Review of Contemporary Philosophy
ISSN: 1841-5261, e-ISSN: 2471-089X
Vol 24 (01), 2025
pp. 530 - 540

Medication Safety Practices with Smart Infusion Pumps and Automated Systems: A Review Study

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Abstract

Background: Administration errors of medicines (MAEs), primarily those through intravenous (IV) therapy, impose significant risk for patient safety and cause adverse drug events (ADEs) and increased mortality rates. Medication infusion pumps that are smart with dose error reduction systems (DERS), along with automated solutions with electronic health record (EHR) interoperability, aim to prevent the same threats.

Aim: This analysis assesses the effectiveness of smart pumps and automated systems at preventing MAEs, reveals barriers and facilitators for implementation, and suggests optimization recommendations.

Methods: A systematic search of the databases of PubMed, Embase, Scopus, Web of Science, and CENTRAL (2010–2024) was conducted with regard to hospital studies of automated and smart pumps. Error minimization, compliance, alert fatigue, and implementation strategies were taken as data.

Results: Up to an 80% decrease in MAEs was seen with smart pumps, and hard limits avoided severe overdoses. Interoperability decreased error rates by 15.4–90.5%. Drawbacks are alert fatigue, 75.8% of soft alert overrides, and drug library non-compliance.

Conclusion: Automated systems and smart pumps increase the safety of IV drugs, and non-compliance and alert fatigue hamper efficiency. Standardized drug libraries, education, and interoperability are the optimization solution.

Keywords: Smart infusion pumps, drug safety, dose error reduction, interoperability, alert fatigue.

Received: 20 April 2025 **Accepted**: 30 May 2025 **Published**: 16 Jun 2025

Introduction

Medication error is one of the most serious issues in healthcare, leading to preventable adverse drug events (ADEs) causing harm to patients, longer hospital lengths of stay, and higher mortality rates (Panagioti et al., 2019). Medication administration errors (MAEs), especially those involving intravenous (IV) meds, are of particular concern because of their high-risk status, complicated dosing regimens, complex pump programming requirements, and the ability for fast onset of harm (Schnock et al., 2017). In order to mitigate their associated risk, healthcare organizations increasingly use smart infusion pumps with dose error reduction systems (DERS) and drug libraries to impose pre-programmed safety limits and issue real-time alerts to clinicians (Ohashi et al., 2014).

Automated systems, such as those coupled with electronic health records (EHRs) and barcode medication administration (BCMA) systems, were also deployed for the purpose of workflow streamlining, elimination of manual error, and patient safety enhancement (Skog et al., 2022). Even though the usage of these devices

is commonplace—about 87.9% of the hospitals within the United States use smart infusion pumps—traditional issues such as alert fatigue, failure for safety protocol compliance, and suboptimum integration into clinical workflows hamper their usability (Alamer et al., 2023). In the present comprehensive review, evidence from several peer-reviewed studies is synthesized for the purpose of assessing the efficacy of smart infusion pumps and automated systems for the purpose of medication safety enhancement, for the identification of significant barriers to their effective usage, and for the development of evidence-based solutions for their optimization.

Methods

A systematic literature search was conducted via PubMed/Medline, Embase, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL) from January 2010 to November 2024. The search terms were "smart infusion pumps," "IV medication errors," "dose error reduction systems," "interoperability," and "medication safety." Inclusion criteria were peer-reviewed studies published in English evaluating smart infusion pumps or automated systems within hospital facilities focusing on medication safety outcomes. Exclusion criteria were studies that were not peer reviewed, studies carried out outside the hospital setting, and studies lacking quantitative or qualitative error reduction information.

Effectiveness of Intelligent Infusion Pumps for Reducing Drug Errors

Intelligent infusion pumps, loaded with DERS and drug libraries, have shown great promise for minimizing MAEs, especially in high-stakes situations like intensive and neonatal intensive care units (ICUs and NICUs). A systematic review by Ohashi et al. (2014) emphasized that smart pumps equipped with DERS intercepted successfully errors associated with incorrect doses and pump programming and dramatically decreased both MAEs and clinical ADEs (Ohashi et al., 2014). In a NICU scenario, Melton et al. (2019) mentioned that smart pumps stopped 160 tries at administering doses above hard maximum limits, with doses up to 29 times the protected limit, and reminded hospitalists of the need for reprogramming or cancellation of 2,093 infusions after issuing soft alerts (Melton et al., 2019). Likewise, Larsen et al. (2005) cited an astounding infusion error reduction of 80% in an adult ICU, and they attributed the achievement primarily to the introduction of DERS, whose real-time alerts and forced safety parameters yielded the results (Larsen et al., 2005; Lyons et al., 2018).

In spite of these advances, the value of soft limits—alerting that can be overridden by clinicians—is frequently undercut by high override rates. Obuseh et al. (2022) reported that nurses overrode medication libraries on propofol infusions and insulin infusions in 70% and 60%, respectively, making the total bypass rate for all infusion types 25% (Obuseh et al., 2022). In a multihospital observational study, Schnock et al. (2017) reported that 75.8% of the soft alerts for high-alert meds, such as anticoagulants and opioids, were overridden, thus substantially undercutting the safety advantage of smart pumps (Schnock et al., 2017). By comparison, hard limits, which must be reprogrammed for the infusion to remain within the limits of safety, were more effective. Manrique-Rodríguez et al. (2013), for example, reported documenting hard limits catching 166 potential life-threatening infusion mistakes over a year in a pediatric ICU and preventing high-risk medication overdoses (Manrique-Rodríguez et al., 2013). Table 1 summarizes the medication error reduction with smart infusion pumps.

Table 1. Medication Error Reduction with Smart Infusion Pumps' Summary

Study	Setting	Error Reduction Outcomes	Key Findings
Ohashi et al., 2014	Multiple hospitals	Reduced MAEs and ADEs	Hard limits are highly effective; soft limits are frequently overridden due to alert fatigue
Melton et al., 2019	NICU	Prevented 160 hard limit violations	Intercepted doses 7–29 times maximum; 2,093 infusions reprogrammed or canceled after soft alerts

Larsen et al., 2005	Adult ICU	80% reduction in infusion errors	DERS is critical for intercepting programming and dosing errors
Schnock et al., 2017	Multihospital	75.8% soft alert overrides	Non-compliance with drug libraries reduced safety benefits
Manrique-Rodríguez et al., 2013	Pediatric ICU	Intercepted 166 significant errors	Hard limits prevented high-risk overdoses, particularly for critical medications.

Impact of Interoperability with Automated Systems

Interoperability between EHRs and smart infusion pumps is an exciting development toward decreased manual programming errors through automation of medication order transfer directly from the EHR to the pump. A systematic review by Skog et al. (2022) up through the year 2025 identified that interoperability decreased MAEs by 15.4% to 54.8% for directly automated error impact and by 21.2% to 90.5% for total MAEs, depending on the contextual implementation (Skog et al., 2022). In one multicenter study across seven hospitals, interoperability increased integration rates from 79.4% to 91.8% and elevated compliance with programming on smart pumps from 84.7% to 93.6%, dramatically improving the accuracy of medication administration (Romp et al., 2024). Nevertheless, interoperability continues to be underutilized, with only 9–15% of U.S. hospitals deploying such systems, for the most part owing to lofty expenses and operational complexities (Wei et al., 2021).

Even where interoperability is present, bypassing safety programs continues to be a problem. Schnock et al. (2017) reported that 50% of MAEs might have been avoided if clinicians had implemented interoperability features and followed drug library protocols (Schnock et al., 2017). The incorporation of barcode-enabled pumps provides still another layer of safety by preventing errors like administering the wrong medication to the wrong patient. Trbovich et al. (2010) reported that barcode pumps were used by nurses who corrected 88% of "wrong patient" errors compared to 46% for traditional pumps and 58% for smart pumps without BCMA technology (Trbovich et al., 2010). These results highlight the synergy of integrating smart pumps and automated systems to achieve an effective safety net for infusion medication administration (Figure 1).

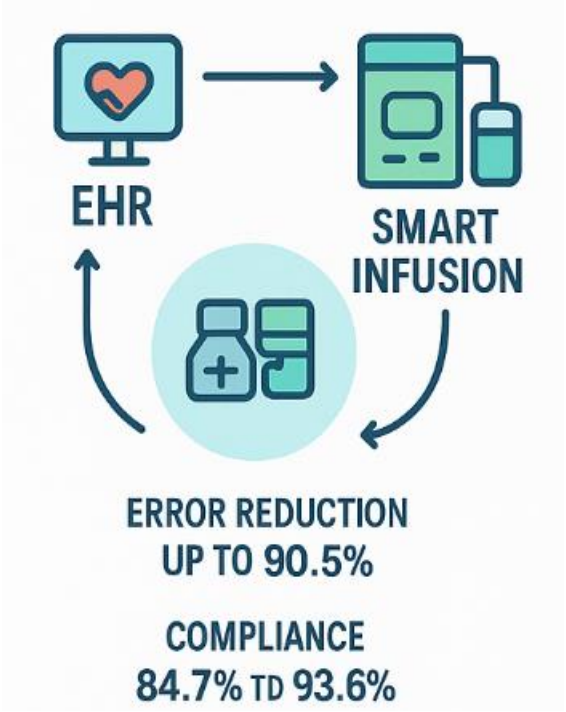

Figure 1. Interoperability Benefits

Problems of Implementation

Alert Fatigue

Alert fatigue is one of the significant deterrents for the proper utilization of smart infusion pumps, since too many alerts can desensitize clinicians and cause them to become desensitized (Giuliano, 2018). Smart pumps produced alarms for one-third of their usage, producing more than 106 hours of alerts per month at one institution and causing considerable disruption of clinical workflow (Giuliano, 2018). High volumes of alerts are responsible for override rates, and Schnock et al. (2017) reported that there was an override of 75.8% for the soft alerts for high-alert medications, usually because the clinicians considered the alerts as possessing a low risk or unreliability (Schnock et al., 2017). Alamer et al. (2023) identified more reasons for alert fatigue, such as workflow pressure, lack of time, and lack of confidence regarding the reliability of the alerts, and all such factors nullify the safety advantage of smart pumps (Alamer et al., 2023).

Non-Compliance with Drug Libraries

Non-compliance with drug libraries is another key issue that hinders the performance of smart infusion pumps. Obuseh et al. (2022) indicated that the drug libraries were bypassed by the nurses for 70% of propofol and 60% of insulin infusions, mainly because of the reason of constraints of time, for situations of emergency, or because of unfamiliarity with the technology (Obuseh et al., 2022). In their study of ICU nurses, Beaudart et al. (2023) identified system-level factors for non-compliance, such as high patient-nurse ratios, lack of communication among healthcare teams, and high turnover of staff, among others, that de-prioritize the safety protocols (Beaudart et al., 2023). These results call for targeted interventions focused on both individual and system-level barriers to compliance.

Workflow Integration

Proper integration of smart infusion pumps into hospital workflow is desirable but difficult. Daher et al. (2020) reported that 67% of infusions had discrepancies, including incorrect programming or failure to use drug libraries, even though smart pumps were available (Daher et al., 2020). Discrepancies typically arise from the error of programming manually or a lack of interoperability with EHRs, which means that the EHR must be entered manually by the nurse, thus exposing the information to the risk of error (Haghbin et al., 2016; Fawaz et al., 2017; Alghamdi et al., 2019). Ni et al. (2020) showed that workflow interventions, such as pharmacist annotation of the medication chart, decreased the error rate from 16.6% to 8.1%, with the smart pumps automatically reducing the rate further to 3.9% when fully implemented into clinical workflows (Ni et al., 2020). These results highlight the necessity for the alignment of the incorporation of technology within existing workflows for the best benefits for the safety of the patient. Figure 2 provides an overview of the challenges versus the optimization strategies.

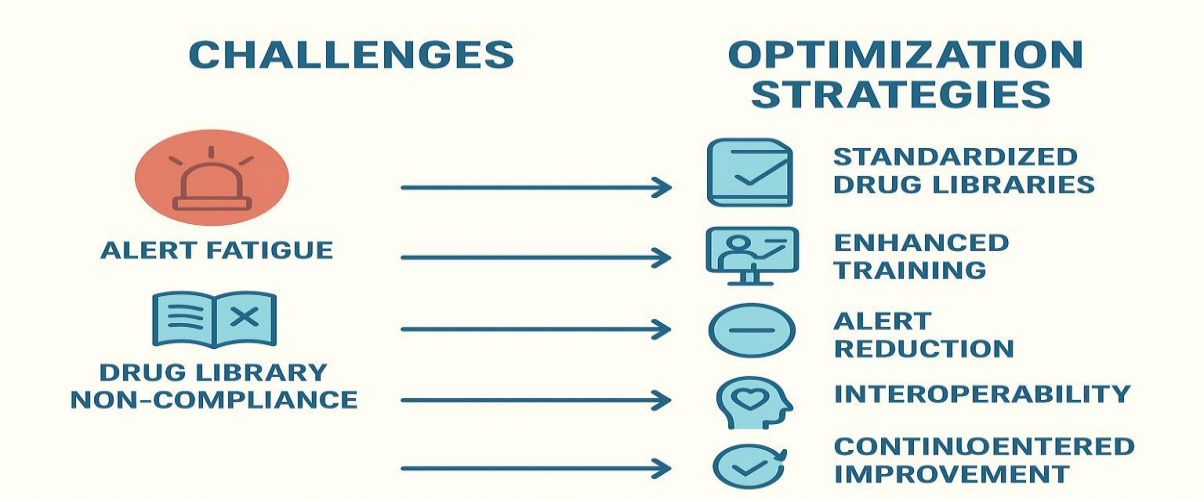

Figure 2. Challenges vs. Optimization Strategies

Role of the Pharmacists and Multidisciplinary Teams

Pharmacists play a key role in the development and ongoing support of comprehensive drug libraries, which are essential for the success of smart infusion pumps. In their scoping review, Shah and Jani (2020) emphasized the pharmacists' expertise in harmonizing medication concentration standards and establishing specific safety thresholds for high-risk meds, such as opioids and chemotherapy agents (Shah & Jani, 2020). Multidisciplinary teams, including pharmacists, nurses, physicians, and biomedical engineers, are necessary for ensuring the effective utilization of smart pumps and automated systems. As an example, Manrique-Rodríguez et al. (2013) detailed the development of a pediatric ICU drug library over seven months among a clinical pharmacist, a hospitalist director, and a chief nurse, ultimately producing an incredibly effective safety system that intercepted 166 serious errors (Manrique-Rodríguez et al., 2013).

In the same manner, Howlett et al. (2020) cited that a regional working group of pharmacists, nurses, and engineers harmonized drug libraries across multiple facilities, limiting variability associated with medication administration and augmenting the safety outcome (Howlett et al., 2020). These multidisciplinary projects highlight the necessity for interdisciplinary expertise for maximizing medication safety technology. In order to achieve the full safety advantage of smart infusion pumps and automated systems, healthcare organizations need to adopt evidence-based solutions that deal with the recognized barriers and system performance improvements. The solutions, gleaned from the literature reviewed, aim to boost compliance, minimize errors, and make technology an unobtrusive extension of clinical workflows (Bacon & Hoffman, 2020).

Standard Drug Libraries

Incorporating standardized drug libraries is a key to proper smart pump utilization. Through the uniform establishment of medication concentrations throughout health systems, the use of standardized libraries minimizes variability that can contribute to the occurrence of dosing miscalculations. Standardization of pumps simplifies the programming process, provides for the utilization of ready-to-administer solutions, and maintains uniformity for the safety limits, especially for high-risk agents like opioids, anticoagulants, and chemotherapy drugs. Literature establishes that standardization not only improves safety but also facilitates workflow simplification by minimizing the cognitive load experienced by the clinicians at the point of medication administration (Jones et al., 2021; Howlett et al., 2020).

Increased Instruction

In-depth and sustained training programs are needed for the purpose of ensuring clinicians become competent regarding the use, upkeep, and alert management of intelligent infusion pumps. Education ought to cover both procedural skills, for example, working with pump interfaces and setting up infusion programming, and the necessity for compliance with the safety protocol, for instance, the utilization of drug libraries. Through the elimination of knowledge deficits and the establishment of a culture of safety, training programs can help minimize non-compliance and mistakes dramatically. Literature suggests there is an enhancement of clinician compliance and usage of safety features through the usage of scheduled education sessions on an ongoing basis (Wei et al., 2021; Brown et al., 2018).

Alert Reduction

Alert fatigue because of excessive or non-life-critical alerts undermines the effectiveness of smart pumps via elevated override rates. Reduction of drug libraries for high-priority alerts and elimination of unnecessary or low-risk alerts can assist in the significant reduction of alert fatigue. This involves inspection of alert logs for the identification of patterns and the tailoring of safety parameters such that alerts are both specific and clinically relevant. Via the minimization of interruptions of clinical workflows, alert-reducing strategies can facilitate clinicians responding more readily and accurately to life-critical warnings and thus increase safety (Giuliano, 2018; Alamer et al., 2023).

Enforcing Interoperability

Broadening interoperability among EHRs and smart pumps is paramount for automating the transfer of medication orders, lowering the number of manual programming mistakes, and enhancing documentation precision. Through interoperability, medication orders can automatically be sent from the EHR directly to the pump, thus preventing the necessity for data entry by hand and the danger of transcription error. Although it is known to be effective, interoperability isn't widely used owing to the barriers, both technical and financial. Infrastructure investment and cooperation among healthcare organizations and technology suppliers are needed in order to break through these barriers and achieve the maximum amount of safety benefits (Skog et al., 2022; Romp et al., 2024).

Human-Centered Design

Usability of the smart infusion pumps is one factor contributing to their success. Development of pumps with user-friendly interfaces, portable pumps, and easy-to-use controls can minimize the errors related to the complexity or ambiguity of the system (Sutherland et al., 2022). Human factors design considers the clinicians' needs first and, therefore, makes the pumps easy enough for use under the pressured and time-sensitive situations of clinical practice. Through the enhancement of usability, the design enhancements facilitate compliance and minimize the chance for programming error (Alamer et al., 2023; Jones et al., 2021).

Continuous Quality Improvement

Ongoing monitoring of pump data, for example, alert logs, compliance rates, and error reports, is required for the identification of opportunities for improvement and the making of repeated refinements for safety protocols. The establishment of feedback loops within which clinicians are involved in the scrutiny and optimization of smart pump systems creates a culture of ongoing improvement. In turn, the latter facilitates the systems adapting over the longer term to real-world problems and becoming more effective over time. Regular analysis of data and feedback from clinicians has been reported as resulting in prolonged improvements in medication safety (Mansfield & Jarrett, 2013; Ohashi et al., 2014). Table 2 provides an overview of the implementation strategy for optimizing smart infusion pumps. Figure 3 summarizes the smart infusion pump effectiveness.

Table 2. Implementation Strategy for Optimizing Smart Infusion Pumps

Strategy	Description	Supporting Studies
Standardized Drug Libraries	Use uniform concentrations to reduce variability and simplify programming	Jones et al., 2021; Howlett et al., 2020
Enhanced Training	Provide ongoing education on pump use, maintenance, and alert management	Wei et al. 2021; Shah & Jani, 2020
Alert Reduction	Refine drug libraries to minimize unnecessary alerts and reduce fatigue	Giuliano, 2018; Alamer et al., 2023
Interoperability	Integrate pumps with EHRs for automated programming and documentation	Skog et al., 2022; Romp et al., 2024
Human-Centered Design	Develop user-friendly, portable pumps with intuitive interfaces	Alamer et al., 2023; Jones et al., 2021
Continuous Quality Improvement	Use pump data and feedback loops for iterative safety enhancements	Mansfield & Jarrett, 2013; Ohashi et al., 2014

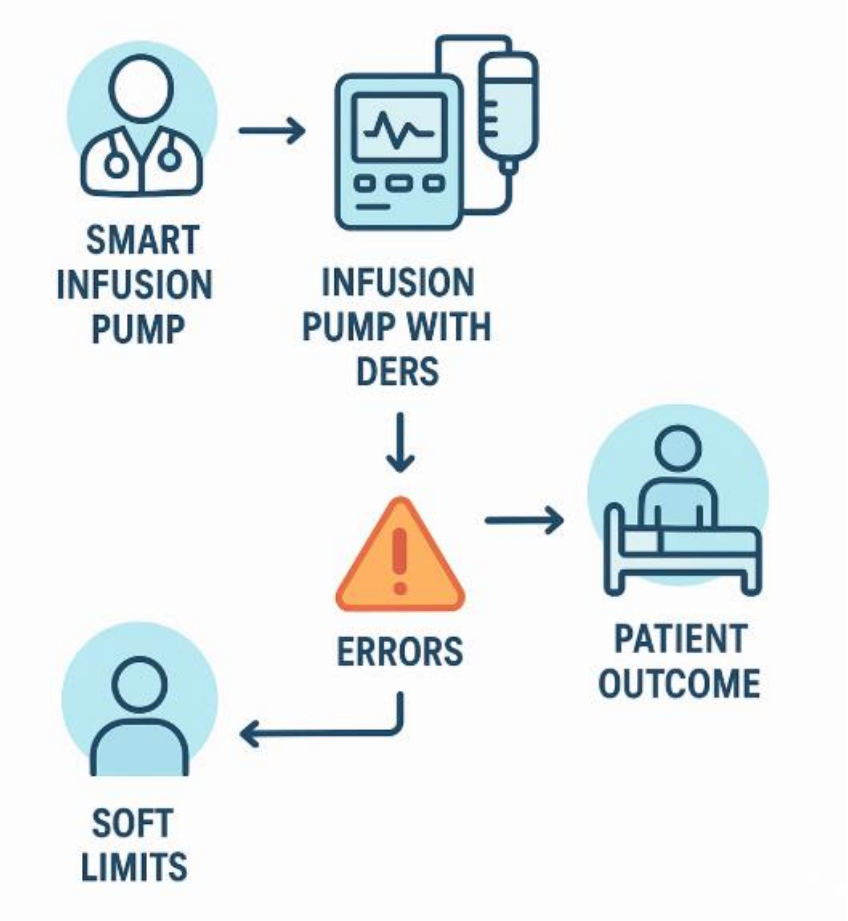

Figure 3. Smart Infusion Pump Effectiveness

Discussion

Intelligent infusion pumps and automated systems have transformed medication safety through the establishment of powerful mechanisms for intercepting dosing errors and minimizing programming errors through the human interface. Hard limits, preventing administration of doses beyond safe parameters, were especially effective, as the following cases attest: NICU and ICU cases where severe overdoses were avoided (Manrique-Rodríguez et al., 2013; Wolf, 2016; Melton et al., 2019). Integration with EHRs enlarges these advantages through the automation of workflows and minimization of human error, the latter reduced by up to 90.5% under ideal circumstances (Skog et al., 2022; Sheikh et al., 2017). Nevertheless, issues like alert fatigue, non-compliance with drug libraries, and suboptimal workflow integration still undercut the full potential of these tools. Overriding of soft alerts (Schnock et al., 2017) and repeated bypassing of drug libraries (Shah et al., 2018; Obuseh et al., 2022) serve as an impetus for specific interventions designed to assist clinicians toward increased compliance and system usability.

Pharmacists and multidisciplinary work can resolve such concerns through the development of standardized libraries and joint implementation strategies (Shah & Jani, 2020; Howlett et al., 2020). However, the sparse utilization of interoperability—in just 9–15% of the U.S. hospitals deploying such systems—indicates the significant investment required for such technologies to reach their full potential (Wei et al., 2021). Human factors and ongoing quality improvement strategies hold the key to the resolution of usability issues and reaping the long-term rewards of safety (Mansfield & Jarrett, 2013; Wang et al., 2019). In addition, BCMA integration with smart pumps offers a better mechanism for the prevention of "wrong patient" errors and fortification of the overall safety net for IV medication (Quattromani et al., 2018).

There are a few limitations of this review. The variability of study designs and outcome variables among the included studies ruled out a meta-analysis, thus narrowing the ability to calculate overall effect sizes. Also, the emphasis on hospital facilities might not reflect the full extent of the problem and potential within ambulatory or outpatient facilities. Future studies should give prominence to longitudinal studies for the evaluation of the interoperability impact on the ADE rates, the workflow of clinicians, and the outcomes of the patients across different facilities. In addition, studies on alert fatigue and compliance-enhancing strategies like machine learning-based alert prioritization can maximize the efficiency of smart infusion pumps and automated systems.

Conclusion

Automated and smart infusion pumps are transformative technologies for medication safety improvement, especially within the high-risk practice of IV medication administration. Through the interception of dosing errors, workflow automation, and integration with EHR and BCMA systems, these devices can dramatically prevent MAEs and ADEs. Their impact is constrained by limitations such as alert exhaustion, non-compliance with drug libraries, and suboptimal workflow integration. To overcome these barriers, healthcare organizations should prioritize standardized drug libraries, improved clinician education, alert minimization strategies, increased interoperability, human-centered pump design, and ongoing quality improvement programs. Multidisciplinary programs, especially those involving pharmacists, are required for the establishment and sustainability of effective safety systems. Through the execution of these evidence-based strategies, healthcare organizations can maximize the safety advantage of automated and smart infusion pumps, and preventable harm reduced and improve patient outcomes.

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ممارسات سلامة الأدوية باستخدام مضخات التسريب الذكية والأنظمة الآلية: دراسة مراجعة

الملخص

الخلفية: أخطاء إعطاء الأدوية(MAEs) ، وبشكل رئيسي تلك المتعلقة بالعلاج الوريدي(IV) ، تشكل خطراً كبيراً على سلامة المرضى وتتسبب في حدوث أحداث دوائية ضارة (ADEs) وزيادة معدلات الوفاة. تهدف مضخات التسريب الذكية المزودة بأنظمة تقليل أخطاء الجرعات(DERS) ، بالإضافة إلى الحلول الآلية المتكاملة مع سجلات الصحة الإلكترونية(EHR) ، إلى الوقاية من هذه المخاطر.

الهدف: تهدف هذه الدراسة إلى تقييم فعالية المضخات الذكية والأنظمة الآلية في الوقاية من أخطاء إعطاء الأدوية، والكشف عن العوائق والمحفزات لتطبيقها، واقتراح توصيات للتحسين.

الطرق: تم إجراء بحث منهجي في قواعد بيانات PubMed و Embaseو Scopusو Web of Scienceو CENTRAL خلال الفترة من 2010 إلى 2024 فيما يتعلق بالدراسات في المستشفيات عن المضخات الذكية والآلية. تم تحليل تقليل الأخطاء، والالتزام، وإرهاق التنبيهات، واستراتيجيات التطبيق.

النتائج: لوحظ انخفاض في أخطاء إعطاء الأدوية يصل إلى 80% مع استخدام المضخات الذكية، وتجنب الحدود الصارمة للجرعات حالات الجرعة الزائدة الشديدة. خفضت التكاملية مع النظام الإلكتروني معدلات الأخطاء بنسبة 15.4% إلى 90.5%. من المعيقات إرهاق التنبيهات وتجاوز 75.8% من التنبيهات اللينة وعدم الالتزام بمكتبة الأدوية.

الخلاصة: تعزز الأنظمة الآلية والمضخات الذكية سلامة الأدوية الوريدية، ويعيق عدم الالتزام وإرهاق التنبيهات من كفاءتها. تعد مكتبات الأدوية الموحدة، والتدريب، والتكاملية الحل الأمثل للتحسين.

الكلمات المفتاحية: المضخات الذكية، سلامة الأدوية، تقليل أخطاء الجرعات، التكاملية، إرهاق التنبيهات.