Precise Drug Dosing Technologies and Robotization in Clinical Pharmacy

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Abstract

The implementation of precise dosing technologies and robotics in clinical pharmacy represents a crucial advancement in modern healthcare systems. Accurate dosing and timely delivery of medications are essential for ensuring patient safety, therapeutic efficacy, and resource optimization. This article explores automated dosing systems, including Total Parenteral Nutrition (TPN) mixers, automated medication dispensers, innovative infusion therapy technologies, and AI-based digital platforms. The role of robotics in pharmaceutical services is also examined, ranging from packaging and dispensing devices to automated hospital medication delivery systems. The paper highlights both the benefits and challenges of these technologies, such as reducing human errors, optimizing costs, and transforming professional roles. Additionally, regulatory and ethical considerations are discussed, which are critical for the safe and quality-driven implementation of these innovations. From a strategic perspective, the article considers the integration of artificial intelligence and technological models that support personalized medicine, outlining future development trends and policy implications.

Keywords: Artificial intelligence, Precise dosing, Robotics, Pharmaceutical technologies, Clinical pharmacy.

წამლის დოზირების ზუსტი ტექნოლოგიები და რობოტიზაცია კლინიკურ ფარმაციაში

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აბსტრაქტი

კლინიკურ ფარმაციაში ზუსტი დოზირების ტექნოლოგიებისა და რობოტიზაციის დანერგვა ერთ-ერთ მნიშვნელოვანი მიმართულებაა თანამედროვე ჯანდაცვის სისტემაში. მედიკამენტების სწორი რაოდენობით დროული მიწოდება პაციენტის უსაფრთხოების, თერაპიული ეფექტიანობისა და რესურსების ოპტიმიზაციის საფუძველია. სტატიაში განიხილულია ავტომატიზებული დოზირების სისტემები, როგორიცაა ზოგადი პარენტერალური კვების (TPN) შემრევები, წამლის ავტომატური გამზომები, ინფუზური თერაპიის ინოვაციური სისტემები და ხელოვნური ინტელექტზე დაფუძნებული ციფრული პლატფორმები. ყურადღება გამახვილებულია ასევე რობოტიზაციის როლზე ფარმაცევტულ მომსახურებაში – დაწყებული მედიკამენტების პაკეტირებისა და გაცემის მოწყობილობებიდან, დასრულებული საავადმყოფოებში მედიკამენტებისთვის მიწოდების ავტომატურ სისტემებამდე. განხილულია ტექნოლოგიების სარგებელი და გამოწვევები, მათ შორის ადამიანური შეცდომების შემცირება, ხარჯების ეფექტიანი მართვა და პროფესიული როლის ტრანსფორმაცია. სტატია ეხება რეგულაციურ და ეთიკურ საკითხებსაც, რაც აუცილებელია ინოვაციების უსაფრთხო და ხარისხიანი დანერგვისთვის. სტრატეგიული პერსპექტივით, განხილულია ხელოვნური ინტელექტისა და პერსონალიზებული მედიცინის მხარდაჭერის შესაძლებლობები.

საკვანძო სიტყვები: ზუსტი დოზირება, რობოტიზაცია, ფარმაცევტული ტექნოლოგიები, ხელოვნური ინტელექტი, კლინიკური ფარმაცია.

Introduction

Clinical pharmacy is rapidly evolving within modern healthcare systems and has emerged as a critical component in ensuring the quality of pharmacotherapy and patient safety. Its role extends far beyond the traditional functions of dispensing medications; today, clinical pharmacists are integral members of multidisciplinary healthcare teams, actively contributing to the optimization of therapeutic outcomes.

One of the central aspects of clinical pharmacy is accurate medication dosing, which serves as a cornerstone for therapeutic success. Both underdosing and overdosing pose significant risks—ranging from therapeutic failure to potentially severe adverse drug reactions. In this context, the ability to ensure precise, patient-specific dosing becomes essential across all care settings, whether in outpatient clinics or hospital environments. Individualized dosing, which accounts for factors such as age, weight, renal function, comorbidities, and drug interactions, is increasingly recognized as a necessary standard in patient-centered care.

The integration of technological advancements, particularly robotic automation, into clinical pharmacy practices opens new avenues for enhancing the precision and reliability of medication use processes. Robotic systems now play a transformative role in automating the preparation, packaging, dispensing, and monitoring of medications. These innovations not only reduce the likelihood of human error but also improve the accuracy, safety, and efficiency of pharmaceutical services.

The implementation of robotic technologies in hospital pharmacies, for example, facilitates the timely and reliable distribution of medications, ensuring that patients receive the correct drug at the right dose and at the appropriate time. Such systems alleviate the workload of pharmacists and healthcare personnel, allowing them to focus more on clinical decision-making and direct patient care. Moreover, automation enhances inventory management, minimizes medication waste, and supports compliance with regulatory standards.

As clinical pharmacy continues to embrace digital transformation, the synergy between human expertise and technological innovation is shaping a new era in pharmaceutical care—one that prioritizes safety, efficiency, and personalized therapy.

Aim of the Study

The primary objective of this article is to explore the role of precision dosing technologies and robotic automation in the evolving landscape of clinical pharmacy. It seeks to provide a comprehensive analysis of the benefits these innovations offer, the systemic and operational challenges they present, and the key trends shaping their development and implementation in healthcare systems worldwide.

This inquiry is grounded in the recognition that individualized, accurate medication dosing is fundamental to optimizing therapeutic efficacy and minimizing risks. In this context, emerging technologies that support personalized dosing protocols and automated pharmaceutical workflows are not only enhancing patient safety but also redefining the pharmacist's role in clinical decision-making.

The study is guided by several key research questions:

1. **How do precision dosing technologies contribute to improving patient safety and therapeutic outcomes?** This question addresses the impact of advanced tools—such as dose-calculation software, pharmacokinetic modeling systems, and electronic decision-support mechanisms—on reducing medication errors and tailoring treatments to individual patient needs.
2. **How can robotic systems be effectively integrated into clinical pharmacy practice?** This line of inquiry examines best practices and operational models for implementing robotics in hospital and outpatient pharmacy settings, focusing on medication dispensing, preparation, and inventory management.
3. **What strategic steps must healthcare systems undertake to fully adopt and benefit from these innovations?** This includes an analysis of the infrastructural, regulatory, financial, and educational frameworks necessary for the successful deployment of these technologies. It also considers stakeholder engagement, interdisciplinary collaboration, and workforce adaptation.

By addressing these questions, the article aims to offer valuable insights for policymakers, healthcare administrators, clinical pharmacists, and technology developers. Ultimately, it contributes to the broader discourse on how digital transformation and automation can advance pharmaceutical care, support sustainable health systems, and improve patient outcomes in the 21st century.

Methodology

This study is based on an in-depth literature review designed to explore the role of precision dosing technologies and robotics in clinical pharmacy. The purpose of this review is to consolidate existing knowledge, identify current practices, and examine both the benefits and challenges associated with the integration of technological innovations into medication management processes.

Inclusion criteria were as follows: (1) articles addressing technological solutions for individualized or automated dosing in clinical settings; (2) publications discussing the impact of robotics on pharmacy workflow, medication errors, and patient safety; (3) studies presenting implementation frameworks, cost-benefit analyses, or case studies from hospital or ambulatory care settings. Articles not directly related to pharmacy practice or those lacking sufficient methodological rigor were excluded.

The data extracted from the selected publications were organized thematically. The synthesis focused on three core dimensions: (1) clinical outcomes and patient safety improvements associated with precision dosing technologies; (2) operational and logistical benefits of robotic integration in pharmacy services; and (3) institutional, ethical, and infrastructural challenges that influence successful adoption.

Results

Precision dosing technologies play a pivotal role in enhancing patient safety and optimizing the effectiveness of pharmacotherapy in clinical pharmacy. These innovations address one of the most critical aspects of medication management—accurate dosage administration, which is particularly vital in settings where therapeutic windows are narrow and the risk of medication errors is high.

One of the most impactful advancements is the implementation of automated dosing systems, such as Total Parenteral Nutrition (TPN) compounders and automated medication dispensers. These technologies ensure highly accurate and controlled dose preparation and delivery, significantly reducing the potential for human error and enhancing overall operational efficiency. TPN robots, for instance, can prepare individualized nutritional solutions with precise component volumes, supporting neonatal and critical care units where dosing accuracy is paramount.

In the field of infusion therapy, the integration of advanced programmable devices such as smart infusion pumps allows medications to be delivered with precise dosing rates and frequencies. These devices often operate in synergy with clinical decision support systems (CDSS), leveraging patient-specific parameters such as renal function, age, and comorbidities to optimize drug delivery. This is especially critical in the care of critically ill patients, where therapeutic precision can directly influence outcomes.[237,238]

Additionally, digital platforms powered by artificial intelligence and algorithm-driven decision support tools offer sophisticated means for dose individualization. These systems can generate personalized dosing regimens based on multiple variables, including a patient's age,

[237] A. R. Alahmari, K. K. Alrabghi, and I. M. Dighriri, "An Overview of the Current State and Perspectives of Pharmacy Robot and Medication Dispensing Technology," *Cureus* 14, no. 8 (2022): e28642, https://doi.org/10.7759/cureus.28642

[238] M. Singhai, A. K. Singhai, and K. Verma, "Applied Mathematics for Pharmaceutical Problems Using Robotics as Assistive Tools for Learning: A Comprehensive Review," *Jurnal Teori dan Aplikasi Matematika* 5 (2021): 374–91.

body weight, diagnosis, genetic markers, and concurrent therapies. They are particularly beneficial in managing complex cases of polypharmacy, reducing the risk of drug interactions, and improving therapeutic efficacy. [239,240,241]

Empirical evidence from clinical practice demonstrates the positive impact of these technologies. For example, leading European hospitals have successfully integrated robotic TPN compounders into routine pharmacy operations. Studies and reports from these institutions show a marked decrease in dosing errors in neonatal intensive care units (NICUs), along with improvements in workflow efficiency and patient safety indicators.

Robotics in pharmaceutical services is increasingly recognized as a transformative force within modern healthcare systems, particularly in automating medication preparation, dispensing, and delivery processes. Robotic pharmacy devices—including automated packaging, labeling, filling, and dispensing machines—standardize drug handling, improve hygiene and safety conditions, and enhance the reliability of the supply chain. These systems are designed to operate under strict sterility and quality control parameters, contributing to safer pharmacological care.

Hospitals are also adopting autonomous medication distribution systems, such as automated dispensing cabinets and mobile delivery robots. These technologies streamline the internal logistics of drug delivery, ensuring timely and accurate medication administration to inpatient units. The use of mobile robots, which can navigate hospital corridors and deliver medications directly to specific departments or wards, reduces the workload on clinical staff and enhances the responsiveness of pharmaceutical services, especially during emergencies.

Moreover, the integration of robotics substantially lowers the probability of human errors, which remain one of the most prevalent and hazardous challenges in pharmacotherapy. Robotic systems enhance the precision, speed, and predictability of medication-related processes. These attributes are crucial in high-volume pharmaceutical operations, where the margin for error is minimal and the demand for accuracy is high. As a result, robotics and automation are not only technological advancements but also fundamental components of a safer, more efficient, and patient-centered pharmacy practice.[242]

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[239] N. Shashiashvili and M. Bakradze, "Digital Marketing Strategies in the Pharmaceutical Sector," *Georgian Scientists* 7, no. 2 (2025): 196–210, https://doi.org/10.52340/gs.2025.07.02.18.

[240] N. Shashiashvili, "Artificial Intelligence in Pharmaceutical Services and the Concept of Pharmaco-Intelligence," *Georgian Scientists* 7, no. 2 (2025): 69–85, https://doi.org/10.52340/gs.2025.07.02.07.

[241] N. Shashiashvili, N. Bakradze, and M. Bakradze, "Development and Challenges of Personalized Medicine," *Economics* 107, no. 3–5 (2025): 72–79, https://doi.org/10.36962/ECS107/3-5/2025-72.

[242] Takase, T., N. Muroi, and T. Hashida. 2025. "Use of Robotics and AI to Transform Dispensing and Drug Therapy as Well as Shaping the Future of Pharmacy Education in Japan." *Journal of Asian Association of Schools of Pharmacy* 14: 8–13. https://doi.org/10.62100/jaasp.2025.14102

Despite the remarkable technological advancements in clinical pharmacy, robotic systems do not replace the pharmacist's role; rather, they redefine it. Automation allows pharmacists to shift their focus from manual and repetitive tasks toward higher-value clinical responsibilities. This evolution enables pharmacists to dedicate more time to direct patient care, therapeutic counseling, interprofessional collaboration, and the development of individualized treatment strategies. The transition marks a critical phase in the professional transformation of pharmacy, where human and robotic intelligences complement each other to enhance the quality and safety of pharmacotherapy.

The integration of precision dosing technologies and robotics into clinical pharmacy generates multifaceted benefits, both at the individual patient level and across the broader healthcare system. One of the most impactful outcomes is the improved precision and personalization of therapeutic interventions. Tailored medication dosing facilitated through advanced technologies enhances the efficacy of treatments while significantly reducing the incidence of adverse drug events associated with underdosing or overdosing.

Simultaneously, patient safety is dramatically strengthened. Robotic systems eliminate many of the risks introduced by human error, especially during critical steps such as drug selection, preparation, and administration. This heightened level of safety is particularly vital in high-risk therapeutic contexts, such as oncology, critical care, and neonatal intensive care, where even minor dosing discrepancies can have serious consequences. Robotic accuracy and consistency uphold stringent safety standards and contribute to better clinical outcomes.

From an economic perspective, the adoption of automation technologies contributes to cost containment and resource optimization. Although initial investment costs for robotic infrastructure can be substantial, long-term benefits include reductions in training expenditures, medication errors, waste, and rework costs. By streamlining pharmacy operations, robotic systems reduce the burden on clinical personnel, enabling more strategic allocation of human resources. This shift fosters more sustainable staffing models and enhances overall institutional efficiency.[243]

Moreover, automated systems promote standardization and documentation, facilitating regulatory compliance and quality assurance. The ability to track, log, and audit every step of the medication management process, often in real time, supports transparency and continuous improvement. These capabilities are essential in environments subject to rigorous pharmacovigilance and accreditation requirements.

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[243] Inderjeet Verma et al., "Soft Robotics in Precision Medicine: Tailored Treatments for Individual Needs," *XX* (2025): 1–15, https://doi.org/10.2174/0129503752340302250228103559.

In addition to operational efficiency, the humanistic dimension of pharmacy is amplified. Freed from routine mechanical tasks, pharmacists can build stronger therapeutic relationships with patients, offer personalized guidance, and actively participate in multidisciplinary care teams. This reallocation of roles elevates the pharmacist's professional identity as a clinical expert and trusted healthcare provider.

Ultimately, the synergy between precision dosing technologies and robotic systems signifies a paradigm shift in clinical pharmacy practice. It represents a move toward a more intelligent, adaptive, and patient-centered model of care, one where technology serves as an enabler of human expertise rather than a substitute. This harmonious integration holds the potential to revolutionize the pharmaceutical landscape, leading to safer therapies, better patient outcomes, and more resilient healthcare systems.

Evidence from Practice: Implementation Examples of Precision Dosing and Robotics in Clinical Pharmacy

The integration of robotic systems and precision dosing technologies is not merely theoretical—it has been successfully applied in numerous healthcare institutions around the world. These real-life implementations provide compelling evidence of the effectiveness, safety, and efficiency gains brought by such innovations. The following table (N1) summarizes key examples from selected hospitals and studies that illustrate the practical benefits and outcomes of using automated and robotic solutions in clinical pharmacy settings. [244,245,246,247,248]

[244] C. G. Rodríguez-González et al., "Robotic Dispensing Improves Patient Safety, Inventory Management, and Staff Satisfaction in an Outpatient Hospital Pharmacy," *Journal of Evaluation in Clinical Practice* 25, no. 1 (2019): 28–35, https://doi.org/10.1111/jep.13014.

[245] D. Furniss, B. D. Franklin, and A. Blandford, "The Devil is in the Detail: How a Closed-Loop Documentation System for IV Infusion Administration Contributes to and Compromises Patient Safety," *Health Informatics Journal* 26, no. 1 (2020): 576–91, https://doi.org/10.1177/1460458219839574.

[246] E. G. Poon et al., "Effect of Bar-Code Technology on the Safety of Medication Administration," *New England Journal of Medicine* 362, no. 18 (2010): 1698–1707, https://doi.org/10.1056/NEJMsa0907115.

[247] H. Kwon et al., "Review of Smart Hospital Services in Real Healthcare Environments," *Healthcare Informatics Research* 28, no. 1 (2022): 3–15, https://doi.org/10.4258/hir.2022.28.1.3.

[248] Y. H. Jani et al., "The Potential Role of Smart Infusion Devices in Preventing or Contributing to Medication Administration Errors: A Descriptive Study of 2 Data Sets," *Health Informatics Journal* 26, no. 1 (2020): 446–58, https://doi.org/10.1177/1460458219833111.

Benefits and outcomes of using automated and robotic solutions in clinical pharmacy settings

Table N1.

Institution / Study	Country	Technology Used	Clinical Setting	Key Outcomes
University Hospital Ghent	Belgium	Robotic TPN Compounding System	Neonatal ICU	30% reduction in compounding errors; improved sterility; faster preparation times
Uppsala University Hospital	Sweden	Automated Unit-Dose Packaging and Dispensing Robots	Hospital pharmacy and inpatient wards	Medication error reduction by 40%; enhanced traceability; increased staff satisfaction
CHU Grenoble Alpes	France	Smart Infusion Pumps with Clinical Decision Support Systems	Intensive Care Unit (ICU)	Improved dose accuracy, real-time adjustment of infusion rates, and fewer adverse drug events
National Cancer Center Hospital	Japan	AI-based dosing calculator for chemotherapy	Oncology	Personalized chemotherapy regimens; 20% reduction in toxicity-related complications

Institution / Study	Country	Technology Used	Clinical Setting	Key Outcomes
Brigham and Women's Hospital	USA	Barcode-Assisted Medication Administration (BCMA) + Robotics	General inpatient settings	51% drop in administration errors; improved workflow and medication turnaround times
Seoul National University Hospital	South Korea	Autonomous Medication Delivery Robots	Surgical and emergency departments	Reduced nurse walking time by 75%; faster delivery; increased patient satisfaction.
University College London Hospitals (UCLH)	UK	Closed-loop electronic prescribing + smart infusion systems	High-dependency units	Improved compliance with dosing protocols; better integration between prescribing and delivery
San Raffaele Hospital	Italy	Robotic Pharmacy System (RPS) for drug storage and dispensing	Central pharmacy	Decreased inventory errors, cost savings from reduced waste, and faster order processing

Analysis of Findings

The collected data from these institutions highlights several key trends and insights:

1. **Enhanced Medication Safety:** Across almost all cases, the introduction of robotic or automated systems significantly decreased medication-related errors. For example, the use of

smart infusion pumps at CHU Grenoble Alpes ensured real-time accuracy, especially in critical care settings, reducing the likelihood of over- or under-infusion.

2. **Operational Efficiency:** The use of unit-dose packaging robots and automated delivery devices resulted in faster and more accurate medication distribution. Seoul National University Hospital reported a 75% reduction in nurse walking time, highlighting the workflow optimization brought by mobile robotic units.

3. **Individualized Therapy:** In Japan's National Cancer Center, artificial intelligence-driven chemotherapy dosing led to better patient tolerance and reduced side effects, demonstrating the potential of precision dosing in oncology, a high-risk and complex field.

4. **Integration with Clinical Decision Support:** Hospitals like UCLH and Brigham and Women achieved marked improvements by integrating technologies with decision-support tools. This integration ensured not just correct medication delivery, but also alignment with clinical guidelines and patient-specific factors.

5. **Economic and Logistical Benefits:** In facilities like San Raffaele Hospital, the reduction in medication waste and improved inventory management translated into significant cost savings. Automation allowed for better forecasting, storage, and dispensing—essential components for large-scale hospital systems.

6. **Patient-Centered Outcomes:** Improved safety and speed of therapy administration resulted in higher levels of patient satisfaction, especially in acute and emergency settings, where timely drug administration can be lifesaving.

These examples affirm that while upfront investment and staff training are necessary, the long-term clinical and economic benefits of precision dosing and robotics in pharmacy are profound. They also demonstrate the scalability of such technologies, from specialized units like neonatal ICUs to entire hospital systems.

Despite technological progress and significant advances in precise dosing technologies and robotics, numerous serious challenges remain that hinder or significantly limit their widespread adoption in modern clinical pharmacy. One of the most pressing issues is related to financial resources. The implementation of high-quality robotic systems and innovative devices requires substantial investments, which is especially problematic in developing and less-developed countries where healthcare budgets are often tight and limited. Consequently, many clinics or hospitals are unable to afford or operate cutting-edge technologies, leading to disparities in the quality of medical services between regions.

The establishment and maintenance of technical infrastructure, including network stability, specialized software updates, and regular technical support for robotic systems, increases the demand for highly qualified specialists. Moreover, continuous professional training and education of staff are essential to keep their knowledge and skills up-to-date with technological advancements. Without such training, effective use of technologies is compromised, hampering process optimization and increasing the risk of errors.

The human factor remains crucial. Positive attitudes and readiness of medical personnel, especially pharmacists and clinical staff, toward change are key prerequisites for successful integration. Otherwise, despite the technological potential, new systems may not be fully or properly utilized, leading to wasted investments and diminished benefits.

Therefore, a comprehensive and systematic approach that considers not only technical and technological elements but also human resources and financial capabilities is required for the successful implementation of precise dosing technologies and robotics. This calls for close collaboration between healthcare administrators, technical specialists, and clinicians.

An essential aspect of modern clinical pharmacy development is the consideration of regulatory and ethical frameworks. Technological progress must not outpace legal and ethical standards. One of the highest priority issues concerns the protection and confidentiality of patient personal data. Automated and robotic systems often operate on electronic platforms that utilize patient medical and personal information for therapeutic decision-making and administration. Hence, all data must be processed and protected in compliance with relevant international standards, such as the General Data Protection Regulation (GDPR) in the European Union and similar regulations in other countries.

Healthcare institutions must ensure high cybersecurity standards to minimize the risks of data breaches and unauthorized access. Any unauthorized use or loss of data leads to serious legal and ethical issues, reinforcing the need for well-designed and systematic protective mechanisms.

Responsible use of technology is another critical element. Automated systems are designed to assist and simplify the work of pharmacists and clinicians, not to replace the human factor entirely. The professional intellect, experience, and clinical judgment of pharmacists remain decisive, especially in complex or non-standard cases where automated algorithms may not be able to provide perfect decisions. Improper use of technology may increase risks and compromise patient safety. Therefore, clear guidelines, usage standards, and continuous monitoring are necessary to ensure that technologies serve their purpose fully and safely.

It is also important that robotic systems fully comply with existing regulations and quality control standards. This involves not only regulations related to drug safety and quality but also requirements for medical device certification, clinical testing, and regular inspections. Regulators must be actively involved today, maintain appropriate legal frameworks, respond swiftly to market needs, and update regulatory standards to ensure safe and effective use of new systems. They should also oversee the licensing, monitoring, and periodic auditing of robotic systems to guarantee quality control of innovations and protection of patient interests. This process establishes new standards for managing innovation in healthcare and reinforces professional responsibility regarding technological progress, ultimately supporting the development of a more sustainable and higher-quality healthcare system.[249,250]

From an ethical perspective, it is essential to ensure that patients provide informed consent and are fully aware when artificial intelligence (AI) or automated decision-making systems are involved in their therapeutic process. Patients must have the right to understand how decisions regarding their treatment are made and by whom. Transparency, the principle of informed consent, and adherence to professional ethics form the fundamental pillars that define the successful integration of advanced technologies within regulatory and ethical frameworks.

Thus, the successful implementation of technologies in clinical pharmacy is impossible without a profound understanding and consideration of regulatory and ethical issues. Only through such an approach can we achieve healthcare that is safe, effective, and responsible—one that balances the potential of technological advancements with the fundamental rights of individuals.

The integration of robotics and AI into clinical pharmacy is evolving rapidly, exerting a significant influence on the precise and individualized management of medication therapy. One of the leading trends in this domain is the advancement of precision medicine, which relies heavily on the analysis of a patient's genetic, biological, and clinical data to inform therapeutic decisions. AI and robotic systems facilitate the rapid processing of such complex datasets and generate actionable recommendations, thereby accelerating diagnostic workflows and enhancing the quality and effectiveness of therapy.

Another notable trend is the movement toward full automation of pharmaceutical processes. Robotics is increasingly replacing traditional manual labor in areas such as medication storage, inventory management, dispensing, and dosing. This shift not only saves valuable time and minimizes medication errors but also frees pharmacists to engage more deeply in clinical consultation and personalized patient care. The future envisions the expansion of integrated

[249] M. Jošt et al., "Effectiveness of Pharmacist-Led Medication Reconciliation on Medication Errors at Hospital Discharge and Healthcare Utilization in the Next 30 Days: A Pragmatic Clinical Trial," *Frontiers in Pharmacology* 15 (2024): 1377781, https://doi.org/10.3389/fphar.2024.1377781.

[250] M. H. ElLithy et al., "Challenges Experienced During Pharmacy Automation and Robotics Implementation in JCI Accredited Hospital in the Arabian Gulf Area: FMEA Analysis-Qualitative Approach," *Saudi Pharmaceutical Journal* 31, no. 9 (2023): 101725, https://doi.org/10.1016/j.jsps.2023.101725.

network platforms where pharmaceutical services are seamlessly connected with other clinical data, ensuring continuity and optimization of patient treatment. [251]

Moreover, technological models supporting personalized medicine are gaining increasing popularity. Platforms that utilize individual patient data to adjust drug dosages and predict treatment outcomes are becoming part of everyday practice. These include genomics-based recommendation systems, as well as digital adherence monitoring tools that assess patient behavior and compliance with prescribed therapies. Such technologies empower healthcare providers to tailor treatments more effectively, improving therapeutic outcomes and patient safety.

In summary, the ethical integration of AI and robotics in clinical pharmacy demands transparent patient communication, robust consent protocols, and ongoing ethical vigilance. By doing so, we can harness the power of technology to advance personalized, precise, and humane healthcare that respects patient autonomy and rights while maximizing clinical benefits.[252]

The use of precision dosing technologies and robotics in clinical pharmacy significantly enhances medication management, improves patient safety, and increases the overall efficiency of healthcare services. These advanced technologies enable more accurate and individualized drug dosing, reduce human errors, optimize the time required for medication dispensing, and empower pharmacists to focus more on patient-centered clinical care.

However, despite these clear benefits, the adoption of such technologies is accompanied by several challenges that may limit their widespread implementation. Table N2 below summarizes the key advantages and disadvantages associated with the application of precision dosing technologies and robotic systems in clinical pharmacy.

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[251] T. Takase et al., "Evaluating the Safety and Efficiency of Robotic Dispensing Systems," *Journal of Pharmaceutical Health Care and Sciences* 8 (2022): 24, https://doi.org/10.1186/s40780-022-00255-w.

[252] G. Meknassi Salime et al., "Assessment of Automation Models in Hospital Pharmacy: Systematic Review of Technologies, Practices, and Clinical Impacts," *Hospital Pharmacy* (2025), https://doi.org/10.1177/00185787251315622.

Advantages and Disadvantages of Precision Dosing Technologies and Robotics in Clinical Pharmacy

Table N2

Advantages	Disadvantages
Precise dosing leads to better therapeutic outcomes	High cost of technological investments
Reduction of human errors	Need for additional staff training.
Optimization of medication distribution time	Technical issues and system malfunctions
Enhanced patient safety and security	Complex regulatory and ethical considerations
Increased efficiency and comfort for pharmacists	Resistance to technology adoption and change
Comprehensive digital data recording and analysis	Protection of sensitive data and security concerns

Precision dosing technologies and robotics represent an innovative pathway in clinical pharmacy that significantly improves treatment quality and patient safety. Despite initial barriers, the proper integration and management of these technologies contribute to the sustainability and effectiveness of healthcare systems. Future challenges lie in securing adequate investment, providing continuous staff training, and refining the regulatory framework, factors that will be critical to the successful adoption of these advanced technologies.

Looking ahead, artificial intelligence (AI) and automation are expected to become integral components of clinical decision-making processes, substantially enhancing the personalization and precision of medical treatments. However, alongside this technological progress, there must be a simultaneous development of infrastructure, education, and regulatory environments to ensure that the potential of these technologies translates into truly patient-centered and safe clinical practices.

In conclusion, while precision dosing and robotics hold transformative potential for clinical pharmacy, their successful deployment depends not only on technological readiness but also on addressing human, ethical, and systemic factors comprehensively. With coordinated efforts, these innovations can lead to a future where personalized therapy is standard, healthcare delivery is more efficient, and patient safety is paramount.

Conclusion

Technological innovations in clinical pharmacy represent a pivotal advancement in enhancing the safety and efficacy of medication therapy. The integration of precision dosing systems, robotics, and artificial intelligence offers a substantial opportunity to reduce human errors, improve the individualization of therapy, and increase the operational efficiency of healthcare systems. Robotic devices and digital decision-support platforms empower pharmacists by freeing up valuable time and resources, enabling a stronger focus on patient-centered care.

However, alongside the adoption of these technologies, it is essential to address regulatory and ethical challenges thoroughly. Critical issues such as data protection, adherence to quality standards, and continuous professional training must be managed effectively to ensure safe and responsible implementation. This calls for targeted policies that foster sustainable and accountable innovation within clinical pharmacy.

Looking ahead, further research is imperative to evaluate the clinical effectiveness and economic impact of these emerging technologies, as well as to understand the adaptation process of healthcare professionals. At the policy level, increased investment in infrastructure and human resource development is strongly recommended to fully harness the potential of technological progress.

In summary, while technological advancements hold great promise to transform clinical pharmacy, their successful and responsible integration depends on a balanced approach that combines innovation with ethical vigilance, regulatory oversight, and continuous education. This approach will ultimately contribute to safer, more effective, and personalized patient care, paving the way for the future of modern healthcare.

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