determine independent risk factors for errors occurring that were not preventable by IT. A medication error was defined as a medication-related failure of a planned action to be completed as intended or the use of a wrong plan to achieve an aim. An IT-preventable error was defined as having an IT system in place to aid in prevention of the error at the phase and location of its origin.

Results There were 936 medication errors (identified by voluntarily reporting or a trigger tool system) included and analyzed. Drug administration errors were identified most frequently (53.4%), but prescribing errors most frequently caused harm (47.2 % of harmful errors). There were 470 (50.2 %) errors that were IT preventable at their origin, including 155 due to IT system bypasses, 103 due to in-

Key Points

Approximately one-half of pediatric medication errors identified by voluntary reporting or a trigger tool system were not preventable by information technology (IT) systems available at the studied institution.

Inappropriate use of IT systems was a common cause of medication errors that were IT preventable.

Errors occurring during dispensing, administration, and documentation, as well as in the operating room and outpatient setting had higher odds for being not preventable by IT systems.

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sensitivity of IT alerting systems, and 47 with IT alert overrides. Dispensing, administration, and documentation errors had higher odds than prescribing errors for being not preventable by IT [odds ratio (OR) 8.0, 95 % CI 4.4–14.6; OR 2.4, 95 % CI 1.7–3.7; and OR 6.7, 95 % CI 3.3–14.5, respectively; all $p < 0.001$). Errors occurring in the operating room and in the outpatient setting had higher odds than intensive care units for being not preventable by IT (OR 10.4, 95 % CI 4.0–27.2, and OR 2.6, 95 % CI 1.3–5.0, respectively; all $p \leq 0.004$).

Conclusions Despite extensive IT implementation at the studied institution, approximately one-half of the medication errors identified by voluntarily reporting or a trigger tool system were not preventable by the utilized IT systems. Inappropriate use of IT systems was a common cause of errors. The identified risk factors represent areas where IT safety features were lacking.

1 Introduction

Adverse events (AE) are a common problem in healthcare and may cause significant morbidity and mortality [1]. While multiple definitions exist for an AE, the World Health Organization (WHO) defines an AE as "an injury related to medical management, in contrast to complications of the disease" [2]. AEs due to medication use are referred to as adverse drug events (ADE). An ADE can be further classified based on the reason for the injury. Drugs can cause harm even when used "as directed and in the usual dosage," and these ADEs are considered to be adverse drug reactions (ADRs) [2]. Another important cause of ADEs is medication errors [3]. The WHO defines an error as the "failure of a planned action to be completed as intended or the use of a wrong plan to achieve an aim" [2]. It is important to note that not all medication errors cause ADEs [2, 3].

Some medication errors are detected before they reach the patient ('near-misses'), others reach the patient but cause no harm ('potential ADEs'), and still others cause significant morbidity and mortality ('preventable ADEs') [2, 4]. Pediatric patients have been identified as having a threefold higher rate of potential ADEs than adults [5]. The prescribing and administration phases of the medication use process are reported to cause the majority of pediatric medication errors [5–7].

Due to the continued risk of human error [1], information technology (IT) has been developed to automate and safeguard error-prone medication use processes and decrease medication errors and preventable ADE rates. Before extensive implementation of IT systems at pediatric institutions in the USA, it was suggested that 93 % of medication errors could have been prevented by IT such as computerized provider order entry (CPOE) and computerized clinical decision support (CDS) [5]. Implementation of CPOE and CDS have thus increased over the last decade worldwide [8, 9]. Overall, these systems appear to have decreased prescribing errors in the pediatric population, but results have been variable and outcomes related to these systems are likely dependent on the implementation strategy [10, 11]. In addition to CPOE and CDS aimed towards preventing prescribing errors, other IT systems such as barcode medication administration (BCMA) [12, 13], medication infusion pumps [14, 15], and automated dispensing cabinets have been implemented to decrease the incidence of medication administration and dispensing errors.

While most of the currently implemented IT systems have led to decreased medication errors and potential ADEs, medication errors still exist in patient care [16, 17]. Medication errors could be persisting despite IT advancements for numerous reasons, such as lack of sensitivity of the IT system for errors (e.g., a dosing error occurred during the prescribing phase that did not cause an alert to notify the prescriber or pharmacist) [17], alert fatigue [18], inappropriate user errors (e.g., prescribing medication selection errors, medication timing errors, and system bypasses) [19], inappropriate system design or implementation [11], and lack of IT to prevent particular types of errors (e.g., barcoding not being implemented at certain locations). Most studies categorizing ADEs have focused on determining general ADE preventability, and not whether the errors are IT preventable [20]. Those studies that have assessed error preventability by IT have only analyzed whether the identified errors could have been prevented if an IT intervention, such as CPOE or CDS functionalities, had been utilized [5, 21–23]. While these studies are beneficial to show the potential impact an IT system could have on errors, they are not helpful in identifying which error characteristics (e.g., location of error occurrence or step of the medication use process) are at a higher risk of error occurrence without the presence of an IT-related safeguard. Identification of these risk factors would be of great benefit to identify gaps in the available IT safeguards where IT safety systems and functionalities need either to be improved or newly developed to prevent errors from occurring. Thus, we chose to investigate reported or trigger tool-identified medication-related events occurring at a tertiary pediatric institution to identify the types of errors lacking or associated with suboptimal IT support.

Our research objectives were fourfold. First, we sought to categorize reported or trigger tool-identified medication errors and ADEs occurring at Nationwide Children's Hospital (NCH) in Columbus, Ohio, USA. Second, we aimed to identify whether medication errors that reached patients were preventable by the IT systems utilized at NCH. Third, we sought to determine why IT-preventable

errors were not prevented. Last, we aimed to identify risk factors for the occurrence of errors that reached patients and were not preventable by IT systems utilized at NCH.

2 Methods

2.1 Institution Description

This was a retrospective study conducted from 1 July 2011 to 30 June 2012 at NCH. NCH is a pediatric referral center, with more than 350 beds at the time of this study, including neonatal, pediatric, and cardiothoracic intensive care units, an emergency department, and other specialized inpatient units. In addition, it has numerous associated clinics and urgent care centers across Columbus, Ohio, USA. IT was consistently used in the NCH network and included the Epic electronic health record (EHR) and CPOE system (Epic Systems Corporation, Verona, WI, USA), CDS (e.g., dosing alerts, drug–allergy alerts, drug–drug interaction alerts), BCMA, intravenous infusion pumps with drug libraries including rate and dose alerts, automated medication repackaging systems, medication management systems with individual patient drawers, and a total parenteral nutrition compounding system, among other safety-related IT as previously described [7, 24]. There were some additions to the IT safety systems at NCH during this study, including implementation of an immunization checking functionality, an insulin dosing calculator, and revised policies regarding ADE prevention strategies (all occurring between October 2011 and February 2012), as previously described [7]. For some of the descriptive analyses, the year was divided in half to detect any impact these changes may have had on the reported ADE characteristics.

Outpatient centers also utilized Epic and had CDS for electronically submitted subscriptions, but did not have barcoding and medication dispensing systems available to the inpatient and main campus facilities. Operating rooms in the inpatient setting utilized a separate EHR with CPOE (although some orders were still transcribed), but this system did not directly connect to Epic, did not have the CDS capabilities of Epic, and barcoding technologies were not used for all medications administered during procedures. The NCH healthcare network utilized an electronic AE monitoring system where patients, families, and clinicians could enter any ADEs, ADRs, potential ADEs, and medication errors identified during routine care [25]. In addition, an automated trigger tool system was used to detect common medication adverse effects without the need for voluntary reporting (e.g., the use of reversal agents and addition of laxatives for opioid-induced constipation would be automatically collected in the trigger tool database) [7, 26].

2.2 Data Collection and Categorization

A query of the AE reporting system and trigger tool database was performed that included any medication-related events reported or detected from 1 July 2011 to 30 June 2012 at NCH or any outpatient affiliates. Each event report included the patient's age, medication(s), location, severity, origin, month, and a brief description of the event by the reporter. While it was possible to identify and obtain information regarding the reporters, the database query did not contain information about the reporter for this study, as it was not relevant to the study objectives. The first author analyzed each event and discrepancies were verified with the second author. If the reported data were incomplete, the EHR was reviewed to ensure accuracy of the event. If an event did not have evidence either in the report or in the EHR to determine the information required for this study, the event was removed from the analysis. The EHR was reviewed for each event identified by the trigger tool system to determine if the AE occurred while using the medication appropriately (e.g., within normal dosage ranges, free of drug interactions, and for the correct indication) or if the adverse effect could have been prevented or occurred due to erroneous medication utilization. Events were excluded if they were not related to a medication, were duplicate reports, or if the event was not an actual error or ADE. Errors that did not reach the patients were also excluded from the regression analysis, although they were collected for descriptive analysis. This was done because the goal of IT safety systems is to prevent medication errors from getting to patients. In addition, many errors that do not get to the patient due to pharmacist intervention (e.g., dosing, drug interaction, contraindications) were separately reported in an electronic pharmacy intervention database, which was not queried for this study and thus makes these data less complete for errors that did not reach patients. The authors utilized the WHO definition of an error to determine whether an error occurred [2].

Medications associated with the events were categorized based on American Hospital Formulary Service (AHFS) Pharmacologic–Therapeutic Classifications [27]. Any event involving more than one medication was categorized as an event involving multiple medications. If it could not be clearly determined that an event causing harm had an associated error based on the WHO error definition [2], then the event was determined to be an ADR and excluded from the logistic regression model. The remaining events were considered medication errors. The errors were then categorized based on the stage of medication use where the error originated (e.g., prescribing, dispensing, administration, and monitoring), the location of the error (e.g., emergency department, outpatient, intensive care), the month in which it occurred, and the age of the patient based

on previously utilized age categories [28]. Events for separate medications in the same patient were counted as different events. Although reporters categorized medication error severity, the authors independently used the National Coordinating Council for Medication Error Reporting and Prevention Index for Categorizing Medication Errors (NCCMERP) to determine the severity of the error [29]. The independent review was completed to ensure accuracy of reports and increase external validity as the NCH reporting system used a slightly modified severity index [25]. This NCCMERP index categorized medication errors from A to I based on the severity of the outcome, as follows:

(A) Circumstances of events that have the capacity to cause error.
(B) An error occurred but did not reach the patient.
(C) An error occurred that reached the patient but did not cause the patient harm.
(D) An error occurred that reached the patient and required monitoring to confirm that it resulted in no harm to the patient and/or required intervention to preclude harm.
(E) An error occurred that may have contributed to or resulted in temporary harm to the patient and required intervention.
(F) An error occurred that may have contributed to or resulted in temporary harm to the patient and required initial or prolonged hospitalization.
(G) An error occurred that may have contributed to or resulted in permanent patient harm.
(H) An error occurred that required intervention necessary to sustain life.
(I) An error occurred that may have contributed to or resulted in the patient's death.

Each medication error determined to be category C or greater was classified as being IT preventable or not IT preventable by the authors. IT preventability was defined as having an IT system in place to aid in prevention of the error at the phase and location of its origin. Generalizing IT preventability of different types of errors based on previous studies regarding IT system implementation for each different type of error was not possible, as similar types of errors may or may not have been IT preventable based on additional pertinent aspects of the error. For example, administration-related dosing errors were considered IT preventable if the medication was a pre-packaged product in the correct dosage and the medication could be barcoded before administration, but not IT preventable if it was a liquid that had to be measured by the nurse before administration and thus the final dose administered could not be verified by barcoding. Thus, each error was reviewed individually to determine if an IT system or functionality was implemented and targeted towards preventing the specific error from occurring. Additional examples of errors and their IT preventability categorizations are provided in Table 1. IT systems included both interventional

Table 1 Examples of information technology preventability categories

Origin of error	IT preventable	Not IT preventable
Prescribing	Dosage error or drug–drug interaction error when CDS *dosing or interaction alerts* were implemented	Dosage error or drug–drug interaction error when CDS alerts were not available at the site of the error
	Incorrect home medication ordered when it was correctly documented in the *electronic medication history* used to enter orders	Incorrect home medication ordered due to use of incorrect medication list in the absence of an available electronic list
Dispensing	Wrong medication when the medication was dispensed from an *automated dispensing cabinet with barcoding*	Wrong medication due to admixture error or dispensing a medication that lacked barcode verification
	Inappropriate adjustment of administration times during verification with available *electronic administration history*	Inappropriate adjustment of administration times during verification due to unavailable electronic administration history
Administration	Infusion rate error despite appropriate line connections, carrier fluid set-up, and use of the *infusion pump library*	Infusion rate error due to inappropriate line connections or carrier fluid set-up
	Wrong time error with *BCMA and MAR medication scheduling reminders*	IV infusion incompatibility (requires going to a separate reference or program)
Monitoring	Blood samples for serum drug concentration or laboratory data not drawn at the time requested on the *electronic order*	Medication requiring close monitoring (e.g., desmopressin) ordered and monitoring parameters not performed (in the absence of an order set)
Documentation	Weight not entered into EHR before ordering a medication, and *dosing weight required alerts* available during order entry	Wrong weight entered and dosing weight range alerts not implemented

Italicized text denotes the IT functionality intended to prevent the error

BCMA barcode medication administration, *CDS* clinical decision support, *EHR* electronic health record, *IT* information technology, *IV* intravenous, *MAR* medication administration record

(e.g., medication barcoding, drug interaction alerts) and informational IT systems [e.g., presence of the administration rate on the medication administration record (MAR) or reminders on the MAR regarding administration times]. Errors that could have been prevented by unimplemented or investigational IT interventions were not considered IT preventable. Errors that were not IT preventable at the error origin (e.g., error during dispensing), but were at a later medication use phase (e.g., during administration) were not considered IT preventable for the regression analysis. Further stratification of IT preventable and not IT-preventable errors was performed for descriptive analysis. An override was defined as overriding an alert or alarm that was presented to a practitioner notifying them that there may be an error (e.g., barcoding alarm or dosing alert), and this resulted in error occurrence. A bypass was defined as intentionally not using or working around a given IT system to avoid the occurrence of alerts or alarms (e.g., not barcoding before administration or not using an order set), which resulted in error occurrence. Since there were IT system changes implemented during the study period, errors related to the IT implementation changes were categorized based on the IT systems available at the time of the error.

2.3 Statistical Analyses

Percentages were used to describe event occurrence for each category. We used logistic regression to model the probability of a medication error being not IT preventable. A univariable and multivariable model was used to determine which risk factors of interest were significantly associated with being not IT preventable at the origin of the medication error. The model contained the independent variables patient age, month, location, error origin, error severity, and involved medication(s), and controlled for these error characteristics to determine independent risk factors that affected the odds of an error occurring that was not IT preventable. Errors that did not reach patients (categories A or B) were excluded from the logistic regression model. An omnibus test was also used to determine if each order characteristic independently affected the probability of an error. Significance was set at $\alpha = 0.05$. The goal of the regression analysis was to identify areas where IT systems either needed to be improved or newly developed in order to increase error prevention capabilities.

3 Results

There were 1694 unique reported events during the study period. After detailed analysis, 45 were duplicate reports, not actual medication-related errors or ADEs, or had inadequate information. Included for descriptive purposes only were 641 errors that did not reach patients and 72 ADRs without error. The remaining 936 medication errors that reached patients were included for descriptive analysis and in the logistic regression model. The characteristics of the reported errors are reported in Table 2. Severity assessment agreement between the reporters and the authors for all 1577 reported events was 70.8 %. After accounting for disagreement due to differences in the severity scales used (NCH vs. NCCMERP), the agreement rate was 86.7 % for all errors and 92.7 % for those errors that reached patients. The 936 medication errors categorized as C–H severity errors (there were no category G or I errors) most frequently originated from the administration (53.4 % of errors) and prescribing (27.1 % of errors) phases of the medication use process. For those categorized as D–H severity medication errors (382 errors), administration errors predominated from July to December 2011 (155 errors, 64.8 %), whereas prescribing errors predominated from January to June 2012 (70 errors, 49.3 %). Of the medication errors categorized as E–H severity (144 errors), prescribing errors were the most common cause (68 errors, 47.2 %) followed by administration errors (59 errors, 41.0 %). For the reported errors that did not reach the patients, dispensing errors were the most common (212 errors, 33.0 %), followed by prescribing errors (187 errors, 29.3 %).

The most commonly reported medications involved in the C–H severity errors were mixed intravenous fluids (79 errors, 8.4 %), total parenteral nutrition (50 errors, 5.3 %), vaccinations (50 errors, 5.3 %), vancomycin (43 errors, 4.6 %), albuterol (29 errors, 3.1 %), and morphine (24 errors, 2.6 %). The majority (84.6 %; 554 category C and 238 category D errors) of the reported errors did not cause harm to the patient. Of the 26 severity F and H errors, ten (40 %) involved central nervous system (CNS) agents and three (12 %) involved antineoplastic agents.

Table 3 identifies additional details regarding the IT preventability of the errors. The reasons why IT-preventable errors were not prevented are listed in Table 4. Importantly, 57.4 % of IT-preventable errors (270 errors) involved the inappropriate use of available IT at the origin of the error (i.e., overrides, bypasses, and other inappropriate use), with an additional 130 errors involving inappropriate IT use at any point during the medication use process (300 errors total, or 32.1 % of overall errors). The proportion of preventable errors that involved IT alert overrides was higher when the origin of the error was at the prescribing phase (28 errors, 11.4 % of prescribing errors) than at the administration phase (17 errors, 4.5 % of administration errors). An available IT safety system was bypassed in 22.2 % of administration errors (111 errors), 18.5 % of documentation errors (ten errors), and 10.2 % of

Table 2 Medication error characteristics (936 reported medication errors that reached the patient)

Error characteristic	IT preventable ($n = 470$) [n (%)]	Not IT preventable ($n = 466$) [n (%)]	Univariable odds ratio (95 % CI), p value	Multivariable odds ratio (95 % CI), p value
Origin of error				
Prescribing, $n = 254$	151 (59.4)	103 (40.6)	Reference	Reference
Dispensing, $n = 114$	30 (26.3)	84 (73.7)	4.1 (2.5–6.7), $p < 0.001$	8.0 (4.4–14.6), $p < 0.001$
Administration, $n = 500$	264 (52.8)	236 (47.2)	1.3 (0.97–1.8), $p = 0.08$	2.5 (1.7–3.7), $p < 0.001$
Monitoring, $n = 14$	10 (71.4)	4 (28.6)	0.59 (0.18–1.9), $p = 0.38$	0.71 (0.18–2.8), $p = 0.63$
Documentation, $n = 54$	15 (27.8)	39 (72.2)	3.8 (2.0–1.9), $p < 0.001$	6.7 (3.3, 14.5), $p < 0.001$
Location of error[a]				
Subspecialty floors, $n = 268$	139 (51.9)	129 (48.1)	1.4 (1.0–2.0), $p = 0.04$	1.3 (0.87–2.0), $p = 0.20$
Intensive care, $n = 305$	185 (60.7)	120 (39.5)	Reference	Reference
Hematology/oncology, $n = 109$	62 (56.9)	45 (42.1)	1.1 (0.71–1.7), $p = 0.64$	0.90 (0.50–1.6), $p = 0.73$
ED, $n = 91$	41 (45.1)	50 (55.0)	1.9 (1.2–3.0), $p = 0.01$	1.5 (0.82–2.6), $p = 0.20$
OR/PACU, $n = 33$	7 (21.2)	26 (78.8)	5.7 (2.4–13.5), $p < 0.001$	10.4 (4.0–27.2), $p < 0.001$
Outpatient/same day, $n = 114$	22 (19.3)	77 (67.5))	4.5 (2.8–7.3), $p < 0.001$	2.6 (1.3–5.0), $p = 0.004$
Pharmacy, $n = 18$	8 (44.4)	10 (55.6)	1.9 (0.74–5.0), $p = 0.18$	0.78 (0.23–2.7), $p = 0.70$
Medication class involved with error (with >50 errors)[b]				
Electrolyte, caloric, water balance agents, $n = 201$	111 (55.2)	90 (44.8)	0.60 (0.26–1.4), $p = 0.22$	0.67 (0.24–1.8), $p = 0.43$
Anti-infective agents, $n = 177$	84 (47.4)	93 (52.5)	0.81 (0.35–1.9), $p = 0.62$	0.72 (0.26–2.0), $p = 0.51$
CNS agents, $n = 212$	120 (56.6)	92 (43.4)	Reference	Reference
Hormones and synthetic substitutes, $n = 67$	30 (44.8)	37 (55.2)	0.90 (0.36–2.3), $p = 0.83$	0.78 (0.26–2.3), $p = 0.65$
Serums, toxoids, and vaccines, $n = 59$	6 (10.2)	53 (89.8)	6.5 (2.1–20.4), $p = 0.001$	6.2 (1.5–25.3), $p = 0.01$
Age of patient involved in error[c]				
Neonates/preterm infants <44 weeks PMA, $n = 96$	53 (55.2)	43 (44.8)	0.67 (0.39–1.2), p=.15	0.92 (0.47–1.8), $p = 0.81$
Infants, 44 weeks PMA to <1 year, $n = 158$	97 (61.4)	61 (38.6)	0.52 (0.32–0.84), $p = 0.01$	0.49 (0.27–0.88), $p = 0.02$
Toddlers, 12–23 months, $n = 68$	40 (58.8)	28 (41.2)	0.58 (0.31–1.1), $p = 0.08$	0.48 (0.24–0.99), $p = 0.046$
Young children, 2–5 years, $n = 141$	65 (46.1)	76 (53.9)	0.96 (0.59–1.6), $p = 0.88$	0.85 (0.47–1.6), $p = 0.60$
Children, 6–12 years, $n = 194$	93 (47.9)	101 (52.1)	0.89 (0.56–1.4), $p = 0.63$	0.79 (0.45–1.4), $p = 0.39$
Adolescents, 13–17 years, $n = 162$	70 (43.2)	92 (56.8)	1.1 (0.67–1.8), $p = 0.75$	1.0 (0.58–1.8), $p = 0.92$
Adults, ≥18 years, $n = 113$	51 (45.1)	62 (54.9)	Reference	Reference

The multivariable regression model contained the independent variables patient age, month, location, error origin, error severity, and involved medication(s) and was used to determine which risk factors of interest were significantly associated with being not IT preventable at the origin of the medication error

CNS central nervous system, *ED* emergency department, *OR/PACU* operating room/post-anesthesia care unit, *PMA* post-menstrual age

[a] Accurate location could not be ascertained for 1 error

[b] Accurate medication class could not be ascertained for 6 errors

[c] Accurate patient age could not be ascertained for 4 errors

prescribing errors (26 errors). In addition, 110 errors (11.8 % of overall errors and 21.8 % of those IT-preventable errors at any point) still occurred because the utilized alert-based system was not sensitive enough to detect the error (e.g., a dosing error occurred at the prescribing phase, but a dosing alert did not occur).

Table 2 provides a detailed analysis of the IT preventability of errors that reached the patient based on the error-specific characteristics. The origin of the error ($p < 0.001$), severity ($p = 0.02$), location ($p < 0.001$), medication class involved ($p < 0.005$), and patient age ($p = 0.04$) all independently affected the IT preventability

Table 3 Detailed categorization of error preventability by information technology safety measures ($n = 936$ medication errors)

Error categorization	*n* (% errors)
Not IT-preventable error (at origin of error)	
Not an IT-preventable error	293 (31.3)
IT mechanism available, but not at the location of the error	129 (13.8)
IT mechanism not available at error origin, but IT mechanisms present at a future step of the medication process	44 (4.7)
IT-preventable error (at origin of error)	
IT preventable with interventional IT	388 (41.5)
IT preventable with informational IT	82 (8.8)

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of the error. Thirty-seven percent of category D errors were not preventable by IT, and these errors were less likely than category C errors (52.5 % not IT preventable) to be not IT preventable (multivariable odds ratio 0.64, 95 % CI 0.44–0.92; $p = 0.02$). The other error severity categories (E, F, and H) did not differ significantly in IT preventability compared with category C errors. The IT preventability also did not significantly differ based on the month of error occurrence. Errors involving the serums, toxoids, and vaccines medication class had the highest risk of being not IT preventable compared with other classes, and 54 of these 59 errors were related to inappropriate childhood vaccinations.

The majority of not preventable ADRs were identified from trigger tools. Of the 72 ADRs, 25 (34.7 %) were due to CNS agents (of which 19, or 76.0 %, were opioid related), ten (13.9 %) involved antibiotics, nine (12.5 %) involved antineoplastic agents, nine (12.5 %) included multiple medications, and 19 (26.4 %) were from other medication categories. Of the ADRs, 62 (86.1 %) caused temporary harm to the patient requiring an intervention, six (8.3 %) increased length of stay or initiated hospitalization, and four (5.6 %) caused harm requiring life-sustaining interventions, two of which were allergic reactions.

4 Discussion

Our analysis of overall reported errors and ADEs provided a reflection of pediatric medication safety in the era of IT. The errors and ADEs were categorized based on their severity and other error characteristics. Medication errors (of all severity categories) encompassed more than 95 % of the reported or trigger tool-identified events, with 85 % of the medication errors that reached patients not causing harm (less than NCCMERP category E errors). We determined that about 50 % of medication errors that reached patients were not preventable by the IT systems being utilized at NCH. Those errors that were IT preventable still occurred most commonly due to system bypasses by practitioners. We also identified the following risk factors for errors occurring that were not IT preventable: errors occurring during the dispensing, administration, and documentation phases; errors occurring in the operating room/post-anesthesia care unit and in the outpatient setting; and errors involving the serums, toxoids, and vaccines medication class.

In previous studies, the most commonly reported origins of errors were either at the prescription phase or the administration phase [5, 7]. Our study was in agreement with these reports and also led to additional unique observations. Among errors that did reach the patients, administration errors were the most prevalent. Other studies have reported prescribing errors as being the most frequent [5, 7]. Further analysis of our data revealed that prescribing errors were more common when only considering more severe errors.

Table 4 Reasons why information technology systems did not prevent errors

Reason	IT preventable at origin of error ($n = 470$)	IT preventable at any part of the medication use process[a] ($n = 44$)
IT functionality was bypassed	155	17
IT alert-based functionality was not sensitive enough to detect error	103	7
Informational IT system ineffective (e.g., electronic dose due reminders did not prevent a wrong time administration error)	82	0
IT system used inappropriately (e.g., medication timing errors)	68	0
IT alerts occurred and were overridden	47	13
IT system default or malfunction led to error	13	0
IT system prevented error continuation	2	7

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[a] Not considered IT preventable for the regression analysis in this study

Some of these prescribing errors could be resolved by incorporating systematic double-checks for the prescription phase that consider patient specific factors (e.g., dosing alerts utilizing laboratory parameters such as serum drug concentrations or renal function parameters). In addition, the most commonly occurring origin of error for the more severe errors changed throughout the year (administration during the first 6 months vs. prescribing in the second 6 months). While causality cannot be definitively proven, recognition of the increase in administration errors and the resultant changes made during the studied period may have contributed to a decrease in the proportion of administration errors occurring over the 1-year study period. This was also illustrated in a recent publication also from NCH comparing 2010–2012, where ADEs occurring in 2012 were more commonly due to prescribing than administration [7]. This change highlights the fluctuating nature of medication errors and the effect systematic change could have on the distribution of medication errors. Among errors that did not reach the patients (categories A–B) in our study, dispensing errors were the most common. It is important to note that these data are not complete as not all pharmacy interventions were recorded in this study. However, the fact that these errors did not get to the patients illustrated the efficacy (although not 100 %) of the numerous double-check systems in place before the patient received a dispensed medication. Our data highlighted how the most commonly reported medication error origin changed based on the severity of errors analyzed and potentially due to changes in the safety culture that occurred at the institution.

One striking finding from this study was that more than 32 % of the errors were IT preventable at some point during the medication use process, but still occurred due to various inappropriate uses of IT systems (Table 4). These findings strongly reaffirm the need for improved human to computer interfaces and the need for continual staff education regarding IT system capabilities and limitations. Notably, administration errors were commonly not prevented because the IT system was bypassed. This was a concern discussed previously in the literature and could be rectified by improved staff education and enforcement of compliance regarding IT safety utilization [19, 30]. Overriding of IT system alerts occurred frequently, suggesting practitioner alert fatigue, particularly for prescribers, may have been a problem. In addition to concerns regarding alert fatigue and inappropriate IT use, there was a lack of IT system sensitivity evidenced by the errors in the current study where there were IT systems in place but the systems did not alert the practitioners to the error. Previous studies have shown decreased sensitivity of pediatric dosing alerts for dosing errors [17] and drug interaction systems for relevant drug interactions in the outpatient setting [31]. Our study reveals that multiple IT safety systems likely do not have optimal sensitivity for errors. These data corroborate the importance of ranking alarm hazards as the top health technology hazard concern by the Emergency Care Research Institute [32].

Documentation, dispensing, and administration errors were all at higher risk for being not IT preventable than prescription errors. These data offered multiple observations. First, this illustrated that most IT prevention strategies that have been implemented have been targeted towards the prescription phase. While this may be appropriate when comparing prescribing error IT needs with those of dispensing and documentation (which less frequently reached patients), it may not be appropriate compared with administration errors. Administration errors occurred frequently and could have occurred less often had more IT systems been in place focused on administration errors, and thus the administration process may require further IT advancements to prevent errors. For example, CPOE was implemented to prevent prescribing errors. IT systems, however, may not allow integration between CPOE and infusion pumps, thus creating a potential for error occurrence at the administration phase. This was illustrated in a previous study regarding infusion pump discrepancies and also caused some of the errors in our study that were not prevented because of a missing link between the IT safety systems [33]. Our study data also showed that the IT systems, specifically CDS, geared toward prescribing error prevention need extensive refinement because prescribing errors are still occurring frequently. This need has also been identified previously [34].

Inappropriate childhood vaccination errors were at high risk for being not IT preventable. This likely occurred because most outpatient clinics did not have barcoding and dosing alerts were not capable of preventing these types of errors. Inappropriate vaccination in children is a common problem and can lead to painful and unnecessary injections in children. This continual problem at NCH led to the implementation of an alert functionality to help practitioners prescribe and administer the appropriate vaccines [7].

The effect of patient location on error preventability was not surprising. Outpatient clinics, urgent care centers, and operating rooms did not have the same IT support as other inpatient areas, and thus were more at risk for having an error occur that was not IT preventable. The majority of IT studies have been completed in the inpatient setting [10, 35], and a future area for research and IT implementation could be implementation in the outpatient setting. Identification of common medications and locations that are associated with errors should be done to identify areas where IT systems could be developed and implemented to optimize error prevention.

Patient age and error severity also played a role in the IT preventability of an error. Medication errors in infants and

toddlers were less likely to not be IT preventable than those in adults taken care of at NCH. While one would expect the opposite result (because immunizations were at a higher risk for being not IT preventable and they are administered often to infants and toddlers), multivariable analysis was able to control for this factor and surprisingly showed that these age groups were at less risk for being not IT preventable. Category D errors also had less risk for being not IT preventable than category C. It remains unclear why these types of errors had less risk for being not IT preventable, and this could be an area for additional research. Intriguingly, the month of the year did not have an effect on the IT preventability of errors in our study. One could presume that medical residents would be less accustomed to the computer system in July and thus more IT-preventable errors would occur during July, but there was not a significant difference noted in our study. A difference may not have been found because we did not include the errors that did not reach the patients in the regression analysis. Thus, interventions from other clinicians may have prevented common medical resident errors due to unfamiliarity with IT systems from reaching patients.

Our descriptive findings about drug classes commonly causing ADRs are similar to previous studies, suggesting that CNS agents, usually opioid agents, and antibiotics are the most frequent causes of AEs when used within normal dosing ranges [36]. Some of these ADRs and some errors included in this study may not have been reported if a trigger tool system was not used. This correlates well with other studies suggesting multiple methods are needed to detect the most ADEs in the clinical setting [7, 37].

There are some limitations to our study. First, we only studied events occurring at a single institution with extensive IT safety measures. While our data may be similar to other large academic institutions, other pediatric centers may not have the same level of IT safety measures and thus their error characteristics may differ. Our regression model did not include errors that did not reach the patients, and this could be construed as a limitation. This was done intentionally as the main goal of error prevention is to prevent medication errors from reaching the patients. Also, the data for category A and B errors were likely not complete and if included could have skewed the regression analysis as described in the Methods section. Our study was retrospective in nature and included a combination of trigger tool ADEs, reported errors, and reported ADEs. Thus, our data were limited to the reported information and the information documented in the EHR, and some unreported errors were likely not included. While a prospective observational study may have provided more complete data and different results, the costs and resources required may be prohibitive to completing such a study [38]. We utilized two data sources to help provide more complete data, rather than using only trigger tool-identified events or only reported events [38, 39]. While the safety culture at NCH allowed for high rates of error and ADE reporting as described in previous studies [7, 25], institutions should always strive to continually improve the completeness of error and ADE voluntary reporting. There were also changes in the safety culture and systems at NCH during the study period [7], which may have affected our results. However, this cannot be avoided due to the dynamic nature of medication safety within an institution. In addition, the multivariable logistic regression included the month of error occurrence and thus would have controlled for any changes these interventions may have had on the results from this analysis. Descriptive results were also presented in 6-month periods (with the interventions occurring around the 6-month point) to note any differences these changes may have had on these results.

5 Conclusions

Despite extensive IT implementation, about one-half of medication errors identified by voluntarily reporting or a trigger tool system were not preventable by IT safety systems at NCH. Inappropriate use of IT systems and insensitivity of IT systems were common reasons why IT-preventable errors still occurred. This study uniquely identified risk factors for medication errors that are not preventable by IT. The origin of the error, severity, location, medication class involved, and patient age all independently affected the IT preventability of the error. The types of errors presented in this study with high rates of errors not preventable by IT can be used to target future IT functionality development and implementation.

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Ethical standards This study was deemed exempt by the Nationwide Children's Hospital Institutional Review Board.

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