Drug Saf (2014) 37:1011–1020
DOI 10.1007/s40264-014-0232-1

SYSTEMATIC REVIEW

Benefits and Risks of Using Smart Pumps to Reduce Medication Error Rates: A Systematic Review

Kumiko Ohashi · Olivia Dalleur · Patricia C. Dykes · David W. Bates

Published online: 8 October 2014

Abstract

Background Smart infusion pumps have been introduced to prevent medication errors and have been widely adopted nationally in the USA, though they are not always used in Europe or other regions. Despite widespread usage of smart pumps, intravenous medication errors have not been fully eliminated.

Objective Through a systematic review of recent studies and reports regarding smart pump implementation and use, we aimed to identify the impact of smart pumps on error reduction and on the complex process of medication administration, and strategies to maximize the benefits of smart pumps.

Methods The medical literature related to the effects of smart pumps for improving patient safety was searched in PUBMED, EMBASE, and the Cochrane Central Register of Controlled Trials (CENTRAL) (2000–2014) and relevant papers were selected by two researchers.

Results After the literature search, 231 papers were identified and the full texts of 138 articles were assessed for eligibility. Of these, 22 were included after removal of papers that did not meet the inclusion criteria. We assessed both the benefits and negative effects of smart pumps from these studies. One of the benefits of using smart pumps was intercepting errors such as the wrong rate, wrong dose, and pump setting errors. Other benefits include reduction of adverse drug event rates, practice improvements, and cost effectiveness. Meanwhile, the current issues or negative effects related to using smart pumps were lower compliance rates of using smart pumps, the overriding of soft

Electronic supplementary material The online version of this article (doi:10.1007/s40264-014-0232-1) contains supplementary material, which is available to authorized users.

K. Ohashi (✉) · O. Dalleur · P. C. Dykes · D. W. Bates
Division of General Internal Medicine and Primary Care, Brigham and Women's Hospital, 1620 Tremont Street, OBC-3, Boston, MA 02120-1613, USA
e-mail: kohashi@partners.org

D. W. Bates
e-mail: dbates@partners.org

O. Dalleur
Louvain Drug Research Institute/Cliniques universitaires Saint-Luc, Université catholique de Louvain, Brussels, Belgium
e-mail: ODALLEUR@PARTNERS.ORG

P. C. Dykes
Center for Excellence in Nursing Practice, Brigham and Women's Hospital, Boston, MA, USA
e-mail: pdykes@partners.org

Key Points

Smart pumps reduce but do not eliminate programming errors.

The literature noted a number of limitations of current smart pumps, including lower compliance rates of using smart pumps, overriding soft alerts, non-intercepted errors, and the possibility of using the wrong drug library.

Opportunities for improvement of smart pumps include upgrading drug libraries, developing standardized drug libraries, decreasing the number of unnecessary warnings, and developing stronger approaches to minimize workarounds.

alerts, non-intercepted errors, or the possibility of using the wrong drug library.

Conclusion The literature suggests that smart pumps reduce but do not eliminate programming errors. Although the hard limits of a drug library play a main role in intercepting medication errors, soft limits were still not as effective as hard limits because of high override rates. Compliance in using smart pumps is key towards effectively preventing errors. Opportunities for improvement include upgrading drug libraries, developing standardized drug libraries, decreasing the number of unnecessary warnings, and developing stronger approaches to minimize workarounds. Also, as with other clinical information systems, smart pumps should be implemented with the idea of using continuous quality improvement processes to iteratively improve their use.

1 Introduction

Administration of intravenous medications can cause adverse drug events (ADEs) and is a major issue for patient safety in any hospital setting [1]. Infusion pumps were first introduced to the healthcare industry 40 years ago, serving as basic rate/volume devices and used primarily for the purpose of administering nutritional and cardiovascular drugs initially [2]. However, over time these simple infusion pumps have evolved into sophisticated systems with multiple safety features.

The term 'smart pump' was coined by the Institute for Safe Medication Practices (ISMP) [3]. Smart pumps (also called smart infusion pumps or intelligent infusion devices) incorporate software programs known as dose error reduction systems (DERS) and drug libraries [2]. Drug libraries are key components of smart pumps. They contain predefined parameters for the drug type, strength, and dosing limits of specific drugs and can be set up for continuous infusions, boluses, and intermittent infusions [4]. The drug library is usually customized for each hospital's practice, and is also generally tailored for specific care units and needs. The main functions of smart pumps include clinical advisories and alert indications. One of the expected benefits of smart pump technology is a reduction in errors related to oversight and miscalculated doses [4, 5]. By ensuring that the selected dosing is appropriate for the specific medication and the patient, errors can potentially be averted through pump alerts to clinicians, allowing them to recognize and correct possible programming errors [1]. Soft limits are simple alerts that can be overridden by clinicians, while hard limits are restrictive and cannot be overridden. To override soft limits, the system usually requires confirmation by clinicians in order to set the smart pump. As an added value, pump software typically automatically logs data on all alerts, medications, and programming events, providing information to guide quality improvement and to determine the impact of the pumps on medication safety [6]. Wireless connectivity to enable remote updating of drug libraries and downloading of logs is one of the important features for newer smart infusion pumps.

According to the American Society of Health System Pharmacists (ASHP) national survey of pharmacy practice in hospital settings, overall 77.0 % of hospitals in the USA used smart infusion pumps in 2012 [7]. The use of smart pumps varied by hospital size, with the largest hospitals being the most likely to employ the technology (96.2 % in hospitals with more than 600 beds). The smart pump adoption rate in the USA has doubled since 2005 [7]. This growing adoption rate of smart pumps corresponds with the implementation of other technologies for quality and safety improvement such as electronic health records (EHRs), computerized physician order entry (CPOE), and barcode-assisted medication administrations (BCMA) [7].

Implementing a new system can be challenging and some authors have reported their experience with implementation of smart pumps and lessons learned [1, 8–10]. The implementation of smart pumps requires changes in nursing workflow and is not a single process of implementation. Maximizing the benefits of smart pumps requires continuous training of users, maintenance of pumps, and updates of drug libraries. Some early studies tried to identify the safety impact of smart pump use; however, their effects on the medication error rate were typically unclear or mixed, often in part because of workarounds [1, 8, 11]. Clearly, the technology has not eliminated all intravenous medication errors.

Several literature reviews have also been conducted to identify the effects of smart pumps on medication error prevention [5, 12]. One of the reviews assessed the potential for improved patient safety with the introduction of smart pumps in a hospital setting [5]. Another review study pointed out the lack of well-designed research with respect to the effectiveness of smart pumps in preventing medication errors [12]. These summaries were conducted as literature reviews from 2008 to 2009. Since smart pump technology has progressed over the past 5 years, a systematic review is needed to meaningfully assess these recent progressions. We performed a systematic review of the literature to assess the potential benefits and risks of smart pumps. We assessed not only the impact of smart pumps on error reduction and on the complex process of medication administration, but also tried to identify strategies for maximizing the benefits of smart pumps.

2 Methods

2.1 Search Strategy

Medical literature from January 2000 to April 2014 using PUBMED, EMBASE, and the Cochrane Central Register of Controlled Trials (CENTRAL) were searched by two authors (OD/KO). Combinations of the following keywords were used to retrieve the articles regarding smart pumps (MeSH and Emtree): 'smart pump' OR 'smart pumps' OR 'intravenous smart pumps' OR 'smart IV pump' OR 'smart pump safety' OR 'smart pump technology'. After reviewing the results, references of relevant articles and volumes of the *Journal of Infusion Nursing* were hand searched. These results were pooled using bibliographic software (Refworks; Refworks-COS, Bethesda, MD, USA) and duplicates were eliminated.

2.2 Inclusion and Exclusion Criteria

The search was limited to original papers written in English only. Reviews, case reports, abstracts, and proceedings were excluded. Inclusion criteria for study design were descriptive observational, randomized controlled trials (RCTs), and before–after comparison study (see Electronic Supplementary Material 1). One author (OD) reviewed the titles and abstracts to identify potentially relevant articles, of which two authors (OD/KO) independently reviewed the full manuscripts.

The criteria for inclusion in the quantitative analysis were description of the following:

- Implementation of smart pumps, including large infusion pumps or patient-controlled analgesia (PCA) pumps. Pumps for administration of blood products, total parenteral nutrition, or insulin were excluded.
- Pump-related quality outcomes measures, including frequency and type of alerts generated, compliance rate to the drug library, and user's behavior after an alert.
- Safety outcomes measures such as prevention of errors and/or ADE.

The compliance rate with use of the drug library was defined as the number of infusions programmed through the safety software per 100 infusions started rather than manual programming [13]. The user's behavior after a smart pump's alert includes override of the alert, reprogram according to the library recommendation, and cancel the administration [13, 14]. The design and manuscript structure of this systematic review conform to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statements [15].

3 Results

3.1 Characteristics and Main Outcomes of Included Studies

The flow chart in Fig. 1 describes the selection process of the studies that met the inclusion criteria. The search of databases using all keywords identified 219 papers after removal of duplicates. Twelve articles were added following the hand search. Of these 231 articles, 93 were considered irrelevant on the basis of their title and abstract and were removed. The full texts of the remaining 138 articles were assessed for eligibility. Of these, 22 were included in the quantitative analysis and 116 were excluded because they did not meet inclusion criteria, such as non-original research papers, not reporting outcomes using smart pumps, or non-English papers (see Table 1). Two papers were published by different authors that described the same study, but different sets of findings [10, 16]. Therefore, the two papers were counted as a single study. A categorization of excluded papers is shown in Table 1. The characteristics and main outcomes of each study that met the inclusion criteria are summarized in the Electronic Supplementary Material 1.

Most of the studies (16/21) were conducted in the USA and others were conducted in Canada, Australia, Spain, and Germany. One study was an RCT [8], ten studies described results after implementation [6, 14, 16–23], seven studies compared data before and after implementation of smart pumps [1, 23–28], and one study used an experimental design in a high-fidelity simulated inpatient unit [11].

The main outcomes of the study included medication errors intercepted and recorded in the smart pump logs in 12 studies [6, 8, 13, 14, 16, 17, 20, 22, 23, 28–30], errors observed in ten studies [1, 8, 11, 16, 18–21, 27, 29], and ADEs or error reports in nine studies [8, 22–29]. Depending on the study, the smart pumps were used in isolation or integrated into information systems (e.g., CPOE, BCMA) [20, 25, 29].

Implementation of the smart pumps was accompanied by an education intervention in four cases [1, 6, 16, 22]. Five studies focused on specific drugs, namely anticoagulants [17, 23] and analgesics administered through PCA pump [25, 27, 28].

The included studies were heterogeneous in terms of methodology and outcome measures, including a limited description of the design and variability in the comprehensiveness of the data provided. There was only one RCT. Therefore, we did not attempt to summarize the data statistically. Moreover the measure of self-reported ADEs or errors of administration might induce a bias by underreporting. Variables potentially affecting the results were not always reported or their influence may not have been assessed [25, 28].

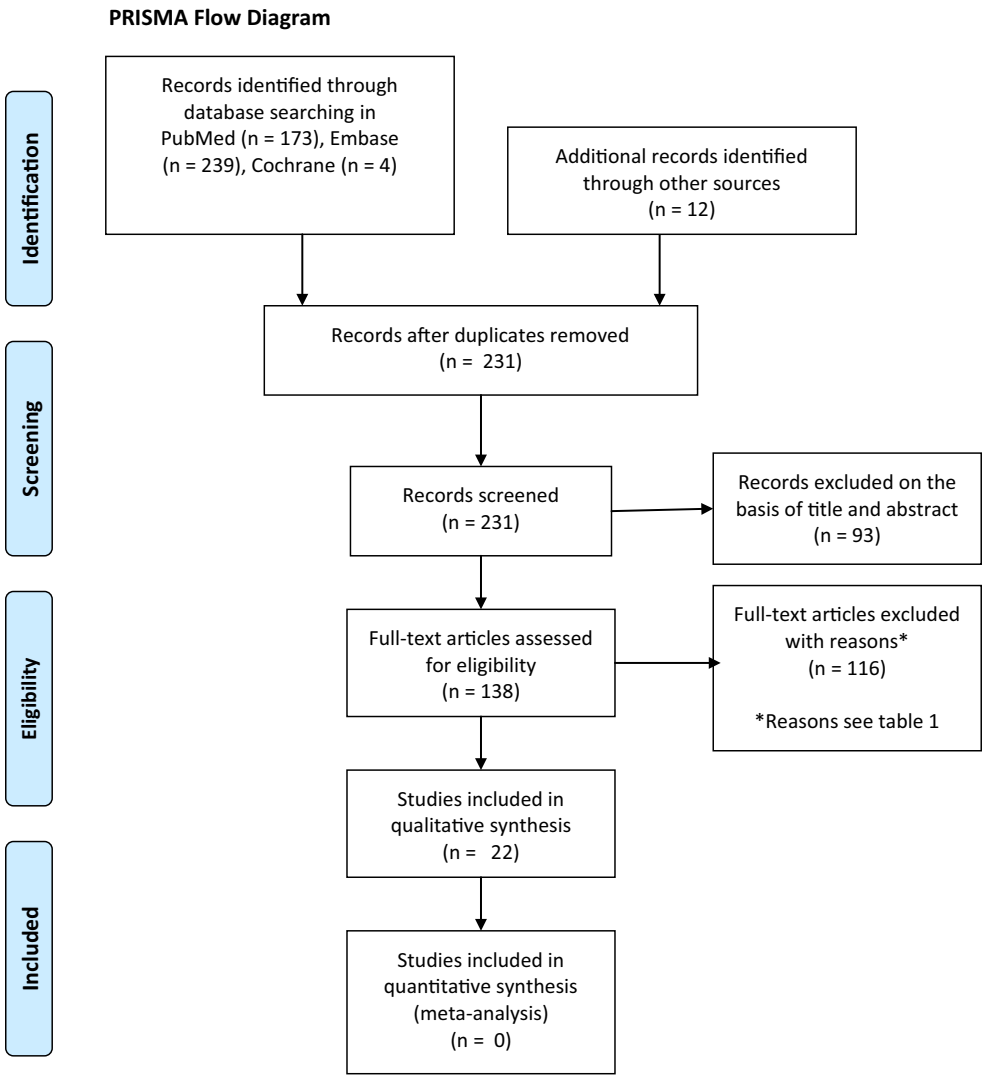

Fig. 1 The literature selection process

Table 1 Reasons for exclusion from the review

Category	Number of citations
Review, letter, comment	54
Case report, proceeding, abstract	17
Intervention where outcomes were not measured, or outcome does not meet inclusion criteria	37
Irrelevant or wrong indexing (including glucose, non-English papers)	8
Total	*116*

3.2 Benefits Associated with Smart Pumps

3.2.1 Intercepted Errors with a Smart Pump Drug Library

Smart pump technology intercepted and prevented various error types, mostly wrong rate, and wrong dose and pump setting errors [1, 11, 18, 21, 28]. These errors occurred mainly due to keypad entry errors (transposition of doses and rates) or transcript of medication orders (e.g., misplaced zeros and/or decimal points which may cause over-/under-dosing errors) [28].

Numbers of hard limit alerts and soft limit alerts that were canceled or reprogrammed were interpreted as potentially prevented errors by the authors of the studies [6, 13, 16, 28, 30]. A study conducted in a simulated care unit observed the behavior of nurses with smart pumps; nurses corrected 75 % of hard limits for wrong dose but the rest used the pump in its standard rate-based mode (no safeguard) [11]. When the smart pump was combined with barcode scanning, the proportion of remedied errors rose to 79 %.

The severity of the errors was assessed and rated with the National Coordinating Council for Medication Error Reporting and Prevention (NCC MERP) Index in a few studies [8, 18, 21, 27, 28]. In these studies, the majority of errors were rated as category C (e.g., no harm event

occurred) but a few errors were rated as the most severe error category H (e.g., patient required intervention to sustain life [28]). Also, some studies included examples of potentially fatal errors prevented (e.g., norepinephrine drip at 100 times the intended dose, heparin drip programmed at 13 times the intended dose) [16], or summarized the severe errors by how severe the dosing errors were (e.g., 6.5 % of >100-fold potential overdoses, 25.2 % of 100-fold potential underdoses) [23]. In one study performed in a pediatric hospital, the implementation of smart pumps resulted in a 73 % decrease in the reported medication error rate [24]. Also in the pediatric setting, Manrique-Rodriguez et al. [13] performed an assessment of the severity of intercepted errors in a pediatric intensive care unit. Half of the intercepted errors were rated as being of moderate, serious, or catastrophic impact. Another study showed that smart pumps prevented 717 potentially dangerous overdoses over a period of 20 months in a German hospital [30].

3.2.2 Impact of Smart Pumps on Adverse Drug Events

A few studies evaluated the impact of smart pumps on ADEs, with variable results. On one hand, a before–after study on PCA smart pumps showed a significant 22 % decrease in ADEs recorded by an automated surveillance system [25]. Voluntary report events also decreased significantly by 72 % [25]. On the other hand, another study, by Nuckols et al. [26] failed to show an impact of the smart pumps on the incidence of preventable ADEs. In an RCT by Rothschild et al. [8], no difference in the ADE rate was observed in the intention-to-treat analysis. However, after correcting for compliance, the group using smart pumps had a lower preventable ADE rate, which decreased from 0.28 to 0.18 per 100 patient-pump days, but this difference was not significant ($p = 0.27$).

3.2.3 Practice Improvement and Other Benefits

A number of studies provided examples of practice improvements after implementation of smart pumps. For example, at one site the protocol previously in use for weight-based heparin required manual rate calculation by steps, but after implementing smart pumps at least three steps were eliminated [16]. Another frequently reported advantage of smart pumps is their capacity to record data about the infusion process that was previously unavailable [6, 8, 16, 17, 30]. Smart pump logs are a major recourse for obtaining objective data about intercepted potential errors, which can be utilized to improve medication safety. Unlike incident reports, which have reporting bias, hospitals can calculate objectively how often errors are being prevented. These types of data are also useful for feedback and to educate care teams [6]. For example, analysis of the smart pumps data logs in the Carolinas HealthCare System helped them to identify a problem with a high-risk drug, vancomycin, which was repeatedly being underdosed because of programming in milligrams instead of grams. Consequently, they modified the library, using a system-wide approach to increase patient safety [6]. Other perceived benefits include giving nurses a feeling of safety and improved satisfaction [14, 16].

3.2.4 Cost Effectiveness

One study assessed cost avoidance achieved through the averting of potential ADEs. One way to analyze cost avoidance related to smart pumps is to calculate return on investment by examining the number of critical errors prevented. The Institute of Medicine (IOM) estimated that each preventable ADE that took place in a hospital added about US$8,750 (2006 values) to the cost of a hospital stay (IOM report). Mansfield and Jarrett [6] used this number to estimate cost avoidance for 3,328 errors and estimated a total savings of US$29,120,000 per year in an 860-bed medical center. However, it is unclear whether all of these errors would actually have resulted in harm. Furthermore, smart pumps have substantial costs—both the hardware and implementations are costly [17], and the safety benefits are not guaranteed [11].

3.3 Negative Impact of Smart Pumps

3.3.1 Drug Library Compliance

Compliance with the drug library is a critical aspect of the success of the smart pump in preventing adverse events and increasing medication safety [13]. The compliance rates reported in the studies ranged widely, from 62 % [1] to 98 % [16]. Education and feedback to the care teams can be used to improve compliance [1, 16, 22]. Bypassing of the library varies according to the drug involved. In the study by Rothschild et al. [8], users bypassed the library in 68 % of proprofol infusions and 61 % of insulin infusions, while the average bypass rate was 25 %.

3.3.2 Override of Soft Alerts

Several studies report high override rates for soft alerts [14, 16, 28], which may limit the benefits of the pumps if users develop alert fatigue. Analysis of override rates by drug can enable refinement of drug libraries. In a continuous quality improvement (CQI) program, Skledar et al. [22] refined the drug library of the smart pumps on several occasions, taking into account the most frequently involved

drugs, recent evidence, and experts' advice. These library revisions reduced the number of alerts by 72 % [22].

3.3.3 Non-Intercepted Errors by Smart Pumps

Smart pumps have a limited effect without the use of the DERS [1]. A before–after study showed a 79 % reduction of errors when using the software, but no significant difference without it [1]. All studies reported that errors persisted after implementing smart pumps; one study detailed the types of errors that persisted [23]. These errors included programming errors, prescribing errors, omission, and administration preparation errors [18, 21]. Errors that cannot be caught by smart pumps alone include wrong drug administration [11, 21], unauthorized drug administration [21], wrong patient [11, 21], secondary infusion errors [11], label errors [18, 21], and clamped intravenous lines [18]. Combination of smart pumps with barcode scanning systems can prevent wrong patient errors [11]. However, without an interface with other systems, only rate errors are preventable by smart pumps [21]. The lack of integration with other systems is a limiting factor to achieving the potential benefits of smart pumps [11, 19, 26, 30]. Lack of access to wireless connectivity is perceived as a barrier to the implementation of smart pumps [13].

3.3.4 Limited Functionality of Smart Pumps

Drugs requiring dose titration present a particular challenge in the use of smart pumps [20]. Evans et al. [20] showed that nurses often felt that the response of the patient to dopamine was not quick enough and they then increased the dose to get a response sooner, generating an alert; the pumps need to include logic for titrated drugs. Lack of bolus doses in the libraries is also a frequently reported reason for overrides [14, 16, 26].

3.3.5 Potential Negative Effects Associated with Use of Smart Pumps

Some studies indicated errors that might be introduced by the use of smart pumps. First, Husch et al. [21] described the risk of having errors in the library and also the risk of needing drugs not available in the library [13]. Second, the risk of causing an error by selecting the wrong library has been mentioned in several studies [1, 18], although it has not actually been observed often [8, 21, 26]. Tran et al. [28] did report one error of selecting the wrong drug library in a study including 16,249 PCAs over 1 year. Several studies, including the RCT, specified that they did not observe any negative impacts, errors, or injuries related to smart pumps [8, 13, 21, 26].

4 Discussion

4.1 Key Prescribing and Administration Processes Improved by Smart Pumps

Smart pumps represent a technology that can address the major clinical risks associated with the use of intravenous medications, which can cause substantial harm. However, the studies that have been performed to date have been mixed, and the pumps have substantial costs and are just one of many safety technologies that hospitals might want to implement. Therefore, we performed a systematic review to assess both their benefits and risks. We found substantial variability in impact by study, with one study finding a substantial reduction in the medication error rate [25], while other studies found limited benefits [8, 21]. It is clear that compliance with the drug library is a key determinant of whether or not benefit will be achieved.

Figure 2 illustrates the potential errors in the process of administering infusions with smart pumps. In previous studies, our research team members have investigated the effects of health information technology at key stages in the process of medication use (ordering [31], transcription [32], dispensing [33], and administration [32]). In this study, our team focused on the administration phase, specifically errors that can be prevented by using smart pumps. This chart also shows how smart pump functionality can intercept errors. In the medication ordering phase, if nurses did not administer the drug or delayed the administration for a certain time, that is an 'omission' or 'delay' error. In contrast, if there was no physician order but a medication was administered, then that is an 'unauthorized medication error'. In the administration phase, regardless of whether the order was written or not, errors may also occur, despite the smart pumps, such as patient identification error, documentation errors, or labeling errors on intravenous medications [18, 21]. Some errors such as pump setting errors (secondary intravenous clamp was closed and being delayed) or wrong patient errors occurred during the preparation phase [18, 21]. Therefore, it is important to include the ordering and preparation of medication phases as a part of the practice of using smart pumps.

4.2 Smart Pump Drug Library Use Compliance

This review showed that the compliance rate with drug library use varied depending on hospitals, and the use of drug libraries for solution libraries were very common.

In a process chart (Fig. 2), it is clear that a lower compliance rate of drug library use itself limits the beneficial effects of using smart pumps. Bypassing use of the drug library can cancel all the benefits of the smart pump safety features. Some studies showed reasons for the

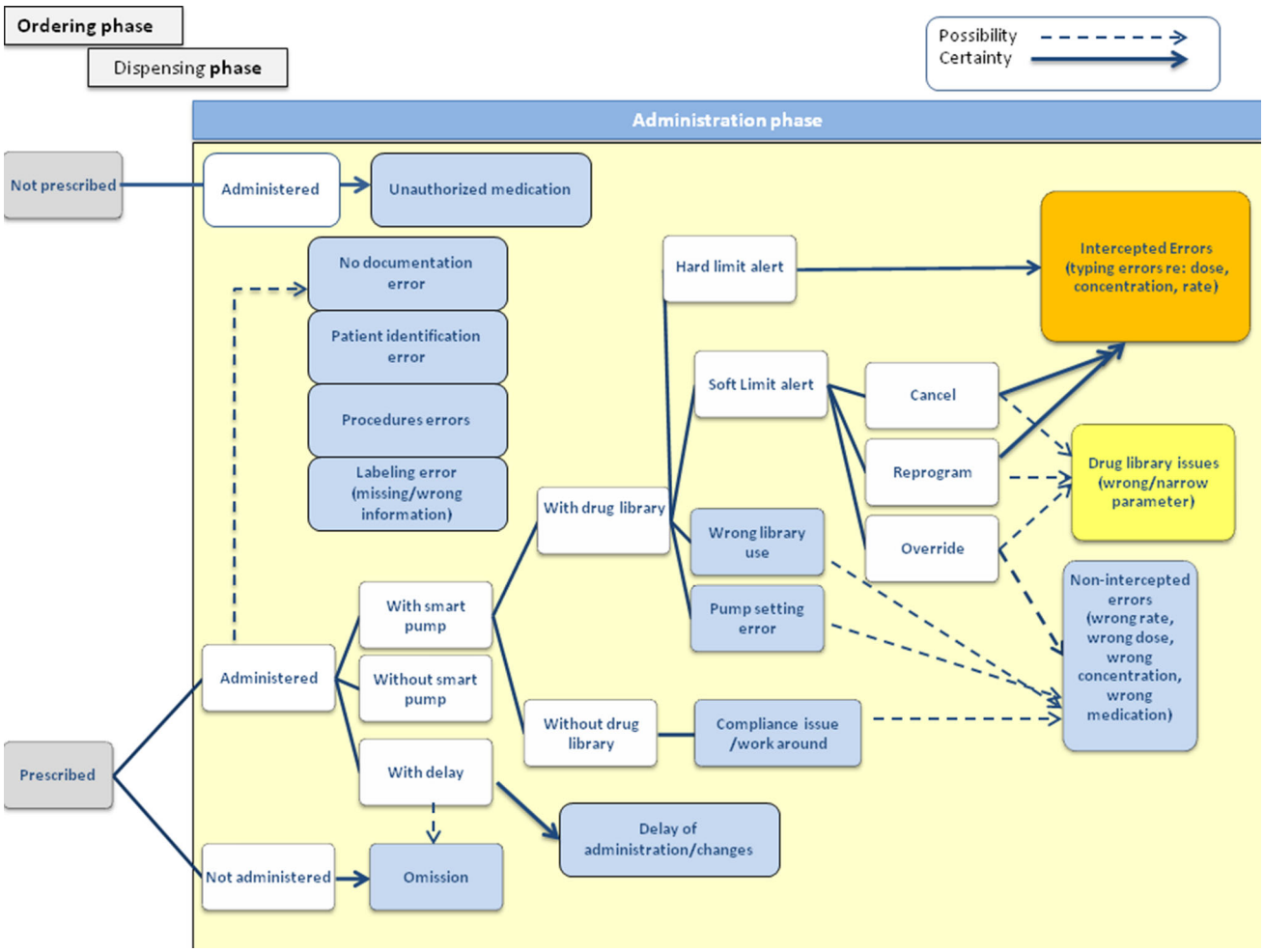

Fig. 2 Processes of intravenous medication administration with smart pumps and potential errors/intercepted errors in the prescribing phase to the administration phase

bypass of the libraries [8, 12, 34]. First, the nurses can be in a situation where the library is not available (depending on hospital nursing practices and processes of developing drug libraries, experimental drugs or uncommon use dosing/rates for rare diseases). Second, the drug library is available but the nurse could not find a specific entry and choose basic modes, which is manually programming the pumps. This includes selecting the same drug name but free-typing drug concentration (ranges of hard and soft limits may be larger than in the specific concentration drug library for the same drug). Trbovich et al. [11] showed user interface issues such as confusion between dosing units and/or concentrations.

The ISMP has listed several reasons why users choose to bypass the dose-checking features of smart pumps. These reasons included a false low perception of risk; failure to make adjustments in the drug library when alerts are not credible; extra work required to use the technology; time pressure; clinical emergencies; and a culture that inadvertently supports at-risk behavior, including not using the technology features properly [12]. These can lead to bypassing of drug libraries and may create a disconnection with safe administration during the process of medication administration. This is common in an early stage of implementation of smart pumps. Two studies found that an improvement in the compliance rate directly led to dramatic reductions of medication errors with smart pumps [8, 13]. There is no doubt that compliance with use of the drug library is a critical aspect of the success of the smart pump in preventing adverse events and increasing medication safety [13]. Having a high percentage of compliance with the drug library is the first goal to achieve in order to demonstrate the capability of smart pumps to prevent programming errors [8].

4.3 Effects of Reducing Medication Errors

During the administration phase, the studies clarified that the DERS plays a main role in intercepting medication errors such as wrong dose, wrong rate, and pump-setting

errors. In particular, subsequent user action after getting an alert is key in effectively preventing errors. As several life-threatening errors were intercepted by the hard limit of the drug library, this would be a direct and major benefit of smart pump technology. Meanwhile, soft limits were still not as effective as hard limits because of the risk of high override rates. However, if the pump is reprogrammed based on alerts or upon noticing a mistake, these will intercept errors, including near-miss errors. It is hard to identify the reason why clinicians overrode soft limit alerts, when low compliance rates are present, and therefore it is important to ask clinicians about the reasons for their behavior. Hypotheses to explain poor compliance and overrides include inappropriate alerts, busy environment, alert fatigue [6], lack of perceived risk, poor role model [30], and unavailable drug library.

It is important to have flexibility when administering medications depending on the situation or patients' status so that intravenous pumps will not hinder the clinical practice or cause a delay in treatment. Evaluating the effectiveness of soft limit alerts may be useful in order to determine that a smart pump is working as an effective and efficient decision support system. In particular, investigating the percentage of infusions reprogrammed after soft limit alerts may cause us to reconsider the parameters of soft limits to avoid alert fatigues. Furthermore, the San Diego consortium has been working on a standardized drug library across different vendors [35]. The consortium is not trying to use one standardized drug library across the sites, but is attempting to implement a standardized drug library as a base drug library and each institution can select subsets based on their hospital practice and area of care. If all hospitals used a drug library, which is in compliance with the standardized library, this would produce tremendous results currently directed towards creating a drug library at individual institutions. We believe each institution would still be required to maintain a drug library and to reconcile with the standardized library over time. A guideline for updating the drug library and an evidence-based standardized drug library list would be beneficial, allowing hospitals to have higher standards of smart pump use [6].

4.4 Negative Effects of Smart Pumps

Overall, there were few major negative effects of smart pumps, but many opportunities for improving their use were identified. Alarm fatigue, which occurs when staff become overwhelmed by the number of alarms and thus become desensitized, was one of the concerns and can lead to missed alarms or delayed alarm response [6]. Alarm fatigue can also cause staff to act inappropriately by adjusting alarm limits outside the safe range to reduce the number of alarms or by turning down the volume of alarms to an inaudible level in an attempt to reduce alarm fatigue and reduce stress on the patient and family [6, 22]. Therefore, each institution needs to examine the impact of the upper soft limit values of the drug libraries, and determine if the values should be increased to prevent 'alarm fatigue' from unnecessary alarms [28].

4.5 Future Improvement of Smart Pumps

4.5.1 Data Logs for Quality Improvement

It is useful to collect and analyze the data log from smart pumps to find out how clinicians use them from a human interaction perspective. Although we can capture the usage of smart pumps, including data related to every keystroke, it is still hard to track down the patient's condition or the physician's order for a single pump. If this is the case, when an error occurs we can only track the log retrospectively and it is hard to follow up with staff and find out the reasons why the medication error or deviation of nursing practice occurred. Current smart pumps do not capture individual patient identification data, but in the near future this will be feasible. Wireless connections with other clinical systems would help make this a good resource for continuous review of the data and CQI [17, 30].

4.5.2 Wireless Connection with Smart Pumps

Trbovich et al. [11] tested the feasibility of the barcode pump (smart pump with scanning barcode function and closed-loop pump), and they emphasized the importance of integrating with other clinical systems so that systems can directly communicate with the EHR and consequently ensure compliance with the five 'rights' of medication administration (i.e., the right patient, the right drug, the right dose, the right route, and the right time).

When integrated with other computerized care interfaces [CPOE, electronic medication administration record (eMAR), etc.], the benefit of the smart pumps will be further increased [30]. They can prevent more major errors, including wrong patient and wrong drug errors [29]. An integrated system also allows all caregivers, including the pharmacy, to benefit from real-time data [29].

4.6 Limitations of the Review

The main limitations of the selected studies were that the outcome measures were not standardized to measure the effectiveness of smart pump use, and it was not feasible to compare quantitative data. Although we assessed the severity of intercepted errors, actual patient outcomes were usually unknown unless tracking from patient incident

reports or prospective studies was reviewed. Most of the studies were conducted retrospectively and reflect only one aspect of nursing practice when using smart pumps. We also did not focus on other factors related to medication errors occurring such as the dispensing phase, which is the workflow from the pharmacy department to each nursing unit, or any malfunctions or equipment issues. This may need to be considered when analyzing the overall effects of implementing smart pumps in a hospital.

5 Conclusions

Based on the existing literature, smart pumps appear to be an asset in the improvement of medication safety and prevention of infusion errors, though the evidence continues to be mixed. Overall, smart pumps can reduce programming error rates, but there are some types of errors that still persist after implementing smart pumps (e.g., wrong drug administration, unauthorized drug administrations, wrong patient). A combination with other clinical systems can prevent these errors; however, a lack of integration with those systems may limit the benefit of smart pumps. Compliance with using smart pumps, including using a drug library, is one of challenges after implementation of smart pumps. Each institution has to work with clinicians to improve the compliance rate of using the pump and the drug library so that the system can be fully functional as designed. To date, there is still not sufficient literature to conduct a meta-analysis to analyze the effects of smart pumps, as another review pointed out 5 years ago [5, 12]. We found one observational study conducted by Husch et al. [21]; however, this has not been widely used to evaluate the impact of the smart pump system. We believe conducting a similar observational study in multiple institutions will add important findings and directions for further future improvement of the use of smart pumps.

The literature did note a number of limitations of current smart pumps and desired future improvements. Among the suggested feature improvements, upgrading of drug libraries, developing standardized drug libraries, a recommendation to maintain an up-to-date drug library to obtain maximum effects of reducing errors, and avoiding negative effects such as alarm fatigue and workarounds were most notable. Additionally, as with other clinical information systems, smart pumps should be implemented with the idea of using a CQI process to iteratively improve the practice of smart pumps use and their features.

Acknowledgments We thank Meaghan Muir for her support in searching the literature. We acknowledge founding support from the Association for the Advancement of Medical Instrumentation (AAMI) and Carefusion Foundation in 2012–2015 and Foundation Saint-Luc. Kumiko Ohashi, Patrica Dykes, and David Bates are funded by the AAMI and Carefusion Foundations to conduct a national smart pump study. Olivia Dalleur is funded by Foundation Saint-Luc and has no other conflict of interests. Dr. Bates serves on the board for SEA Medical Systems, which makes intravenous pump technology. He is on the clinical advisory board for Zynx, Inc., which develops evidence-based algorithms, and Patient Safety Systems, which provides a set of approaches to help hospitals improve safety. He consults for EarlySense, which makes patient safety monitoring systems. He receives equity and cash compensation from QPID, Inc., a company focused on intelligence systems for electronic health records. Dr. Bates' financial interests have been reviewed by Brigham and Women's Hospital and Partners HealthCare in accordance with their institutional policies.

References

1. Pang RKY, Kong DCM, deClifford JM, Lam SS, Leung BK. Smart infusion pumps reduce intravenous medication administration errors at an Australian teaching hospital. J Pharm Pract Res. 2011;41(3):192–5.
2. Snodgrass RD. Smart pump technology. Biomed Instrum Technol. 2005;39(6):444–6.
3. Institute for Safe Medication Practices. "Smart" infusion pumps join CPOE and bar coding as important ways to prevent medication errors. http://www.ismp.org/Newsletters/acutecare/articles/20020207.asp. Accessed 3 Jun 2014.
4. Institute for Safe Medication Practices. Proceedings from the ISMP Summit on the use of smart infusion pumps: guidelines for safe implementation and use: 1–19 http://www.ismp.org/tools/guidelines/smartpumps/printerversion.pdf. Accessed 3 Jun 2014.
5. Murdoch LJ, Cameron VL. Smart infusion technology: a minimum safety standard for intensive care? Br J Nurs. 2008;17(10):630–6.
6. Mansfield J, Jarrett S. Using smart pumps to understand and evaluate clinician practice patterns to ensure patient safety. Hosp Pharm. 2013;48(11):942–50.
7. Pedersen CA, Schneider PJ, Scheckelhoff DJ. ASHP national survey of pharmacy practice in hospital settings: monitoring and patient education—2012. Am J Health Syst Pharm. 2013;70(9):787–803.
8. Rothschild JM, Keohane CA, Cook EF, et al. A controlled trial of smart infusion pumps to improve medication safety in critically ill patients. Crit Care Med. 2005;33(3):533–40.
9. Manrique-Rodriguez S, Sanchez-Galindo A, Fernandez-Llamazares CM, et al. Smart pump alerts: all that glitters is not gold. Int J Med Inform. 2012;81(5):344–50.
10. Williams CK, Maddox RR. Implementation of an i.v. medication safety system. Am J Health Syst Pharm. 2005;62(5):530–6.
11. Trbovich PL, Pinkney S, Cafazzo JA, Easty AC. The impact of traditional and smart pump infusion technology on nurse medication administration performance in a simulated inpatient unit. Qual Saf Health Care. 2010;19(5):430–4.
12. Hertzel C, Sousa VD. The use of smart pumps for preventing medication errors. J Infus Nurs. 2009;32(5):257–67.
13. Manrique-Rodriguez S, Sanchez-Galindo AC, Lopez-Herce J, et al. Impact of implementing smart infusion pumps in a pediatric intensive care unit. Am J Health Syst Pharm. 2013;70(21):1897–906.
14. Malashock CM, Shull SS, Gould DA. Effect of smart infusion pumps on medication errors related to infusion device programming. Hosp Pharm. 2004;39(5):460–9.
15. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7):e1000097.

16. Fields M, Peterman J. Intravenous medication safety system averts high-risk medication errors and provides actionable data. Nurs Adm Q. 2005;29(1):78–87.
17. Wilson K, Sullivan M. Preventing medication errors with smart infusion technology. Am J Health Syst Pharm. 2004;61(2):177–83.
18. Ohashi K, Dykes P, McIntosh K, Buckley E, Wien M, Bates DW. Evaluation of intravenous medication errors with smart infusion pumps in an academic medical center. AMIA Annu Symp Proc. 2013;2013:1089–98.
19. Russell RA, Murkowski K, Scanlon MC. Discrepancies between medication orders and infusion pump programming in a paediatric intensive care unit. Qual Saf Health Care. 2010;19(Suppl 3):i31–5.
20. Evans RS, Carlson R, Johnson KV, Palmer BK, Lloyd JF. Enhanced notification of infusion pump programming errors. Stud Health Technol Inform. 2010;160(Pt 1):734–8.
21. Husch M, Sullivan C, Rooney D, et al. Insights from the sharp end of intravenous medication errors: implications for infusion pump technology. Qual Saf Health Care. 2005;14(2):80–6.
22. Skledar SJ, Niccolai CS, Schilling D, et al. Quality-improvement analytics for intravenous infusion pumps. Am J Health Syst Pharm. 2013;70(8):680–6.
23. Fanikos J, Fiumara K, Baroletti S, et al. Impact of smart infusion technology on administration of anticoagulants (unfractionated heparin, argatroban, lepirudin, and bivalirudin). Am J Cardiol. 2007;99(7):1002–5.
24. Larsen GY, Parker HB, Cash J, O'Connell M, Grant MC. Standard drug concentrations and smart-pump technology reduce continuous-medication-infusion errors in pediatric patients. Pediatrics. 2005;116(1):e21–5.
25. Prewitt J, Schneider S, Horvath M, Hammond J, Jackson J, Ginsberg B. PCA safety data review after clinical decision support and smart pump technology implementation. J Patient Saf. 2013;9(2):103–9.
26. Nuckols TK, Bower AG, Paddock SM, et al. Programmable infusion pumps in ICUs: an analysis of corresponding adverse drug events. J Gen Intern Med. 2008;23(Suppl 1):41–5.
27. Paul JE, Bertram B, Antoni K, et al. Impact of a comprehensive safety initiative on patient-controlled analgesia errors. Anesthesiology. 2010;113(6):1427–32.
28. Tran M, Ciarkowski S, Wagner D, Stevenson JG. A case study on the safety impact of implementing smart patient-controlled analgesic pumps at a tertiary care academic medical center. Jt Comm J Qual Patient Saf. 2012;38(3):112–9.
29. Gerhart D, O'Shea K, Muller S. Advancing medication infusion safety through the clinical integration of technology. Hosp Pract (1995). 2013;41(4):7–14.
30. Kastrup M, Balzer F, Volk T, Spies C. Analysis of event logs from syringe pumps: a retrospective pilot study to assess possible effects of syringe pumps on safety in a university hospital critical care unit in Germany. Drug Saf. 2012;35(7):563–74.
31. Bates DW, Leape LL, Cullen DJ, et al. Effect of computerized physician order entry and a team intervention on prevention of serious medication errors. JAMA. 1998;280:1311–6.
32. Poon EG, Keohane CA, Yoon CS, et al. Effect of bar-code technology on the safety of medication administration. N Engl J Med. 2010;362(18):1698–707.
33. Poon EG, Cina JL, Churchill W, et al. Medication dispensing errors and potential adverse drug events before and after implementing bar code technology in the pharmacy. Ann Intern Med. 2006;145:426–34.
34. Manrique-Rodriguez S, Sanchez-Galindo A, Fernandez-Llamazares CM, et al. Developing a drug library for smart pumps in a pediatric intensive care unit. Artif Intell Med. 2012;54(3):155–61.
35. Eastham J, Rizos A, Gama J, et al. Reduction in variation of intravenous drug administration in seventeen San Diego hospitals with standardized drug concentrations and dosage units. Hosp Pharm. 2009;44(2):150–8.