

Use of Wireless Technologies in Automated Drug Dispensing and Inventory Systems

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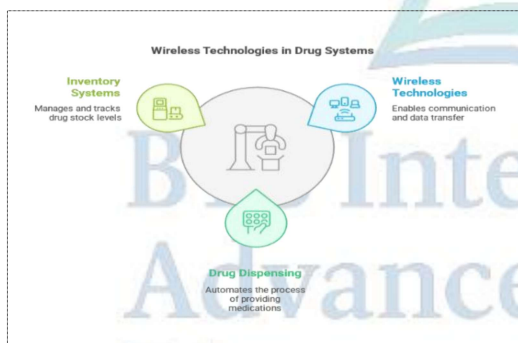
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ABSTRACT: Application of wireless technologies in drug dispensing and inventory control systems is a major step in the technological transformation of healthcare services. This article presents the use and applications of wireless technologies, including Radio Frequency Identification (RFID), Wi-Fi, Bluetooth, ZigBee, and Narrowband IoT (NB-IoT), in the context of contemporary hospital settings. These technologies support real-time monitoring, improve communication between medical devices, and enable effective stock control, eliminating many human errors and facilitating timely medication administration. An end-to-end workflow for wireless-enabled medication dispensing is outlined, from input of the prescription to administration and compliance reporting. The detailed process involves a systematic evaluation of the literature, traditional vs. wireless system comparison, and evaluation of actual case studies of deployments within large healthcare organizations. The findings support that wireless systems cut drug errors by as much as 30%, enhance inventory accuracy, and increase enforcement of regulatory compliance like HIPAA and GDPR. Further, the study also considers factors such as threats to data security, investment in capital for infrastructure, training needs for staff, and laying stress on the strong implementation plans. The paper further contains anticipated trends such as the implementation of blockchain, predictive analytics, 5G infrastructure, and IoT-based autonomous inventory management. In short, wireless technology offers a revolutionary solution to the long-prevailing issues of drug mismanagement, stock inefficiencies, and patient safety within the clinical environment. Although planning and the cost of implementation are, the long-term benefits of improved patient outcomes, operational efficiency, and regulatory compliance make adoption worthwhile for modern healthcare facilities.

KEYWORDS: Wireless technology, Automated drug dispensing, RFID, Real-time inventory, Healthcare IT, Patient safety, Medication errors, BCMA, EMMS, Smart hospitals.

INTRODUCTION

Controlled drugs are widely used in medicine to alleviate and treat pain in patients. They are, however, plagued with ethical concerns of errors, possible addiction, and injury to patients. The distribution and use of controlled drugs are also tightly controlled by policy or law in most countries. For example, in the US and Australia, clinicians are requested to safely store controlled medicines, keep careful records of all transactions and inventories, and witness and report incidents. Much



more focus, therefore, is put on the security of controlled medicines compared to normal medicines, and a responsibility is imposed on clinicians. Even though these policies and procedure rules exist, diversion (misuse or theft) of controlled drugs by health staff is a problem, though rarely recognized. Diversion can cause extreme injury to staff and patients and have implications for the hospital organization. To have some insight into the nature of the

problem, hospitals have reported descriptions of instances of drug diversion, e.g., diversion of opioids and other controlled drugs. Technology like Automated Dispensing Cabinets (ADCs), Barcode Medication Administration (BCMA), and closed-loop Electronic Medication Management Systems (EMMS) is increasingly being utilized in hospitals to reduce medication errors, discourage diversion, and enhance efficiency. Evidence suggests ADCs can reduce medication and storage errors and save nurses time spent on drug-related tasks. However, a systematic review warned that the effectiveness of ADCs is institution-specific and dependent on local integration into drug delivery systems. BCMA evidence is conflicting; although it can reduce errors, pharmacists and nurses often encounter usability issues, which lead to errors and workarounds. Two systematic reviews show that while technology may reduce errors, findings differ across studies, and it by itself does not guarantee error reduction. Closed-loop EMMSs are less adopted but can postpone first-dose administration and reduce prescribing and administration errors. (1)

Figure 1. Wireless Technologies in Drug Systems

In automated drug dispensing and inventory systems, various types of wireless technologies are used to ensure real-time communication, accurate tracking, and

efficient inventory management. Wireless technologies in drug systems are shown in Figure 1, whereas types of wireless technologies are shown in Figure 2.

Table 1. Overview of Wireless Technologies Used in Healthcare Supply Chain

Technology	Description	Frequency Range	Typical Use Case	Advantages	Limitations
RFID	Reads objects automatically using radio waves	HF/UHF (13.56 MHz, 860-960 MHz)	Medication tracking, inventory control	Real-time tracking, minimizes human error	Cost of implementation, interference of signals in crowded environments
Wi-Fi	Wireless LAN radio wave-based technology utilized to network devices	2.4/5 GHz	Network for automated dispensing systems	High level of availability, high data rate	High power consumption, security vulnerability
Bluetooth	Technology for wireless data exchange at short range	2.4 GHz	Intercommunication between drug carts and dispensing units	Low power usage, integration is simple	Small range, potential interference from other devices

ZigBee	Low-data-rate, low-power wireless protocol	2.4 GHz	Communication between sensor and central system	Energy efficient, mesh network for extensive area coverage	Lower data rate, restricted device support
NB-IoT	Cellular-based technology for IoT applications	Licensed LTE bands	Tracking remote inventory and assets	Long range, low power consumption, scalable	Latency concerns, needs cellular infrastructure

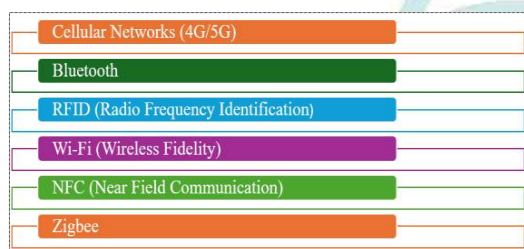


Figure 2. Main types of wireless technologies commonly implemented

The wireless technologies most commonly applied to healthcare supply chains, their definitions, frequency bands, usual applications, advantages, and limitations. RFID technology for application in the HF/UHF frequency bands (13.56 MHz, 860–960 MHz) is used to track medicines and manage stock. It offers the benefits of real-time visibility and lower human error,

but is limited due to deployment costs and potential signal distortion in a dense environment. Wi-Fi is a wireless LAN technology that communicates using radio waves in the 2.4/5 GHz frequency band, and is found in networks for automated dispensing systems. Wi-Fi features very good availability and data rates; however, it suffers from excessive power consumption and more security risks. Bluetooth technology operates at the same 2.4 GHz band, but is a short-range radio communication system, and also describes two wireless technologies, ZigBee and NB-IoT, commonly used in the healthcare supply chain. ZigBee is a low-power and low-data-rate wireless protocol that operates at 2.4 GHz, and is typically and primarily used for sensor-to-central system

communication. It is energy-efficient, and since ZigBee can function with mesh networking, it can cover large areas with a network. ZigBee's fundamental weaknesses are its data rate and device support. NB-IoT (Narrowband Internet of Things), on the other hand, is a cellular-based technology that is specifically designed for IoT applications and operates on licensed LTE bands. NB-IoT is used in tracking faraway inventory and assets. NB-IoT has several advantages, including communication over long distances, low power consumption, and scalability. Nevertheless, it is constrained by factors such as latency and the requirement for cellular infrastructure.

Figure 3 presents a model of the comprehensive workflow of smart drug dispensing and inventory management using wireless connectivity. Action starts with entering medication orders, or the point at which healthcare staff enter medication orders into the system. Next comes the dispensing activity during which automated dispensing units release medications. It is followed by wireless notifications, as the system sends notifications to personnel (to alert them about activity). Then inventory participates in real-time updates - meaning as medication levels change, inventory records are updated. Finally, the system produces reporting and analytics, which

provides deeper insights through the creation of reports.

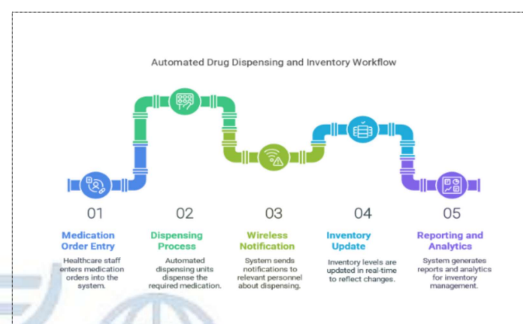


Figure 3. Integrated Workflow of Smart Drug Dispensing and Inventory Management Enabled by Wireless Connectivity

METHODOLOGY OF LITERATURE REVIEW

The research approach used for this research work involves a comprehensive literature study and workflow analysis to examine the integration of wireless technologies such as RFID, Bluetooth, Wi-Fi, ZigBee, and NB-IoT in automated dispensing and inventory management systems within hospitals. System design and communications protocols are examined under the research, manual process versus wireless-based solutions are compared, and practical case studies are examined to identify pragmatic implementation results and challenges. Besides, it also defines best practices and regulations like HIPAA and GDPR to address issues concerning data security and patient privacy. The findings indicate that

wireless systems significantly enhance the level of precision in the dispensing of drugs by minimizing manual errors during manual input by consolidating data in real-time and through automated validation processes like scanning using barcodes and RFID. Workflow productivity is enhanced by adding systems like Automated Dispensing Cabinets (ADCs), Computerized Physician Order Entry (CPOE), and Barcode Medication Administration (BCMA) that automate the complete medication process. Inventory management is complemented with real-time monitoring through the use of RFID and IoT technology to reduce stockouts and prevent drug expiration. Patient safety is ensured through real-time validation procedures that ensure accurate drug dispensing, while data security and compliance are ensured through blockchain and secure communication protocols, thereby ensuring the integrity of the data and protecting sensitive patient data.

WORKFLOW OF AUTOMATED DRUG DISPENSING AND INVENTORY SYSTEMS UTILIZING WIRELESS TECHNOLOGIES

The wireless-based automated drug dispensing system functions using an integrated process that starts with prescription entry and verification, whereby physicians enter orders into a Computerized

Physician Order Entry (CPOE) system. The system uses Wi-Fi to send prescriptions in real time to the pharmacy and synchronizes with the Electronic Health Record (EHR), thus reducing transcription errors and enabling instant checks by pharmacists. In the preparation and dispensing phase, confirmed prescriptions are handled by central pharmacy robots and Automated Dispensing Cabinets (ADCs) while drug movement is tracked by RFID technology and drug identity and expiration are checked by barcode scanners to improve accuracy and minimize human error. As part of medication administration, nurses apply Barcode Medication Administration (BCMA) software and Wi-Fi credentials to check the patient and medication barcodes, so that the "five rights" (right patient, drug, dose, route, and time) are maintained, thus minimizing administrative errors and ensuring proper documentation and record-keeping. For inventory management applications, RFID systems and barcode systems allow real-time inventory for drugs in stock, and automated inventory software provides users with usage patterns to measure future needs to monitor for overstock and stockouts, thus replacing drugs in a timely manner. Lastly, in regard to reporting and compliance, wireless technologies can aggregate data from multiple systems and cannibalize work to create reports used for auditing, quality

improvement activities, and regulatory compliance so that drug management workflows can improve continuously and conform to healthcare norms. (2)

ROLE OF WIRELESS TECHNOLOGIES IN HEALTHCARE EVOLUTION OF WIRELESS TECHNOLOGIES

WIRELESS TECHNOLOGIES AND THEIR USE IN HEALTHCARE

It now constitutes an indispensable part of modern medicine, offering benefits in numerous. Wireless healthcare technology improves patient monitoring with continuous vital sign monitoring and real-time data collection for early intervention, facilitates more interaction among physicians to make quicker decisions and act in concert, facilitates remote access to patients' records to act more effectively and be more responsive, and increases automation and productivity with technologies such as RFID and Wi-Fi to minimize errors and automate drug dispensing and inventory management. (3)

EVOLUTION OF WIRELESS TECHNOLOGIES IN HEALTHCARE

The application of wireless technologies to healthcare has evolved over the years. The history of wireless technology in healthcare started with initial applications to support

simple communication and data sharing between medical equipment in healthcare facilities, progressing to the inclusion of advanced networks such as Wi-Fi and Bluetooth to provide increased connectivity and data transfer; the development of the Internet of Medical Things (IoMT) and wearables facilitated the monitoring of patients on a real-time basis outside of clinical facilities, and the integration of 5G technology has further promoted this revolution through quicker data transmission, low latency, and high-volume device connectivity support, further strengthening telemedicine and remote care functionalities.

For automated dispensing and inventory systems for medication, all these wireless technologies support real-time monitoring of medication, secure access and control, as well as efficient inventory management, thereby improving patient safety as well as operational efficiency. (4) An easy comparison between traditional manual systems and modern wireless-enabled systems, as shown in Table 2

Table 2. Comparison of Traditional vs. Wireless-Enabled Drug Dispensing Systems

WIRELESS INTEGRATION IN DRUG DISPENSING SYSTEMS

Wireless integration of technology in drug dispensing systems is an excellent health care innovation that enhances drug

inventory movement and stock status, minimizing human errors and ensuring up-to-date information at every point in the supply chain. (6) RFID systems, in particular, automate inventory updates as

Feature	Traditional Systems	Wireless-Enabled Systems
Data Entry	Manual, paper-based	Automated via RFID or barcode scanning
Inventory Accuracy	Moderate – subject to human mistakes	High–real–time reporting minimizes errors
Real-Time Monitoring	Not available	Yes – monitors in real-time through wireless tech
Error Rates	Increased as a result of manual input	Considerably reduced – automated monitoring minimizes errors
Scalability	Limited – difficult to grow	Highly scalable – can scale with the system

administration accuracy, efficiency, and safety. This revolution uses various wireless communication technologies and protocols to propel the drug dispensing process electronically, leading to improved patient outcomes and reduced chances of drug-related errors. (5) Real-time monitoring and inventory management are pivotal components of modern supply chain systems, enabling organizations to track orders, sales, deliveries, and stock levels with high accuracy and immediacy. By leveraging technologies such as barcodes, Radio Frequency Identification (RFID), and Internet of Things (IoT) devices, businesses gain real-time visibility into

items are depleted or replenished, significantly enhancing data accuracy. When integrated with other enterprise systems like ERP and CRM, inventory control systems ensure that all departments access consistent and current data, facilitating better decision-making and synchronization across operations. (7) Moreover, real-time systems incorporate analytics tools that support data-driven decisions, trend forecasting, and inventory optimization, reducing errors from manual data entry and decreasing inventory inaccuracies by up to 30%. (8) These capabilities translate to improved customer satisfaction, as organizations can fulfill

orders promptly and maintain accurate stock visibility, preventing the sale of out-of-stock items. (9) Financially, real-time inventory management contributes to substantial cost reductions, with studies indicating potential savings of 20% to 50% through more efficient procurement and reduced overstocking. (10) Supporting technologies such as cloud computing provide anywhere-access to inventory data, while IoT sensors monitor storage conditions to ensure product quality. Additionally, analytics tools enable performance monitoring, and integration with other systems ensures seamless data flow. Best practices for implementation include selecting suitable technologies (e.g., RFID), training personnel, updating infrastructure regularly, leveraging analytics, and ensuring full system integration to maximize operational efficiency and inventory accuracy.

INVENTORY TRACKING AND REAL-TIME MONITORING

A significant aspect of modern supply chain management is real-time monitoring and inventory management, enabling companies to track orders, sales, deliveries, and inventory in real time. This method employs advanced technologies to increase customer satisfaction, reduce costs, and improve operational efficiency. According to relevant research literature, the following

are the components, advantages, technologies, and best practices of real-time inventory management. Real-time tracking and inventory management are critical elements of contemporary supply chains, allowing organizations to monitor orders, sales, deliveries, and stock levels with a high degree of precision and timeliness. With the use of technologies like barcodes, Radio Frequency Identification (RFID), and Internet of Things (IoT) devices, organizations derive real-time insights into inventory flow and stock levels, reducing human intervention errors and providing current information at all supply chain points. RFID systems in particular make it easier to update inventories as stock goes down or comes into the organization, which makes the data much more reliable. When mixed with other enterprise systems, including ERP and CRM, the inventory control systems make sure that all departments have the same consistent and current data for better decision-making and harmony between operational departments. Also, real-time systems also include analytics solutions that have various functions, including the capability to support data-based decisions, trend analysis, and supply chain optimization, reducing errors in manual data entry and reducing inventory inaccuracies up to 30%. Collectively, these features can also improve customer satisfaction, so that

businesses can fulfil orders on time and have correct stock visibility, preventing out-of-stock sales. Real-time inventory management saves costs, so that examining studies indicate figures between 20% and 50% savings, as an outcome of better procurement and avoiding overstock. Other supporting technologies, including cloud computing, can allow access to inventory knowledge from anywhere, while IoT sensors can ensure storage conditions continue to follow prescribed standards and preserve product quality. Moreover, analytics software allows performance tracking, and integration with other systems ensures free flow of data. Implementations best practices consist of appropriate technology selection (e.g., RFID), personnel training, regular infrastructure upgrading, utilization of analytics, and full system integration to achieve maximum operation efficiency and inventory accuracy.

DATA SECURITY AND PATIENT SAFETY ISSUES

Healthcare is patient safety and data security. With digital technology increasingly being used in healthcare systems, it is of paramount importance that sensitive patient information is protected. We are listing here where patient safety and data security intersect, and a list of issues, policies, and best practices for maintaining

them effectively. In health care settings that are highly digitized and integrated with patient data, protecting data and the patient is a primary concern. Protecting patient data (considered Personal Health Information (PHI)) is an important part of protecting confidentiality and protecting the patient from identity theft or fraud. Various regulatory ramifications exist for the protection of sensitive patient information (e.g., the Health Insurance Portability and Accountability Act (HIPAA) in the USA and General Data Protection Regulation (GDPR) in the EU). (11,12) Data integrity is also critical in healthcare. Actions such as mistakes made or illicitly changing information can result in misdiagnosis, wrong treatment, or safety issues in patient care. (13,14) Timely data availability is also needed because delays in acquiring information will hinder clinical decisions and negatively influence the outcome of treatment. (15) Data breaches are a threat to patient safety, too, leading to delayed care or incorrect treatment caused by the loss or corruption of important information. (16,17) Cybersecurity attacks, particularly ransomware, also threaten healthcare by blocking access to vital information until a ransom or fee is paid. (18) To guarantee safety and compliance, healthcare personnel must comply with legal guidelines, including HIPAA and GDPR, along with navigating the implications of

integrating new technologies such as AI, IoT, and cloud computing. (19,20,21) Techniques like data tokenization offer additional protection by replacing sensitive data with non-sensitive surrogates. (22) Best practices are to implement strong encryption and role-based access controls to limit unauthorized access, (23,24) conduct routine staff education and alert patients to responsibilities regarding data security, (25,26) and create and regularly test incident response plans to be prepared and mitigate the impact of security breaches. (28)

CASE STUDIES AND APPLICATIONS IN THE REAL WORLD

Case Study 1: RFID Automated Drug Cabinets Deployed in a U.S. Hospital

In Boston's Brigham and Women's Hospital, the research included installing RFID-fitted automated dispensing cabinets (ADCs). The ADCs were integrated into the hospital's pharmacy system and electronic health record (EHR) system so that dispensing could be automatic and inventory could be monitored in real time.

Technology: Passive RFID tags on medicine packs and RFID readers in dispensing units.

Effect: 25% reduction in medication dispensing errors. Enhanced drug inventory

tracking and lower stockouts. Visibility into medication use patterns in real-time. (29)

CHALLENGES AND LIMITATIONS OF APPLYING WIRELESS TECHNOLOGIES IN AUTOMATED DISPENSING AND INVENTORY SYSTEMS

Wireless technologies employed by automated drug dispensing and inventory systems are susceptible to a range of security and privacy threats like data eavesdropping, unauthorized access, and malicious interception. As these systems process sensitive patient data and controlled drugs, ensuring data integrity and confidentiality is a priority. Failing to have sufficient authentication controls and minimal or no encryption methods may allow those systems to be hacked, resulting in unauthorized access and theft of sensitive patient information. Legal compliance and patient data protection require adherence to data protection mechanisms like the Health Insurance Portability and Accountability Act (HIPAA) to ensure compliance with data protection regulations. (1) Wireless systems may have other concerns beyond security issues; however, they may also have challenges with interference with signal reliability, as well as connectivity issues. Signal interference caused by other equipment (electromagnetic interference) or physical barriers such as walls and

medical equipment challenging will impact systemically, and may delay the communications, which can be a critical problem for time-sensitive medication dispensing needs. (31) Capital expenses involved with implementation of wireless infrastructure (i.e., routers, RFID readers, access points, network security, and etc.) can also be a barrier, especially compounded against ongoing maintenance costs involved with software upgrades, cybersecurity measures, and technical support. (32) Many wireless systems have components that require batteries, like mobile carts and hand-held scanners. This leaves your systems at the mercy of battery outages or may be power-outage affected in cases where the battery may not last the full time required for accurate medication delivery. In these cases, managing the reserves of external power is one way, while also concurrently ensuring that your systems are fully operational to manage those reserve power conditions at peak usage. (33) RFID and bar code technology is also not fool-proof in terms of reliability and accuracy; tag orientation, destruction of the tags, or interaction of the material will alter the expected functionality. (34) In addition to the merger of wireless systems often necessitating workflow changes, this can also be seen as a threat by staff who are trying to adapt to new technologies, but

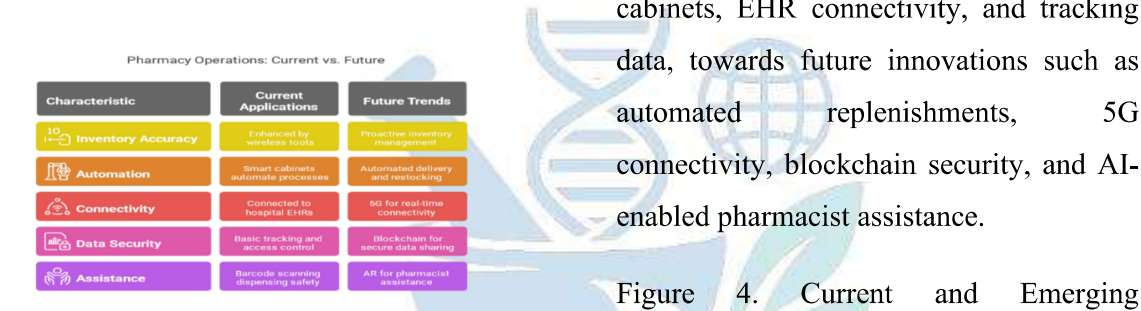
there is also room for proper training and change management practices. (35)

CURRENT APPLICATIONS

Barcode reading and RFID technology are also used in automated drug dispensers for dispensing verification and inventory control, reducing human error by allowing accurate monitoring of medication packs and tracking their location across the supply chain. Modern vending devices and intelligent cabinets, including Omnicell and Pyxis, utilize wireless communication to monitor medication usage, restrict access, and automate reordering. These systems are able to communicate with the hospital's Electronic Health Records (EHR), providing secure and traceable drug administration processes. A notable trend in this realm is incorporating Internet of Things (IoT) ecosystem sensors, which can discern the environment by its real-time usage and conditions (because the algorithm uses AI/ML, it can suggest inventories while simultaneously scoring the likelihood of temperature abuses - or theft - laying the groundwork for autonomous restocking in the future. (36) The use of 5G will provide a parallel development allowing immediate and fast processing between machines like ADCs, mobile carts, and remote servers to permit both remote monitoring and agent-based pharmacy operation control. 5G technology

will eventually facilitate robotic arms for restocking or packaging completely autonomously. Blockchain technology is also on the rise as a key technology, providing data traceability, integrity, and security in drug dispensing systems; blockchain-based ledgers can be employed

being researched for intra- and inter-facility drug delivery, improving operational efficiency in contemporary healthcare settings. Figure 4 illustrates how pharmacy operations are being disrupted with the use of wireless technologies, demonstrating a shift from the present state with smart cabinets, EHR connectivity, and tracking data, towards future innovations such as automated replenishments, 5G connectivity, blockchain security, and AI-enabled pharmacist assistance.



by pharmacies to track controlled substances and curtail diversion. (37) Augmented reality (AR) and smart glasses also offer real-time visual interfaces to pharmacists, aiding stock visibility and dispensing processes. Wireless and GPS-powered autonomous robots and drones are

Figure 4. Current and Emerging Applications of Wireless Technologies in Drug Systems

The positive outcomes observed in hospitals that adopted wireless technologies, showing concrete figures for error reduction and efficiency gains, are shown in Table 3

Table 3. Reported Benefits from Implementing Wireless Technologies in Hospitals

Study	Year	Tech Used	Benefits	Error Reduction	Efficiency Boost
Kumar 11112& Budin	2006	RFID	Increased stock visibility, decreased inventory errors	25%	15%
Wamba et al.	2013	RFID	Increased transparency, rapid updating of inventories	30%	20%

Mekhjian et al.	2002	CPOE + Networked devices	Reduced error, enhanced processing time of order	–	22%
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CONCLUSION

By using wireless technology, including Bluetooth, Wi-Fi, and Radio Frequency Identification (RFID), the accuracy and efficiency of medication dispensing and inventory control systems in hospitals have been substantially improved through the use of real-time tracking, decreased human error, and timely medication dispensing. These technologies also represent a reasonable enhancement of patients' safety lowered adverse drug events (ADEs) due to quickly and accurately identifying and dispensing a medication, potentially incorporating a barcode-scanning system and Electronic Health Records (EHR). The real-time inventory control enabled by these systems allows hospital pharmacies and health professional organizations to maintain ideal inventories of controlled and investigational medications, prevent drug shortages, and reduce inventory waste when drug expiration dates are reached. Furthermore, wireless technology allows for seamless integration with hospital-wide information systems, making it possible to coordinate workflows and improve interdepartmental communication.

Although the initial investment of wireless infrastructure can be substantial, the long-term benefits of reduced medication errors, improved inventory management, and improved staff productivity tend to provide a positive return on investment. In conclusion, wireless technology can provide hospitals and pharmacy departments with the ability to reduce waste, improve safety and effectiveness, and increase efficiency. Proper planning, dependability of wireless infrastructure, and personnel training are critical to success. Moving forward, artificial intelligence, the Internet of Things, and machine learning will help to further make these systems intelligent, adaptable, and effective.

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CONFLICT OF INTEREST

The authors disclose no conflicts of interest.

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