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The Effectiveness of Pharmacist-Led Interventions in Preventing Medication Administration Errors in Pediatric Patients

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ABSTRACT: Medication administration errors represent a major preventable threat to patient safety in pediatric healthcare settings, particularly among neonates, infants, and critically ill children who require complex pharmacological treatment, individualized dose calculations, weight-based prescribing, and frequent medication adjustments. Unlike adults, pediatric patients demonstrate substantial physiological variability throughout growth and development, which affects drug absorption, distribution, metabolism, and elimination and increases the complexity of medication preparation and administration. Medication administration errors may involve incorrect doses, wrong medications, incorrect routes, inappropriate infusion rates, omitted doses, timing errors, preparation errors, and

inaccurate documentation, potentially resulting in clinically significant adverse drug events, prolonged hospitalization, increased healthcare costs, and preventable morbidity. Pharmacists have an essential role in improving pediatric medication safety through medication review, dose verification, clinical decision support, prescription screening, medication reconciliation, intravenous preparation supervision, bedside consultation, interdisciplinary collaboration, staff education, and continuous monitoring of medication-related outcomes. Pharmacist-led interventions have demonstrated promising effectiveness in reducing medication errors and drug-related problems among hospitalized pediatric patients, with evidence suggesting that proactive clinical pharmacy involvement, particularly during multidisciplinary rounds and medication preparation processes, may substantially reduce the likelihood of errors reaching patients. Educational interventions, standardized medication protocols, electronic prescribing systems, barcode-assisted administration, smart infusion pumps, and structured medication safety practices can further strengthen the effectiveness of pharmacist-led strategies. However, the magnitude of improvement varies according to healthcare setting, intervention design, staffing resources, institutional medication safety culture, and the availability of technological infrastructure.

INTRODUCTION

Medication safety is a fundamental component of healthcare quality and patient protection, and medication errors remain a significant source of preventable morbidity and mortality across healthcare systems worldwide. The medication-use process involves several interconnected stages, including prescribing, transcription, dispensing, preparation, administration, and monitoring, and errors may occur at any stage because of individual, organizational, technological, or communication-related factors. Medication errors are generally defined as preventable events that may cause or lead to inappropriate medication use or patient harm while the medication is under the control of a healthcare professional, patient, or caregiver, regardless of whether an adverse outcome actually occurs. The complexity of medication-use systems, increasing numbers of prescribed drugs, frequent transitions between healthcare settings, and inadequate communication among healthcare professionals contribute to the persistence of medication-related safety problems despite improvements in clinical practice and healthcare technology [1,2]. Medication safety has consequently become a major international healthcare priority, requiring systematic interventions that address both individual professional performance and the organizational conditions under which medications are prescribed, prepared, administered, and monitored [1,2].

Pediatric patients represent a particularly vulnerable population because medication therapy must be individualized according to age, body weight, body surface area, developmental stage, clinical condition, renal function, hepatic function, and the characteristics of the administered drug. Unlike adult patients, children frequently receive doses calculated using milligrams per kilogram or body surface area, and these calculations may require repeated adjustments as body weight changes during hospitalization or clinical deterioration. The need to convert between units, concentrations, dosage forms, and administration volumes creates multiple opportunities for mathematical and procedural errors, particularly when medications are prepared from concentrated solutions or adult formulations that are not suitable for children. In addition, developmental differences in drug metabolism, protein binding, renal elimination, and physiological responses can substantially influence medication exposure and toxicity, making accurate dosing and administration essential for achieving therapeutic benefit while minimizing harm [3,4].

The consequences of medication errors in pediatric patients may be more serious than those observed in adults because relatively small deviations from the intended dose can result in substantial differences in drug exposure, particularly in neonates and infants with limited physiological reserves. Children may also be unable to recognize, communicate, or report medication-related symptoms because of their age, developmental limitations, altered consciousness, or underlying illness, which may delay the identification of adverse effects. In hospitalized pediatric patients, medication errors have been associated with potentially harmful events involving incorrect doses, inappropriate drug selection, infusion-related mistakes, medication omissions, and inadequate monitoring, with the severity of consequences influenced by the medication involved, the patient's age, comorbidities, and the duration of exposure. These considerations emphasize that pediatric medication safety requires

specialized knowledge, careful attention to details, and preventive systems designed specifically to accommodate the physiological and operational differences of children [3,5].

Medication administration is a particularly critical stage of the medication-use process because errors occurring during preparation or administration may directly expose patients to incorrect medications, doses, concentrations, routes, or infusion rates. Although prescribing errors may be intercepted during subsequent verification processes, administration errors can reach patients when safeguards are absent, ineffective, or inconsistently implemented. Medication administration in pediatric wards, emergency departments, neonatal intensive care units, and pediatric intensive care units often involves complex preparation procedures, multiple medication schedules, intravenous infusions, enteral feeding tubes, liquid formulations, and frequent interruptions, all of which increase the possibility of procedural failures. Errors may also occur when healthcare professionals use inaccurate weight measurements, outdated medication orders, inappropriate concentrations, unclear instructions, or incomplete documentation, making medication administration a multifactorial process that requires coordinated preventive strategies [6,7].

The increasing complexity of pediatric pharmacotherapy has created a strong need for specialized medication safety services capable of identifying risks before they result in patient harm. Clinical pharmacists possess professional expertise in pharmacokinetics, pharmacodynamics, drug interactions, therapeutic dosing, medication preparation, dosage-form selection, drug compatibility, and medication monitoring, allowing them to contribute directly to the prevention and management of medication-related problems. Their involvement may include reviewing medication orders, validating doses according to current patient characteristics, evaluating laboratory results, identifying contraindications, assessing drug interactions, providing recommendations for appropriate formulations, and supporting nurses and physicians during medication preparation and administration. The integration of pharmacists into pediatric healthcare teams provides an additional layer of clinical review that complements the responsibilities of physicians and nurses and facilitates the early identification of medication-related risks [8,9].

Pharmacist-led interventions are not limited to correcting individual medication orders but may encompass comprehensive approaches aimed at improving the safety of the entire medication-use process. These interventions include prospective prescription screening, participation in multidisciplinary rounds, medication reconciliation, direct observation of medication preparation and administration, development of standardized protocols, implementation of electronic clinical decision support systems, educational activities, and provision of timely drug information. Pharmacists may also identify system-level problems, including unsafe medication concentrations, confusing labeling, inadequate storage practices, insufficient documentation, and recurrent medication administration errors, and collaborate with healthcare professionals to redesign processes and reduce the likelihood of error recurrence. Such activities reflect the evolution of pharmacy practice from a primarily dispensing-oriented function toward a patient-centered clinical service that actively contributes to medication safety and therapeutic outcomes [8–10].

The evidence supporting clinical pharmacist involvement in pediatric healthcare has progressively expanded, with systematic reviews reporting improvements in medication safety, reductions in medication errors, and substantial acceptance of pharmacist recommendations by other healthcare professionals. Pharmacist interventions frequently address inappropriate dosing, medication selection, treatment duration, drug interactions, administration schedules, contraindications, and monitoring requirements, with dosing errors consistently identified as a major reason for pharmacist intervention. Studies have demonstrated that pharmacists can identify clinically significant medication errors that may otherwise remain undetected, including errors with the potential to cause serious or fatal consequences, and their recommendations may prevent inappropriate medication exposure before administration occurs. Nevertheless, the effectiveness of pharmacist-led interventions depends on the timing of involvement, accessibility of patient information, integration into clinical workflows, communication with the healthcare team, and the availability of pharmacists with specialized pediatric knowledge [9–12].

Despite the growing recognition of pharmacists as essential members of pediatric healthcare teams, medication administration errors remain challenging to prevent because they arise from interactions among human factors, clinical complexity, organizational conditions, and weaknesses in medication-use systems. Educational interventions alone may improve knowledge but may not adequately address workload, staffing shortages, interruptions, inadequate medication preparation areas, confusing medication labels, or the absence of technological safeguards. Consequently, contemporary medication safety approaches emphasize the development of multifaceted interventions that combine professional expertise with standardized medication procedures, electronic systems, independent verification when clinically appropriate, medication safety education, incident

reporting, and continuous quality improvement. The integration of pharmacist-led interventions into such comprehensive systems may provide a sustainable approach to reducing medication errors and protecting pediatric patients from avoidable medication-related harm [13- 15].

Pediatric Medication Administration Errors

Definition and Classification of Medication Administration Errors

Medication administration errors are preventable deviations from the prescribed medication regimen or accepted medication administration procedures that occur during the preparation, dispensing-related handling, or administration of medications and may result in inappropriate medication exposure or potential patient harm. These errors may occur independently or in combination, and a single medication administration episode may involve more than one error, such as incorrect dose preparation followed by administration through an inappropriate infusion rate. Classification systems are important because they facilitate standardized incident reporting, comparison of medication safety outcomes, identification of recurring patterns, and development of targeted preventive interventions. Pediatric medication administration errors are commonly classified according to the type of deviation from the intended medication process, including wrong patient, wrong medication, wrong dose, wrong route, wrong time, wrong frequency, wrong concentration, omission, unauthorized administration, preparation errors, infusion-rate errors, and documentation errors [3,6,16].

Wrong-dose errors are particularly important in pediatric practice because dose calculations frequently depend on body weight, body surface area, age, and maximum recommended dose limits. These errors may involve administration of doses that are higher or lower than prescribed, incorrect conversion between units, inaccurate measurement of liquid medication volumes, inappropriate rounding, failure to account for maximum adult doses, or use of incorrect concentrations during medication preparation. Dose-related errors may also occur when the patient's weight is outdated, when kilograms are incorrectly converted into pounds, when decimal points are misplaced, or when a calculated dose is not compared with a clinically appropriate dose range. The consequences may include therapeutic failure, inadequate symptom control, toxicity, severe physiological disturbances, or the need for additional medical treatment [3,4,16].

Wrong-medication errors occur when a patient receives a drug different from the medication prescribed, and these errors may arise from similar packaging, confusing drug names, inadequate labeling, incorrect storage, dispensing mistakes, or failures in medication verification. Wrong-route errors may involve administering oral medications intravenously, using inappropriate enteral routes, or administering medications through the wrong access device, while timing errors may involve delayed doses, early administration, incorrect intervals, or failure to coordinate medications with feeding schedules. Omission errors occur when prescribed medications are not administered, whereas unauthorized medication errors involve administration of medications without an appropriate order or outside the established clinical protocol. Preparation-related errors include incorrect dilution, inaccurate reconstitution, inappropriate solvent selection, contamination, incorrect concentration, and inadequate mixing, which are particularly relevant to intravenous medications and pediatric liquid formulations [6,7,16].

Documentation errors may occur when medication administrations are recorded inaccurately, incompletely, or at the wrong time, potentially creating uncertainty about whether a medication has been administered and increasing the risk of duplicate doses or omissions. Failure to document medication administration accurately may also compromise communication during shift changes, transfers, and emergency situations, particularly when multiple healthcare professionals are involved in the patient's treatment. Errors related to infusion rates and infusion pump programming are especially important because intravenous medications may be delivered continuously or intermittently over prolonged periods, and incorrect pump settings can produce rapid changes in drug exposure. Understanding these categories allows pharmacists to design interventions that target the specific mechanisms of medication administration errors rather than relying on generalized safety education [6,16,17].

Epidemiology and Burden of Pediatric Medication Errors

Medication errors occur throughout pediatric healthcare settings, including inpatient wards, emergency departments, neonatal intensive care units, pediatric intensive care units, outpatient clinics, and community healthcare environments. Published studies have reported considerable variation in error rates because of differences in definitions, detection methods, patient populations, medication-use processes, reporting systems, and study designs. Direct observation frequently identifies errors that are not captured through voluntary incident reporting, while retrospective chart reviews and electronic surveillance may identify different types of medication-related problems. Therefore, reported error rates should be interpreted according to the specific

denominator used, including medication orders, doses administered, patients, admissions, patient-days, or observed medication administration episodes [3,6,18].

Pediatric medication errors are particularly common in hospital settings where patients receive multiple medications, complex infusions, emergency treatment, and frequent dose adjustments. Neonates and infants are often considered among the most vulnerable groups because of developmental immaturity, low body weight, limited availability of standardized formulations, and the frequent use of medications requiring individualized calculations or off-label prescribing. Children receiving care in intensive care units may have additional risk factors, including organ dysfunction, hemodynamic instability, multiple infusion lines, complex medication schedules, and the need for high-alert medications. These factors increase the clinical complexity of medication administration and create opportunities for errors during medication preparation, verification, administration, and monitoring [3,6,18].

The burden of medication administration errors extends beyond the immediate clinical consequences of an incorrect dose or medication because errors may result in additional diagnostic investigations, prolonged hospitalization, increased monitoring, treatment delays, additional medication exposure, and greater healthcare expenditure. Medication errors may also cause psychological distress among parents and caregivers, reduce confidence in healthcare professionals, and contribute to emotional distress among healthcare workers involved in medication-related incidents. The actual burden of medication errors is likely underestimated in institutions that depend primarily on voluntary reporting because healthcare professionals may fail to report near misses, minor errors, or events that are intercepted before reaching patients. Comprehensive medication safety surveillance incorporating direct observation, pharmacist review, electronic reporting, and clinical outcome assessment is therefore necessary to understand the true magnitude of medication administration errors in pediatric healthcare [2,3,18].

Vulnerability of Pediatric Patients to Medication Errors

The vulnerability of pediatric patients to medication administration errors is primarily related to developmental pharmacology, individualized dosing requirements, limited communication abilities, and the complexity of medication preparation. Drug doses are frequently calculated according to body weight or body surface area, and the same medication may require substantially different doses, concentrations, and formulations depending on the child's age and clinical condition. Neonates may demonstrate immature renal and hepatic function, altered drug distribution, and developmental differences in receptor sensitivity, while older children may experience changes in metabolic pathways and drug clearance during growth. These physiological differences require careful assessment of patient-specific factors before medication administration and increase the importance of pharmacist involvement in dose verification and therapeutic monitoring [4,19].

The limited availability of pediatric formulations may necessitate manipulation of adult dosage forms, including tablet splitting, crushing, dilution, reconstitution, or preparation of extemporaneous liquid formulations. Such practices may introduce additional risks related to concentration accuracy, stability, compatibility, bioavailability, measurement precision, and administration through feeding tubes. The use of different concentrations of the same medication within a healthcare facility may also create confusion and increase the risk of concentration-related errors, particularly when nurses prepare medications under time pressure or when patients are transferred between units. Pharmacists can reduce these risks by promoting standardized concentrations, identifying appropriate formulations, establishing preparation instructions, and providing practical guidance regarding medication administration techniques [4,7,19].

Children are also vulnerable because they may be unable to independently verify medication identity, recognize inappropriate administration, communicate symptoms of adverse drug reactions, or question discrepancies in medication instructions. Infants and young children depend almost entirely on healthcare professionals and caregivers to ensure accurate medication administration, while children with developmental disorders, neurological conditions, severe illness, or altered consciousness may have additional communication limitations. These characteristics increase the importance of caregiver participation, age-appropriate medication safety education, accurate identification procedures, and professional verification before administration. Medication safety interventions in pediatrics must therefore address not only the technical accuracy of medication preparation and administration but also the developmental needs and communication capabilities of the child [3,19,20].

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Risk Factors Contributing to Pediatric Medication Administration Errors

Patient-Related Risk Factors

Patient-related factors include low body weight, young age, prematurity, renal or hepatic dysfunction, complex medical conditions, polypharmacy, allergies, and rapidly changing clinical status. Accurate medication administration requires current patient information because doses may need to be modified according to weight changes, laboratory findings, organ function, therapeutic response, or clinical deterioration. Failure to update patient-specific information may result in inappropriate doses or medication selection, while incomplete allergy documentation may increase the possibility of administration of medications associated with hypersensitivity reactions. Patients receiving multiple medications may also be exposed to drug interactions, overlapping therapeutic effects, incompatible intravenous preparations, and complex administration schedules that increase the likelihood of error [3,4,19].

Medication-Related Risk Factors

Medication-related risk factors include high-alert medications, narrow therapeutic index drugs, intravenous medications, concentrated electrolytes, insulin, anticoagulants, opioids, chemotherapy agents, sedatives, and medications requiring complex calculations or specialized preparation procedures. These medications may cause serious harm when administered incorrectly, even when the deviation from the prescribed regimen is relatively small. Pediatric medication preparation may require multiple calculations, dilution steps, concentration conversions, and adjustments for available dosage forms, creating additional opportunities for error. Pharmacists can identify high-risk medications, recommend standardized concentrations, establish dose limits, develop administration instructions, and provide additional verification procedures for medications associated with significant potential harm [7,16,21].

Healthcare Professional-Related Risk Factors

Healthcare professional-related factors include inadequate pediatric pharmacology knowledge, insufficient medication administration training, calculation errors, fatigue, stress, interruptions, communication failures, unfamiliarity with medication formulations, and excessive workload. Nurses may experience difficulties when administering unfamiliar medications, interpreting complex prescriptions, calculating doses, preparing intravenous medications, or managing several patients simultaneously. Physicians may also contribute to medication administration errors through incomplete prescribing instructions, unclear orders, incorrect dose calculations, inappropriate formulations, or insufficient communication regarding medication changes. Pharmacist-led education and direct clinical consultation can improve healthcare professionals' understanding of medication safety and provide timely support when medication-related decisions involve complex clinical or technical considerations [6,10,13].

Organizational and Environmental Risk Factors

Organizational factors include inadequate staffing, poor workflow design, insufficient medication preparation areas, lack of standardized protocols, inadequate pharmacy services, interruptions, ineffective communication systems, and limited access to medication information. Environmental distractions may interfere with concentration during medication preparation, particularly in busy pediatric wards, emergency departments, and intensive care units where multiple urgent tasks occur simultaneously. The absence of standardized medication concentrations, confusing labeling, poorly organized storage, and inadequate separation of medications with similar names or packaging may also contribute to medication errors. Effective medication safety programs must therefore address system-level conditions rather than focusing exclusively on individual healthcare professional accountability [2,13,17].

Table 1. Major risk factors associated with pediatric medication administration errors [3,6,7,13,16,19,21].

Risk factor category	Examples	Potential mechanism of error	Recommended pharmacist-led preventive approach
Patient-related	Prematurity, low weight, organ dysfunction, allergies	Incorrect individualized dosing or inappropriate drug selection	Patient-specific dose verification and clinical monitoring

Medication-related	High-alert medications, concentrated solutions, intravenous drugs	Incorrect dose, concentration, dilution, or infusion rate	Standardized concentrations and high-alert medication review
Professional-related	Knowledge deficits, fatigue, interruptions, calculation errors	Preparation errors and incorrect administration	Education, bedside consultation, practical training, and feedback
Organizational	Inadequate staffing, poor workflow, limited medication information	Delayed doses, omissions, and unsafe medication handling	Workflow redesign and integrated clinical pharmacy services
Technological	Poor electronic alerts, lack of barcode systems, pump programming problems	Incorrect medication selection or infusion programming	Electronic decision support, barcode verification, and smart pumps
Communication-related	Incomplete orders, unclear handovers, inconsistent documentation	Wrong dose, duplicate dose, omission, or delayed administration	Medication reconciliation and structured interdisciplinary communication
Formulation-related	Adult formulations, multiple concentrations, dilution requirements	Concentration errors, inaccurate measurement, or inappropriate dosage forms	Formulation review, preparation protocols, and standardized products

Clinical Consequences of Medication Administration Errors

Adverse Drug Events and Patient Harm

Medication administration errors may result in adverse drug events ranging from temporary discomfort and mild physiological disturbances to severe toxicity, organ dysfunction, prolonged hospitalization, permanent disability, and death. The clinical consequences depend on the medication involved, the magnitude of the dosing error, the route of administration, the patient's age, physiological status, and the speed with which the error is identified and managed. Incorrect administration of antibiotics may result in inadequate treatment of infection or toxicity, while errors involving opioids, sedatives, insulin, anticoagulants, or concentrated electrolytes may produce serious consequences requiring immediate intervention. The prevention of medication administration errors is therefore particularly important for medications with a high potential for harm and for patients whose clinical condition makes them less able to tolerate medication-related complications [3,16,21].

Dose-related errors may cause both underexposure and overexposure, and the clinical significance of these errors differs according to the therapeutic indication and pharmacological properties of the medication. Underdosing may result in inadequate treatment, persistent symptoms, delayed recovery, treatment failure, or the development of complications associated with uncontrolled disease. Overdosing may cause toxicity, excessive sedation, respiratory depression, cardiovascular instability, metabolic abnormalities, neurological complications, or organ injury. Medication errors involving incorrect infusion rates may be particularly dangerous because rapid administration of a medication intended for gradual delivery can produce sudden physiological changes and potentially life-threatening reactions [3,6,21].

Impact on Hospitalization and Healthcare Utilization

Medication-related harm may increase healthcare utilization through additional laboratory investigations, therapeutic monitoring, medication discontinuation, administration of antidotes, treatment of adverse reactions, consultations, and prolonged hospitalization. Medication errors may also interrupt planned therapeutic interventions and delay the achievement of clinical goals, particularly when errors involve medications required for acute illness, infection management, seizure control, pain management, or cardiovascular stability. Although the financial burden associated with pediatric medication errors is difficult to quantify because of differences in reporting and healthcare systems, preventable medication-related complications may contribute to substantial institutional costs through additional treatment, increased length of stay, and utilization of healthcare resources [2,3,18].

Psychological and Professional Consequences

Medication errors may also affect parents and caregivers by increasing anxiety, reducing trust in healthcare professionals, and creating uncertainty regarding the safety of subsequent medication administration. Families may experience distress when children develop unexpected symptoms following medication administration or when they are informed that an error has occurred, particularly if the event results in additional monitoring or hospitalization. Healthcare professionals involved in medication errors may experience guilt, emotional distress, fear of disciplinary action, and reduced confidence, especially when incidents result in serious patient harm. The development of supportive, transparent, and non-punitive medication safety cultures is therefore important for promoting incident reporting, learning from errors, and preventing recurrence [2,13,17].

Role of Clinical Pharmacists in Pediatric Medication Safety

Medication Order Review and Dose Verification

Medication order review represents one of the most important pharmacist-led interventions for preventing pediatric medication errors because it allows potential problems to be identified before medications are prepared or administered. Pharmacists assess the indication, medication selection, dose, dosing interval, route, duration, formulation, contraindications, allergies, drug interactions, and monitoring requirements while considering the patient's current weight, age, diagnosis, organ function, laboratory findings, and clinical condition. Pediatric dose verification may require independent calculations using weight-based or body-surface-area-based dosing, assessment of maximum recommended doses, comparison with established therapeutic ranges, and evaluation of whether the prescribed dose is appropriate for the child's developmental stage. These activities may prevent inappropriate medication exposure and reduce the likelihood that prescribing errors will progress into administration errors [8,9,11].

Pharmacists may also identify discrepancies between prescribed doses and available formulations, particularly when medication concentrations differ between products or when intravenous and oral formulations are used interchangeably. They can recommend more appropriate dosage forms, clarify ambiguous instructions, identify unnecessary medication duplication, and assess whether administration schedules are compatible with the patient's clinical needs. Their review may be particularly valuable for high-alert medications, drugs requiring therapeutic monitoring, medications with narrow therapeutic indices, and treatments involving complex calculations or multiple preparation steps. Timely pharmacist recommendations can therefore improve medication accuracy and support safer medication administration across pediatric healthcare settings [8,11,12].

Participation in Multidisciplinary Clinical Rounds

Participation in multidisciplinary rounds allows pharmacists to identify medication-related problems through direct interaction with physicians, nurses, and other healthcare professionals involved in patient care. During rounds, pharmacists may review medication regimens, assess therapeutic response, evaluate laboratory results, recommend dose adjustments, identify drug interactions, discuss medication administration challenges, and provide information regarding compatibility, stability, preparation, and monitoring. Their presence during clinical decision-making may facilitate immediate clarification of medication orders and reduce delays associated with communication through separate consultation processes. Clinical pharmacy involvement during rounds also allows medication safety recommendations to be integrated into treatment planning before medications are prepared and administered [8,9,12].

The benefits of pharmacist participation in multidisciplinary rounds may be particularly important in intensive care settings, where patients frequently receive multiple medications, complex intravenous therapies, and rapidly changing treatment regimens. Pharmacists can help identify medication-related risks associated with renal impairment, hepatic dysfunction, hemodynamic instability, therapeutic drug monitoring, sedation, antimicrobial treatment, and medication compatibility. Their participation may also facilitate the development of individualized medication plans, improve communication among healthcare professionals, and support the timely implementation of medication-related recommendations. Evidence from pediatric clinical pharmacy literature suggests that pharmacist interventions may be more effective when pharmacists are directly integrated into clinical workflows rather than providing medication review services only after errors have occurred [8,9,12].

Medication Reconciliation

Medication reconciliation is a systematic process of obtaining the most accurate medication history, comparing it with current medication orders, identifying discrepancies, and resolving unintended differences during transitions of care. Pediatric patients

may experience medication discrepancies during admission, transfer between departments, changes in clinical status, discharge, or transitions between hospital and community healthcare settings. These discrepancies may involve omitted medications, incorrect doses, duplicate therapies, inappropriate continuation of medications, changes in administration schedules, or inaccurate documentation of home medications. Pharmacists are particularly well positioned to conduct medication reconciliation because of their expertise in medication histories, dosage forms, medication adherence, therapeutic indications, and drug-related problems [9,15,20].

Medication reconciliation may be especially challenging in pediatric patients because medication histories frequently depend on parents, caregivers, previous medical records, community pharmacies, or multiple healthcare providers. Information may be incomplete when caregivers cannot recall medication names, doses, administration schedules, or recent changes, while different formulations and concentrations may complicate the interpretation of medication histories. Pharmacist-led reconciliation can help verify medication information, clarify discrepancies, identify medication-related risks, and support accurate communication between healthcare professionals. Although the evidence supporting specific pediatric medication reconciliation interventions remains variable, reconciliation is an important component of comprehensive medication safety systems because it addresses discrepancies that may otherwise contribute to prescribing, dispensing, and administration errors [9,15,20].

Prevention of Preparation and Administration Errors

Pharmacists contribute directly to the prevention of medication preparation and administration errors by developing standardized procedures, reviewing medication preparation techniques, providing drug information, and supporting nurses during complex medication administration. Their interventions may include establishing appropriate dilution instructions, confirming compatibility with intravenous fluids and other medications, recommending safe infusion rates, clarifying reconstitution requirements, identifying suitable administration devices, and promoting the use of standardized concentrations. These measures are particularly relevant to pediatric patients because medication doses may involve small volumes, multiple dilution steps, and specialized preparation procedures that increase the risk of calculation and measurement errors [7,10,16].

Clinical pharmacists may also participate in direct observation of medication preparation and administration processes to identify unsafe practices and opportunities for improvement. Observational assessments may reveal recurring problems such as incorrect dose calculations, inappropriate medication concentrations, inaccurate infusion pump programming, inadequate labeling, preparation under distracting conditions, or insufficient verification before administration. Pharmacist-led feedback can be provided to nurses and physicians through educational sessions, individualized consultations, safety discussions, and revised protocols designed to address the specific causes of identified errors. Such interventions may improve awareness of medication administration risks and support the adoption of safer medication handling practices [10,13,16].

Medication Safety Education and Training

Medication safety education is an essential component of pharmacist-led interventions because healthcare professionals require ongoing knowledge and practical skills to manage the complexity of pediatric pharmacotherapy. Pharmacists can provide structured educational programs covering pediatric dose calculations, weight-based dosing, high-alert medications, medication preparation, intravenous dilution, infusion pump programming, drug compatibility, administration routes, medication reconciliation, adverse drug reactions, and error reporting. Education may be delivered through lectures, bedside teaching, simulation-based training, case discussions, medication safety bulletins, competency assessments, and practical demonstrations. Educational interventions should be tailored to the professional responsibilities and experience of participants and should address the specific medication administration errors identified within the clinical environment [10,13,14].

The effectiveness of educational interventions may be enhanced when pharmacists provide practical training and repeated feedback rather than relying exclusively on one-time theoretical sessions. Simulation-based education may allow nurses and other healthcare professionals to practice medication calculations, identify medication discrepancies, prepare high-risk medications, manage infusion devices, and respond to medication administration challenges in a controlled environment. Pharmacist-led educational programs may also include discussion of real medication incidents, analysis of contributing factors, and development of strategies to prevent recurrence. Integrating education with standardized protocols, clinical decision support, direct observation, and continuous evaluation may produce more sustainable improvements in medication safety than education alone [10,13,14].

Clinical Decision Support and Electronic Medication Systems

Clinical pharmacists may support the implementation, optimization, and monitoring of electronic medication systems designed to reduce medication administration errors. Computerized physician order entry systems can improve the clarity and completeness of medication orders, reduce illegibility, standardize prescribing information, and facilitate communication between healthcare professionals. Clinical decision support systems may provide alerts regarding dose limits, allergies, drug interactions, contraindications, duplicate therapy, renal dose adjustments, and inappropriate medication selection, helping pharmacists and prescribers identify potential medication-related problems before administration. However, electronic systems may also generate excessive alerts, incomplete recommendations, or workflow interruptions if they are poorly designed or insufficiently tailored to pediatric practice [14,22].

Pharmacists can contribute to the development of pediatric-specific electronic medication safety systems by establishing appropriate weight-based dosing ranges, age-specific recommendations, maximum dose limits, standardized concentrations, and clinically relevant alert thresholds. They may also assess the accuracy of medication databases, review alert performance, identify inappropriate alert overrides, and collaborate with information technology professionals to improve medication-related workflows. Electronic systems may be particularly useful when integrated with pharmacist review because clinical expertise can help distinguish clinically meaningful alerts from low-value warnings and reduce the risk of alert fatigue. The effectiveness of electronic medication systems therefore depends on appropriate configuration, continuous evaluation, and integration with clinical pharmacy services rather than technological implementation alone [14,22].

Pharmacist-Led Interventions for Preventing Medication Administration Errors

Prospective Medication Review and Clinical Screening

Prospective medication review is a proactive intervention in which pharmacists evaluate medication orders before administration to identify potential errors, inappropriate prescribing practices, and clinically significant drug-related problems. In pediatric settings, this process involves checking medication doses against the child's current weight, reviewing dose frequency and duration, evaluating maximum dose limits, confirming the appropriateness of dosage forms, and assessing the suitability of the prescribed route. Pharmacists may also examine relevant laboratory values, organ function, therapeutic response, medication allergies, drug interactions, and the potential need for therapeutic monitoring. By identifying problems before medications reach patients, prospective medication review can prevent medication errors from progressing through subsequent stages of the medication-use process [8,9,11].

The effectiveness of medication review depends on the availability of accurate clinical information, the timing of pharmacist involvement, and the ability to communicate recommendations promptly to prescribing and nursing staff. Pharmacists may prioritize high-risk patients, including neonates, children receiving multiple medications, patients with renal or hepatic dysfunction, patients receiving high-alert medications, and those undergoing complex medication regimens. Structured medication review systems may improve the consistency of screening and facilitate documentation of interventions, including the type of error identified, clinical significance, recommended action, acceptance of the recommendation, and potential consequences if the error had not been intercepted. This approach allows medication safety interventions to be evaluated systematically and provides valuable information for institutional quality improvement initiatives [8,9,11].

High-Alert Medication Management

High-alert medications are drugs that carry a heightened risk of causing significant patient harm when used incorrectly, and their administration requires additional safeguards because the consequences of errors may be severe. Pediatric high-alert medications include insulin, anticoagulants, opioids, sedatives, concentrated electrolytes, chemotherapy agents, vasoactive medications, and selected intravenous antimicrobials. Pharmacists may contribute to the development of high-alert medication policies, standardized concentrations, dose limits, preparation instructions, administration procedures, storage requirements, labeling systems, and monitoring protocols. Their involvement can help reduce unnecessary variability in medication preparation and administration while ensuring that safety procedures are appropriate for pediatric patients [7,16,21].

High-alert medication management should be incorporated into the entire medication-use process rather than restricted to the final administration stage. Pharmacists may identify medications requiring additional verification, recommend the use of standardized infusion concentrations, review infusion pump programming procedures, establish appropriate dilution methods, and develop specific instructions for medications associated with significant risk. Independent double-checking may be

recommended for selected high-risk medications when evidence and institutional policies support its use, although it should not replace other safety measures or be applied indiscriminately to all medications. The most effective approaches combine pharmacist oversight, standardized medication processes, technological safeguards, staff competency, and appropriate monitoring [7,13,16,21].

Medication Administration Information and Bedside Consultation

Medication administration information services represent an important pharmacist-led intervention because healthcare professionals frequently require immediate access to accurate information regarding medication preparation, administration, compatibility, stability, dose adjustments, and monitoring. Pediatric medication administration may involve specialized questions concerning oral liquid formulations, enteral tube administration, intravenous dilution, infusion rates, compatibility with other medications, administration with food, and the availability of alternative dosage forms. Pharmacists can provide timely recommendations that help nurses and physicians resolve uncertainties before medication administration and reduce the likelihood of errors resulting from incomplete knowledge or inappropriate procedures [8,10,13].

Bedside consultation may be particularly valuable when patients receive complex medication regimens or when clinical conditions change rapidly and require immediate medication adjustments. Pharmacists can assist with the selection of appropriate formulations, preparation of intravenous medications, evaluation of medication compatibility, calculation of individualized doses, interpretation of therapeutic drug monitoring results, and management of adverse drug reactions. The accessibility of pharmacists within pediatric wards and intensive care units may facilitate rapid communication, reduce delays in resolving medication-related problems, and support the implementation of evidence-based medication safety practices. Integration of medication information services with clinical pharmacy activities may therefore improve both the technical accuracy of medication administration and the quality of interdisciplinary communication [8,9,12].

Educational Interventions and Medication Safety Competency

Educational interventions aim to improve the knowledge, practical skills, awareness, and professional behaviors of healthcare workers involved in medication prescribing, preparation, administration, and monitoring. Pharmacists may provide educational programs addressing common pediatric medication administration errors, weight-based dose calculations, dose-range verification, medication dilution, concentration selection, administration routes, infusion rates, high-alert medications, medication reconciliation, and safe documentation. Education may be tailored to nurses, physicians, pharmacists, students, and other healthcare professionals according to their responsibilities within the medication-use process. Structured educational programs are particularly important in pediatric settings because healthcare professionals may encounter medications, dosage forms, and clinical situations that differ substantially from those encountered in adult practice [10,13,14].

Educational interventions may include didactic sessions, workshops, case-based discussions, simulation exercises, bedside demonstrations, individual coaching, written reference materials, medication safety bulletins, and competency assessments. Simulation-based training may allow healthcare professionals to practice medication calculations, preparation techniques, infusion pump programming, identification of medication discrepancies, and responses to medication administration challenges without exposing patients to risk. Pharmacists may also conduct practical assessments to identify knowledge gaps and determine whether staff members demonstrate appropriate competencies before administering selected high-risk medications. These approaches can improve the translation of theoretical knowledge into safe clinical practice and help reinforce medication safety behaviors during routine patient care [10,13,16].

Repeated education and feedback may be more effective than isolated training sessions because medication administration practices are influenced by ongoing workload, professional experience, clinical complexity, staff turnover, and changing medication protocols. Pharmacists can reinforce educational messages by reviewing medication errors identified during clinical practice, discussing their underlying causes, providing targeted feedback, and updating staff regarding new medications or changes in institutional procedures. Educational programs should also encourage healthcare professionals to recognize near misses, report medication incidents, and participate in medication safety improvement activities without fear of inappropriate blame. Continuous learning and practical reinforcement may help sustain improvements in medication administration accuracy and strengthen the institutional medication safety culture [10,13,17].

Table 2. Major pharmacist-led educational interventions and their expected impact [10,13,14,16].

Educational intervention	Main content	Target healthcare professionals	Expected medication safety benefit
Pediatric dose calculation training	Weight-based dosing, body surface area, dose limits, unit conversion	Nurses, physicians, pharmacists	Reduction in dose calculation and conversion errors
Medication preparation training	Reconstitution, dilution, concentration, labeling, compatibility	Nurses and pharmacy staff	Reduction in preparation-related errors
High-alert medication education	Insulin, opioids, anticoagulants, electrolytes, vasoactive medications	Nurses, physicians, pharmacists	Reduction in errors involving high-risk drugs
Intravenous medication training	Infusion rates, pump programming, line compatibility, administration procedures	Nurses and clinical staff	Reduction in infusion and administration errors
Simulation-based training	Medication scenarios, emergency situations, calculation exercises	Multidisciplinary teams	Improvement in practical competency and error recognition
Medication safety case discussions	Review of errors, near misses, contributing factors, corrective actions	Multidisciplinary healthcare teams	Improved awareness and prevention of recurring errors
Continuous feedback	Performance assessment, audit results, targeted coaching	Nursing and medical staff	Sustained improvement in medication safety behaviors

Technology-Assisted Pharmacist-Led Medication Safety Interventions

Computerized Physician Order Entry

Computerized physician order entry (CPOE) systems allow healthcare professionals to enter medication orders electronically and reduce the risks associated with illegible handwriting, incomplete prescriptions, transcription errors, and communication problems. Pediatric CPOE systems may incorporate standardized medication order templates, patient-specific weight information, dose calculation functions, maximum dose limits, standardized concentrations, and predefined administration instructions. Pharmacists can contribute to system design and validation by reviewing pediatric dosing rules, identifying inappropriate default values, and ensuring that medication-related alerts are clinically meaningful and appropriate for the age and weight of the patient [14,22].

The effectiveness of CPOE may be enhanced when systems are integrated with clinical decision support and pharmacist review. Electronic medication orders may improve the completeness of prescribing information and facilitate medication verification, but they do not eliminate the possibility of errors because incorrect patient information, inappropriate default settings, inaccurate calculations, and poorly configured alerts may introduce new risks. Pharmacists can identify these limitations through ongoing evaluation, medication order audits, and analysis of reported incidents. The combination of electronic prescribing, pediatric-specific clinical decision support, and pharmacist oversight may provide stronger protection against medication errors than electronic prescribing alone [14,22].

Barcode Medication Administration

Barcode medication administration (BCMA) systems use barcode technology to verify patient identification and medication identity before administration, thereby reducing the risk of wrong-patient and wrong-medication errors. In pediatric settings, barcode systems may also support verification of medication doses, administration schedules, and selected patient-specific medication information when integrated with electronic medication administration records. Pharmacists may contribute to barcode implementation by reviewing medication labeling, ensuring barcode accuracy, identifying medications that require special handling, and supporting the development of procedures for medications that cannot be scanned reliably. Barcode-

assisted administration may strengthen medication verification processes and provide an additional safety barrier against errors [7,14,22].

Barcode systems are most effective when they are incorporated into standardized medication administration workflows and supported by appropriate staff training, reliable scanning equipment, accurate electronic medication records, and clear procedures for handling scanning failures. Potential barriers include incomplete barcode coverage, workarounds, damaged labels, technical failures, and difficulties scanning medications prepared in small pediatric doses or transferred into syringes and containers. Pharmacists may assist in identifying these barriers and developing corrective measures to ensure that barcode technology supports rather than disrupts medication administration practices. The effectiveness of barcode systems should therefore be evaluated through medication safety indicators, compliance monitoring, and assessment of errors that occur despite barcode verification [7,14,22].

Smart Infusion Pumps and Dose Error Reduction Systems

Smart infusion pumps incorporate dose error reduction software that may provide alerts when programmed infusion parameters exceed predefined limits or fall outside recommended ranges. Pediatric infusion therapy frequently involves medications administered at relatively small volumes or rates, increasing the importance of accurate pump programming and appropriate selection of infusion parameters. Pharmacists can contribute to the development and maintenance of drug libraries containing standardized concentrations, dosing units, recommended infusion rates, maximum limits, and clinical guidance for high-risk medications. These systems may reduce programming errors and provide additional safeguards during intravenous medication administration [7,14,21].

Smart infusion pumps are not completely protective because incorrect medication selection, inappropriate concentration, inaccurate patient weight, improper programming, bypassing safety alerts, and incomplete integration with electronic prescribing systems may still result in medication errors. Pharmacists can support safe pump use by reviewing drug libraries, standardizing concentrations, educating healthcare professionals, evaluating alert overrides, and monitoring medication-related incidents. The implementation of smart pumps should be accompanied by standardized preparation protocols, medication verification, appropriate training, and continuous evaluation of pump-related error patterns to maximize their safety benefits [7,14,21].

Standardization of Medication Preparation

Standardization of medication preparation involves reducing unnecessary variation in medication concentrations, dilution methods, preparation instructions, labeling, and administration procedures. Pediatric medications may require complex calculations and manipulation of dosage forms, and variability in preparation methods may increase the likelihood of concentration errors, inaccurate measurement, and administration of inappropriate volumes. Pharmacists can develop standardized preparation protocols, establish preferred concentrations, recommend commercially available formulations when appropriate, and provide clear instructions regarding reconstitution, dilution, stability, compatibility, storage, and administration. Standardization may simplify medication preparation, reduce cognitive workload, and improve consistency among healthcare professionals [7,10,16].

Standardized medication preparation protocols may be particularly useful in neonatal and pediatric intensive care units, where medications are frequently administered intravenously and patients receive multiple continuous infusions. Pharmacists may collaborate with nurses, physicians, and pharmacy technicians to identify medications suitable for standardized preparation and develop procedures that minimize calculation requirements. Standardized concentrations may also facilitate the use of smart infusion pumps, reduce the possibility of confusion between different medication strengths, and improve communication during patient transfers. The effectiveness of standardization depends on institutional acceptance, appropriate clinical validation, clear documentation, regular protocol review, and availability of the standardized products [7,10,16].

Evidence Supporting the Effectiveness of Pharmacist-Led Interventions

Systematic Reviews and Meta-Analyses

Evidence from systematic reviews indicates that clinical pharmacist interventions may reduce medication errors in hospitalized pediatric patients, although the magnitude of effect varies across studies and healthcare settings. A systematic review and meta-analysis published in 2020 evaluated pharmacist interventions in pediatric hospital patients and reported that pharmacist

involvement was associated with a significant reduction in medication error occurrence, with a pooled odds ratio of 0.27 and a 95% confidence interval of 0.15–0.49 across six studies involving 29,291 patients. The interventions included prescription review, educational sessions, participation in clinical rounds, and implementation of clinical pharmacist services, suggesting that pharmacist involvement may improve medication safety through multiple complementary mechanisms [9].

A systematic review of clinical pharmacist interventions in pediatric hospital patients also reported that pharmacists identified medication errors involving inappropriate doses, missed doses, medication history discrepancies, allergies, and near misses. The review highlighted the importance of pharmacists participating directly in ward rounds because their involvement during prescribing and clinical decision-making may facilitate earlier identification of errors and more rapid communication of recommendations to prescribers. The acceptance of pharmacist recommendations was generally high, indicating that clinical pharmacy interventions can be integrated into multidisciplinary pediatric care and may contribute to safer medication management [8,9].

Evidence concerning interventions specifically targeting medication administration errors suggests that education, medication information services, clinical pharmacist involvement, double checking, interruption reduction strategies, smart infusion pumps, and quality improvement approaches may contribute to reductions in error rates. A systematic review and meta-analysis published in 2021 identified 18 studies evaluating nursing interventions to reduce medication errors in pediatric and neonatal populations and reported a pooled odds ratio of 0.36, indicating a substantial reduction in medication errors following interventions. However, the interventions were heterogeneous, and the results suggest that medication safety improvements may require combinations of strategies rather than reliance on a single intervention [13].

A systematic review examining interventions to reduce medication dispensing, administration, and monitoring errors in pediatric healthcare settings identified multiple intervention approaches, including educational strategies, technological systems, standardized procedures, and medication safety bundles. The review suggested that interventions classified as substitution or engineering controls were more likely to achieve significant reductions in errors than administrative interventions alone, supporting the importance of designing medication safety systems that reduce opportunities for human error. Pharmacist-led interventions may therefore be particularly effective when combined with technological safeguards and standardized medication-use processes rather than implemented as isolated educational activities [7].

Table 3. Summary of major evidence evaluating pharmacist-led or related medication safety interventions in pediatric patients [8–13,16].

Study	Design / evidence type	Intervention	Main findings	Relevance
Drovandi et al. (2018)	Systematic review	Clinical pharmacist interventions in pediatric hospitals	Pharmacists identified medication errors and drug-related problems; recommendations were highly accepted	Supports integration of pharmacists into pediatric clinical teams
Naseralallah et al. (2020)	Systematic review and meta-analysis	Clinical pharmacist interventions	Pooled OR for medication errors: 0.27 (95% CI 0.15–0.49)	Demonstrates significant reduction in medication errors
Koeck et al. (2021)	Systematic review	Interventions targeting administration, dispensing, and monitoring errors	Higher-level engineering and substitution controls were more likely to reduce errors	Supports technology and system-based interventions
Nursing intervention review (2021)	Systematic review and meta-analysis	Education, pharmacist involvement, double checking, smart pumps, and improvement strategies	Pooled OR 0.36 (95% CI 0.21–0.63)	Supports multifaceted medication safety interventions

Chua et al. (2017)	Pre–post intervention study	Pharmacist-led information sharing and feedback	Administration error rates decreased following intervention	Supports pharmacist-led education and feedback
Niemann et al. (2015)	Prospective intervention study	Three-step educational intervention	Reduction in medication handling errors	Supports structured training and practical education
Fernández-Llamazares et al. (2012)	Observational study	Clinical pharmacist intervention and prescription review	Identified substantial numbers of prescribing and dosing errors; recommendations were highly accepted	Demonstrates clinical significance of pharmacist error interception
NICU pharmacist intervention trial (2023)	Randomized controlled study	Clinical pharmacist-led intervention	Evaluated reduction in neonatal drug-related problems	Supports pharmacist involvement in high-risk neonatal care

Reduction in Medication Administration Error Rates

The reduction in medication administration error rates represents an important outcome when evaluating pharmacist-led medication safety interventions. Pharmacist-led programs may reduce errors through early detection of medication-related problems, improved medication knowledge, standardized preparation procedures, better communication, and identification of unsafe practices. Studies involving direct observation of medication administration have demonstrated that educational interventions and pharmacist-led feedback may reduce the proportion of observed medication administration episodes containing errors, particularly when interventions address specific error patterns identified within the clinical setting [10,13,16].

The magnitude of improvement may vary according to the baseline error rate, type of intervention, duration of implementation, medication complexity, professional experience, and characteristics of the patient population. Interventions that address multiple contributing factors may be more effective because medication administration errors frequently arise from interactions between knowledge deficits, environmental distractions, workload, calculation complexity, and system weaknesses. Therefore, reductions in medication administration errors should be interpreted within the context of the intervention components and the clinical environment in which they were implemented [7,10,13].

Reduction in Clinically Significant Medication Errors

The clinical significance of pharmacist-led interventions is not limited to the number of errors identified because pharmacists may intercept errors that have the potential to cause serious patient harm. Clinical pharmacists frequently identify inappropriate doses, contraindications, medication interactions, incorrect administration schedules, formulation problems, and medication-related discrepancies that may require urgent correction. The prevention of clinically significant errors is particularly important in pediatric patients receiving high-alert medications or complex treatment regimens because small deviations from intended doses may produce substantial clinical consequences [8,9,11].

Clinical significance may be assessed according to the potential consequences of an error, the probability of harm, the need for additional monitoring, the likelihood of treatment failure, and the potential for toxicity or serious adverse events. Pharmacist interventions may improve patient safety by identifying errors that require immediate action and preventing medication exposure that could result in significant harm. However, studies evaluating medication error reductions should distinguish between errors intercepted before administration, errors reaching patients without harm, and errors associated with actual adverse drug events, because these outcomes represent different levels of clinical impact [9,11,15].

Acceptance of Pharmacist Recommendations

The acceptance of pharmacist recommendations by physicians and other healthcare professionals represents an important indicator of the feasibility and effectiveness of clinical pharmacy interventions. High acceptance rates may indicate that pharmacist recommendations are clinically relevant, clearly communicated, appropriately timed, and compatible with existing treatment workflows. Pharmacists may improve recommendation acceptance by participating directly in clinical rounds,

communicating recommendations in a concise manner, providing supporting clinical evidence, and prioritizing interventions according to the severity and urgency of identified medication-related problems [8,9,11].

Recommendation acceptance may also depend on professional relationships, organizational culture, availability of pharmacists, physician workload, institutional medication policies, and the quality of communication between healthcare professionals. Pharmacists may need to provide repeated consultation or follow-up when recommendations involve changes in treatment plans, medication administration schedules, dosage forms, or monitoring requirements. Evaluating recommendation acceptance alongside medication error outcomes can help institutions determine whether pharmacist-led interventions are effectively integrated into clinical practice and identify opportunities to improve collaboration [8,9,11].

Impact on Neonatal and Pediatric Intensive Care Units

Neonatal and pediatric intensive care units represent high-risk environments in which medication errors may occur because patients receive complex therapies, frequent medication adjustments, multiple infusions, and medications requiring individualized preparation. Neonates may have immature organ function, low body weight, altered drug distribution, and limited physiological reserves, making medication dosing and monitoring particularly challenging. Clinical pharmacists can contribute to medication safety in these settings through dose verification, therapeutic drug monitoring, medication compatibility review, infusion preparation guidance, clinical consultation, and participation in multidisciplinary rounds [8,12,16].

Evidence from neonatal clinical pharmacy studies suggests that pharmacist-led interventions may reduce drug-related problems and improve medication safety when integrated into patient care. Pharmacists may identify dosing errors, inappropriate medication selection, potential drug interactions, medication omissions, administration-related problems, and inadequate monitoring. Their involvement may also facilitate the development of standardized medication preparation protocols and provide support to healthcare professionals managing complex neonatal pharmacotherapy. However, the effectiveness of specific interventions may differ according to staffing models, availability of clinical pharmacists, the types of medications used, and the complexity of patient care [8,12,16].

Implementation of Pharmacist-Led Medication Safety Programs

Establishing a Structured Medication Safety Framework

The implementation of pharmacist-led medication safety interventions requires a structured framework that identifies the most frequent and clinically important medication administration errors within the healthcare institution and establishes targeted preventive strategies. Initial assessment may include medication incident reports, direct observation of medication preparation and administration, review of pharmacy interventions, analysis of medication administration records, assessment of high-alert medication use, and evaluation of existing medication safety procedures. This assessment allows healthcare organizations to identify local priorities, including dose calculation errors, medication omissions, infusion-related errors, preparation errors, incorrect administration routes, and communication failures. A structured baseline assessment is essential because medication safety interventions should be designed according to the specific risks, resources, and clinical workflows of the pediatric setting rather than implemented as generalized programs without clear priorities [7,10,13].

Clinical pharmacists may coordinate the development of medication safety protocols in collaboration with pediatric physicians, nurses, pharmacy technicians, hospital administrators, and information technology professionals. These protocols should define responsibilities for medication review, dose verification, preparation, administration, documentation, monitoring, incident reporting, and follow-up of pharmacist recommendations. Standardized procedures may also include guidance regarding medication reconciliation, high-alert medications, intravenous medication preparation, standardized concentrations, use of electronic medication systems, and communication during patient transfers. A multidisciplinary approach is essential because medication administration errors frequently arise from interactions between different stages of the medication-use process and cannot be adequately prevented by a single healthcare professional acting independently [7,8,13].

Integration of Clinical Pharmacists into Pediatric Healthcare Teams

The integration of clinical pharmacists into pediatric healthcare teams may improve medication safety by ensuring that specialized medication expertise is available during routine and complex clinical decision-making. Pharmacists may be assigned to pediatric wards, neonatal intensive care units, pediatric intensive care units, emergency departments, or other high-risk clinical environments according to institutional needs and available resources. Their responsibilities may include daily medication

review, participation in clinical rounds, consultation regarding high-risk medications, review of medication preparation procedures, provision of drug information, monitoring of medication-related outcomes, and communication of recommendations to healthcare professionals [8,9,12].

The effectiveness of pharmacist integration may depend on the availability of pharmacists during periods of high medication administration activity, the ability to access patient records, the quality of communication with nursing and medical staff, and the degree to which pharmacist recommendations are incorporated into clinical workflows. Pharmacists who are physically or electronically accessible to healthcare professionals may provide timely support when medication-related questions arise and facilitate rapid resolution of problems before administration. Institutions should therefore consider the clinical workload, patient acuity, medication complexity, and distribution of pharmacy services when designing pediatric clinical pharmacy staffing models [8,9,12].

Collaboration Between Pharmacists, Nurses, and Physicians

Interprofessional collaboration is a central component of effective medication safety interventions because medication prescribing, preparation, administration, and monitoring involve shared responsibilities among physicians, pharmacists, and nurses. Pharmacists provide expertise in medication selection, dosing, interactions, formulation, compatibility, and monitoring, while nurses contribute direct knowledge of medication administration procedures, patient responses, practical preparation challenges, and workflow conditions. Physicians contribute diagnostic information, therapeutic decisions, and clinical assessment, and the integration of these professional perspectives can facilitate more comprehensive medication safety review and reduce communication-related errors [8,10,13].

Collaborative medication safety practices may include structured medication discussions during rounds, standardized communication of pharmacist recommendations, medication safety huddles, joint review of medication incidents, shared preparation protocols, and multidisciplinary evaluation of high-risk medication processes. Effective communication should be timely, clear, structured, and supported by accurate patient information, particularly when medication orders are modified or when patients are transferred between clinical units. Pharmacist-led collaboration may also improve the professional culture surrounding medication safety by encouraging healthcare professionals to identify medication-related risks, discuss errors openly, and participate in corrective actions without unnecessary blame [8,10,13,17].

Medication Safety Culture and Incident Reporting

A positive medication safety culture encourages healthcare professionals to recognize medication errors as opportunities for system improvement rather than automatically attributing incidents to individual negligence. Pharmacists may contribute to the development of non-punitive reporting systems, facilitate medication safety discussions, identify recurring errors, and assist in the analysis of contributing factors. Incident reporting systems should encourage the reporting of errors, near misses, unsafe medication conditions, and medication-related concerns, while ensuring that reported information is used to identify patterns and develop preventive interventions [2,7,17].

Pharmacists may participate in root-cause analysis and other structured investigation approaches to determine why medication errors occur and which system changes may reduce recurrence. Investigations may examine patient characteristics, medication complexity, staff knowledge, communication processes, workload, environmental conditions, technology, labeling, storage, and institutional policies. Corrective measures should address the identified causes rather than rely solely on reminders or retraining when underlying system weaknesses remain unresolved. A continuous learning culture supported by pharmacists and other healthcare professionals may strengthen institutional medication safety practices and improve the sustainability of preventive interventions [2,7,17].

Barriers to the Implementation of Pharmacist-Led Interventions

Limited Availability of Clinical Pharmacists

Limited clinical pharmacy staffing represents a major barrier to implementing comprehensive pharmacist-led medication safety programs, particularly in hospitals with large pediatric populations, high patient acuity, multiple clinical units, or limited pharmacy resources. Pharmacists may be required to perform dispensing, inventory management, administrative duties, medication order review, clinical consultations, and other responsibilities simultaneously, reducing the time available for direct patient care and medication safety activities. In institutions where pharmacists are not routinely integrated into pediatric clinical

teams, medication-related problems may remain unidentified until they are detected by nurses, physicians, or other healthcare professionals during later stages of the medication-use process [8,9,12].

The implementation of clinical pharmacy services may require institutional investment in staffing, professional training, workflow redesign, access to clinical information systems, and development of pediatric-specific medication safety resources. Healthcare organizations may prioritize pharmacist involvement in high-risk units, including neonatal and pediatric intensive care units, emergency departments, and wards where patients receive complex medication regimens. Establishing clear clinical pharmacy responsibilities and evaluating the effectiveness of pharmacist interventions may help institutions justify resource allocation and support the gradual expansion of medication safety services [8,9,12].

Workload and Time Constraints

High workload and time constraints may reduce the effectiveness of pharmacist-led interventions by limiting opportunities for comprehensive medication review, bedside consultation, educational activities, and follow-up of recommendations. Nurses and physicians may also experience workload pressures that interfere with medication administration accuracy, particularly during periods of high patient activity, emergencies, shift changes, and staffing shortages. Pharmacist interventions must therefore be designed to fit clinical workflows and prioritize medication-related problems according to their potential severity, urgency, and likelihood of causing harm [6,10,13].

The development of structured medication review tools, electronic clinical decision support, standardized protocols, automated medication information resources, and targeted pharmacist interventions may improve efficiency and help healthcare professionals manage workload more effectively. However, technological systems should not replace clinical judgment or create unnecessary administrative tasks, and implementation should consider the practical requirements of medication administration in pediatric healthcare settings. The balance between workload reduction and comprehensive medication review is particularly important when designing sustainable pharmacist-led medication safety programs [7,14,22].

Resistance to Change and Professional Acceptance

Resistance to change may occur when medication safety interventions modify established clinical workflows, introduce additional verification requirements, require new documentation practices, or change medication preparation procedures. Healthcare professionals may perceive pharmacist interventions as unnecessary restrictions, additional workload, or interference with their professional responsibilities, particularly when recommendations are poorly communicated or introduced without adequate consultation. Successful implementation therefore requires clear explanation of the clinical rationale, collaboration with healthcare professionals, appropriate training, and recognition of the practical challenges associated with medication administration [8,10,13].

Professional acceptance may be improved when pharmacists communicate recommendations respectfully, provide evidence-based explanations, prioritize urgent medication-related problems, and demonstrate the clinical value of their interventions through measurable improvements in medication safety. Involving nurses and physicians in the development of medication safety protocols may also improve adherence because healthcare professionals are more likely to support interventions that address their actual clinical needs and workflow challenges. Continuous evaluation and feedback may help identify concerns, modify procedures, and strengthen the integration of pharmacist-led interventions into routine pediatric practice [8,9,13].

Technological and Infrastructure Limitations

Technological limitations may restrict the implementation of computerized prescribing, clinical decision support, barcode medication administration, smart infusion pumps, and electronic medication administration records. Healthcare institutions may experience inadequate equipment availability, poor system integration, limited barcode coverage, unreliable connectivity, outdated medication databases, or insufficient technical support. These challenges may reduce the effectiveness of technological safeguards and increase the possibility that healthcare professionals will develop workarounds that compromise medication safety [7,14,22].

Pharmacists may contribute to technology implementation by evaluating clinical requirements, validating pediatric dosing databases, reviewing medication concentrations, identifying inappropriate alert thresholds, and monitoring system-related medication errors. Implementation should include appropriate training, testing, continuous technical support, and assessment of medication safety outcomes to ensure that technological systems are functioning as intended. Institutions with limited

infrastructure may initially focus on standardized medication preparation procedures, structured medication review, education, and targeted high-risk medication safeguards while gradually introducing more advanced technologies as resources become available [7,14,22].

Variability in Pediatric Medication Formulations

Variability in medication formulations and concentrations may complicate medication preparation and administration, particularly when pediatric patients require small doses or when commercially available formulations are unsuitable for their clinical needs. Different concentrations of the same medication may be available across hospital departments, pharmacies, or healthcare institutions, creating opportunities for confusion and concentration-related errors. Pharmacists may need to prepare extemporaneous formulations, recommend appropriate dilution methods, or identify alternative dosage forms when standard products cannot be used [4,7,19].

Standardization of formulations and preparation instructions may reduce unnecessary variability and improve medication administration accuracy. Pharmacists may establish preferred concentrations, standardized dilution procedures, appropriate labeling requirements, and preparation guidance for commonly used pediatric medications. The development of standardized medication preparation systems should consider medication stability, compatibility, availability, storage requirements, clinical appropriateness, and the ability of healthcare professionals to administer the prepared medication safely [7,16,19].

Strategies to Improve the Effectiveness of Pharmacist-Led Interventions

Development of Multifaceted Intervention Bundles

Multifaceted intervention bundles combine several complementary medication safety strategies to address the different mechanisms through which medication administration errors occur. A bundle may include pharmacist-led medication review, pediatric dose verification, medication safety education, standardized medication preparation, high-alert medication protocols, electronic decision support, barcode verification, smart infusion pumps, medication reconciliation, and continuous quality improvement. The combination of interventions may provide stronger protection because individual measures address different stages of the medication-use process and different sources of error [7,10,13,14].

The design of intervention bundles should be based on institutional risk assessment and the identification of medication-related problems that occur most frequently or have the greatest potential for patient harm. For example, a pediatric unit with frequent dose calculation errors may prioritize pharmacist-led dose verification, standardized weight documentation, electronic dosing support, and calculation competency training, whereas a unit with frequent infusion-related errors may prioritize standardized concentrations, infusion protocols, smart pumps, and preparation education. Targeted intervention bundles may improve the efficiency of medication safety programs by focusing resources on the risks that are most relevant to the clinical setting [7,10,13].

Standardized Medication Safety Protocols

Standardized medication safety protocols may reduce variation in medication prescribing, preparation, administration, and monitoring and support consistent practice among healthcare professionals. Pharmacists may develop or review protocols addressing weight-based dosing, maximum dose limits, high-alert medications, intravenous dilution, infusion rates, medication compatibility, administration through enteral tubes, medication reconciliation, and monitoring requirements. Standardized procedures should be readily accessible, regularly updated, and designed according to the needs of pediatric patients and the available medication formulations [7,10,16].

Protocol implementation should include training, competency assessment, monitoring of adherence, and evaluation of medication safety outcomes. Pharmacists may identify situations in which protocols are difficult to follow, require clarification, or are inconsistent with current clinical evidence and medication availability. The continuous review of medication safety protocols may help institutions adapt to changes in pediatric pharmacotherapy, medication formulations, clinical practice, and technological systems [7,10,16].

Prioritization of High-Risk Patients and Medications

Prioritizing high-risk patients and medications may improve the effectiveness of pharmacist-led interventions when pharmacy resources are limited. High-risk patients may include neonates, infants, critically ill children, patients with renal or hepatic dysfunction, children receiving multiple medications, patients receiving high-alert medications, and those with complex

medication regimens. High-risk medications may include insulin, opioids, anticoagulants, concentrated electrolytes, vasoactive drugs, chemotherapy agents, and medications requiring complex preparation or monitoring [7,8,21].

Pharmacists may use risk assessment tools, medication safety indicators, clinical information systems, and institutional medication error data to identify patients requiring more intensive medication review. Prioritization should consider the potential severity of medication-related harm, complexity of therapy, likelihood of error, and clinical urgency. Such strategies may allow pharmacists to direct their expertise toward patients and medications with the greatest potential for preventable harm while maintaining essential medication safety services for the broader pediatric population [7,8,21].

Continuous Quality Improvement and Feedback

Continuous quality improvement is essential for ensuring that pharmacist-led interventions remain effective over time and respond to changing medication safety needs. Quality improvement activities may include repeated medication administration audits, direct observation, review of incident reports, assessment of pharmacist recommendations, monitoring of medication safety indicators, and evaluation of staff competency. Pharmacists may use audit results to identify recurring errors, assess intervention effectiveness, modify medication safety protocols, and provide targeted feedback to healthcare professionals [7,10,13].

Feedback should be timely, constructive, and based on objective medication safety data, with an emphasis on identifying contributing factors and improving systems rather than assigning blame. Medication safety performance may be reviewed through multidisciplinary meetings, clinical governance committees, medication safety committees, or pharmacy-led quality improvement programs. Continuous evaluation allows institutions to determine whether interventions are producing sustained improvements, identify unintended consequences, and refine strategies according to the needs of pediatric patients and healthcare professionals [7,10,13,17].

Evaluation of Pharmacist-Led Medication Safety Interventions

Medication Safety Outcome Measures

The evaluation of pharmacist-led medication safety interventions requires the use of clearly defined outcome measures that reflect both the frequency of medication administration errors and their clinical consequences. Medication error rates may be measured according to the number of errors per medication administration, medication doses administered, medication orders, patients, admissions, or patient-days, depending on the study design and data collection method. The use of standardized definitions and denominators is important because differences in measurement approaches may affect comparisons between healthcare settings and intervention studies. Medication safety evaluations should distinguish between errors identified before administration, errors that reach patients without harm, and errors associated with actual adverse drug events [3,7,13,15].

Medication safety indicators may include the frequency of wrong-dose errors, wrong-medication errors, administration omissions, incorrect routes, infusion-rate errors, preparation errors, documentation errors, and medication-related adverse events. Additional indicators may assess the percentage of medication orders reviewed by pharmacists, number of pharmacist interventions, recommendation acceptance rates, time required to resolve medication-related problems, adherence to medication safety protocols, and staff competency following educational interventions. These indicators may provide a more comprehensive assessment of pharmacist-led interventions because they evaluate both the clinical outcomes and the processes through which medication safety improvements are achieved [8,9,13].

Process Indicators

Process indicators assess whether medication safety interventions are implemented as intended and whether healthcare professionals adhere to established procedures. These indicators may include the percentage of medication orders reviewed before administration, percentage of high-alert medications receiving appropriate verification, compliance with barcode scanning procedures, adherence to standardized medication preparation protocols, completeness of medication reconciliation, and participation in pharmacist-led educational activities. Process indicators may help identify implementation gaps and determine whether the intended medication safety mechanisms are functioning effectively within the clinical environment [7,10,13].

Pharmacists may use process indicators to evaluate the integration of clinical pharmacy services into pediatric healthcare teams and identify opportunities to improve medication safety workflows. For example, a low percentage of medication orders

reviewed before administration may indicate insufficient pharmacist staffing, inadequate electronic workflow integration, or difficulties prioritizing clinical activities. Similarly, low adherence to standardized medication preparation procedures may suggest the need for additional training, improved access to protocols, or redesign of medication preparation areas. Process evaluation can therefore provide valuable information for interpreting medication safety outcomes and guiding corrective actions [7,8,13].

Clinical Outcome Indicators

Clinical outcome indicators assess whether pharmacist-led interventions improve patient safety and reduce medication-related harm. These indicators may include preventable adverse drug events, medication-related complications, treatment delays, additional interventions required to manage medication errors, length of hospitalization, medication-related intensive care utilization, and severity of medication-related incidents. Clinical outcome assessment is particularly important because reductions in the number of medication errors do not necessarily translate into equivalent reductions in patient harm, and some medication errors may have limited clinical consequences while others may be potentially life-threatening [3,7,15].

The assessment of clinical outcomes should consider patient characteristics, medication exposure, severity of illness, baseline risk, and the type of medication error involved. Pharmacist-led interventions may reduce the likelihood of harmful medication exposure by identifying clinically significant errors before administration, but the extent to which they influence broader patient outcomes may depend on the severity of the underlying illness and the effectiveness of other clinical interventions. Comprehensive outcome evaluation should therefore include both medication safety indicators and patient-centered clinical outcomes when feasible [8,9,12,15].

Economic Evaluation and Resource Utilization

Economic evaluation may help healthcare organizations determine the value of pharmacist-led medication safety interventions and support decisions regarding clinical pharmacy staffing, technological investment, and quality improvement resources. Potential economic benefits may arise from preventing medication-related complications, reducing additional treatment requirements, shortening hospitalization, minimizing unnecessary laboratory investigations, and improving the efficiency of medication-use processes. Although the direct financial value of prevented medication errors may be difficult to calculate, medication safety interventions can contribute to improved resource utilization by reducing avoidable medication-related harm [2,8,9].

Economic evaluation should consider the costs associated with pharmacist staffing, education, technology implementation, standardized medication preparation systems, medication safety audits, and continuous quality improvement activities. These costs should be compared with potential savings associated with preventing medication-related complications and improving medication-use efficiency. Institutions may use cost-effectiveness analyses, cost-benefit assessments, or budget impact analyses to determine whether pharmacist-led interventions provide sufficient value to justify their implementation and expansion. Economic evaluations should also recognize that the prevention of serious patient harm represents an important clinical and ethical benefit that may not be fully captured by financial measures alone [2,8,9].

Table 4. Recommended indicators for evaluating pharmacist-led medication safety interventions [3,7,8,9,13,15].

Indicator	Definition or measurement	Purpose
Medication administration error rate	Errors per defined number of doses administered	Measures overall medication administration safety
Wrong-dose error rate	Incorrect doses identified per medication administration episodes	Evaluates pediatric dose accuracy
Medication omission rate	Prescribed doses not administered within the defined interval	Assesses medication delivery completeness
Preparation error rate	Errors involving dilution, reconstitution, concentration, labeling, or preparation	Evaluates medication preparation safety

Infusion-related error rate	Incorrect infusion rate, pump settings, or infusion administration	Evaluates intravenous medication safety
Preventable adverse drug event rate	Preventable medication-related harm per defined patient denominator	Measures clinically meaningful patient harm
Pharmacist intervention rate	Number of medication-related interventions per patient, admission, or patient-day	Assesses clinical pharmacy activity
Recommendation acceptance rate	Accepted pharmacist recommendations divided by total recommendations	Evaluates professional integration and clinical relevance
Medication review coverage	Percentage of eligible medication orders or patients reviewed by pharmacists	Evaluates implementation reach
Protocol adherence	Percentage of medication administration episodes compliant with safety procedures	Assesses process reliability
Staff competency	Performance on knowledge or practical competency assessments	Evaluates educational intervention effectiveness
Medication safety reporting	Number and types of reported errors and near misses	Supports organizational learning
Medication-related length of stay	Hospitalization duration associated with medication-related complications	Evaluates healthcare utilization
Cost-effectiveness	Costs of interventions relative to medication safety outcomes	Supports resource allocation decisions

Evidence-Based Recommendations for Pediatric Healthcare Institutions

The integration of clinical pharmacists into pediatric medication management should be considered an important component of institutional medication safety strategies because pharmacists possess specialized expertise that supports accurate prescribing, preparation, administration, and monitoring of medications. Healthcare institutions should prioritize clinical pharmacist involvement in high-risk pediatric settings, particularly neonatal and pediatric intensive care units, emergency departments, and wards where patients receive complex medication regimens. Pharmacist participation in multidisciplinary rounds and prospective medication review may facilitate early identification of medication-related problems and improve communication between healthcare professionals [8,9,12].

Medication safety programs should incorporate standardized pediatric dose verification procedures, high-alert medication protocols, standardized concentrations, preparation instructions, and administration guidance to reduce unnecessary variability and prevent recurring errors. These procedures should be supported by appropriate clinical decision support, computerized medication ordering, barcode medication administration, and smart infusion pumps when available and clinically appropriate. Technological interventions should be integrated with clinical pharmacy services and evaluated continuously to ensure that they provide meaningful protection against medication administration errors [7,14,22].

Healthcare institutions should also establish pharmacist-led medication safety education programs that provide ongoing training in pediatric dose calculations, medication preparation, intravenous administration, high-alert medications, medication reconciliation, adverse drug reactions, and error reporting. Educational interventions should be practical, multidisciplinary, and tailored to the medication safety risks identified within each clinical setting. Competency assessments, direct observation, simulation-based education, and continuous feedback may improve the sustainability of educational interventions and help healthcare professionals translate knowledge into safer medication administration practices [10,13,16].

Medication safety culture should be strengthened through the development of non-punitive incident reporting systems, multidisciplinary medication safety committees, systematic analysis of errors and near misses, and continuous quality improvement activities. Pharmacists should be actively involved in identifying recurring medication-related problems, evaluating the effectiveness of corrective actions, developing standardized procedures, and communicating safety findings to

healthcare professionals. Institutional medication safety programs should focus on preventing errors through system redesign, appropriate technology, education, communication, and continuous evaluation rather than relying exclusively on individual vigilance [2,7,13,17].

Table 5. Proposed comprehensive pharmacist-led pediatric medication safety program [7–14,16].

Program component	Proposed activities	Expected outcome
Clinical pharmacy integration	Assign clinical pharmacists to pediatric wards and high-risk units	Earlier identification and resolution of medication-related problems
Prospective medication review	Review doses, indications, interactions, allergies, formulations, and monitoring	Reduction in medication-related prescribing and administration risks
Pediatric dose verification	Verify current weight, dose calculations, maximum doses, and concentrations	Reduction in dose calculation and concentration errors
High-alert medication program	Establish standardized concentrations, labeling, preparation procedures, and verification	Reduction in high-risk medication errors
Medication safety education	Conduct regular training, simulation, practical demonstrations, and competency assessments	Improvement in professional knowledge and practical skills
Technology implementation	Optimize electronic prescribing, clinical decision support, barcode systems, and smart pumps	Reduction in preventable medication process errors
Medication reconciliation	Review medication histories and discrepancies during transitions of care	Reduction in medication omissions, duplications, and discrepancies
Medication safety reporting	Encourage reporting of errors, near misses, and unsafe conditions	Improved organizational learning and prevention of recurrence
Quality improvement	Conduct audits, feedback, root-cause analysis, and repeated evaluation	Sustained improvement in medication safety outcomes
Multidisciplinary collaboration	Conduct joint medication safety meetings and structured communication	Improved coordination among pharmacists, nurses, and physicians

CONCLUSION

Pharmacist-led interventions are crucial for preventing medication administration errors and enhancing medication safety in pediatric patients. The inherent complexities of pediatric pharmacotherapy necessitate specialized safety strategies, where clinical pharmacists play a key role through various activities such as medication reviews, dose verification, and multidisciplinary collaboration. Evidence shows that integrated pharmacist involvement can considerably reduce medication errors in hospitalized children. Employing additional strategies like electronic prescribing and clinical decision support alongside pharmacist oversight can further improve safety. A comprehensive, multidisciplinary approach addressing multiple risk factors is essential, with healthcare institutions encouraged to prioritize clinical pharmacy services, establish standardized protocols, and promote continuous quality improvements to ensure safer pharmacotherapy for pediatric patients.

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