> “...the system automatically verifies that the correct medication is being administered to the right patient, at the right time and at the right dose...

HUMBER RIVER HOSPITAL is one of Canada's largest community acute care hospitals, serving a population of more than 850,000 people in the northwest Greater Toronto Area.

The multi-site hospital currently operates out of its Wilson Avenue acute care site and Finch and Church Street reactivation care centres with a total of 722 beds, just over 3,800 employees, approximately 700 physicians and over 1,000 volunteers.

Affiliated with the University of Toronto and Queen's University, Humber River Hospital is North America's first fully digital hospital. Part of Humber River Hospital's digital infrastructure includes completely automated laboratory services, robots sorting and mixing medications, electronic health records, tracking systems for patients undergoing surgery that update families through their cellphones and patient computer bedside terminals – all varieties of technologies that automate information, eliminate paper and provide a connected experience for patients, staff and families.

Humber River Hospital was awarded Accreditation with Exemplary Standing in 2018 and since its opening in 2015 has received numerous awards and accolades for technological advancements and innovation (www.hrh.ca).

Closed-Loop Medication System: Leveraging Technology to Elevate Safety

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WHAT WE LEARNED:

1. The implementation of CLMS requires interprofessional and cross-functional collaboration to successfully integrate the requirements of each respective discipline and service.
2. HRH implemented CLMS in several stages, which allowed time for nursing staff to learn how to incorporate barcode scanning of patients and medications into their daily work-flows.
3. There is a need for ongoing planning and implementation of automated system-level improvements for CLMS that interconnect the EMR and other digital devices, such as smart infusion pump drug libraries.

Abstract

Background: Healthcare organizations have long been dependent on the vigilance of nurses to identify and intercept medication errors before they can adversely affect patients. New technologies have been implemented in an effort to reduce medication errors; however, few studies have evaluated the long-term effects of technology-based interventions in reducing medication errors.

Aim: The aim of this study was to evaluate the effects of barcode medication administration (BCMA) and the closed-loop medication system (CLMS) interventions on medication errors and adverse drug event (ADE) rates.

Methods: An autoregressive integrated moving average model for interrupted time series design was used to evaluate the impact of the BCMA and CLMS interventions on the monthly reported medication error and ADE rates at Humber River Hospital between September 2013 and August 2018. Descriptive statistics were generated to evaluate the types of error and their gravity.

Results: A total of 1,712 medication errors and ADEs were reported in the five-year study period. The results of the interrupted time series indicated that the introduction of the BCMA intervention was associated with a statistically significant gradual decrease in reported medication error and ADE rates at 0.002 percentage points per month ($p = 0.003$). The introduction of the CLMS intervention was associated with an immediate absolute decrease in reported medication error and ADE rates of 0.010% ($p = 0.020$).

Conclusion: The findings from this study support the adoption of both BCMA and CLMS interventions to prevent medication errors. Staged implementation of CLMS allows time for learning and incorporating barcode scanning. Interprofessional and cross-functional collaboration is necessary to successfully integrate the requirements of each respective discipline and service in the CLMS.

Background

In Canada, an estimated 1,600 adult patients suffer harm in hospitals across the country each day (Chan and Cochrane 2016). The 2004 Canadian Adverse Events Study reported that more than 185,000 adverse drug events (ADEs) occurred in Canadian hospitals and nearly 40% of these were potentially preventable (Baker et al. 2004). In the decade since the study was published, a follow-up report concluded that there had been only "limited evidence of substantial improvement"

(Baker 2015). These estimates are alarming as medication errors can result in negative health consequences for patients, including increased length of hospital stay, disability and death (Forster et al. 2004; Weingart et al., 2000). Addressing medication safety issues has become a top priority for many Canadian healthcare organizations.

Errors can occur at any stage of the medication management process, from ordering, to preparing and dispensing and, finally, to the administration of the medication to the patient. Nurses are the primary clinicians responsible for administering medications to patients in the acute care hospital setting. The interception of medication errors is highly dependent on the vigilance of nurses to identify discrepancies in the process of medication administration among frequent interruptions and competing priorities (Garrett 2008; Tang et al. 2007). To maximize the safety of medication administration, Humber River Hospital (HRH) has implemented a number of medication safety technologies that establish a systematic safeguard for preventing errors.

Medication Safety Technologies

Barcode medication administration (BCMA) systems have been advocated as a technology that reduces medication errors occurring at the administration phase. The BCMA process begins when the clinician prescribes a medication for the patient, the pharmacist then receives the order and verifies it and the medication order then populates into the electronic medication administration record (eMAR). All medications are dispensed in a unit-dose format and have scannable barcodes. To administer the medication, the nurse must scan the barcode on individually packed medication delivered from the pharmacy as well as the barcode on the patient's identification wristband (Figure 1). The patient's information will then appear on the eMAR, and if there are any discrepancies the computer system alerts, and a warning will appear on the screen. By scanning the patient and medication barcodes, the system automatically verifies that the correct medication is being administered to the right patient, at the right time and at the right dose and automatically documents that it was administered. In the absence of BCMA technology, the nurse must manually ensure the correct medication, dosage, timing, documentation and patient identity for safe administration.

An additional systematic safeguard is the closed-loop medication system (CLMS), which includes the BCMA system and integrates computerized physician order entry (CPOE) technology and automated dispensing technology (robots/units) (Figure 2). CPOE technology enables clinicians to electronically enter a medication order in the eMAR, which is also integrated with the pharmacy information system. CPOE technology's designed use is an integrated systems approach to

Figure 1. Barcode medication administration.

decrease transcription errors associated with written prescription orders. The eMAR system can then also alert the clinician if there are any drug interactions, allergies or ADEs based on the patient's information in the electronic medical record (EMR). Once the pharmacy department receives the order, it will also be

Figure 2. Closed-Loop medication system.

alerted by the safety checks in the system. The information is then electronically sent to the automated dispensing technology (robot/unit), and a medication-dispensing robot will package the medications into unit-dose plastic bags that feature a barcode that can then be scanned by the nurse using the BCMA system. The CLMS provides an end-to-end, safe and efficient electronic medication management system across the full cycle of the medication ordering to administration processes. Nurses have the benefit of a consistently clear and complete medication order from which they can determine its appropriateness before administration to the patient (CNO 2017).

Electronic medication management systems have been recognized as valuable tools in optimal healthcare provision, decreasing turnaround time, increasing efficiency and, most notably, reducing error rates (Franklin et al. 2007; Seibert et al. 2014; Strudwick et al. 2018). However, the published evidence on the effectiveness of BCMA and full CLMS have been limited, and some studies have reported no change in medication error rates before and after implementation of these technologies (Bowers et al. 2015; Helmons et al. 2009). However, these studies only examined the short-term effects of these technologies, without acknowledging that these systems have a moderate learning curve.

The aim of this study was to evaluate the long-term impact of BMCA and CLMS technologies on medication errors and ADEs.

Methods

Setting

The reported medication incident data were collected from three 200- to 250-bed acute community care hospitals, Humber Memorial Hospital, York-Finch Hospital and Northwestern General Hospital (known collectively as the Humber River Regional Hospital Network [HRRH Network]), between September 2013 and September 2015 and one 656-bed acute care community hospital, HRH, between October 2015 and August 2018. The HRRH Network sites closed their doors in October 2015 upon the opening of the new HRH. HRH was built as an all-digital hospital that uses emerging health technologies that enhance patient care. The HRH site was built to replace the HRRH Network sites and serve the same catchment area. The majority of nursing staff transferred employment from the HRRH Network sites to the new HRH, which provided for a consistent and stable nursing workforce. BCMA technology was originally introduced at the HRRH Network sites, with the CLMS integrated later when the new HRH site opened.

Study design and data collection

A quasi-experimental design was used to assess the impact of the BCMA and CLMS interventions on the reported medication error and ADE rate at the HRRH Network and HRH sites. A retrospective audit of self-reported incidence of patient-related medication errors and ADEs submitted through the hospital's EMR into an electronic database was conducted over a five-year period between September 2013 and August 2018. The system is used to report any medication errors and ADEs that caused or had the potential to cause patient harm whether they were preventable or non-preventable.

The main outcome measure was the monthly reported medication error and ADE rate, which was calculated by dividing the total number of reported medication errors and ADEs per month by the number of medication doses administered that month. The monthly number of doses administered was obtained from electronic pharmacy records. Information regarding incident classification (e.g., wrong dose, known medication allergy, etc.) and severity of harm (e.g., no harm, moderate harm) were also extracted from the reporting database.

The study did not require research ethics board approval as the study was considered a program evaluation and involved secondary use data provided without any patient or staff identifiers.

Interventions

Training on the use of BCMA technology was provided to all nurses and other healthcare professionals (as required) at the HRRH Network sites prior to implementation. BCMA technology was then rolled out over four months between May and August 2014. Training on CLMS technology was provided to all nurses and involved hospital staff prior to the relocation of the HRRH Network sites to the HRH site in October of 2015.

Data analysis

The monthly reported medication error and ADE rate was plotted from September 2013 to August 2018. Descriptive statistics were used to present the mean frequencies and percentages of reported medication errors and ADEs across time by incident classification and severity of harm. The dates of the interventions were used to divide the monthly data into three periods: pre-intervention (September 2013 to April 2014); BCMA intervention (May 2014 to September 2015) and CLMS intervention (October 2015 to August 2018).

To evaluate the effects of the BCMA and CLMS interventions on the reported medication error and ADE rate, interrupted time series (ITS) analysis was performed using the autoregressive integrated moving average (ARIMA) model (Bernal et al. 2017). ITS analysis is superior to simple before-and-after study designs due to its ability to evaluate the effect of an intervention while accounting for underlying secular trends.

The reported medication error and ADE rate was analyzed as the outcome variable with calendar month as the unit of analysis. The four months corresponding to the BCMA phase-in period (May 2014 to August 2014) were excluded from the ARIMA model. There were a total of 56 monthly intervals, providing eight pre-intervention, 13 post-BCMA intervention and 35 post-CLMS intervention data points. ITS analysis was used to estimate the changes in level and trend following each intervention. Ljung-Box Q fit statistic and visual inspection of autocorrelation (ACF) and partial autocorrelation (PACF) plots were used to assess for autocorrelation, seasonality and stationarity. Ljung-Box Q fit statistic and visual inspection of the ACF and PACF plots did not indicate the presence of autocorrelation. Examination of the series ACF plot for cyclical or periodic fluctuations at four, six and 12 lags indicated that seasonality was absent. Lastly, the ACF patterns show a clear exponential decay indicative of stationarity. Therefore, adjustments and transformation to the data were not necessary. All analyses were conducted in SPSS version 25 Forecasting module. The results were considered to be statistically significant at $p < 0.05$.

Results

A total of 1,712 medication errors and ADEs were reported in the five-year study period, with a mean of 28.5 ± 7.4 reports per month. The mean medication error and ADE rate for the five-year period was 0.0141% ± 0.0060%.

Severity breakdown is presented in Table 1. Among 1,712 errors and ADEs, the most frequent severity grading across all time periods was "no harm" (43.3–50.2%) and "near miss" (14.6–18.7%). Importantly, in the pre-intervention and post-BCMA intervention time periods, there was no force option to grade the severity of the error/ADE; therefore, 16.6% of the errors and ADEs during these two time periods were classified as "unknown." Because of the large number of errors and ADEs categorized as unknown, it is not possible to accurately compare severity across time periods.

Table 1. Monthly average distribution of severity of harm by pre-intervention, post-BCMA intervention and post-CLMS intervention time points (n = 1,712).

	Time period, mean frequency (%)		
Severity of harm	**Pre-intervention**	**Post-BCMA intervention**	**Post-CLMS intervention**
No harm	14.9 (43.3)	13.5 (44.8)	13.3 (50.2)
Near miss	5.4 (15.6)	5.6 (18.7)	3.9 (14.6)
Mild harm	2.8 (8.0)	3.0 (9.9)	5.7 (21.5)
Moderate harm	0.9 (2.5)	0.8 (2.5)	1.5 (5.7)
Severe harm	0.3 (0.7)	0.1 (0.4)	0.1 (0.3)
Major permanent harm	0.0 (0.0)	0.1 (0.2)	0.0 (0.1)
Reportable incident	3.3 (9.5)	2.6 (8.8)	1.9 (7.4)
Unknown*	7.0 (20.4)	4.4 (14.6)	0.0 (0.1)

* Force option to select error severity was only introduced post-CLMS.
BCMA = barcode medication administration; CLMS = closed-loop medication system.

Incident classification is presented in Table 2. The most frequent errors across the three time periods were related to "medication error – other" (18.5–30.2%) and "dose omission" (18.2–24.9%). There were slight decreases in the average number of "controlled drug count error," "medication – no order," "wrong dose/quantity," "wrong frequency/rate," "wrong medication" and "wrong patient" errors per month across time periods.

Table 2. Monthly average distribution of incident types by pre-intervention, post-BCMA intervention and post-CLMS intervention time points (n = 1,712).

	Time period, mean frequency (%)		
Incident classification	**Pre-intervention**	**Post-BCMA intervention**	**Post-CLMS intervention**
Adverse reaction/effect	1.8 (5.1)	0.9 (2.9)	1.6 (6.2)
BPMH problem*	0.0 (0.0)	1.8 (5.8)	1.2 (4.5)
Controlled drug count error	1.3 (3.6)	1.0 (3.3)	0.4 (1.5)
Dose omission	6.3 (18.2)	5.6 (18.7)	6.6 (24.9)
Duplicate or extra dose	1.0 (2.9)	1.1 (3.7)	0.8 (3.1)
Expired medication	0.3 (0.7)	0.4 (1.2)	0.1 (0.4)
Known medication allergy	0.1 (0.4)	0.4 (1.4)	0.3 (1.1)
Medication – no order	2.1 (6.2)	1.8 (5.8)	1.0 (3.9)
Medication error – other	10.4 (30.2)	5.6 (18.5)	6.0 (22.8)
Medication pump problem**	0.0 (0.0)	0.0 (0.0)	0.2 (0.9)
ADM issue**	0.0 (0.0)	0.0 (0.0)	0.4 (1.5)
Other equipment problem**	0.0 (0.0)	0.0 (0.0)	0.3 (1.2)
Wrong dose/quantity	3.6 (10.5)	2.0 (6.6)	2.2 (8.4)
Wrong duration	0.0 (0.0)	0.2 (0.6)	0.3 (1.3)
Wrong frequency/rate	1.0 (2.9)	1.2 (3.9)	0.5 (1.9)
Wrong medication	3.5 (10.2)	4.1 (13.5)	1.7 (6.5)

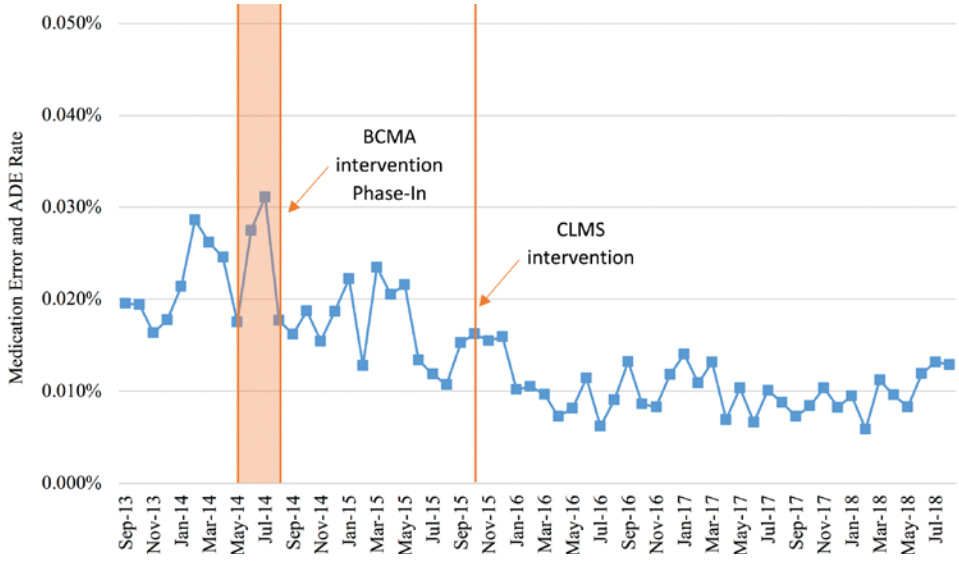
Incident classification	Time period, mean frequency (%)		
	Pre-intervention	Post-BCMA intervention	Post-CLMS intervention
Wrong patient	1.9 (5.5)	1.7 (5.7)	0.8 (2.9)
Wrong route	0.3 (0.7)	0.6 (1.9)	0.4 (1.4)
Wrong strength/concentration	0.4 (1.1)	1.2 (4.1)	0.5 (2.1)
Wrong technique	0.1 (0.4)	0.2 (0.8)	0.2 (0.6)
Wrong time	0.5 (1.5)	0.5 (1.6)	0.7 (2.7)

ADM = administration; BCMA = barcode medication administration; BPMH = best possible medication history; CLMS = closed-loop medication system.
* Category introduced post-BCMA time period.
** Category introduced post-CLMS time period.

Effect of BCMA and CLMS

Overall, there was a general decrease in the rate of reported medication errors and ADEs each month over the observation period (Figure 3). Average medication error and ADE rates reported in the pre-intervention, post-BCMA and post-CLMS periods were 0.0217%, 0.0185% and 0.0102%, respectively. Intervention analysis (Table 3) indicated that there was no immediate effect of the BCMA on reported medication error and ADE rates. However, the introduction of the BCMA intervention was associated with a statistically significant gradual decrease in reported medication error and ADE rates at 0.002 percentage points per month ($p = 0.003$). The CLMS was associated with an immediate absolute decrease in reported medication error and ADE rates of 0.010% ($p = 0.020$) and remained stable, with no statistically significant change in trend.

Figure 3. Interrupted time series showing monthly rate of reported medication errors and ADEs (full model) .



ADEs = adverse drug events; BCMA = barcode medication administration; CLMS = closed-loop medication system.

Table 3. Changes in level and trend of reported medication errors and ADE rate (%): results from the ARIMA analysis.

	Reported medication errors and ADE rate (%)			
	BCMA intervention		CLMS intervention	
	Estimate (*SE*)	*p*	Estimate (*SE*)	*p*
Level change	0.007 (0.004)	0.119	-0.010 (0.004)	**0.020**
Trend change	-0.002 (0.001)	**0.003**	0.000 (0.000)	0.186

ARIMA = autoregressive moving average; ADEs = adverse drug events; BCMA = barcode medication administration; CLMS = closed-loop medication system.

Discussion

Safe administration of medication is essential to improving the quality of patient care (Durham et al. 2016). BCMA and CLMS interventions have been suggested as a highly reliable and proactive approach to reducing medication errors (Seibert et al. 2014; Shi et al. 2018). The process of administering medications safely to patients requires that nurses have high concentration (Qian et al. 2015). Additionally, competence to administer medication, including knowledge and appropriateness of medication, are key requirements for safe medication administration practices (CNO 2017). BCMA and CLMS have a significant impact on the professional practice of nurses by serving as a *systematic safety net* in medication administration and assisting nurses in preventing adverse events (Vanderboom et al. 2016).

The findings from this five-year study revealed that there was a significant, gradual decrease in the rate of reported medication errors and ADEs coinciding with the introduction of the BCMA technology and a significant immediate decrease following the introduction of the CLMS intervention. HRH has taken the lead in adopting advanced information technology to improve patient safety. Because the hospital administers approximately 3.2 million doses of medications per year, BCMA and CLMS technologies are expected to prevent approximately 366 potential medication errors and adverse events per year within the hospital.

The results of this study add to the evidence base providing support for implementing life-saving medication administration technology to reduce medication errors and ADEs.

There have been limited studies assessing the effectiveness of CLMS technology, and much of the previous literature on BCMA has only assessed its short-term impact (Bowers et al. 2015; Helmons et al. 2009). The results of this study suggest that the prevention of medication errors with the BCMA occurs gradually, likely due to the moderate learning curve associated with using the BCMA. The current research study also addresses the gap in the literature regarding the effectiveness of CLMS technology, which resulted in an immediate reduction in the incidence of errors.

There are limitations to the study design which are important to consider in the interpretation of the findings. First, it is likely that some medication errors were not detected or reported to the hospital electronic database; thus, such errors may only represent a portion of all medication errors. Second, this study did not have a control group comparator to further support the hypothesis that the interventions were causally associated with the decrease in medication error and ADE rate. Next, it is impossible to rule out concurrent interventions or changes associated with moving to a new facility that may have influenced the decrease in medication error and ADE rate post-CLMS integration. There may also have been underlying changes that occurred during the five-year span of the study that would have influenced the reported incidence rate, including changes in reporting practices, changes in organizational practices, implementation of smart infusion pumps and definitional changes to the outcome variable. In addition, the study was unable to compare improvements in incident classification and severity of harm over time due to the frequent reporting of the incidents as "other." Finally, analyses were based on a short pre-intervention trend due to the lack of digital data prior to September 2013.

Conclusion

These findings indicate that BCMA and CLMS medication administration technologies can be leveraged to prevent medication errors. The current research study adds to the body of knowledge regarding the effectiveness of CLMS technology, which resulted in an immediate reduction in the incidence of errors.
The findings from this study support the adoption of these technologies in other acute care hospitals to improve the safety of the practice environment, in particular for nurses as the predominant clinicians administering medications to patients.

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