OPEN

The Impact of Smart Pump Interoperability on Errors in Intravenous Infusion Administrations: A Multihospital Before and After Study

Jilian Skog, PharmD, Sally Rafie, PharmD,† Kumiko O. Schnock, PhD,‡ Catherine Yoon, MS,§ Stuart Lipsitz, ScD,§ and Pauline Lew, PharmD||*

Objective: The objective of this study was to assess the frequency, type, and severity of errors associated with intravenous medication administration before and after smart pump interoperability.

Methods: We conducted an observational study at a community healthcare system before and after implementing smart pump interoperability. Point prevalence methodology was used to collect data on medication administration and errors in adult inpatient settings.

Results: Observations were completed for 350 infusions preintervention (178 patients) and 367 postintervention (200 patients). Total errors significantly decreased from 401 (114.6 per 100 infusions) to 354 (96.5 per 100 infusions, $P = 0.02$). Administration errors decreased from 144 (41.1 per 100 infusions) to 119 (32.4 per 100 infusions, $P = 0.12$). Expired medication errors significantly reduced from 11 (3.1 per 100 infusions) to 2 (0.5 per 100 infusions, $P = 0.02$). Errors involving high-risk medications significantly reduced from 45 (12.8 per 100 infusions) to 25 (6.8 per 100 infusions, $P = 0.01$). Errors involving continuous medications significantly reduced from 44 (12.6 per 100 infusions) to 22 (6.0 per 100 infusions, $P = 0.005$). When comparing programming type, manual programming resulted in 115 (77.2%) of administration and user documentation errors compared with 34 errors (22.8%) that occurred when autoprogramming was used. Of these, errors involving high-risk medications reduced from 21 (84.0%) to 4 (16.0%) after using autoprogramming.

Conclusions: Smart pump interoperability resulted in a 16% reduction in medication administration errors. Despite using dose error reduction software and autoprogramming, some types of errors persisted. Further studies are needed to understand how technology use can be optimized.

Key Words: smart infusion pumps, safety, intravenous infusions, autoprogramming, interoperability, medication errors, integration

(*J Patient Saf* 2022;18: e666–e671)

Across the continuum of care, medication errors are widely recognized as significant contributors to patient harm and sources of preventable healthcare expenditure.[1,2] Intravenous (IV) medication errors often involve high-risk medications and require multiple steps for administration.[3] Several technologies have been used to address these errors including computerized prescriber order entry, barcode-assisted medication administration, and smart infusion pumps.[4] These technologies have improved quality and safety, but a high rate of errors still persists.[5] Multiple errors can often result from a single infusion, and errors continue to be prevalent among high-risk medications.

More recent advances in smart infusion pumps permit 2-way integration with the electronic health record (EHR).[6] This smart pump interoperability, also known as autoprogramming, has the potential to decrease errors by prepopulating smart pumps with ordered infusion parameters directly from the EHR, instead of through manual keystroke programming. Prepopulating a smart pump using integration also facilitates automatic utilization of the embedded dose error-reduction software (DERS). Dose error-reduction software functionality can avert errors through the use of customizable drug libraries with standard concentrations, dosing limits, and alerts (i.e., clinical notifications, soft limits, and hard limits).[7]

In a national survey of smart pump use among U.S. hospitals, the Institute for Safe Medication Practices found more than half reported that at least 1 error occurred during the prior year despite the use of smart pumps.[7] Among frontline nurses, 13% experienced wrong rate errors for secondary infusions, 12% experienced dose-rate confusion during pump programming, and 5% experienced the omission of a decimal point. Despite these challenges, only 15% of responding hospitals had implemented smart pump interoperability.

To determine the safety impact of smart pump interoperability across a variety of hospital settings, we conducted a prospective observational study using a point prevalence methodology. The objective of this study was to assess the frequency, type, and severity of errors associated with IV medication administration before and after smart pump interoperability.

METHODS

Study Design and Setting

This study was conducted at a community healthcare system of 3 hospitals, ranging from 181 to 524 beds in San Diego, California. Data were collected over 2 days per hospital site immediately before smart pump interoperability between June to August 2017 and again approximately 1 year after smart pump interoperability from August to September 2018.

Point prevalence methodology was used to collect data that compared actual medication administration with the EHR in a wide range of adult acute care patient care areas. Most hospital care areas, including critical care, medical-surgical, orthopedics, postoperative, and emergency care, were included; the operating room, labor and delivery, and outpatient infusion centers were excluded. Intravenous infusions that were included consisted of active continuous infusions, intermittent infusions, and IV fluids for patients not on contact precautions. Medications that were inactive (not infusing)

From the *Sharp Healthcare, Chula Vista; †Department of Pharmacy, University of California San Diego Health, San Diego, California; ‡Brigham and Women's Hospital, Harvard Medical School; §Brigham and Women's Hospital, Boston, Massachusetts; and ||Sharp Grossmont Hospital, Pharmacy, La Mesa, California.

Correspondence: Jilian Skog, PharmD, Sharp Healthcare, 2573 Oak Springs Dr, Chula Vista, CA 91915 (e-mail: Jilian.skog@sharp.com).

The authors disclose no conflict of interest.

This research was funded by Becton, Dickinson and Company.

or not administered using smart pumps, as well as epidural or patient controlled analgesia medications, were excluded.

Each hospital site, one at a time, went live with smart pump interoperability over a 2-week period, beginning in September 2017. To prepare for implementation, each hospital merged and streamlined pump libraries to meet autoprogramming requirements. Nurses and pharmacists were provided didactic, autoprogramming education with pump simulation and interactive online tutorial videos. After this, staff had to demonstrate competency with autoprogramming basics of medication selection, dose, infusion rate, and automated documentation. Staff competency was assessed through completion of a multiple scenario checklist during the hands-on demonstration portion of didactic training. Staff who required additional instruction were assisted individually. The checklists were reviewed and signed off by the class instructor. On-site education and information technology support were available for 2 weeks after each implementation.

The study protocol was deemed exempt by the Sharp Healthcare Institutional Review Board.

Data Collection

Study data were collected and managed using REDCap electronic data capture tools (Vanderbilt University, Nashville, TN) hosted at Partners HealthCare Research Computing.[8,9] REDCap (Research Electronic Data Capture) is a secure, web-based software platform designed to support data capture for research studies, providing 1) an intuitive interface for validated data capture; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for data integration and interoperability with external sources.

The data collection tool was adapted from those originally developed and used in previous studies.[5,10] Adaptations consisted of removing some data fields related to patient controlled analgesia because they were excluded from autoprogramming and adding an option to capture medications infused outside of drug library parameters. An additional adaptation was made to the postintervention data collection tool to collect data on whether the infusion was autoprogrammed using smart pump interoperability or manually programmed.

Three observers (2 pharmacist specialists and 1 clinical nurse specialist) compared the infusing medication, dose, and rate on the pump with the prescribed medication, dose, and rate in the EHR. Data collected included pump programming method, pump channel, whether infusion was actively infusing or not at the time of the observation, medication, concentration, dose, rate, medication omissions, EHR documentation accuracy, and smart pump use compliance. Labeling of the IV infusions according to the hospital policies was also assessed. Severity of each error was rated using the National Coordinating Council for Medication Error Reporting Prevention (NCC MERP) Index for Categorizing Medication Errors.[11]

Data Analysis

The collected data were analyzed as frequency of IV medication errors, broken down by error types and their NCC MERP severity rating. Error rate (per 100 infusions) was calculated as the number of identified errors per the number of observed infusions. Multiple errors could be recorded per single administration. We compared the error rates in the preintervention phase and the postintervention phase using a Poisson regression, with a dichotomous covariate for time. Administration errors were defined as any medication errors reaching the patient (i.e., any error with NCC MERP severity rating of C or greater). The error of bypassing the use of the smart pump or drug library is considered a violation of the institution's policy, and although it does not reach the patient, these errors were included as administration errors because of their high potential risk of harm. Errors with severity rating of D or greater were rated retrospectively by observers as to whether smart pump interoperability would have prevented the error.

The primary outcome was the administration error rate—those with the severity rating of C or greater (excluding labeling or user documentation error). A secondary outcome was medication errors and harm involving high-risk medications, defined by the Institute for Safe Medication Practices high-alert medication list.[12] High-risk medications included antiarrhythmics, anticoagulants (therapeutic doses only), electrolytes, insulin, neuromuscular blocking agents, opioids, vasopressors, and parenteral nutrition. This error type was a secondary outcome because of limited power to detect significant changes in frequency. All analyses were performed using SAS Version 9.4 (SAS Institute, Cary, NC).

RESULTS

A total of 350 infusions (178 patients) were observed during the preintervention phase and 367 infusions (200 patients) were observed during the postintervention phase. Table 1 shows the frequency and types of IV errors observed during the 2 periods. Of the infusions evaluated, 401 total errors (114.6 per 100 infusions) were observed during preintervention, which significantly reduced to 354 total errors (96.5 per 100 infusions) during postintervention ($P = 0.02$).

Labeling errors, the most frequent type of error in both phases, decreased postintervention, from 239 to 220 (68.3 to 59.9 per 100 infusions, $P = 0.16$).

Administration errors decreased from 144 to 119 (41.1 to 32.4 per 100 infusions, $P = 0.12$). These errors are specified in Table 1. Expired medication errors significantly declined from 11 to 2 (3.1 to 0.5 per 100 infusions, $P = 0.02$). Reductions were also seen in other administration errors from preintervention to postintervention, although these results were not statistically significant.

User documentation errors reduced from 18 to 15 (5.1 to 4.1 per 100 infusions, $P = 0.51$).

Errors associated with high-risk medications significantly decreased from 45 to 25 (12.8 to 6.8 per 100 infusions, $P = 0.01$). These included administration errors such as omitted medication, bypassing drug library use, unauthorized medication, wrong rate, expired medication, wrong library selection, and wrong dose, as shown in Table 1.

Drug library usage compliance rate increased from 92% (n = 291) during preintervention to 94.4% (n = 301) during postintervention.

Use of autoprogramming during postintervention was 83.2% (n = 321).

The number of infusions with errors (per single administration) by infusion type is shown in Table 2. The overall error rate declined from 138 to 122 (39.4 to 33.2 per 100 infusions, $P = 0.17$). Particularly with IV continuous medications, the error rate significantly reduced from 44 to 22 (12.6 to 6 per 100 infusions, $P = 0.005$), whereas nonsignificant increases were seen with IV fluids from 89 to 94 (25.4 to 25.6 per 100 infusions, $P = 0.96$) and IV intermittent medications from 5 to 6 (1.4 to 1.6 per 100 infusions, $P = 0.82$).

In reviewing postintervention errors by programming type, as shown in Table 3, 115 (77.2%) of all administration and user documentation errors occurred when manual programming was still used, as compared with 34 errors (22.8%) that occurred when autoprogramming was used. Of these, errors involving high-risk medications reduced from 21 (84.0%) to 4 (16.0%) after using autoprogramming. Improvements in errors that were directly related to autoprogramming were unauthorized medication, bypassing drug library use, wrong rate, wrong dose, and user documentation error. Improvement in error rates, which were independent of

TABLE 1. Summary of Medication Errors Observed Among IV Infusions

	Infusions*											
	Pre (n = 350)		Post (n = 367)		Potential Harm Using NCC MERP Index (Pre | Post)							
l	n	Rate†	n	Rate†	*P*	E	D		C		B		A
Total errors	401	114.6	354	96.5	0.02		1	143	119	256	235	1
Labeling errors	239	68.3	220	59.9	0.16					239	220	
Administration errors	144	41.1	119	32.4	0.12		1	143	119			
Omitted medication	43	12.3	47	12.8	0.84			43	47			
Unauthorized medication	35	10.0	24	6.5	0.11			35	24			
Bypassing drug library use	20	5.7	17	4.6	0.52			20	17			
Wrong rate	13	3.7	10	2.7	0.46			13	10			
Expired medication	11	3.1	2	0.5	0.02			11	2			
Wrong library selection	9	2.6	10	2.7	0.9			9	10			
Wrong dose	8	2.3	6	1.6	0.53		1	7	6			
Primary/secondary setting	2	0.6	1	0.3	0.55			2	1			
Wrong medication	1	0.3	2	0.5	0.6			1	2			
Wrong concentration	1	0.3	0	0	—			1				
Delay	1	0.3	0	0	—			1				
Wrong patient	0	0.0	0	0	—							
Wrong module/channel	0	0.0	0	0	—							
User documentation error	18	5.1	15	4.1	0.51					17	15	1
Patients with at least 1 error‡	88	49.4	98	49.0	0.95							
High-risk medication error	45	12.8	25	6.8	0.01							
Potentially harmful error§	1	0.29	0	0	—							

*Total patients in pre = 178. Total patients in post = 200.

†Rate per 100 infusions.

‡Rate per 100 patients.

§Any error rated harm D or greater.

autoprogramming included labeling, omitted medication, primary/secondary setting, delay, high-risk medication, and expired medication. These are shown in Table 1.

The study team defined each error type and assessed the preventability by autoprogramming for each error type (Table 4). Many errors were considered preventable with use of the technology.

DISCUSSION

Our study showed reductions in many medication errors associated with IV infusion pump programming after implementing smart pump interoperability or autoprogramming. Total errors and errors associated with high-risk medications were significantly reduced. Errors with expired medications also significantly decreased, which was an unexpected finding because this error type is independent of the technology. This may have been due to increased awareness regarding safety and accuracy among staff in the postintervention phase, which helped standardize variability in institutional policies or practices between the hospitals.

Other administration errors, which reduced after smart pump interoperability, were not statistically significant; however, they could be considered clinically significant. For example, unauthorized medication errors may occur when the technology is not used because of noncompliance and a medication is programmed manually, without an order, on the pump. This can create a patient safety concern if the infusing medication cannot be accounted for in the EHR. Preventing 1 error in bypassing drug library use can also be clinically significant because it may improve the overall safety of a patient. Programming the wrong dose or rate for 1 infusion can result in substantial patient harm, especially with high-risk medications. In addition, the number of infusions that had at least 1 error also trended downward. This can be clinically meaningful because 1 patient may have multiple infusions, each with the potential for multiple errors that may compound the potential for harm.

Labeling errors also declined, which was not statistically significant, but may represent another indirect benefit of the technology because of increased adherence to hospital policies.

A slight increase was seen with omitted medication, wrong library selection, and wrong medication errors. Omitted medication errors can still occur while using smart pump interoperability because these errors are independent of the technology. The technology only records data for medications while they are infusing

TABLE 2. Infusions With Errors by Infusion Type

	Pre			Post			
	n	Errors, n	Rate*	n	Errors, n	Rate*	*P*
All infusions	350	138	39.4	367	122	33.2	0.17
IV fluids	192	89	25.4	232	94	25.6	0.96
IV continuous medication	123	44	12.6	92	22	6.0	0.005
IV intermittent medication	35	5	1.4	43	6	1.6	0.82

*Rates per 100 infusions.

TABLE 3. Postintervention Errors by Pump Programming Type

	Manual Programming, n (%)	Autoprogramming, n (%)	Total
Observation/infusion data			
No. patients	59 (29.5)	141 (70.5)	200
No. infusions	111 (30.2)	256 (69.8)	367
IV fluids	72 (19.6)	160 (43.6)	232
IV continuous medication	29 (7.9)	63 (17.2)	92
IV intermittent medication	10 (2.7)	33 (9.0)	43
Nonlabeling error types			
Administration and user documentation errors	115 (77.2)	34 (22.8)	149
Administration errors	107 (79.9)	27 (20.1)	134
Omission of medication	46 (97.9)	1 (2.1)	47
Unauthorized medication	21 (87.5)	3 (12.5)	24
Bypassing drug library use	17 (100.0)	0	17
Wrong rate	5 (50.0)	5 (50.0)	10
Wrong library selection	3 (30.0)	7 (70.0)	10
Wrong dose	4 (66.7)	2 (33.3)	6
Expired medication	2 (100.0)	0	2
Wrong medication	1 (50.0)	1 (50.0)	2
Primary/secondary setting	0	1 (100.0)	1
Wrong concentration	0	0	0
Delay	0	0	0
Wrong patient	0	0	0
Wrong module/ channel	0	0	0
User documentation error	8 (53.3)	7 (46.7)	15
Administration and user documentation errors involving high-risk medications	21 (84.0)	4 (16.0)	25

intravenously from the smart pump. It does not detect when an ordered medication is not currently hung at the bedside because of human error. Manual programming was not completely eliminated by the technology, especially for drugs that had multiple indications and still required manual selection within the drug library. This combination of manual and autoprogramming was challenging to adopt and could have created new types of errors. Wrong medication errors are preventable using barcoding technology, which works with, but is not included in, autoprogramming. Although the increase in these errors were not statistically significant, they may have been related to the steep learning curve associated with the technology, lack of compliance with new workflow, or inadequate training regarding autoprogramming.

Regarding infusions with errors by infusion type, there was not a consistent pattern in our study. Intravenous continuous medication errors reduced significantly, which is of particular benefit because these may require a higher level of critical thinking for safe pump programming and usually have a narrow therapeutic window. A published study of 2 high-risk continuous infusions, epinephrine and norepinephrine, found improved documentation and fewer alerts after integration.[13] In contrast, fluid and intermittent errors slightly increased in our study. These were not significant but may be explained by the previous limitations of the technology and knowledge gaps in its adoption.

When further comparing errors by programming type, nearly all errors decreased when smart pump interoperability or autoprogramming was used, as compared with manual programming. This was true, despite the sample size of infusions in the autoprogramming group, being twice that of the manual programming group. Improvements were seen even among errors that previously measured higher in the postintervention period. For example, omitted medication errors increased in the postintervention measurements; however, these predominantly occurred when autoprogramming was not maintained. In our study, postintervention was not synonymous with autoprogramming. This was because, during postintervention, autoprogramming was available but not used 100% of the time because of staff noncompliance. One would expect that manual errors would be reduced using technology. Literatures states that autoprogramming reduces manual keystrokes by an average of 86% of all IV administrations.[6] This may allow staff the ability to focus on other aspects of patient care or safety. Expert use of the technology at 100% compliance can further reduce errors; however, it may be difficult to achieve after adopting new technology.

Other added benefits, after implementation of smart pump interoperability, included the increased use of the pump drug library. This reduced the use of "basic infusion," which does not apply any safeguard dosing or infusion limits and does not identify the infusing medication name. We achieved library compliance above the 90% benchmark, before beginning the study, which demonstrates the success of library use at our institution. In addition, the autoprogramming compliance rate of 83.2%, during postintervention, also represented a high degree of successful implementation at our facilities. To improve this further, obstacles in using the technology need to be reviewed and perhaps supplemented with additional education.

User documentation error was reduced in the postintervention phase, however, not substantially. This may have been related to the challenges described earlier in learning the new technology. Integration with the EHR allows for autodocumentation of infusion volumes, doses, and times. However, a nurse must still review and sign off the data before it flows to the EHR. This was a change in nursing workflow and required additional, manual steps, which might have introduced new errors. Perhaps not all aspects of medication administration can or should be automated; however, future advances that streamline the technical workflow may be helpful.

Finally, we assessed whether the identified errors could be prevented by smart pump interoperability. Many of the errors, with correct use of the technology, were considered preventable. Errors that were both directly and indirectly related to using the technology improved. This may represent opportunities for improvement in the medication administration process and may demonstrate the indirect benefits of autoprogramming. Although our results do not demonstrate elimination of errors, patient safety may have been improved.

Our study had several limitations. First, the study design was observational, using a point prevalence approach; thus, the number of observations was limited by what infusions were available on the data collection days. Data collection only occurred over 2 days, during day shift, in each period and was conducted in a manner that would not interfere with patient care. This may have limited the sample size or sampling times and may not have represented nursing practice in its entirety. In addition, the observers were not able to capture all of the active infusions at each site, because of

TABLE 4. Error Definitions and Preventability by Autoprogramming Technology

Error type	Definition	Preventability by Autoprogramming Technology
Labeling errors		
Labeling	Documented information on the medication label is different from required information per institution policy.	No. This is independent of the technology.
Administration errors		
Omitted medication	The medication ordered was not administered to a patient or administered any time after 4 h of the intended start time.	No. Technology does not prevent IV fluid or medication that is not administered.
Unauthorized medication	Fluids/medications are administered to the patient, but no order is present in medical record. This includes failure to document a verbal order.	Yes.
Bypassing drug library use	Smart pump is not used (bypassing smart pump) or smart pump was used but the drug library was not selected and manual entry mode was used (bypassing drug library)	Partially. User can manually bypass during autoprogramming.
Wrong rate	A different rate is displayed on the pump from that prescribed in the medical record. Also refers to weight-based doses calculated incorrectly including using a wrong weight.	Yes, upon initial, autoprogramming. Subsequent rate titrations are manually programmed and independent of technology.
Expired medication	The expiration date or time of the fluids/medications has passed.	No. This is independent of the technology.
Wrong library selection	A pump library item was selected that is different from the prescribed order.	Yes, upon initial autoprogramming. Subsequent therapy selections are manually programmed and independent of technology.
Wrong dose	The same medication but the dose is different from the prescribed order.	Yes, upon initial, autoprogramming. Boluses are manually programmed and independent of technology.
Primary/secondary setting	Setting programmed into the pump is different from the prescribed order.	No. This is independent of the technology.
Wrong medication	A different fluid/medication, as documented on the IV bag label, is being infused compared with the order in the medical record.	No. This is independent of technology.
Wrong concentration	An amount of a medication in a unit of solution that is different from the prescribed order.	Yes.
Delay	An order to start or change medication or rate not carried out within 4 h of the written order or intended start time per institution policy.	No. This is independent of the technology.
Wrong patient	Patient has either no identification band on or information on the identification band or label is incorrect.	Yes
Wrong module/channel	Use of a module/channel that is different from the intended module/channel.	No. User sets up pump. This is independent of technology.
Documentation errors		
User documentation	User incorrectly signs infusion data, signs on the wrong medication, wrong patient or manually changes infusion rates/volumes to an incorrect amount.	No. Technology does not prevent incorrectly signed documentation.

the standardized infusion times set forth by each site. This was most apparent with the IV intermittent infusions, which were only infused at designated times. We did not select the study sample with randomization or blinding. This may have introduced study bias because an observer may assume higher accuracy after observing that autoprogramming was used. Therefore, our results may show an association but not causation. Not all hospital care areas implemented the technology, so that may have represented missed opportunities in our research. Outpatient areas, operating rooms, and infusion centers were excluded from implementation. Furthermore, there were multiple data set updates to the pump's drug library to improve workflow and reduce the potential for errors between the 2 study periods. This continual and dynamic process, although helpful for autoprogramming success, may have caused interruptions in workflow or utilization of the technology. Last, our study was industry sponsored, which may have also contributed to study bias.

These findings helped identify important learning lessons. When the technology was used correctly, errors for IV infusions were reduced dramatically. The study investigators reflected on implementation and believed that the hands-on training and data set library updates were critical in transitioning to the new technology. Additional education to address troubleshooting, along with extending the on-site support period, could have reduced implementation obstacles and errors further. Of course, advanced technologies cannot replace critical thinking because the infusion of IV medications is a complex and multistep process.

CONCLUSIONS

Smart pump interoperability resulted in a 16% reduction in medication administration errors. Before smart pump interoperability, errors persisted despite using dose error reduction software, medication barcode scanning, and pump autoprogramming. Severe

errors reaching patients may be reduced with smart pump interoperability, especially when the technology is used properly. We observed reductions in errors that were directly related to, and also independent of, the technology. However, clinicians must still use professional judgment for safe medication administration to gain the full benefit. Further studies are needed to understand how technology optimization can affect practice improvement.

ACKNOWLEDGMENTS

The authors thank Julie DeVaney, RN, for assisting with data collection, Sally Rafie, PharmD, from Becton, Dickinson and Company (BD) as a consultant, and Nicole Wilson, RN, and Sneh Ringwala, PharmD, from Becton, Dickinson and Company (BD) for assisting with text and providing definitions. The authors also thank Albert Rizos, PharmD, for helping initiate study coordination and clarify Sharp Healthcare policies and protocols.

REFERENCES

1. Agency for Healthcare Research and Quality. Medication errors and adverse drug events. September 7, 2019. Available at: https://psnet.ahrq.gov/primer/medication-errors-and-adverse-drug-events. Accessed September 12, 2020.
2. Hug BL, Keohane C, Seger DL, et al. The costs of adverse drug events in community hospitals. *Jt Comm J Qual Patient Saf*. 2012;38:120–126.
3. Lahue BJ, Pyenson B, Iwasaki K, et al. National burden of preventable adverse drug events associated with inpatient injectable medications: healthcare and medical professional liability costs. *Am Health Drug Benefits*. 2012;5:1–10.
4. Pedersen CA, Schneider PJ, Scheckelhoff DJ. ASHP national survey of pharmacy practice in hospital settings: monitoring and patient education-2015. *Am J Health Syst Pharm*. 2016;73:1307–1330.
5. Schnock KO, Dykes PC, Albert J, et al. The frequency of intravenous medication administration errors related to smart infusion pumps: a multihospital observational study. *BMJ Qual Saf*. 2017;26:131–140.
6. Biltoft J, Finneman L. Clinical and financial effects of smart pump-electronic medical record interoperability at a hospital in a regional health system. *Am J Health Syst Pharm*. 2018;75:1064–1068.
7. Institute for Safe Medication Practices. Smart pumps in practice: survey results reveal widespread use, but optimization is challenging. Medication Safety Alert! *Acute Care*. 2018;23:1–5.
8. Harris PA, Taylor R, Thielke R, et al. Research Electronic Data Capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform*. 2009;42:377–381.
9. Harris PA, Taylor R, Minor BL, et al. The REDCap consortium: building an international community of software platform partners. *J Biomed Inform*. 2019;95:103208.
10. Schnock KO, Dykes PC, Albert J, et al. A multi-hospital before-after observational study using a point-prevalence approach with an infusion safety intervention bundle to reduce intravenous medication administration errors. *Drug Saf*. 2018;41:591–602.
11. Hartwig SC, Denger SD, Schneider PJ. Severity-indexed, incident report-based medication error-reporting program. *Am J Hosp Pharm*. 1991;48:2611–2616.
12. Institute of Safe Medication Practices. List of high-alert medications in acute care settings. 2018. Available at: https://www.ismp.org/sites/default/files/attachments/2018-08/highAlert2018-Acute-Final.pdf. Accessed September 12, 2020.
13. Joseph R, Lee SW, Anderson SV, et al. Impact of interoperability of smart infusion pumps and an electronic medical record in critical care. *Am J Health Syst Pharm*. 2020;77:1231–1236.