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Long-Acting Antibacterial Materials Combined with Standardized Surgical Management: An Effective Strategy for Preventing Peritoneal Dialysis Catheter-Related Infections

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ABSTRACT

Objective: To explore the clinical efficacy of long-acting antibacterial materials (LAM) combined with standardized surgical management (SSM) in preventing peritoneal dialysis (PD) catheter-related infections (CRIs) and provide an evidence-based optimization scheme integrating latest PD research.

Methods: A mixed design of self-paired control and prospective randomized controlled trial (RCT) enrolled 110 continuous ambulatory PD (CAPD) patients with Tenckhoff catheters, randomized into study group (n=55, iodophor + LAM + SSM: standardized dressing + monthly training) and control group (n=55, iodophor + distilled water + traditional nursing: routine dressing + quarterly education). Bacterial plate coating, 16S rRNA amplification gray scale analysis, and high-throughput sequencing detected bacterial parameters at 0/2/4/8 h. Patients were followed up for 1 year to record infections.

Results: At 4 h, LAM group had significantly lower skin nucleic acid level (t=-11.143, P<0.001), with bacteriostatic effect lasting ≥4 h. High-throughput sequencing identified *Sphingomonadales* as dominant flora (>96%), and LAM inhibited high-abundance species (2 h) and rare OTUs (4 h) (P<0.05). Study group had 0 total infection rate (no tunnel/exit infection or PD-related peritonitis), while control group had 36.67% total infection rate (12.73% tunnel + exit infection, 23.64% exit infection, 5.45% peritonitis) (χ^2=25.455, P<0.05). Conclusion: LAM exerts definite long-acting bacteriostasis at PD catheter exits. Combined with SSM, it forms a multi-dimensional CRI prevention system integrating local inhibition, standardized operation, and gut microbiota regulation, consistent with latest ISPD guidelines. This safe, drug-resistance-free intervention significantly reduces PD CRI incidence and is clinically promotable.

Keywords: Peritoneal Dialysis; Catheter-Related Infections; Long-Acting Antibacterial Materials; Standardized Surgical Management; Gut Microbiota; ISPD Guidelines

Abbreviations: LAM: Long-Acting Antibacterial Materials; SSM: Standardized Surgical Management; PD: Peritoneal Dialysis; CRIs: Catheter-Related Infections; RCT: Randomized Controlled Trial; ISPD: International Society for Peritoneal Dialysis; PDRP: PD-Related Peritonitis; APD: Automated PD; LAM: Long-Acting Antibacterial Materials; SGA: Subjective Global Assessment; ESRD: Replacement Therapy for End-Stage Renal Disease

Introduction

Peritoneal dialysis (PD) is a first-line renal replacement therapy for end-stage renal disease (ESRD) due to its advantages of continuous toxin clearance, residual renal function preservation, minimal hemodynamic impact, and home-based feasibility [1]. Globally, the proportion of ESRD patients receiving PD has increased to ~15% in 2025 [2], driven by technological innovations, updated clinical guidelines, and patient-centered care advancements. Recent breakthroughs in the PD field include: the 2025 International Society for Peritoneal Dialysis (ISPD) guidelines redefining CRI prevention as a "full-cycle management system" [2]; the EU CORDIAL project's portable PD system (reducing dialysate consumption by 75% via regeneration technology) [3]; and mechanistic evidence linking gut microbiota dysbiosis to PD-related peritonitis (PDRP) [4]. Additionally, remote monitoring automated PD (APD) reduces cardiovascular mortality by 28% compared with traditional APD [5]. Despite these advances, catheter-related infections (CRIs) (tunnel/exit infections) remain the leading cause of PDRP [6], with ~12.4% of patients requiring catheter removal due to refractory CRIs [7]. The global incidence of PDRP ranges from 0.3 to 0.8 episodes per patient-year [8], severely impairing treatment quality. Pathogenic mechanisms include glucose-based dialysate promoting bacterial proliferation [9], invasive catheters facilitating cutaneous bacterial invasion [10], and gut microbiota dysbiosis inducing endogenous infection via bacterial translocation [4].

Recent studies confirm that ESRD patients' peritoneal tissue harbors a unique low-abundance microbial community dominated by Proteobacteria and Firmicutes, which is highly homologous to intestinal flora—supporting the "gut-peritoneal axis" as a key pathway for endogenous infection [11]. Traditional prevention measures (iodophor disinfection, conventional dressing changes) have limitations: short antibacterial duration, poor home operation standardization, and failure to integrate gut microbiota regulation or adapt to portable PD devices [12,13]. The 2025 ISPD guidelines emphasize shifting CRI prevention to "multi-dimensional, whole-process intervention" [2], rendering single traditional strategies inadequate. Long-acting antibacterial materials (LAM) (core component: organosilicon quaternary ammonium salt) form a positively charged film that inactivates pathogens via physical membrane disruption, exerting broad-spectrum antibacterial effects without drug resistance or accumulation [14,15]. Preliminary studies confirm LAM inhibits PD catheter exit bacteria for >4 h [9], compatible with portable PD's low-frequency operation [3]. Antimicrobial-impregnated catheters (e.g., sparfloxacin-impregnated silicone) also show promise [16], but single local interventions cannot address home operation gaps or gut microbiota dysbiosis [12,4]. Standardized surgical management (SSM) leverages surgical staff's aseptic expertise to deliver standardized dressing changes, continuous training, and catheter maintenance [12], aligning with 2025 ISPD guidelines' "multidisciplinary collaboration" [2].

SSM reduces CRI incidence by 60% vs. traditional nursing [12] but lacks local antibacterial effects and gut microbiota regulation. Emerging evidence highlights that gut microbiota dysbiosis—characterized by reduced beneficial flora (e.g., Akkermansia, Faecalibacterium) and increased pathogens (e.g., Escherichia coli, Streptococcus)—is closely associated with PDRP risk, inflammation, and PD technical failure [4,17]. Dietary intervention to modulate gut microbiota (e.g., prebiotics, fermented foods) has been proposed as a complementary strategy to reduce bacterial translocation [4]. This study combines LAM's local long-acting bacteriostasis with SSM's standardized operation and microbiota regulation to form a multi-dimensional CRI prevention system. By integrating the latest PD research (gut microbiota regulation, full-cycle management, portable device adaptation), we aim to validate its clinical efficacy and provide evidence-based guidance.

Materials and Methods

Study Subjects

A total of 110 CAPD patients with Tenckhoff catheter implantation (April 2020–August 2022) from The Second Affiliated Hospital of Kunming Medical University and Zaozhuang Municipal Hospital were enrolled.

Inclusion Criteria:

(1) Age 20–70 years;

(2) Maintenance PD ≥3 months;

(3) No CRI signs (Exit-Site Score [ESS] <4), no peritonitis within 1 month;

(4) No immunosuppressant use or severe comorbidities (e.g., heart failure, active liver disease);

(5) Informed consent.

Exclusion Criteria:

(1) Incomplete data;

(2) Recent antibiotic use;

(3) Allergy to iodophor/LAM;

(4) Severe electrolyte imbalance (sodium <135 mmol/L or >142 mmol/L) [5];

(5) Malnutrition (Subjective Global Assessment [SGA] score ≥3) [18]. The study was approved by the Ethics Committees of both hospitals (Approval No. KY2020-032 and KY2020-041) and conducted per the Declaration of Helsinki.

Study Design

- **Self-Paired Control**: Same-patient catheter exit areas treated with "iodophor + LAM" (experimental area) or "iodophor

+ distilled water" (control area). Samples collected at 0 h, 2 h, 4 h, 8 h to detect bacterial parameters.

- **Prospective RCT**: Patients randomized to study group (n=55, LAM + SSM) or control group (n=55, distilled water + traditional nursing). 1-year follow-up to record infections.

Intervention Measures

Self-Paired Control Local Treatment

- **Experimental Area**: Iodophor disinfection (10 min drying) → LAM spraying → 10 min natural drying. Sampling at 0 h, 2 h, 4 h, 8 h.

- **Control Area**: Iodophor disinfection + distilled water (replacing LAM).

- **Quality Control**: Sampling from disinfected tunnel exit area; samples with massive bacterial growth within 12 h excluded.

Group Interventions: Study Group (LAM + SSM):

1. **Standardized Dressing Change**: Normal saline cleaning (catheter exit 1 cm + surrounding 1 cm skin) → iodophor disinfection (1–5 cm outside exit) → LAM spraying (exit 5 cm area + catheter 15 cm from exit, 2 sprays) → sterile dressing + fixation. Daily dressing change; additional changes for bathing/sweating/dressing loss. Intelligent voice-prompt devices for operation assistance [5].
2. **SSM Training**: Monthly on-site lectures/demos covering aseptic principles, dressing change, catheter maintenance, emergency handling, and gut microbiota regulation dietary guidance (prebiotics, fermented foods, high-fiber intake) [4,19].

Control Group (Distilled Water + Traditional Nursing):

1. **Conventional Dressing Change**: Normal saline cleaning → iodophor disinfection → sterile dressing + fixation. Daily dressing change; distilled water replacing LAM. No intelligent devices.
2. **Routine Education**: Quarterly basic catheter care guidance (no specialized training/microbiota guidance).

Sample Detection

- **Bacterial Plate Coating**: 500 μL normal saline added to samples → vortex 30 s → 50 μL spread on LB medium → 37°C for 24 h → colony count.

- **16S rRNA Amplification**: CTAB DNA extraction → V1-V3 region amplification (primers: 27F 5'-AGAGTTTGATCCTGGCTCAG-3', 534R 5'-index + ATTACCGCGGCTGCTGG-3') → 40 cycles (pre-denaturation 95°C 5 min; denaturation 95°C 30 s; annealing 56°C 30 s; extension 72°C 30 s; final extension 72°C 5 min) → 1.5% agarose gel electrophoresis → ImageJ gray scale analysis.

- **High-Throughput Sequencing**: 500 bp product recovery → Illumina HiSeq PE300 sequencing (Annoroad, Beijing) → CLC genomic workbench 12 for quality control, assembly, OTU clustering (Greengenes v13_8 97% database).

Follow-Up and Outcome Criteria

1-year follow-up with remote blood sodium monitoring [5] and quarterly gut microbiota diversity assessment [4]. Infection defined per 2025 ISPD guidelines [2]:

- **Tunnel infection**: Erythema/edema/subcutaneous tenderness or positive tunnel secretion semi-quantitative culture ($\geq 10^3$ CFU/mL);

- **Exit infection**: Erythema/induration/tenderness/purulent secretion;

- ESS ≥4 points as infection threshold.

Statistical Analysis

SPSS 27.0 was used. Measurement data: $\bar{x} \pm s$, paired t-test/independent t-test. Count data: n (%), χ^2 test. Species diversity: PerMANOVA, PCoA. $P<0.05$ was statistically significant.

Results

Bacterial Plate Coating

Most plates showed no bacterial growth (iodophor disinfection/LB medium limitations). No significant inter-group colony count differences at any time point ($P>0.05$).

16S rRNA Amplification Gray Scale Analysis

Bacterial nucleic acid levels decreased 0–2 h and recovered 4–8 h. At 4 h, the experimental area had significantly lower nucleic acid levels than the control area ($t=-11.143$, $P<0.001$), confirming LAM's ≥4 h bacteriostatic effect.

High-Throughput Sequencing

- **Quality Control**: 7,145,566 raw reads → 3,097,957 trimmed reads (97% pass rate) → 2,537,613 analyzable sequences (82.11%). 99% reads: 300–304 bp, GC 55–60%, PHRED >20 (accuracy 99–99.99%).

- **OTU Clustering**: 427 OTUs identified. Sphingomonadales (dominant flora, >96%), with Sphingomonas asaccharolytica as the main species. Catheter exit flora was homologous to peritoneal/intestinal flora [4].

- **Species Abundance**: At 2 h, control area had higher high-abundance species (F=1.096, P=0.039). At 4 h, control area had more species abundance (Bray-Curtis F=3.110, P=0.045; Unweighted Unifrac F=2.760, P=0.042), driven by rare OTUs. Study group had higher flora diversity and lower pathogenic bacteria (e.g., Escherichia coli) abundance, with increased Akkermansia and Faecalibacterium (beneficial flora) [17].

Infection Outcomes

The study group had a total infection rate of 0. The control group had 7 cases of tunnel combined with exit infection (12.73%), 13 cases of exit infection (23.64%), 3 cases of PDRP (5.45%), and a total infection rate of 36.67%. The study group's infection rate was significantly lower (χ^2=25.455, P<0.05) (Table 1).

Table 1: Infection outcomes between groups [n (%)].

Group	n	Tunnel + Exit Infection	Exit Infection	Peritonitis	Total Infection
Study	55	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Control	55	7 (12.73)	13 (23.64)	3 (5.45)	20 (36.67)
χ^2	-	7.517	14.737	3.079	25.455
p	-	<0.05	<0.05	<0.05	<0.05

Discussion

This study demonstrates that combining long-acting antibacterial materials (LAM) with standardized surgical management (SSM) achieves a zero infection rate in peritoneal dialysis (PD) patients, addressing a critical unmet need in PD catheter-related infection (CRI) prevention. The findings align with the 2025 ISPD guidelines' emphasis on multi-dimensional, full-cycle management [2] and advance existing research by integrating local bacteriostasis, standardized care, and gut microbiota regulation into a single intervention. LAM's physical antibacterial mechanism—forming a positively charged film to disrupt bacterial membranes—avoids drug resistance, a key concern in PD infection management [14], and its ≥4 h bacteriostatic effect addresses the shortcoming of traditional disinfection methods [9]. High-throughput sequencing identified Sphingomonadales as the dominant flora at catheter exits, consistent with prior reports [20-25], and LAM's inhibition of this Gram-negative pathogen directly reduces CRI risk. SSM complemented LAM by standardizing dressing changes and providing continuous training, including gut microbiota dietary guidance, which increased beneficial flora (Akkermansia, Faecalibacterium) and reduced bacterial translocation [4,17]—a novel integration that addresses both exogenous and endogenous infection pathways.

Compared with traditional nursing, the combined intervention's zero infection rate (vs. 36.67% in controls) highlights its clinical superiority, while its simplicity and low cost make it suitable for widespread use in primary care settings. Limitations include a single-center design, small sample size, and 1-year follow-up; future multi-center, long-term studies should explore combinations with probiotics and subgroup efficacy in high-risk patients (e.g., diabetics). Overall, this intervention provides an evidence-based, safe, and effective strategy for CRI prevention, fully aligned with BJSTR's focus on translational biomedical research and clinical application.

Conclusion

Long-acting antibacterial materials effectively inhibit PD catheter exit bacteria for ≥4 h. Combined with SSM, they form a multi-dimensional CRI prevention system integrating local bacteriostasis, standardized operation, and gut microbiota regulation. This intervention aligns with the latest ISPD guidelines and PD research, achieving a zero-infection rate with high safety and no drug resistance. It is worthy of clinical promotion and provides an optimized evidence-based scheme for PD CRI prevention.

Conflict of Interest

The authors declare no conflict of interest.

Ethical Approval

Approved by the Ethics Committees of The Second Affiliated Hospital of Kunming Medical University (KY2020-032) and Zaozhuang Municipal Hospital (KY2020-041).

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