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Continuous low-concentration hypochlorous acid for microbial control of endoscope final-rinse water pipelines: a multicenter prospective Study in Shanghai, China

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Abstract

Background

Microbial contamination of final-rinse water can recontaminate flexible endoscopes after high-level disinfection. We evaluated whether continuous low-concentration hypochlorous acid (HOCl) treatment was associated with sustained microbiological control of final-rinse water pipelines in hospital endoscopy units.

Methods

This prospective multicenter before-and-after study included 65 fixed sampling sites (39 automated endoscope reprocessor [AER] outlets and 26 manual-rinse sinks) in 13 tertiary hospitals in Shanghai, China, from May to November 2025. An online HOCl generator was installed at the midpoint of the main final rinse water pipeline to deliver a continuous concentration of 2 mg/L HOCl. Two baseline water samples were collected before installation, followed by repeat sampling on days 1, 7, 30, and 90. Total bacterial count, bacterial identification, endotoxin, and conductivity were assessed. Paired tests and hospital-level mixed-effects models were used for exploratory comparisons of continuous outcomes.

Results

At baseline, 98 of 130 samples (75.38%) exceeded 10 CFU/100 mL; crude non-compliance was 84.62% (66/78) at AER outlets and 61.54% (32/52) at manual-rinse sinks ($P < 0.001$). Identified organisms were predominantly water-associated bacteria, including *Cupriavidus* spp., *Rhizobium* spp., *Stenotrophomonas maltophilia*, and *Moraxella osloensis*. No culturable bacteria were recovered from any of the 260 post-intervention samples collected through day 90. Median endotoxin decreased from 0.0625 to 0.0265 EU/mL ($Z = -3.485$, $P < 0.001$). Conductivity was higher on day 7 than at baseline (median, 42.02 vs 14.25 μS/cm; $P = 0.005$), but the difference was not statistically significant on day 90 (15.98 μS/cm; $P = 0.861$).

Conclusions

Baseline microbial contamination of final rinse water supply pipelines is prevalent across tertiary hospitals in Shanghai, dominated by water-associated opportunistic pathogens. Continuous 2 mg/L HOCl treatment was associated with the absence of culturable bacteria in final-rinse water samples for 90 days and with lower endotoxin concentrations. This approach offers a feasible engineering intervention for continuous microbial control of final rinse water systems in endoscopy units.

Background

Flexible endoscopes are difficult to reprocess because their long, narrow channels and complex distal components can retain organic material and microorganisms(1). Although failures in cleaning and high-level disinfection account for many endoscope-associated events(2, 3), contaminated final-rinse water can reintroduce waterborne organisms after disinfection(4, 5). Recent outbreaks of multidrug-resistant organisms linked to contaminated duodenoscopes—some occurring despite apparent adherence to reprocessing protocols—highlight the persistent risk of endoscope-associated transmission(2, 3, 6). Current guidance therefore recommends engineering controls and microbiological surveillance of the final-rinse water supplied to automated endoscope reprocessors (AERs)(7, 8).

Water supply systems provide persistent wet surfaces on which biofilms can develop(9). Organisms adapted to oligotrophic water, including *Pseudomonas aeruginosa*, *Stenotrophomonas maltophilia*, and nontuberculous mycobacteria, may persist in treatment devices, connecting tubes, terminal outlets, or internal AER water pathways(10, 11). Pseudo-outbreaks and infections associated with nontuberculous mycobacteria contaminating endoscope washer-disinfectors and their rinse water have been repeatedly reported(12, 13). Filtration or purification alone does not ensure consistently bacteria-free final-rinse water, particularly when downstream pipework has become colonized(14). Consequently, one-time disinfection or short-term intervention is insufficient to reduce the risk of recontamination(4).

Hypochlorous acid (HOCl), the uncharged and highly reactive form of free available chlorine, can oxidize microbial proteins and other cellular targets(15, 16). High-concentration shock disinfection, however, is unsuitable for the metal pipelines of endoscopes and precision instruments. Continuous low-concentration HOCl may suppress bacterial regrowth between periodic pipeline-disinfection cycles, but field performance depends on pH, contact time, pipeline material, and the residual concentration delivered to distal outlets(17). Multicenter evidence in endoscopy water systems remains limited(18). We therefore characterized baseline contamination in 13 hospitals and evaluated microbiological counts, endotoxin, and conductivity for 90 days after initiation of continuous 2 mg/L HOCl intervention.

Methods

2.1. Study design

This was a multicenter, prospective, one-group before-and-after field study conducted in 13 tertiary general hospitals in Shanghai, China, from May to November 2025. Fixed water-system outlets were the observational units and were sampled repeatedly before and after the intervention. This study did not involve human participants, human data, or human tissue. Therefore, ethics approval and informed consent were not applicable.

2.2. Study sites and sampling locations

All 13 hospitals operated independent endoscopy units and performed reprocessing flexible endoscopes in accordance with the Chinese technical specification WS 507–2016, which requires a total viable count of ≤ 10 CFU/100 mL in final-rinse water(10). Five fixed final-rinse water outlets (comprising AERs and

manual washing sinks) were designated at each hospital, and the same sites were sampled at every round. The water source, terminal connections, and pipeline maintenance practices of each institution are summarized in Table 1.

Table 1
Baseline characteristics of final rinse water systems at the 13 participating hospitals

Hospital	Independent water treatment room	Rinse water type	Terminal branch	Terminal pipeline material	Pipeline disinfection	Disinfection cycle
A	Yes	Purified water	AER	304 corrugated tube / plastic	Peracetic acid	6 months
B	Yes	Purified water	AER, manual sink	304 corrugated tube / plastic	Available chlorine	Monthly
C	Yes	Purified water	Manual sink	304 braided hose	Peracetic acid + UV	2 months
D	No	Tap water	AER, manual sink	304 braided hose	Peracetic acid	3 months
E	Yes	Purified water	AER, manual sink	304 braided hose	Available chlorine	Weekly
F	Yes	Tap water	AER, manual sink	304 braided hose	Available chlorine	Monthly
G	Yes	Purified water	AER, manual sink	304 braided hose	None	None
H	Yes	Purified water	AER, manual sink	304 corrugated tube / plastic	Peracetic acid	6 months
I	Yes	Purified water	AER, manual sink	PPR + PVC	Peracetic acid	3 months
J	Yes	Purified water	AER, manual sink	304 corrugated tube / PPR	Peracetic acid	3 months
K	Yes	Purified water	AER, manual sink	304 corrugated tube	Available chlorine	6 months
L	Yes	Purified water	AER, manual sink	304 corrugated tube	Available chlorine + UV	6 months

Note. AER, automated endoscope reprocessor; PVC, polyvinyl chloride; PPR, random copolymer polypropylene; UPVC, unplasticized polyvinyl chloride; UV, ultraviolet.

Hospital	Independent water treatment room	Rinse water type	Terminal branch	Terminal pipeline material	Pipeline disinfection	Disinfection cycle
M	Yes	Purified water	Manual sink	UPVC	Peracetic acid + UV	6 months

Note. AER, automated endoscope reprocessor; PVC, polyvinyl chloride; PPR, random copolymer polypropylene; UPVC, unplasticized polyvinyl chloride; UV, ultraviolet.

2.3. Intervention

After the two baseline sampling rounds, an online HOCl generator (JIAMOVER Intelligent Water Sterilization System, Shanghai Rijie Environmental Technology Co., Ltd) was installed in the main final-rinse water supply line at each hospital. The generator was configured to deliver HOCl continuously at a target concentration of 2 mg/L to downstream AER outlets and manual-rinse sinks. The same fixed outlets were sampled on days 1, 7, 30, and 90 after installation (Fig. 1).

2.4. Sampling Methods

Before sampling, water was allowed to run for 5 minutes at each site to flush stagnant water from the pipeline. Two 100 mL water samples were then collected at each site using sterile sampling bottles: one was designated for microbial enumeration and species identification, and the other for endotoxin and conductivity measurements. All samples were transported to the laboratory within 2 hours at 25°C for immediate processing.

2.4.1. Microbiological Testing

For microbial enumeration and identification, a few milliliters of sodium thiosulfate neutralizer were added to each water sample to quench residual free chlorine prior to culture. A 1 mL aliquot was inoculated into sterile enrichment broth and incubated at 35°C for 48 h for qualitative assessment. The remaining water was filtered through a sterile 0.45-μm membrane, which was then placed on R2A agar and incubated at 25°C for 10 days(19). Colony counts were expressed as CFU/100 mL, and values > 10 CFU/100 mL were classified as non-compliant under WS 507–2016. Culture-positive isolates were identified by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS).

2.4.2. Endotoxin Testing

Endotoxin was measured according to the manufacturer's instructions in a 1-mL aliquot using a Gram-negative bacterial lipopolysaccharide detection kit (XSF0296T; Dana [Tianjin] Biotechnology Co., Ltd.,

Tianjin, China). Concentrations were calculated from the manufacturer-specified standard curve and reported as endotoxin units per milliliter (EU/mL). The limit of detection (LOD) was 0.01 EU/mL

2.4.3. Conductivity Testing

Conductivity was measured in a 10-mL aliquot using a DDS-307A conductivity meter (Shanghai Yidian Scientific Instrument Co., Ltd., Shanghai, China) and reported in μS/cm.

2.5. Statistical Analysis

Analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Categorical data are presented as counts and percentages. Crude comparisons between AER and manual-rinse outlets used the chi-square or Fisher exact test, as appropriate. Skewed continuous variables are reported as median (interquartile range [IQR]); paired summaries were compared using the Wilcoxon signed-rank test. Linear mixed-effects models evaluated time and outlet type for endotoxin and conductivity, with hospital included as a random intercept. Model estimates are reported as β coefficients with 95% confidence intervals (CIs). Tests were two-sided, and $P < 0.05$ was considered statistically significant.

Results

3.1. Baseline Microbial Contamination and Isolate Distribution

The two baseline rounds yielded 130 samples: 78 from AER outlets and 52 from manual-rinse sinks. Qualitative enrichment culture was positive in 79 samples (60.77%), while 98 samples (75.38%) exceeded 10 CFU/100 mL by quantitative culture. MALDI-TOF MS identified predominantly water-associated organisms, including *Cupriavidus* sp., *Rhizobium* sp., *Stenotrophomonas maltophilia*, and *Moraxella osloensis* (Figure 2).

3.2. Total Bacterial Count Before and After HOCl intervention

At baseline, non-compliance was respectively observed in 34/39 (87.18%) and 32/39 (82.05%) AER samples and in 19/26 (73.08%) and 13/26 (50.00%) manual-rinse samples. In the pooled crude comparison, non-compliance was more frequent at AER outlets than at manual-rinse sinks (84.62% vs 61.54%; $P < 0.001$). Following intervention, 260 water samples were collected across days 1, 7, 30, and 90. No colonies were recovered at any outlet (Table 2).

Table 2. Non-compliance of total bacterial count in final rinse water before and after intervention

Outlet type	Baseline 1	Baseline 2	Baseline total	Day 1	Day 7	Day 30	Day 90
AER (n = 39)	34 (87.18%)	32 (82.05%)	66 (84.62%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Manual-rinse sink (n = 26)	19 (73.08%)	13 (50.00%)	32 (61.54%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total (n = 65)	53 (81.54%)	45 (69.23%)	98 (75.38%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Note. n denotes the number of fixed outlets sampled in each round.

Mixed-effects modeling further demonstrated that intervention was associated with reduced colony counts ($P < 0.001$). Neither differences among post-intervention time points nor intervention-by-time interactions reached statistical significance ($P > 0.05$), suggesting no attenuation of bactericidal efficacy during the 90-day observation period. Hospital-level trends are shown in Figure 3.

3.3. Endotoxin Concentrations

In the paired pre-post summary, median endotoxin decreased from 0.0625 to 0.0265 EU/mL (Z = -3.485, $P < 0.001$). At manual-rinse sinks, the median decreased from 0.1125 to 0.0260 EU/mL (Z = -3.150, $P = 0.002$). At AER outlets, the change from 0.0315 to 0.0280 EU/mL was not statistically significant (Z = -1.723, $P = 0.085$) (Table 3). Hospital-level trends are shown in Figure 4.

Table 3. Paired comparison of endotoxin concentrations before and after HOCl intervention [EU/mL, median (IQR)]

Site type	Pre-intervention	Post-intervention	Z value	*P* value
Manual-rinse sink (n = 26)	0.1125 (0.0100–2.6130)	0.0260 (0.0110–0.0760)	−3.150	0.002
AER (n = 39)	0.0315 (0.0133–0.2358)	0.0280 (0.0100–0.0590)	−1.723	0.085
Total	0.0625 (0.0100–1.6883)	0.0265 (0.0110–0.0660)	−3.485	< 0.001

With baseline round 2 as the reference, the mixed-effects model estimated lower endotoxin concentrations on days 7, 30, and 90 (all $P < 0.001$), but not on day 1 (P = 0.492). Outlet type was not associated with endotoxin concentration ($P = 0.442$) (Table 4).

Table 4. Mixed-effects model for endotoxin concentration

Variable	β (95% CI)	*P* value
Time		
Baseline 2	Reference	—
Baseline 1	0.15 (−0.07 to 0.37)	0.192
Day 1	−0.08 (−0.30 to 0.14)	0.492
Day 7	−0.73 (−0.95 to −0.51)	< 0.001
Day 30	−0.75 (−0.97 to −0.53)	< 0.001
Day 90	−0.75 (−0.97 to −0.53)	< 0.001
Site type		
AER	Reference	—
Manual-rinse sink	−0.05 (−0.18 to 0.08)	0.442

3.4. Conductivity

Median baseline conductivity was 14.25 µS/cm (IQR, 9.02-36.95), with marked between-hospital variation; hospitals D and F used tap water and had baseline values >380 µS/cm. Relative to the pooled mean of the two baseline rounds, conductivity did not differ on day 1 (median, 13.86 µS/cm; IQR, 8.82-22.58; Z = -0.175, *P* = 0.861), was higher on day 7 (42.02 µS/cm; IQR, 30.58-89.06; Z = -2.830, *P* = 0.005), and was not statistically different on day 30 (20.82 µS/cm; IQR, 19.18-43.88; Z = -0.664, *P* = 0.507) or day 90 (15.98 µS/cm; IQR, 12.44-28.46; Z = -0.175, *P* = 0.861). Comparisons using baseline round 2 as the reference similarly identified an increase only on day 7 (Z = -2.691, P = 0.007)(Table 5).

Table 5. Conductivity by hospital and sampling round (µS/cm, mean ± SD)

	Baseline 1	Baseline 2	Day 1	Day 7	Day 30	Day 90
Hospital A	3.12 ± 0.20	3.15 ± 0.14	2.75 ± 0.13	42.02 ± 25.29	2.80 ± 0.44	2.42 ± 0.41
Hospital B	7.10 ± 1.78	7.51 ± 1.32	7.92 ± 2.58	18.65 ± 3.21	9.71 ± 1.63	7.34 ± 2.56
Hospital C	55.14 ± 2.65	47.92 ± 1.38	41.00 ± 0.90	108.64 ± 29.53	43.88 ± 7.36	43.08 ± 4.47
Hospital D	395.40 ± 9.76	385.20 ± 15.12	401.00 ± 8.92	397.00 ± 6.74	380.00 ± 11.02	367.60 ± 24.44
Hospital E	12.26 ± 0.72	10.22 ± 1.34	13.86 ± 0.44	62.82 ± 13.21	20.60 ± 3.71	12.44 ± 1.33
Hospital F	394.40 ± 13.52	388.00 ± 43.67	406.00 ± 20.09	382.40 ± 55.19	376.60 ± 32.51	379.80 ± 23.12
Hospital G	29.98 ± 13.00	43.92 ± 20.92	11.06 ± 6.00	27.84 ± 1.63	15.06 ± 2.71	15.10 ± 1.36
Hospital H	19.04 ± 3.73	16.72 ± 2.65	17.04 ± 1.76	29.32 ± 12.25	25.82 ± 2.14	25.88 ± 5.77
Hospital I	6.49 ± 0.41	6.19 ± 0.12	6.42 ± 0.64	41.16 ± 9.48	20.82 ± 2.10	10.85 ± 2.34
Hospital J	9.57 ± 0.10	8.46 ± 0.25	8.82 ± 0.13	42.68 ± 4.37	23.34 ± 8.23	16.18 ± 3.49
Hospital K	21.88 ± 0.92	23.14 ± 1.34	22.58 ± 0.99	89.06 ± 10.95	64.54 ± 1.80	28.46 ± 5.56
Hospital L	11.80 ± 0.94	16.70 ± 7.96	11.64 ± 3.39	30.58 ± 3.59	19.80 ± 1.41	15.38 ± 3.45
Hospital M	12.20 ± 0.87	10.55 ± 1.36	21.48 ± 1.99	37.58 ± 1.71	19.18 ± 0.89	15.98 ± 3.89

In the mixed-effects model using baseline round 2 as the reference, conductivity was higher only on day 7 (β = 26.31 μS/cm; 95% CI, 21.02-31.61; $P < 0.001$). Estimates for baseline round 1 and days 1, 30, and 90 were not statistically significant (Table 6). The main effect of site type was not statistically significant (β = 1.07, 95% *CI*: −2.05 ~ 4.19, $P = 0.499$).

Table 6. Mixed-effects model for conductivity

Variable	β (95% CI)	*P* value
Time		
Baseline 2	Reference	—
Baseline 1	0.82 (−4.47 to 6.12)	0.760
Day 1	0.30 (−4.99 to 5.59)	0.912
Day 7	26.31 (21.02 to 31.61)	< 0.001
Day 30	4.19 (−1.10 to 9.49)	0.120
Day 90	−2.09 (−7.38 to 3.20)	0.438
Site type		
AER	Reference	—
Manual-rinse sink	1.07 (−2.05 to 4.19)	0.499

Discussion

In this multicenter before-and-after study, baseline microbial non-compliance of endoscope final-rinse water was common, affecting 75.38% of samples. The predominant contaminants were water-associated opportunistic pathogens, including *Cupriavidus* sp., *Rhizobium* sp., *Stenotrophomonas maltophilia*, and *Moraxella osloensis*. After continuous dosing to a target HOCl concentration of 2 mg/L, no culturable bacteria were recovered from 260 samples collected over 90 days, and endotoxin concentrations were lower in post-intervention summaries. These results suggest that continuous low-concentration HOCl may be a useful engineering control for continuous microbial control of water systems in endoscopy units.

4.1. Baseline contamination and implications for water-system control

The high baseline non-compliance rate is compatible with reports showing that final-rinse water quality varies with water treatment, terminal devices, sampling practice, and pipeline maintenance(10, 18). Walker et al noted that microbial contamination of final rinse water has been directly linked to numerous endoscope-related infection outbreaks and pseudo-outbreaks, and that contamination of the water supply system can lead to reintroduction of waterborne microorganisms during rinsing even in institutions that adhere to standard reprocessing protocols(4). Liu et al also found that contamination of connecting pipelines by opportunistic premise plumbing pathogens (OPPPs) was an important cause of microbial non-compliance in endoscopic final rinse water(10). Some isolated organisms, such as *Sphingomonas* sp., *Herbaspirillum* sp., and *Chryseobacterium* sp., belong to the same category of common water-associated opportunistic pathogens as the *Cupriavidus* sp. and *Rhizobium* sp. identified

in the present study(20). The organisms recovered here were typical of water-associated microbial communities rather than enteric flora, supporting a downstream water-system reservoir(9, 21).

The AER sites in this study had a baseline non-compliance rate of 84.62%, significantly higher than the 61.54% observed at manual washing sinks. This disparity may be attributable to the complex internal waterway architecture of AERs, which contains low-flow dead spaces and periods of intermittent use(22, 23). Multiple international studies have confirmed that internal AER waterways, detergent reservoirs, inlet hoses, and air vents can all develop biofilms and serve as contamination reservoirs(23, 24). More recent outbreaks of carbapenem-resistant organisms, some occurring despite guideline-compliant reprocessing, further illustrate the difficulty of achieving reliable microbial control in complex endoscope-related water pathways(2, 3, 25). The present findings further underscore that AER sites represent a critical and challenging target for microbial control in endoscopy water systems. Focusing solely on the quality of the final rinse water source while neglecting continuous control of supply pipelines and internal AER waterways is unlikely to fundamentally reduce the risk of recontamination.

4.2. Bactericidal efficacy and mechanism of continuous low-concentration HOCl

In this study, continuous perfusion of 2 mg/L HOCl achieved 0 colony counts at all sites within one day, and 0 non-compliance was maintained for 90 days without evidence of efficacy attenuation. This performance exceeds that of conventional periodic shock disinfection, which eliminates only planktonic bacteria and superficial biofilm layers. Limited efficacy against biofilms deeply embedded in the pipeline wall, allowing bacteria to regrow in the pipeline wall, and bacteria can rapidly regrow between disinfection cycles(26). The mechanism of action of HOCl involves direct oxidative destruction of microbial cellular structures, and nucleic acids, ultimately resulting in bacterial death(16). A multi-period crossover randomized controlled trial conducted in two Nigerian hospitals demonstrated that HOCl achieved surface disinfection comparable to that of sodium hypochlorite at a lower concentration, with non-inferior overall microbiological outcomes(27).

Baseline assessment revealed that all 13 hospitals had routinely employed disinfection methods such as available chlorine, peracetic acid, or ultraviolet irradiation, yet substantial bacterial growth persisted in both baseline sampling rounds, suggesting the presence of biofilm in the final rinse water pipelines(28). Studies of drinking water distribution networks have shown that microorganisms within biofilms are 100- to 1000-fold more tolerant to disinfectants than their planktonic counterparts(29), and that a conventional maintenance chlorine concentration of 0.6 mg/L achieves only limited bacterial inactivation, with significant reductions requiring high-concentration available chlorine(30, 31). In the present study, intervention with 2 mg/L HOCl resulted in culture-negative samples within one day, sustained through day 90. This is likely attributable to the maintenance of a stable oxidation-reduction potential within the pipeline, which continuously suppresses regrowth of planktonic bacteria shed from biofilms while gradually penetrating and disrupting the biofilm matrix(16).

4.3. Changes in endotoxin

Endotoxin can persist after Gram-negative bacteria death, so it complements but does not duplicate culture-based assessment(32). In this study, median endotoxin decreased significantly from 0.0625 EU/mL at baseline to 0.0265 EU/mL post-intervention ($P < 0.001$). Stratified analysis showed a significant reduction at manual washing sink sites but not at AER sites, possibly because the more complex and elongated AER waterways require longer flushing to clear endotoxin released from dead bacteria. The mixed-effects model demonstrated significant endotoxin reductions on days 7 and 30 post-intervention (both $P < 0.001$), further supporting a time-lagged pattern of endotoxin clearance.

4.4. Changes in conductivity

A transient elevation in conductivity was observed on day 7 post-intervention, with return to baseline levels by day 90. This phenomenon may be related to the sustained action of HOCl on the pipeline(16). As HOCl disrupts the biofilm matrix, inorganic mineral deposits or corroded metal components adhering to the pipeline wall are shed into the water, raising conductivity. As biofilms are progressively cleared, conductivity gradually declines, returning to baseline by day 90. Hospitals D and F, which used tap water, showed smaller percentage changes in conductivity post-intervention and also returned to baseline by day 90, indicating that the elevation is transient and that long-term continuous use has no cumulative effect.

4.5. Limitations

Several limitations should be acknowledged. First, the self-controlled before-after design lacked a concurrent untreated control, and therefore cannot fully exclude the influence of seasonal variation, maintenance practices, or other co-interventions. Second, biofilm changes were not directly observed by scanning electron microscopy or confocal laser scanning microscopy; thus, the biofilm clearance process remains an inferential conclusion. Third, only four post-intervention time points (days 1, 7, 30, and 90) were selected, which may have missed transient regrowth between intervals. However, the primary outcome—the absence of culturable bacteria—was uniformly observed at every sampled point from day 1 through day 90, the limited sampling density is unlikely to have altered the main conclusion.

Conclusions

In summary, this study demonstrates that baseline microbial contamination of final rinse water distribution pipelines is prevalent across tertiary hospitals in Shanghai, dominated by water-associated opportunistic pathogens, with AER sites more heavily contaminated than manual washing sinks. Continuous perfusion of 2 mg/L low-concentration HOCl achieves complete bacterial clearance within one day, maintains stable efficacy for 90 days, and significantly reduces endotoxin levels. The transient conductivity elevation has no cumulative effect with long-term use. This approach offers a feasible engineering intervention for continuous microbial control of final rinse water systems in endoscopy units. Future work should optimize HOCl maintenance concentrations and device maintenance protocols in light of pipeline material, architecture, and water quality characteristics, and conduct longer-term follow-up of clinical outcomes.

Abbreviations

AER: automated endoscope reprocessor; CFU: colony-forming unit; CI: confidence interval; EU: endotoxin unit; HOCl: hypochlorous acid; IQR: interquartile range; LOD: limit of detection; MALDI-TOF MS: matrix-assisted laser desorption/ionization time-of-flight mass spectrometry; OPPP: opportunistic premise plumbing pathogen; PPR: random copolymer polypropylene; PVC: polyvinyl chloride; UPVC: unplasticized polyvinyl chloride; UV: ultraviolet.

Declarations

Ethics approval and consent to participate

Not applicable. This study involved water-system sampling only and did not involve human participants, human data, or human tissue.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

QFS drafted the manuscript and participated in the investigation. MXW curated the data and performed the formal analysis. YY performed the formal analysis. JBL and XC participated in the investigation and data curation. WS administered the project. XDG conceptualized and administered the project. All authors read and approved the final manuscript.

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Figures

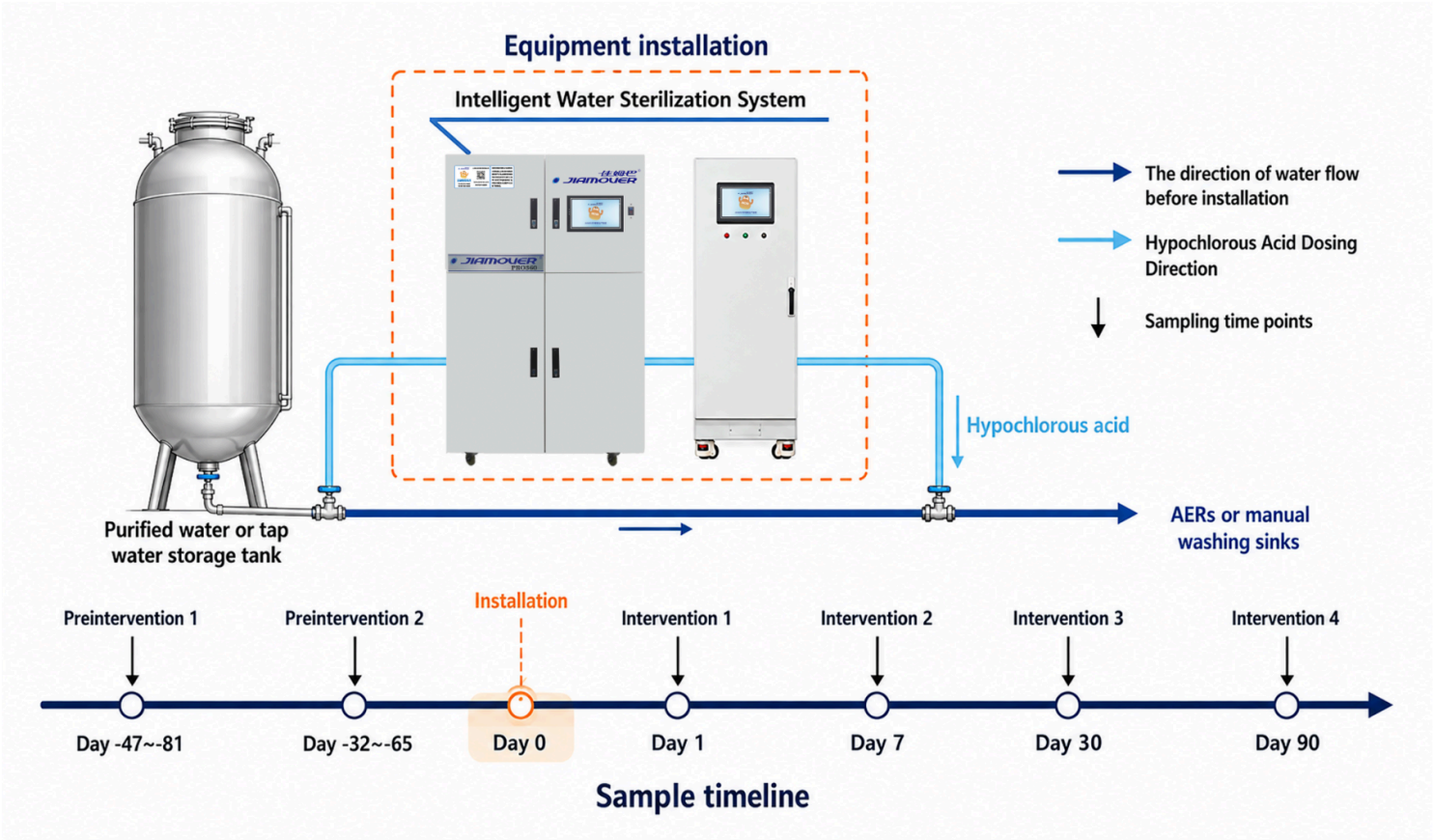


Figure 1

Sampling timeline flowchart.

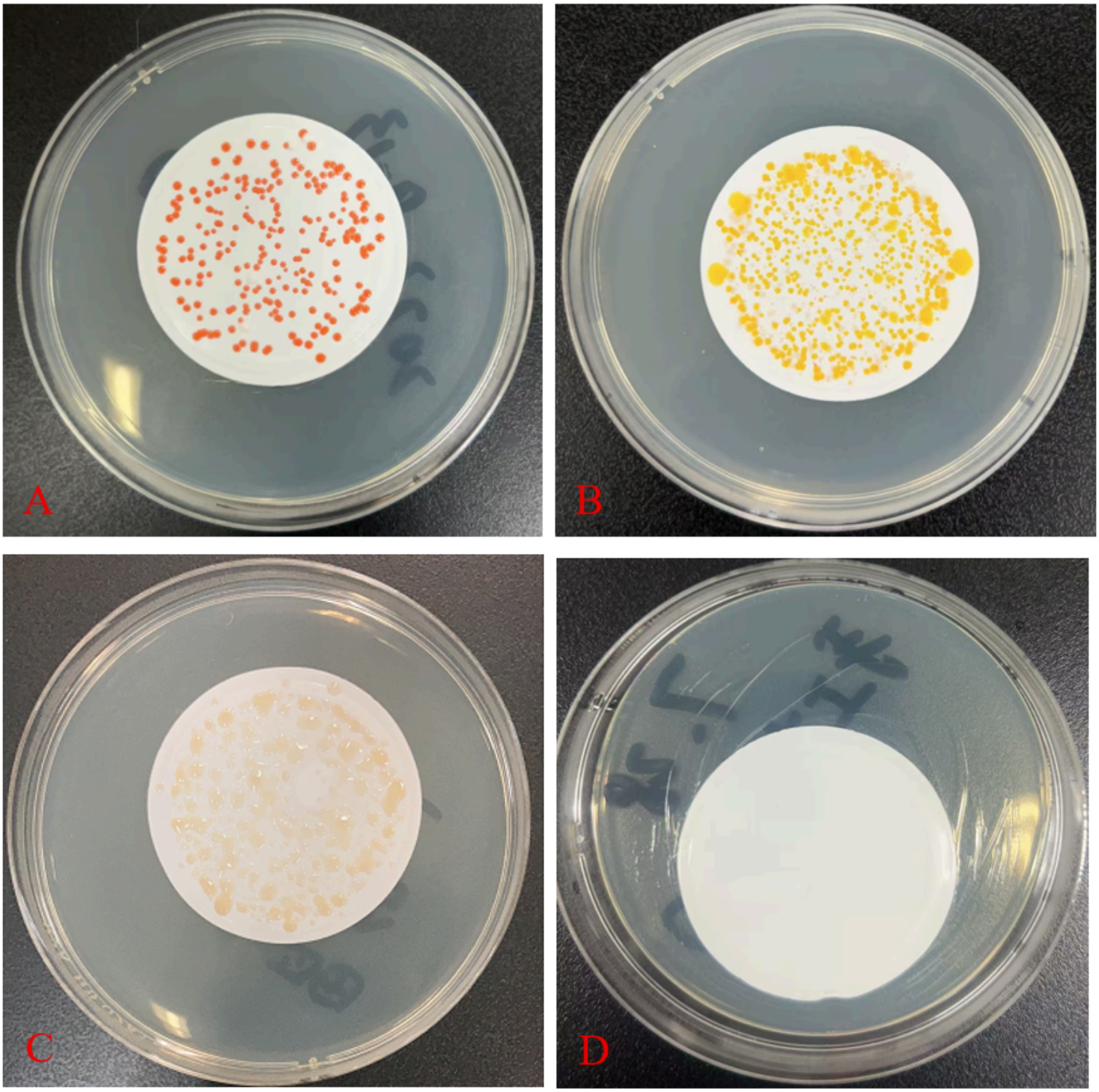


Figure 2

Culture and species identification of representative water samples. A: Cupriavidus sp.; B: Stenotrophomonas maltophilia; C: Rhizobium sp.; D: negative control.

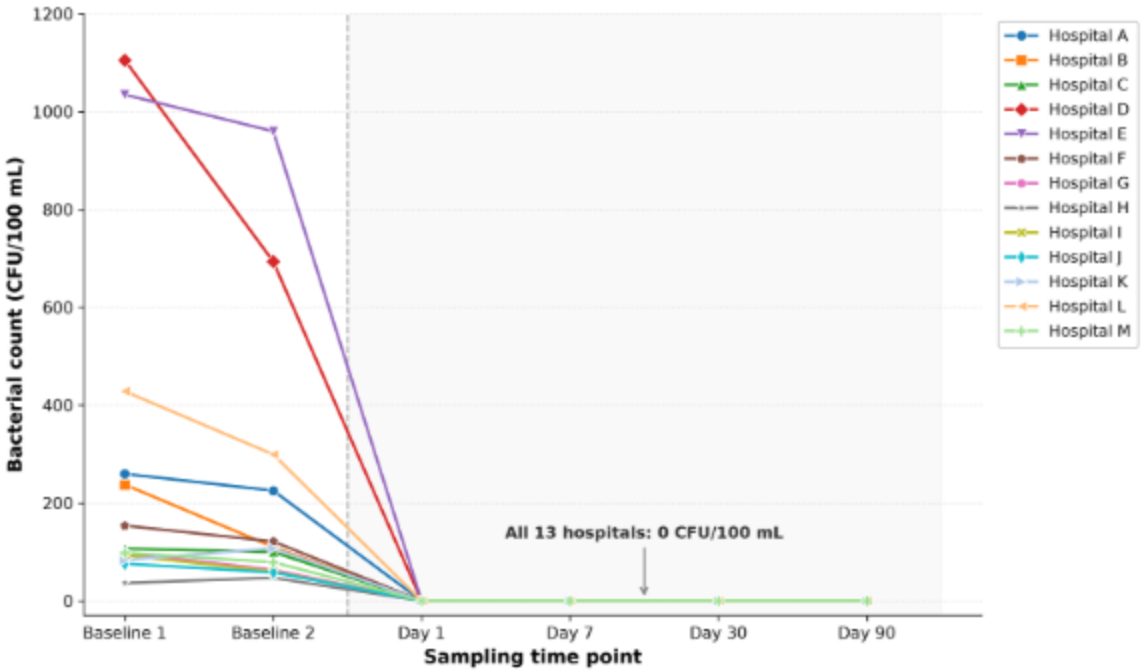


Figure 3

Hospital-level total bacterial count trends across the six sampling rounds.

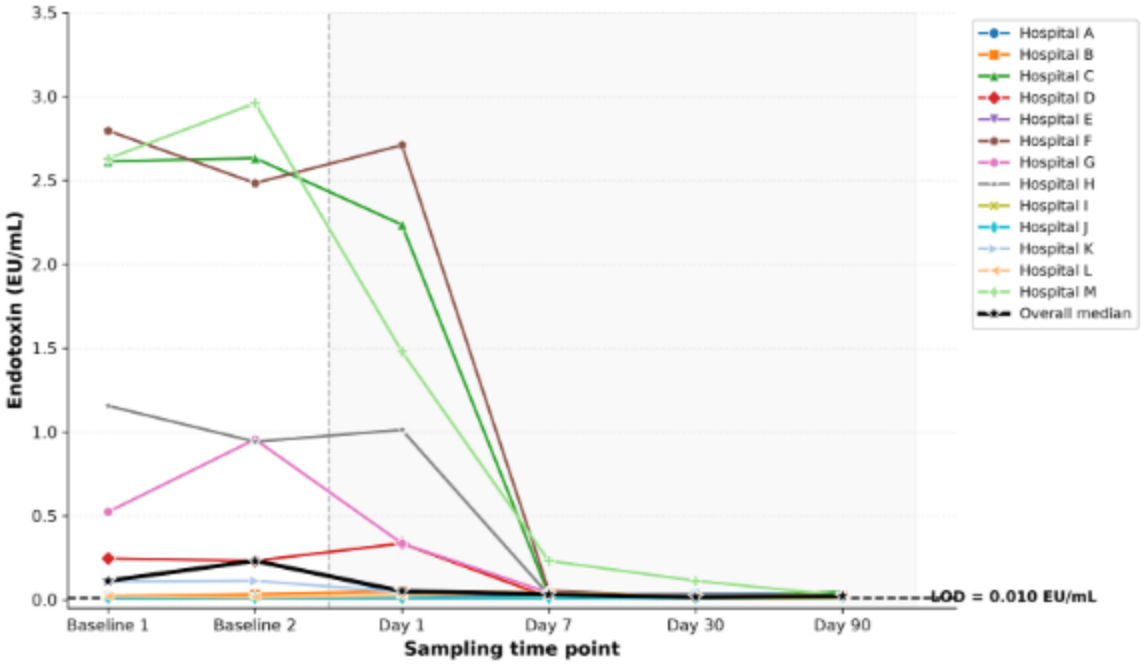


Figure 4

Hospital-level median endotoxin trends across the six sampling rounds.