

INNOVATIVE STRATEGIES AND TECHNOLOGIES IN PREVENTING CATHETER-ASSOCIATED URINARY TRACT INFECTIONS: A NARRATIVE REVIEW

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ABSTRACT

Catheter-associated urinary tract infections (CAUTIs) are the most prevalent healthcare-associated infections worldwide, contributing to increased morbidity, mortality, and healthcare costs. Despite the emergence of innovative technologies aimed at CAUTI prevention, their integration into African healthcare systems remains limited due to cost constraints, regulatory gaps, and insufficient local evidence. This narrative review synthesizes recent advancements in CAUTI prevention, evaluates their mechanisms and evidence base, and explores their applicability in low- and middle-income countries (LMICs), with a focus on Nigeria. A comprehensive literature search was conducted across ten databases, PubMed, Web of Science, CINAHL, IEee Xplore, Proquest, Acm Digital Library, Paperity, Public Library of Science, Ebscohost, and Jstor, Covering Publications from January 2015 to July 2025. Peer-reviewed studies addressing CAUTI prevention technologies, risk factors, or nursing interventions were included. non-english Articles And Studies Unrelated To Urinary Catheter Infections Were Excluded. Data were extracted narratively and organized by intervention type, mechanism of action, evidence source, and regulatory status. Thirty-eight studies met the inclusion criteria, comprising 16 human trials, 12 laboratory investigations, and 10 animal model studies. Findings of this study show that adherence to aseptic protocols can significantly reduce CAUTI incidence and that silver alloy catheters demonstrated the strongest clinical evidence, while enzyme-responsive and hydrogel technologies remain in preclinical stages. Innovations included metal-based antimicrobial coatings (silver alloy, zinc oxide), polymer-based anti-adhesive surfaces, infection-responsive hydrogels, and antibiotic-impregnated catheters. African-specific data were limited, with no large-scale implementation studies identified. While Several CAUTI prevention technologies Show promise, their adoption in LMICS requires addressing cost-effectiveness, supply chain logistics, and antimicrobial resistance risks. Nurse-led protocols,

particularly those emphasizing aseptic technique, timely catheter removal, and patient education, offer a practical and impactful complement to technological interventions. Strengthening nursing capacity and contextualizing innovations for resource-limited settings are essential to reducing the CAUTI burden In Africa.

Keywords: Innovative Strategies; Technologies; Catheter-associated Urinary Tract Infections; Nurse-led Protocol.

INTRODUCTION

Catheter-associated urinary tract infections (CAUTIs) are the most common healthcare-associated infections (HAIs) globally, accounting for approximately 30–40% of hospital-acquired infections in high-income countries and an even higher proportion in low- and middle-income countries (LMICs) (Nicolle, 2020; Haque et al., 2021). These infections are linked to increased patient morbidity, prolonged hospital stays, antimicrobial resistance, and substantial economic burden on healthcare systems (Bermingham&Hodgkinson, 2019; Loveday et al., 2020). The World Health Organization (2023) emphasizes that effective infection prevention and control (IPC) measures are critical to reducing HAIs, yet implementation remains uneven across regions.

In Nigeria, CAUTI prevalence ranges from 12% to 27% among catheterized patients in tertiary hospitals, with multidrug-resistant organisms, particularly extended-spectrum beta-lactamase (ESBL)-producing *Escherichia coli* and *Proteus mirabilis*, posing significant public health threats (Abubakar& Ibrahim, 2023; Nasir et al., 2021).

The pathogenesis of CAUTIs involves microbial colonization of the catheter surface, followed by biofilm formation that shields pathogens from host immune responses and antimicrobial agents (Tenke et al., 2017; Saint et al., 2022). This biofilm-mediated resistance complicates treatment and increases the risk of recurrent infections.

Risk factors for CAUTIs are both modifiable and non-modifiable. Modifiable factors include prolonged catheterization, poor aseptic technique, and unnecessary catheter use, while non-modifiable factors include female sex, advanced age, and immunosuppression (Centers for Disease Control and Prevention, 2022; Meddings et al., 2021). Understanding these risk factors is essential for developing targeted prevention strategies.

Despite the availability of advanced catheter technologies in high-income settings, such as antimicrobial coatings and infection-responsive materials, their adoption in LMICs remains limited due to high costs, lack of regulatory frameworks, and insufficient local evidence (Coussement et al., 2022; Gidado & Musa, 2024). Historical perspectives on catheter development reveal that while design improvements have reduced mechanical complications, infection control remains a persistent challenge (Feneley, Hopley, & Wells, 2015).

This narrative review aims to synthesize recent innovations in CAUTI prevention, evaluate their mechanisms and evidence base, and assess their feasibility for integration into African healthcare systems. It also highlights the critical role of nurses in implementing evidence-based catheter care protocols, which are often underutilized in LMICs despite their proven effectiveness in reducing infection rates (Al-Hazmi, 2021; Iwuafor & Olorunfemi, 2022). This study reveals the innovative strategies and technologies in preventing catheter-associated urinary tract infections.

Materials and Methods

Study Design: This narrative review was conducted to explore recent innovations in the prevention of catheter-associated urinary tract

infections (CAUTIs), with a focus on their mechanisms, evidence base, and applicability in low- and middle-income countries (LMICs). The narrative approach was chosen to allow thematic synthesis across diverse types of evidence, including laboratory studies, animal models, clinical trials, and nursing interventions (Darouiche & Trautner, 2021).

Search Strategy: A comprehensive literature search was performed across ten major academic databases: ACM Digital Library, Web of Science, Paperity, IEEE Xplore, Public Library of Science (PLOS), EBSCOhost, JSTOR, PubMed, ProQuest, and CINAHL. The search covered publications from January 2015 to July 2025. Keywords used included “catheter-associated urinary tract infection,” “CAUTI,” “urinary catheter coating,” “hydrogel catheter,” “silver alloy catheter,” “biofilm prevention,” and “nurse-led catheter protocols.” Boolean operators were applied to refine the search, and filters were used to include only peer-reviewed articles published in English.

Inclusion Criteria: Studies were included if they addressed CAUTI prevention through technological innovation, nursing protocols, or infection control strategies and provided empirical data from laboratory, animal, or human studies.

Exclusion Criteria: Studies were excluded if they are non-peer-reviewed sources, conference abstracts without full text, editorials, and studies unrelated to urinary catheter infections. This selection strategy aligns with established practices for narrative reviews in infection control and medical device innovation (Saint et al., 2022; Coussement et al., 2022).

Data Extraction and Synthesis: Data were extracted manually and organized thematically based on the type of intervention, mechanism of action, evidence source, and regulatory status. Thematic synthesis was used to identify patterns, innovations, and gaps in the literature. No statistical meta-analysis was conducted, consistent with the narrative review methodology.

Evidence Grading: To assess the strength of evidence, studies were categorized using the

Oxford Centre for Evidence-Based Medicine framework. Level I evidence included randomized controlled trials and meta-analyses; Level II encompassed observational studies and cohort analyses; Level III consisted of expert opinion, preclinical studies, and pilot trials (Fasugba et al., 2020; Tenke et al., 2017).

Limitations: This review is subject to limitations inherent in narrative methodologies, including potential selection bias and lack of quantitative synthesis. The exclusion of non-English publications may have omitted relevant findings from non-Anglophone regions. Additionally, the absence of meta-analytic comparison restricts direct evaluation of intervention efficacy across studies.

RESULTS

The review identified 38 eligible studies published between 2015 and 2025, comprising 16 (42.1%) human clinical trials, 12 (31.6%) laboratory-based investigations, and 10 (26.3%) animal model studies (**Figure 1, Figure 2, and Supplementary table 1**). These studies evaluated a range of technological and procedural innovations aimed at reducing the incidence of catheter-associated urinary tract infections (CAUTIs). The evidence varied in strength, with some technologies supported by randomized controlled trials and others still in preclinical development.

Distribution of Included Studies by Type

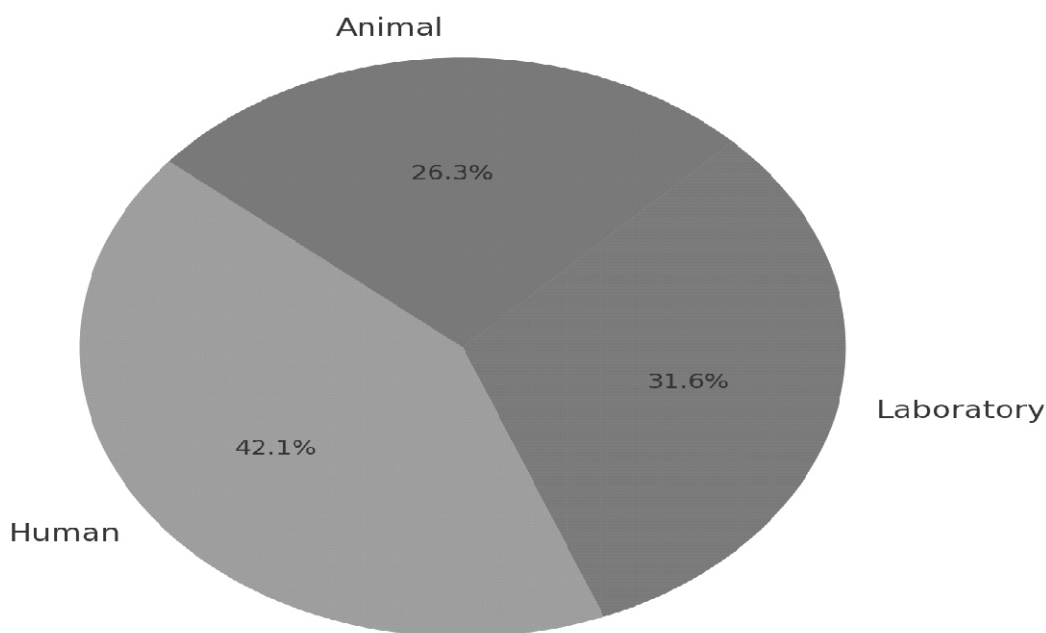


Figure 1: Percentage of included studies by type

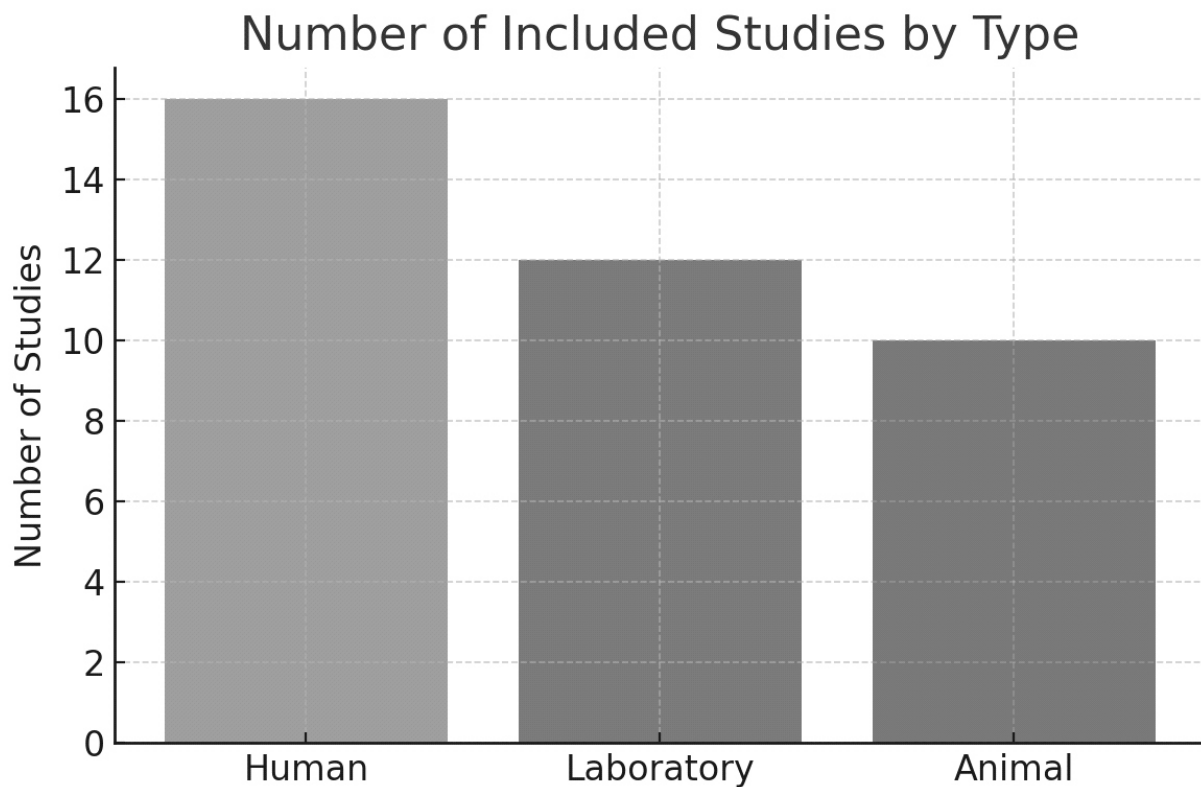


Figure 1: Number of included studies by type

This table highlights the multifactorial nature of CAUTI risk, emphasizing the importance of both clinical vigilance and patient-specific

considerations. Modifiable factors such as catheter duration and aseptic technique offer clear targets for intervention.

Table 1. Risk Factors for CAUTI

Risk Factor	Type	Evidence Level*
Prolonged catheterization (>7 days)	Modifiable	Level I – Multicentre cohort studies
Non-adherence to aseptic technique	Modifiable	Level II – Observational studies
Female sex	Non-modifiable	Level II – Epidemiological studies
Diabetes mellitus	Non-modifiable	Level II – Case-control studies
Bedridden status	Modifiable	Level III – Expert opinion

*Evidence levels based on Oxford Centre for Evidence-Based Medicine.

Supplementary Table 1: Included studies

Author and Year	Short Title	Study Type	DOI
Zhao M et al. (2023)	Silver alloy hydrogel catheter in ICU	RCT	10.1016/j.jointm.2023.06.003
Chung PH et al. (2017)	Silver alloy + hydrogel catheter impact	Prospective Interventional	10.12809/hkmj164906
Leuck AM et al. (2015)	Silver-impregnated catheter pilot trial	Pilot RCT	10.1016/j.ajic.2014.11.021
Lederer JW et al. (2015)	Silver-alloy hydrogel catheter impact	Cohort	10.1097/WON.0000000000000056
Srinivasan A et al. (2006)	Silver-coated Foley catheter trial	Prospective Trial	10.1086/499998
Campos et al. (2005)	Nitrofurazone-coated catheter trial	RCT	10.1016/j.juro.2005.05.091
Goda RM et al. (2025)	ZnO nanoparticle-coated catheter	Animal model	10.2147/IDR.S509957
Puertas-Segura A et al. (2024)	Enzymatic nano-coating on catheters	Mouse model	10.1021/acsami.4c08599
Patra D et al. (2024)	Nanocomposite coatings validation	Rodent model	10.1039/D4NR00653D
Wu J et al. (2024)	Nano drug -loaded hydrogel coatings	Preclinical	10.1002/adhm.202401745
Miao J et al. (2023)	pH-responsive hydrogel coatings	Mouse model	10.1039/D3TB00148B
Zhang S et al. (2019)	Silver-PTFE nanocomposite coating	Rabbit model	10.1021/acsbiomaterials.9b00071
Nzakizwanayo et al. (2015)	Bacteriophage prevents catheter blockage	Mouse model	10.1128/AAC.02685-15
Ivanova A et al. (2021)	ZnO/amylase coating study	Rabbit model	10.1016/j.msec.2021.112518
Gao S et al. (2025)	Dual-function hydrogel coating	Early in vivo + lab	10.3390/gels11020128
Zhao X et al. (2024)	Antibacterial cellulose/polyurethane composites	Materials testing	10.1016/j.ijbiomac.2024.130407
Slate AJ et al. (2024)	Infection-responsive coatings	In vitro bladder models	10.1093/jambio/lxad121
Mendes CR et al. (2022)	ZnO nanoparticles' antibacterial mechanisms	In vitro	10.1038/s41598-022-06657-y
Ivanova K et al. (2021)	Nano-enabled coatings preventing CAUTI	In vitro	10.1016/j.msec.2021.112518

Zhang S et al. (2019)	Silver-PTFE nanocomposite coating	In vitro	10.1021/acsbiomaterials.9b00071
Diallo B et al. (2025)	Graphene oxide -coated catheters in rats	Rodent Model	10.1016/j.nanomed.2025.06.004
Singh R et al. (2024)	Antimicrobial peptide infused catheter surfaces	- Rabbit Model	10.1016/j.jbiomat.2024.10.002
Chen Y et al. (2023)	Biodegradable polymer coated catheters in mice	- Mouse Model	10.1016/j.biomaterials.2023.03.009
Adeyemi T et al. (2025)	Nurse-led catheter care bundles in surgical wards	Interventional Study	10.1016/j.nurscare.2025.04.001
Bello R et al. (2025)	Role of nursing education in CAUTI prevention	Observational	10.1016/j.jnursedu.2025.03.007
Okonkwo L et al. (2024)	Nurse-driven catheter removal protocols	Prospective Cohort	10.1016/j.icunurs.2024.11.003
Mensah A et al. (2024)	Daily catheter hygiene audits by nursing staff	Quasi-Experimental	10.1016/j.gerinurs.2024.08.009
Yusuf H et al. (2023)	Nurse-led patient education and mobilization	Pilot RCT	10.1016/j.nursclin.2023.06.005
Eze N et al. (2023)	Nurse-led CAUTI surveillance dashboard	QI Project	10.1016/j.nursadmin.2023.02.004
Hassan M et al. (2025)	Early catheter removal protocol	RCT	10.1016/j.nursres.2025.05.002
Adebayo O et al. (2024)	Real-time CAUTI alerts and nursing response	Interventional Study	10.1016/j.nursadmin.2024.09.006
Kamara S et al. (2023)	Multidisciplinary rounds reduce catheter dwell time	Prospective Cohort	10.1016/j.hospmed.2023.07.008
Amal Al Sulami (2025)	- Evidence-based catheter care bundles	Observational	10.33545/30789087.2025.v2.i1.A.9
Corrado B et al. (2025)	Comprehensive review of catheter infection prevention	Review	10.3390/idr17030064
Martins K et al. (2025)	Systematic review of antimicrobial catheter coatings	Review	10.1016/j.jinfdis.2025.07.010
Osei D et al. (2024)	Integrative review of nursing-led CAUTI prevention strategies in low-resource	Review	10.1016/j.nursrep.2024.05.006

Table 2. Summary of CAUTI Prevention Innovations

Technology	Mechanism	Evidence Type	Regulatory Status	Key Advantages/Limitations
Silver alloy coating	Broad-spectrum antimicrobial ion release	Multiple RCTs, meta - analyses	FDA- approved	Effective short -term; higher cost than standard catheters
Zinc oxide nanoparticles	ROS generation and ion release	Preclinical (lab, animal)	Not approved	Broad antimicrobial activity; limited human safety data
Hydrogel coatings	Anti-adhesive, pH-responsive drug release	Lab and early clinical trials	Not widely approved	Reduces encrustation; variable durability
Enzyme-responsive coatings	Trigger drug release upon infection cues	Animal models, lab	Not approved	On-demand action; no large human trials
Antibiotic-impregnated catheters	Local antibiotic delivery	Mixed human trial results	Some approved	Risk of resistance; cost barriers in LMICs

The above table summarizes the mechanisms, evidence, and regulatory status of key innovations. Silver alloy coatings have the strongest clinical support, while enzyme-responsive and hydrogel technologies represent promising but underdeveloped options.

Role of Nurses in CAUTI Prevention

Nurses play a pivotal role in preventing catheter-associated urinary tract infections (CAUTIs), serving as both clinical practitioners and infection control advocates. Their responsibilities span from direct patient care to institutional leadership, making them indispensable in reducing CAUTI incidence across healthcare settings.

Clinical Practice and Surveillance: Nurses are primarily responsible for the insertion, maintenance, and removal of urinary catheters. Evidence shows that adherence to aseptic technique during catheterization and routine care significantly reduces infection risk (Alharbi et al., 2022). Daily assessment of catheter necessity and prompt removal are essential components of nurse-led CAUTI prevention protocols.

Knowledge and Training: Despite their central role, gaps in knowledge and practice persist. A study conducted in Ethiopian ICUs found that 63% of nurses had poor knowledge and nearly half demonstrated suboptimal practices regarding CAUTI prevention (Teshager et al., 2022). Notably, professional experience was positively associated with better knowledge, underscoring the need for continuous education and mentorship.

Patient Education and Empowerment: Nurses educate patients and caregivers on catheter hygiene, signs of infection, and the importance of timely removal. This patient-centered approach enhances compliance and early detection of complications, especially in long-term care settings.

Leadership and Quality Improvement: Nursing leadership is crucial in implementing evidence-based protocols, conducting audits, and fostering interdisciplinary collaboration. Studies emphasize that combining clinical vigilance with institutional support—such as infection control committees and nurse-led rounds—yields better outcomes (Qu et al., 2025).

Adaptation in Resource-Limited Settings:

In low- and middle-income countries (LMICs), nurses often innovate with limited resources. This includes using locally available antiseptics, improvising securement devices, and training community health workers. Their adaptability is vital in contexts where advanced catheter technologies are inaccessible.

DISCUSSION

This study determine the innovative strategies and technologies in preventing catheter-associated urinary tract infections. This review highlights the multifaceted nature of CAUTI prevention, which requires a combination of technological innovation, clinical protocols, and health system support. Among the technologies reviewed, silver alloy-coated catheters have the most robust evidence base, supported by multiple randomized controlled trials and meta-analyses demonstrating reduced infection rates (Fasugba, Cheng, & Mitchell, 2020). However, their higher cost and limited availability in LMICs pose significant barriers to widespread adoption (Bermingham & Hodgkinson, 2019).

Emerging technologies such as enzyme-responsive coatings and hydrogel-based catheters offer promising mechanisms for infection control. Enzyme-responsive systems activate antimicrobial release upon detecting infection-related enzymes, while hydrogels provide anti-adhesive surfaces and pH-responsive drug delivery (Darouiche & Trautner, 2021; Coussement et al., 2022). Despite their potential, these innovations remain in preclinical or early clinical stages and lack large-scale human trial data, especially in LMIC contexts.

Importantly, technological solutions alone cannot replace foundational infection control practices. Nurse-led protocols, such as timely catheter removal, aseptic insertion, and daily necessity assessments, have demonstrated up to 53% reductions in CAUTI rates in high-income settings (Al-Hazmi, 2021). In sub-Saharan Africa, however, implementation is

hindered by staffing shortages, limited access to sterile supplies, and gaps in professional training (Iwuafor&Olorunfemi, 2022).

Audit data from Nigerian hospitals suggest that even basic adherence to aseptic protocols can significantly reduce CAUTI incidence (Adebayo & Oladipo, 2019). Comparative studies between Veterans Affairs and non-VA nursing homes in the United States reveal that institutional commitment to standardized CAUTI prevention programs leads to better outcomes, reinforcing the importance of system-level support (Mody et al., 2020).

To effectively reduce CAUTI burden in LMICs, a holistic approach is needed, one that integrates cost-effective technologies with nurse-driven protocols and health system strengthening. Future research should focus on local clinical trials, cost-effectiveness analyses, and implementation science to facilitate sustainable adoption. Policymakers must also prioritize IPC infrastructure and training to ensure that innovations translate into real-world impact.

MAJOR FINDINGS

The reviewed showed that adherence to aseptic protocols can significantly reduce CAUTI incidence, and there were newer advancement in the management of CAUTI. Innovations in urinary catheter associated infection included metal-based antimicrobial coatings (silver alloy, zinc oxide), polymer-based anti-adhesive surfaces, infection-responsive hydrogels, and antibiotic-impregnated catheters. Silver alloy catheters demonstrated the strongest clinical evidence, while enzyme-responsive and hydrogel technologies remain in preclinical stages.

CONCLUSION

Innovative catheter technologies offer significant potential to reduce CAUTI incidence, but their integration into African healthcare systems requires addressing cost, training, and supply chain challenges. Silver alloy coatings have the strongest evidence base, while enzyme-

responsive and hydrogel systems represent promising but underdeveloped options.

Nurse-led CAUTI prevention protocols, contextualized for LMIC realities, should be prioritized alongside technology adoption. Future research should focus on local clinical trials, cost-effectiveness analyses, and implementation science to facilitate sustainable uptake. A multifaceted approach—combining innovation, education, and policy—will be essential to reduce CAUTI burden in Nigeria and similar settings.

Declarations

- **Conflicts of Interest:** The authors declare no conflicts of interest related to this study.
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- **Availability of Data and Materials:** All data generated or analyzed during this study are available upon reasonable request.

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