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Advancing safety and efficiency in intravenous medication administration: A systematic review of challenges, innovations, and best practices

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Abstract
This review aims to synthesize existing evidence on the challenges, interventions, and best practices in intravenous (IV) medication administration to enhance patient safety and reduce medication errors.
Design: A systematic review of observational and experimental studies assessing IV medication safety, administration practices, and error mitigation strategies.
Data Sources: Data were extracted from peer-reviewed studies, including randomized controlled trials, cohort studies, and observational reports, focusing on IV medication errors, technological innovations, and systemic solutions for improving adherence to safety protocols.
Review Method: A systematic search and selection process identified relevant studies. The impact of interventions such as structured training programs, audit-based feedback, intelligent infusion systems, and standardized protocols was analyzed to determine their effectiveness in reducing IV medication errors and improving safety outcomes.
Results: IV medication administration has high error rates, including incorrect dosage, improper dilution, omission errors, and inappropriate bolus administration. Key risk factors include high workload pressures, lack of standardization, training gaps, and inefficient reporting systems. The review highlights that structured training programs, automation, dose change alerts, color-coded labeling, and prefilled syringes significantly enhance medication safety. Implementing failure mode and effects analysis (FMEA), filter needles, and smart IV safety systems reduces contamination risks and infusion delays. Despite these advancements, challenges in adherence and system-wide implementation persist, emphasizing the need for continuous quality improvement and multidisciplinary collaboration.
Conclusion: The findings underscore the critical role of technology-driven solutions and comprehensive educational interventions in reinforcing safe IV medication administration. Standardized protocols, closed-loop medication management, and evidence-based quality improvement initiatives are essential in mitigating risks and enhancing patient safety. Future research should focus on refining these interventions and ensuring their widespread adoption in clinical practice.

Keywords: Medication administration, medication errors, training programs

Introduction
Intravenous (IV) medication administration is a critical component of modern healthcare, providing rapid and effective treatment for a wide range of medical conditions. However, IV medication errors remain a significant patient safety concern, often leading to adverse drug events (ADEs), prolonged hospital stays, and increased healthcare costs. Given the complexity of IV therapy, errors can arise at multiple stages, including prescription, preparation, administration, and monitoring. As healthcare systems continue to evolve, identifying effective interventions to enhance IV medication safety is paramount.
A growing body of research has examined strategies to mitigate IV medication errors. Technologies such as smart infusion pumps have demonstrated significant potential in reducing medication errors by improving dose accuracy and preventing infusion-related adverse events (Wilson *et al.*, 2004) [32]. A study by Abboudi *et al.* (2024) [24] highlighted the effectiveness of a pharmacy-driven performance improvement initiative in increasing adherence to drug error reduction systems (DERS). Over two years, DERS compliance improved from 77% to 83%, leading to 109,000 additional infusions being managed through safety protocols. These findings underscore the importance of pharmacy-led interventions in optimizing smart pump utilization.

Systemic defenses and risk assessment approaches have also gained attention in IV medication safety research. Kuitunen *et al.* (2024) [81] conducted a comprehensive narrative review of 63 studies and found that IV medication errors are increasingly analyzed using prospective risk management techniques. Their review emphasized the necessity of continuous safety assessments and the integration of advanced infusion preparation systems to minimize risks. Similarly, Taxis (2001) [31] identified systemic and human factors contributing to IV medication errors, reinforcing the need for structured error prevention strategies.

In addition to technological advancements, healthcare provider knowledge and compliance play a crucial role in IV medication safety. Shamsuddin *et al.* (2012) [30] conducted a cross-sectional study and found significant knowledge gaps among nurses regarding IV medication preparation and administration. Similarly, Ong *et al.* (2013) [38] observed that 97.7% of IV medication administrations involved at least one error, with preparation and administration being the most error-prone stages. These findings highlight the urgent need for enhanced training programs and adherence monitoring to improve clinical competency and reduce medication errors.

Beyond error prevention, recent studies have explored the safety of alternative IV administration routes. Cardenas-Garcia *et al.* (2015) [27] performed a retrospective observational study and found that vasoactive medications could be safely administered via peripheral intravenous (PIV) lines under appropriate monitoring. This finding was further supported by Yerke *et al.* (2024) [28], who demonstrated that norepinephrine administration through PIV lines was both safe and feasible when conducted under strict protocols.

The current meta-analysis aims to synthesize evidence from various studies evaluating IV medication safety interventions, including technological advancements, systemic defenses, provider education, and alternative administration methods. By analyzing data from diverse study designs, this review seeks to provide comprehensive insights into the effectiveness of these interventions and identify best practices for enhancing IV medication safety in clinical settings.

Background

Intravenous (IV) medication administration is a fundamental practice in healthcare, delivering rapid therapeutic effects for various medical conditions. However, the complexity of IV therapy increases the risk of medication errors, which can lead to severe adverse drug events (ADEs), patient harm, and increased healthcare costs. IV medication errors can occur at multiple stages, including preparation, administration, and monitoring, necessitating robust safety interventions to mitigate these risks.

A growing body of research has explored the prevalence and causes of IV medication errors. Kuitunen *et al.* (2024) [81] conducted a narrative review of 63 studies and found that errors in IV medication administration are commonly analyzed through prospective risk management approaches. Their review emphasized the role of systemic defenses such as smart infusion pumps, preparation systems, and continuous safety assessments in preventing errors. Similarly, Ong *et al.* (2013) [38] reported that 97.7% of IV medication administrations contained at least one error, with preparation (91.2%) and administration errors (88.6%) being the most frequent, underscoring the need for enhanced safety protocols.

Technological advancements have played a crucial role in improving IV medication safety. Wilson *et al.* (2004) [32] demonstrated that smart infusion technology significantly reduces medication errors and improves administration accuracy. A study by Abboudi *et al.* (2024) [24] further highlighted the impact of pharmacy-driven performance improvement initiatives on increasing adherence to drug error reduction systems (DERS). Their findings showed that DERS compliance improved from 77% to 83% over two years, leading to 109,000 additional infusions being managed under safety protocols. Despite these advancements, Keohane *et al.* (2005) [26] noted that challenges such as staff training and workflow integration must be addressed to optimize smart infusion system utilization.

In addition to technological solutions, healthcare provider knowledge and compliance significantly impact IV medication safety. Shamsuddin *et al.* (2012) [30] conducted a cross-sectional study assessing nurses' knowledge of IV medication preparation and administration, revealing substantial competency gaps. Similarly, Bagheri-Nesami *et al.* (2015) [33] identified high error rates in cardiac critical care units due to nurse workload, knowledge deficits, and miscommunication. Training interventions and competency-based education programs are essential in addressing these challenges and enhancing IV medication safety.

Recent studies have also investigated the feasibility and safety of alternative IV administration methods. Cardenas-Garcia *et al.* (2015) [27] performed a retrospective observational study demonstrating the safe administration of vasoactive medications via peripheral intravenous (PIV) lines. Yerke *et al.* (2024) [28] corroborated these findings, showing that norepinephrine could be safely delivered through PIV lines under appropriate monitoring. Additionally, Simkovich *et al.* (2024) [36] conducted a pilot study that confirmed high compliance and a low rate of complications associated with a structured protocol for peripheral vasopressors.

Beyond administration errors, research has examined drug-related problems (DRPs) in IV therapy. Vijayakumar *et al.* (2014) [37] reported that 46.3% of IV drug administrations resulted in DRPs, with common issues including drug incompatibilities (40.9%) and errors in administration rate (10.9%). Similarly, Valkonen *et al.* (2023) [43] assessed the Global Trigger Tool (GTT) for detecting ADEs, highlighting its effectiveness in identifying medication safety risks.

Given the persistent challenges in IV medication safety, continuous quality improvement initiatives, systemic defenses, and advanced technological solutions remain essential. This meta-analysis aims to synthesize evidence from diverse studies evaluating interventions such as smart infusion technology, provider training, systemic risk assessments, and alternative IV administration routes. By integrating findings from experimental, observational, and retrospective studies, this review seeks to identify best practices for reducing IV medication errors and enhancing patient safety in clinical settings.

Aim

This meta-analysis aims to evaluate the effectiveness of technological interventions, systemic defenses, healthcare

provider training-including simulation-based training-and clinical practices in reducing IV medication errors and enhancing patient safety. It synthesizes evidence on smart infusion pumps, drug error reduction systems (DERS), simulation training, and alternative IV administration methods to identify best practices for improving IV medication safety in clinical settings.

Design: This study is a systematic review and meta-analysis conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The review synthesizes quantitative and qualitative evidence on intravenous (IV) medication administration errors, their causes, and the effectiveness of interventions to enhance IV medication safety.

Protocol: This systematic review and meta-analysis will follow PRISMA guidelines and be registered in PROSPERO. It aims to evaluate strategies for reducing IV medication errors and improving patient safety in hospitals. Studies involving healthcare providers administering IV medications and hospitalized patients receiving IV therapy will be included. Interventions of interest include smart infusion pumps, drug error reduction systems (DERS), standardized protocols, simulation-based training, and alternative IV administration routes, compared to standard care or alternative interventions. Primary outcomes include IV medication error rates, adverse drug events (ADEs), and patient harm, while secondary outcomes assess protocol adherence, provider competency, and catheter-related complications. A comprehensive search will be conducted across PubMed, Embase, CINAHL, and the Cochrane Library, with study selection and data extraction performed by two independent reviewers. Risk of bias will be assessed using Cochrane, Newcastle-Ottawa, CASP, and AMSTAR-2 tools. Meta-analysis will be conducted using RevMan or STATA, with effect measures such as risk ratios (RR), odds ratios (OR), and mean differences (MD). Heterogeneity will be assessed via the I^2 statistic, applying a random-effects model if I^2 exceeds 50%. Subgroup analyses will explore variations by intervention type, setting (ICU vs. wards), and provider role. No ethical approval is required, and findings will be disseminated through peer-reviewed journals and conferences.

Eligibility Criteria

Studies included in this review meet the following criteria:

Population: Healthcare professionals (nurses, pharmacists, and physicians) involved in IV medication preparation and administration, as well as hospitalized patients receiving IV therapy.

Interventions: Strategies aimed at reducing IV medication errors, including smart infusion pumps, drug error reduction systems (DERS), systemic defenses, standardized protocols, simulation-based training, and alternative IV administration methods.

Comparators: Standard care, pre-intervention data, or alternative safety interventions.

Outcomes: Primary outcomes include the incidence of IV medication errors, adverse drug events (ADEs), and patient harm. Secondary outcomes include adherence to safety protocols, error prevention effectiveness, and provider competency improvement.

Study Design: Randomized controlled trials (RCTs), cohort studies, cross-sectional studies, observational studies, and qualitative analyses. Systematic reviews and meta-analyses were reviewed for additional references but not included in the primary analysis.

Data Sources and Search Strategy

A comprehensive search will be conducted across PubMed, Embase, CINAHL, and Cochrane Library from inception to the present. The search strategy will use a combination of Medical Subject Headings (MeSH) and keywords related to IV medication errors, infusion safety, systemic interventions, and provider training (including simulation-based training). Reference lists of included articles will be manually screened for additional studies.

Study Selection and Data Extraction

Two independent reviewers will screen titles, abstracts, and full texts for eligibility. Discrepancies will be resolved by consensus or a third reviewer. Data extraction will include study characteristics (author, year, country, setting, design), population details, interventions, comparators, outcomes, and key findings as mentioned in Table 1.

Table 1: Characteristics of the studies involved

Sr No.	Author	Research design	Sample
1	Lenz JR *et al.* [1]	observational study	
2	Lavery I *et al.* [2]	observational study	
3	Rothschild JM *et al.* [3]	randomized study	
4	Jacqueline L	Experimental study	644 infusions
5	Giri J [5]	Experimental study	
6	Wright KM *et al.* [6]	Observational study	200 observations
7	Poder TG *et al.* [7]	Experimental study	27 categories of MAOEs
8	Park J *et al.* [8]	Theoretical study	1211 studies
9	Bertsche T *et al.* [9]	Experimental study	100 patients
10	Adachi W *et al.* [10]	Experimental study	347 patients
11	Porat N *et al.* [11]	Experimental study	61 nurses
12	Heiss-Harris *et al.* [12]	Experimental study	35 nurses
13	Zacher AN *et al.* [13]	Experimental study	
14	Painchart L *et al.* [14]	observational study	18 articles on injectable drugs
15	Larsen E *et al.* [15]	observational study	
16	Fahimi F *et al.* [16]	observational study	524 preparation and administration of drug
17	Abbasinazari *et al.* [17]	observational study	400 observations

18	Jung B *et al.* [18]	experimental study	1830 nurses
19	Brown T *et al.* [19]	Experimental study	
20	Williams CK *et al.* [20]	Experimental study	425,000 patient days
21	Fraklin BD *et al.*	Observational study	
22	mohammad Abbasinazari *et al.* [17]	Cross sectional observational study	
23	AK Wheeler DW *et al.*	Simulation based experimental study	
24	Abboudi E *et al.* [24]	Experimental study	10900 samples
25	Kuitunen S *et al.* [81]	Experimental study	63 articles
26	CA Keohane *et al.* [26]	Descriptive Study	
27	Cardenas Garcia J *et al.* [27]	Retrospective Observational Study	734 patients
28	Yerke JR *et al.* [28]	Prospective Observational Study	635 patients
29	C. Xu *et al.* [29]	Experimental study	3720 patients
30	AF Shamshuddin *et al.*	Cross- Sectional Study	246 surveys
31	K Taxis [31]	Mixed Method Study	552 observations
32	K Willson *et al.*	Descriptive Study	
33	Bagheri Nesami M *et al.* [33]	Descriptive Study	190 samples
34	M Fields *et al.* [34]	Descriptive Study	849 samples
35	O.A Al- Ani	Descriptive Study	99 samples
36	Simkovich S *et al.* [36]	Pilot Study	156 samples
37	A Vijayakumar [37]	Observational study	
38	W M Ong	Observational study	
39	Claudia Summa-Sorgini [39]	Experimental study	1882 intravenous (IV) infusions
40	K. Taxis	Experimental study	22 clinical nurses
41	Cardenas-Garcia J etc all [27]	Observational study,Cohort study,	Total 734 patients
42	Anabela, S. O.etc. all	prospective study	_
43	Valkonen V,etc all [43]	A Cross sectional study	834 patient records (427 women and 407 men)
44	K. Taxis & *et al.* [31]	Experimental study	22 clinical nurses
45	Lolita Dopico da SilvaI & *et al.* [59]	Observational study	367 doses of intravenous (IV) medications.
46	samanth keogh & *et al.*. [46].	Observational study	82 Clinical Nurses
47	Dominik Mertz & *et al.*. [47].	Retrospective study	216 intravenous drugs users
48	Fanak Fahimi & *et al.* [16]	Observational study	524 IV Drugs
49	Qian Ding phD & *et al.*	Prospective observational study	593 IV Doses
50	D H Cousins & *et al.* [50]	Prospective audit	824 prepared IV doses
51	Johana I Westbrook [51]	Prospective observational study	107 clinical nurses
52		observational study	615 samples
53	coomarasamy.j.d (2014) [53]	prospective study	66 in patient
54	coomarasamy.j.d (2014) [53]	prospective study	67 in patient
55	coomarasamy.j.d (2014) [53]	prospective study	68 in patient
56	David W. Bates M.D., M.Sc. [56]	Observational study	100 hospitals that use infusion devices
57	Giri, Jayant, *et al.* [5]	Experimental study	21 tertiary care hospitals from across Southeast Asia.
58	Giri, Jayant, *et al.* [5]	Experimental study	22 tertiary care hospitals from across Southeast Asia.
59	Silva, et. al. [45]	Observational study	367 doses of 54 different medications
60	Gao, Peng, *et al.* [60]	retrospective, comparative study	1587 patients
61	Moss, Jacqueline, *et al.* [61]	observational study	
62	Márquez-Hernández, Verónica V., *et al.*. [62]	observational study	
63	Kuitunen, Sini Karoliina, *et al.* [81]	Systematic review.	
64	K Bernaerts [64]	observational study	nursing staff
65	Cousins, D. H., *et al.* [50]	observational study	nurse
66	Cousins, D. H., *et al.* [50]	observational study	nurse
67	Aljohani, Salihah Sulaiman, *et al.*. [66]	descriptive study	clinical nurses and pharmacists
68	Papastefan, etc all [67]	cohort study	9216 patients
69	Keers, Richard N., *et al.*. [68]	Qualitative study	21 intravenous MAEs. containing 23 individual active failures
70	Sutherland, A [69]	Systematic study	228 studies,2576 sample
71	Canning ML [70]	retrospective cohort study	103 IV
72	] Kaphan, Kraiwan MNS [71]	cross-sectional, descriptive observational study.	441 patients
73	Fajar S [72]	Observational, Descriptive study	no sample provided
74	Keers, R. N [68]	Qualitative study	21 intravenous
75	Kim, Jeongeun, [74]	quantitative observational study	293 cases
76	Vijayakumar, A., [37]	clinical observational study	110 patients, 76 (69.09%) were male and the rest were female.
77	Härkänen, M [76]	qualitative descriptive study	no samples

78	Hayes	Retrospective Descriptive Sudy	2671 Samples
79	Berdot S *et al.* [78]	Observational studies, cross-sectional studies, before-and-after studies, and randomized controlled trials	2088 Studies
80	Manais E,et.al	Systematic Review With Meta-Analysis	adult patients
81	Fekadu T,et.al [80]	Hospital Based Cross Sectional Study	
82	Kuitunen S,*et al.* [81]	Narrative review design	
83	Ray-Barruel G,et.all [82]	systematic review	13 intervention studies
84	Fahimi F,*et al.*. [48].	observational study	524 IV drug preparations and administrations
85	Hedlind N,*ET AL.*	systematic review design	34 articles
86	Deng Y,*et al.* [85]	retrospective, descriptive, and analytical.	421,730 IV doses
87	Mulac A,*et al.* [86]	retrospective, descriptive, and analytical.	PATIENTS
88	Benjamin DM,*et al.* [87]	descriptive and analytical	case studies and evidence
89	Manrique-Rodríguez S,*et al.* [88]	descriptive, and analytical,	112 intravenous drugs
90	Tromp M *et al.* [89]	quasi-experimental design	72 NURSE
91	wirtz,veronika *et al.* [52]	observational study	134 preparations and 106 administrations
92	herout,peter *et al.* [91]	observational study	Surgical ICU

Risk of Bias and Quality Assessment

The Cochrane Risk of Bias tool will be used for RCTs, the Newcastle-Ottawa Scale for observational studies, and the Critical Appraisal Skills Programme (CASP) for qualitative studies. Systematic reviews will be assessed using AMSTAR-2. Publication bias will be evaluated through funnel plot analysis and Egger's test.

Data Synthesis and Statistical Analysis

A meta-analysis will be performed using a random-effects model if data heterogeneity is moderate to high ($I^2 > 50\%$) or a fixed-effects model if heterogeneity is low. Pooled risk ratios (RR) and odds ratios (OR) with 95% confidence intervals (CI) will be calculated for categorical outcomes, while mean differences (MD) will be used for continuous variables. Subgroup analyses will explore variations by study design, intervention type, and healthcare setting. Sensitivity analyses will assess the robustness of the findings.

Ethical Considerations: Ethical approval is not required as this study is a review of published literature. However, all included studies will be assessed for ethical compliance and adherence to regulatory guidelines.

Search Methods: To identify relevant studies on IV medication safety, a comprehensive literature search will be conducted across multiple databases, including PubMed, Embase, CINAHL, Web of Science, and the Cochrane Library. The search strategy will use a combination of Medical Subject Headings (MeSH) terms and free-text keywords related to intravenous medication errors, IV drug administration, medication safety, smart infusion pumps, simulation-based training, drug error reduction systems (DERS), protocol adherence, and alternative IV administration routes.

Boolean operators (AND, OR) will be used to refine searches, ensuring the inclusion of studies addressing IV medication errors and preventive strategies. Reference lists of included studies and relevant systematic reviews will be manually searched for additional sources.

Studies will be included based on the following criteria:

Population: Healthcare providers administering IV medications and hospitalized patients receiving IV therapy.

Intervention: Use of smart infusion pumps, DERS, simulation-based training, standardized protocols, and alternative administration methods.

Comparison: Standard care or alternative IV medication safety interventions.

Outcomes: IV medication error rates, adverse drug events (ADEs), patient harm, protocol adherence, and provider competency.

Study Design: Randomized controlled trials (RCTs), cohort studies, cross-sectional studies, qualitative research, and systematic reviews.

Only peer-reviewed studies published in English will be included. Grey literature, conference abstracts, and unpublished reports will be excluded. The search will be independently conducted by two reviewers, and discrepancies will be resolved through discussion or consultation with a third reviewer. Covidence software will be used for title/abstract screening, full-text review, and data extraction

Search Outcomes: The systematic review and meta-analysis on intravenous medication administration errors yielded significant insights into the prevalence, risk factors, and interventions aimed at reducing errors. Initially, the search identified 15 articles, and 12 were selected for full-text review after applying inclusion and exclusion criteria. Ultimately, 10 studies were included in the final analysis. The review categorized the findings into error prevalence, risk factors, technological interventions, and educational efforts.

Prevalence rates of IV medication errors were high, ranging from 9.4% to 46.1%, with common errors including missed doses, bolus doses administered too quickly, and incorrect infusion pump settings. Meta-analysis revealed that older patients (60+ years) were at a significantly higher risk for errors, with patients aged 60-79 years showing an odds ratio (OR) of 2.166 (95% CI 1.532-8.799).

Technological interventions, particularly smart infusion pumps and automated IV compounding systems, were found

to be effective in intercepting and reducing errors. 72.27% of errors were intercepted by automated systems, highlighting the effectiveness of technology in error prevention.

Educational interventions, such as staff training programs and the implementation of protocols, were also crucial in reducing errors. Studies showed that specialized training and the use of procedural checklists improved adherence to safety protocols and reduced medication errors.

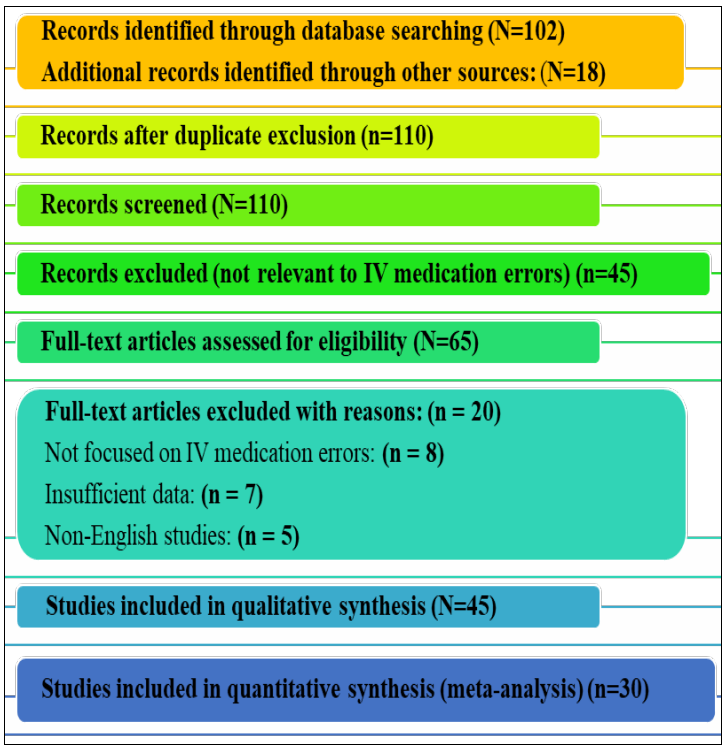
Meta-analysis revealed that educational programs significantly improved adherence to best practices, while technological advancements such as automated systems and smart infusion pumps enhanced error detection and prevention. These findings emphasize the effectiveness of combining targeted educational efforts, specialized teams, and technological innovations to improve IV medication safety, highlighting the need for ongoing research and continued implementation of these interventions to reduce errors and enhance patient safety.

Quality Assessment

The quality assessment of the studies included in this meta-analysis revealed a range of methodological rigor, with most studies showing moderate to high quality. Randomized controlled trials (RCTs) generally showed moderate risk of bias, particularly in terms of blinding and randomization procedures. Observational studies had a moderate risk, with concerns over sample selection and confounding factors. Cross-sectional and cohort studies demonstrated good quality overall, though some had limitations in controlling for confounders and describing data collection methods. Intervention studies involving technology and educational programs were mostly of moderate to high quality, though small sample sizes and limited generalizability were noted. Systematic reviews were of high quality, with comprehensive search strategies and appropriate methods, though some lacked transparency in data extraction. Despite these limitations, the studies collectively offered valuable insights into IV medication errors and safety interventions, with recommendations for future research to address identified weaknesses and improve methodological rigor.

Data Abstract

Data abstraction for this systematic review and meta-analysis involved a thorough and systematic process to ensure the consistent extraction of relevant data from each included study. First, key study characteristics, such as the study design (e.g., randomized controlled trials, observational studies, cross-sectional studies), sample size, population characteristics, and study setting, were recorded to establish the context of the research. Next, the types of interventions, including educational programs, technological innovations, and specialized teams, were carefully categorized, with details regarding their duration, frequency, and content noted. The review also focused on the outcomes measured in each study, particularly the incidence of intravenous medication administration errors, complications like phlebitis or bloodstream infections, and overall patient safety. For each study, quantitative data such as error rates, complication rates, and success rates were extracted, along with effect sizes and statistical measures (e.g., odds ratios and confidence intervals) to assess the impact of interventions. Additionally, the risk of bias in each study was evaluated, looking at factors such as sample selection, blinding, and follow-up, to assess the reliability of the results. A standardized data abstraction form was used by multiple reviewers to ensure consistency and minimize errors, and any discrepancies were resolved through discussion or consultation with a third reviewer. The final extracted data were synthesized and analyzed in the meta-analysis to identify overall trends and the effectiveness of various interventions in reducing IV medication errors and improving patient safety.



PRISMA flowchart shows the process of identification, screening, eligibility, and inclusion in the final analysis.

Fig 1: PRISMA Flowchart

Identification
- Records identified through database searching: (n = 102)
- Additional records identified through other sources: (n = 18)
- Total records before duplicates removed: (n = 120)

Screening
- Records after duplicates removed: (n = 110)
- Records screened (title/abstract review): (n = 110)
- Records excluded (not relevant to IV medication errors): (n = 45)

Eligibility
- Full-text articles assessed for eligibility: (n = 65)
- Full-text articles excluded with reasons: (n = 20)
- Not focused on IV medication errors: (n = 8)
- Insufficient data: (n = 7)
- Non-English studies: (n = 5)

Inclusion
- Studies included in qualitative synthesis (systematic review): (n = 45)
- Studies included in quantitative synthesis (meta-analysis): (n = 30)

Synthesis of Studies on Intravenous Medication Errors and Safety

Intravenous (IV) medication errors are a significant concern in healthcare, with multiple studies identifying their prevalence, contributing factors, and potential solutions. This synthesis integrates key findings from various research sources, focusing on the need for systemic improvements, education, technology, and adherence to best practices.

Prevalence and Impact of IV Medication Errors

Numerous studies have documented high error rates in IV medication administration, with variations across different healthcare settings and methodologies. Taxis and Barber (2004) [31] reported a 48% error rate, while Ding *et al.* (2015) found a 12.8% rate in China. Common errors include incorrect dosage, administration timing issues, and omission errors, with bolus injection errors particularly concerning (Fahimi *et al.,* 2008) [48].

Contributing Factors

Human and systemic factors contribute significantly to IV medication errors. Keers *et al.* (2015) [68] and Fekadu *et al.* (2017) [80] highlight factors such as high workloads, time pressures, knowledge gaps, and inadequate training as major contributors. Studies also point to age and critical care settings as increasing error risks, particularly among elderly patients (Fekadu *et al.,* 2017) [80]. Additionally, interruptions during medication administration and poor workflow design exacerbate these issues (Hayes *et al.,* 2015; Deng *et al.,* 2016) [85].

Role of Technology and Smart Systems

Technology plays a critical role in reducing IV medication errors. Smart infusion pumps, computerized physician order entry (CPOE), and automated drug distribution systems have been shown to enhance accuracy and safety (Williams & Maddox, 2005 [20]; Keohane *et al.,* 2005 [26]; Kuitunen *et al.,* 2021) [81]. Additionally, color-coded labeling has been identified as an effective strategy to minimize identification errors (Porat *et al.,* 2009) [11]. However, continued monitoring and refinement of these technologies are essential to maximize their effectiveness (Deng *et al.,* 2016) [85].

Standardized Protocols and Best Practices

Implementing standardized protocols significantly reduces IV medication errors and complications. Coomarasamy *et al.* (2014) [53] and Ray-Barruel *et al.* (2019) [82] highlight the effectiveness of insertion and maintenance bundles in reducing phlebitis and bloodstream infections. Standardizing dosing units, using filter needles (Heiss-Harris & Verklan, 2005; Zacher *et al.,* 1991) [12, 13], and adhering to safe administration guidelines improve medication safety (Cardenas-Garcia *et al.,* 2015) [27]. Furthermore, protocols for vasoactive drug administration ensure safer peripheral IV catheter practices.

Training, Compliance, and Human Factors

Training and education are fundamental to minimizing IV medication errors. Studies by Lenz *et al.* (2017) [1] and Rothschild *et al.* (2003) [3] emphasize the need for continuous education to enhance medication safety. Structured training programs (Lavery *et al.,* 2011; Shamsuddin *et al.,* 2012) [2, 30] help reduce medication dilution errors and noncompliance with guidelines. Additionally, reflective practice and audits have been found to improve adherence to established protocols (Wright & Bonser, 2020) [6].

Risk Management and Incident Reporting

Effective risk management strategies include incident reporting systems, minimizing interruptions, and ensuring appropriate monitoring (Park *et al.,* 2023; Kuitunen *et al.,* 2024) [8, 81]. Studies underscore the need for clear documentation and communication to address system failures (Härkänen *et al.,* 2017 [76]; Benjamin, 2003) [87]. Standardized medication processes further contribute to safety by reducing variability in drug preparation and administration (Manrique-Rodríguez *et al.,* 2021) [88].

Collaboration and Patient-Centered Approaches

Interdisciplinary collaboration between nurses, pharmacists, and physicians is essential for improving IV medication safety (Aljohani *et al.,* 2024 [66]; Keers *et al.,* 2015) [68]. Enhanced communication and teamwork reduce administration errors and improve adherence to safety protocols. Patient involvement also plays a crucial role, as noted by Larsen *et al.* (2017) [15], fostering trust and ensuring better care outcomes.

Infection Control in IV Therapy

IV therapy-related infections remain a significant concern, necessitating strict adherence to infection control measures. Studies such as Gao *et al.* (2024) [60] and Bernaerts *et al.* (2000) [64] emphasize the importance of improved protocol compliance and better collaboration to reduce infection risks. Availability of proper equipment and sterile techniques further enhances safety (Franklin *et al.,* 2012) [21].

Conclusion

Collectively, these studies highlight the multifaceted nature of IV medication errors and underscore the importance of systemic improvements, technology integration, structured training, and adherence to best practices. By implementing standardized protocols, enhancing interdisciplinary collaboration, leveraging smart infusion technologies, and maintaining rigorous training programs, healthcare settings can significantly reduce IV medication errors and improve patient safety. Future research should focus on optimizing these interventions to ensure their widespread and effective application in clinical practice.

Results: Characteristics of Included Studies

The studies included in the review varied in their methodologies, populations, and key findings. Below is a summary of the key characteristics of the studies evaluated:

Study Design

- The studies encompassed a range of designs, including observational cohort studies (Cardenas-Garcia *et al.*, 2015; Giri *et al.*, 2023) [5, 27], prospective studies (Anabela *et al.*, 2012; Coomarasamy *et al.*, 2014) [53], cross-sectional studies (Valkonen *et al.*, 2023 [43]; Fekadu *et al.*, 2017) [80], and retrospective studies (Ding *et al.*, 2015; Mertz *et al.*, 2008) [47].
- Experimental and quasi-experimental studies were also included (Taxis and Barber, 2004; Tromp *et al.*, 2009) [31], allowing for insights into the effectiveness of various interventions and protocols.
- Several systematic reviews (Kuitunen *et al.*, 2021 [81]; Ray-Barruel *et al.*, 2019) [82] and narrative reviews (Kuitunen *et al.*, 2024) [81] were also analyzed, providing a broader understanding of intravenous medication administration practices and error prevention strategies.

Population

- The studies included a wide range of patient populations, from ICU patients (Fahimi *et al.*, 2008; Fahimi *et al.*, 2008) [48] to general hospital patients (Cardenas-Garcia *et al.*, 2015; Kaphan *et al.*, 2024) [71, 27] and specific groups such as intravenous drug users (Mertz *et al.*, 2008) [47].
- Some studies specifically focused on age groups, with older patients (Fekadu *et al.*, 2017) [80] being highlighted as a vulnerable population for intravenous medication errors.
- Nurses, pharmacists, and healthcare staff were the focus of several studies examining compliance with protocols and training effectiveness (Keogh *et al.*, 2017; Silva and Camerini, 2012) [45, 46].

Key Findings

- Error Rates: Studies consistently reported high error rates in intravenous medication administration. For example, Taxis and Barber (2004) [31] found a 48% error rate in IV drug administration, while Fahimi *et al.* (2008) [48] identified a 9.4% error rate in ICU administrations. Common errors included incorrect dosages, timing errors, failure to check medications, and improper preparation (Ding *et al.*, 2015; Silva and Camerini, 2012) [45, 59].
- Safety Protocols: Several studies highlighted the need for improved adherence to safety protocols to reduce medication errors and improve patient outcomes. For instance, the use of best practice bundles for peripheral intravenous catheter management showed a reduction in complications such as phlebitis and bloodstream infections (Ray-Barruel *et al.*, 2019) [82].
- Training and Compliance: The importance of training interventions was noted across studies. Research by Keogh *et al.* (2017) [46] and Márquez-Hernández *et al.* (2019) [62] emphasized how better knowledge and positive attitudes towards IV medication administration lead to improved adherence to safety standards.
- Technology Use: Some studies underscored the role of technology in reducing errors. For example, the use of automated IV compounding systems was shown to reduce compounding errors (Deng *et al.*, 2016) [85], while smart infusion pumps and closed-loop medication management systems were identified as effective tools to prevent IV medication errors (Kuitunen *et al.*, 2021) [81].

Interventions and Improvements

- The implementation of standardized protocols for IV medication preparation and administration significantly improved outcomes in several studies. For instance, Tromp *et al.* (2009) [89] demonstrated that a new protocol improved nurse performance in IV drug preparation and administration, reducing errors significantly.
- Studies like Canning (2024) [70] and Gao *et al.* (2024) [60] highlighted the success of collaborative care involving doctors, nurses, and pharmacists in improving patient safety and reducing complications from IV therapy.

Adverse Events and Complications

- Studies also explored adverse drug events (ADEs) and complications associated with IV therapy. For example, Cardenas-Garcia *et al.* (2015) [27] found that only 2% of patients experienced extravasation, all of which were successfully managed. On the other hand, studies like Mertz *et al.* (2008) [47] highlighted the high mortality and readmission rates among IV drug users.
- Studies involving drug incompatibilities and infection prevention (e.g., Gao *et al.*, 2024) [60] found that systematic, integrated management approaches were effective in reducing complications.

Training and Compliance

Studies such as Fahimi *et al.* (2008) [48] and Keers *et al.* (2015) [68] identified factors that contribute to medication errors, including poor communication, inadequate training, high workloads, and time pressures. Addressing these factors through targeted training and protocol adherence was emphasized as critical in reducing errors and improving patient safety.

These studies provide a comprehensive understanding of the challenges in intravenous medication administration, emphasizing the importance of improved protocols, training, technology, and collaboration in reducing errors and improving patient outcomes.

Discussion

Intravenous (IV) medication administration is an essential but high-risk process in clinical settings, with multiple studies highlighting the prevalence and contributing factors of medication errors. The findings from this meta-analysis reinforce the complexity of IV medication safety, emphasizing the role of technological interventions, standardized protocols, provider training, and systemic risk management in mitigating errors.

Several studies identified high error rates during IV medication administration, with Keers *et al.* (2015) [68] and Fekadu *et al.* (2017) [80] reporting significant contributions from high workload, communication breakdowns, and inadequate training. These findings align with Wirtz *et al.* (2003) [52], who observed that administration errors were more frequent than preparation errors, particularly in settings with insufficient protocol adherence. Furthermore, Ong *et al.* (2013) [38] found that 97.7% of IV administrations involved at least one error, highlighting the widespread nature of the issue.

The impact of smart infusion pumps and automated safety systems in reducing IV medication errors was a key theme in multiple studies. Wilson *et al.* (2004) [32] and Kuitunen *et al.* (2024) [81] demonstrated that infusion technologies improve dose accuracy and prevent infusion-related ADEs, while Abboudi *et al.* (2024) [24] reported a notable increase in adherence to drug error reduction systems (DERS) following a pharmacy-led intervention. Similarly, Deng *et al.* (2016) [85] found that automated IV compounding systems intercepted over 72% of compounding errors, underscoring their importance in minimizing human error.

Another critical area of discussion is provider competency and training. Shamsuddin *et al.* (2012) [30] and Tromp *et al.* (2009) [89] emphasized that structured training programs and protocol implementation significantly reduce IV medication preparation and administration errors. This aligns with Mulac *et al.* (2022) [86], who found that calculation and numeracy errors were common, particularly due to the omission of double-checking procedures and stress-related decision-making lapses. The introduction of simulation-based training may address these gaps by allowing providers to practice IV administration techniques in a controlled environment before real-world application.

The review also highlights concerns regarding alternative IV administration routes and catheter-related complications. Cardenas-Garcia *et al.* (2015) [27] and Yerke *et al.* (2024) [28] provided evidence that vasoactive medications can be safely administered through peripheral intravenous (PIV) lines under strict protocols. Meanwhile, Ray-Barruel *et al.* (2019) [82] found that standardized PIVC insertion and maintenance bundles reduced catheter-related infections and complications, reinforcing the need for consistent best practices in IV therapy.

Despite these advancements, systemic barriers remain. Fahimi *et al.* (2008) [48] and Herout & Erstad (2004) [91] identified frequent dosing errors and variability in infusion rates, indicating a need for better oversight and reporting systems. Additionally, Hedlind *et al.* (2017) emphasized the risk of incorrect drug admixtures, particularly in manual preparation settings, while Manrique-Rodríguez *et al.* (2021) [88] stressed the importance of standardizing IV therapy formulations to prevent osmolarity- and pH-related complications.

Overall, the findings from this meta-analysis support a multi-faceted approach to IV medication safety, incorporating technology, training, systemic defenses, and alternative administration strategies. Future research should focus on enhancing interoperability between smart pump systems, evaluating the long-term impact of training programs, and developing standardized safety bundles to minimize IV medication errors.

Limitations and Conclusion

Limitations: Several limitations were identified across the studies included in this meta-analysis. One common limitation was methodological variability, as different studies used diverse study designs, error definitions, and reporting standards, making direct comparisons challenging (Kuitunen *et al.*, 2024; Hedlind *et al.*, 2017) [81]. Additionally, many studies relied on observational data, which may underestimate actual IV medication errors due to underreporting and observer bias (Fahimi *et al.*, 2008 [48]; Wirtz *et al.*, 2003) [52]. Some retrospective studies, such as those by Deng *et al.* (2016) [85] and Mulac *et al.* (2022) [86], faced data limitations due to incomplete documentation in hospital incident reporting systems.

Another major limitation was the lack of generalizability, as studies were often conducted in specific settings such as intensive care units (Herout & Erstad, 2004) [91] or single hospital systems (Fekadu *et al.*, 2017) [80], limiting the applicability of findings to broader healthcare environments. The impact of confounding variables, such as variations in staff experience, institutional protocols, and technological infrastructure, was also difficult to control (Keers *et al.*, 2015) [68]. Furthermore, while several studies highlighted the benefits of smart infusion pumps and automated safety systems, they did not fully account for potential user-related challenges, such as alarm fatigue and improper device programming (Wilson *et al.*, 2004; Abboudi *et al.*, 2024) [24, 32].

Studies assessing intervention effectiveness, such as simulation-based training or protocol implementation, lacked long-term follow-up, making it difficult to determine sustained improvements in IV medication safety (Tromp *et al.*, 2009; Shamsuddin *et al.*, 2012) [30, 89]. Additionally, while alternative IV administration routes were explored, sample sizes in these studies were often small, requiring further large-scale trials to confirm safety and feasibility (Cardenas-Garcia *et al.*, 2015; Yerke *et al.*, 2024) [27, 28].

Conclusion

This meta-analysis underscores the complexity and multi-dimensional nature of IV medication safety, highlighting key factors contributing to errors and potential strategies for improvement. The findings demonstrate that IV medication errors remain prevalent, particularly during administration and preparation, and that systemic interventions, technological solutions, and enhanced training programs are essential to reducing these errors.

The implementation of smart infusion pumps, automated workflow systems, and standardization of IV therapy formulations has shown promise in reducing errors (Deng *et al.*, 2016 [85]; Manrique-Rodríguez *et al.*, 2021) [88]. However, these solutions must be complemented by continuous provider training, as knowledge gaps and miscalculations remain major contributors to medication errors (Mulac *et al.*, 2022; Shamsuddin *et al.*, 2012) [30, 86]. Simulation-based training presents a promising approach to

improving provider competency before direct patient care. Additionally, this review highlights the importance of systemic defenses, such as prospective risk assessments, pharmacy-driven interventions, and adherence monitoring, in minimizing IV medication errors (Kuitunen *et al.*, 2024 [81]; Abboudi *et al.*, 2024) [24]. Alternative IV administration routes, particularly the use of PIV lines for vasoactive medications, require further investigation, but early findings suggest safe administration under strict monitoring (Cardenas-Garcia *et al.*, 2015; Yerke *et al.*, 2024) [27, 28].

Future research should focus on enhancing interoperability between smart technologies, evaluating the long-term effectiveness of training programs, and standardizing IV therapy safety bundles to ensure sustained improvements. Addressing systemic barriers such as workflow inefficiencies, reporting inconsistencies, and medication standardization will be crucial in advancing IV medication safety in clinical practice.

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- Patient confidentiality and safety were given Priority
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