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ORIGINAL RESEARCH

Root Cause Analysis for Outbreaks of Carbapenem-Resistant *Acinetobacter baumannii* and *Pseudomonas aeruginosa* in a Pediatric Intensive Care Unit: A Retrospective Study

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Objective: Children in the pediatric intensive care unit (PICU) are inherently susceptible to multidrug-resistant (MDR) bacterial infections due to physiological vulnerabilities and clinical management-related factors. Such infections are prone to outbreaks and confer substantial harm. This study aims to investigate the etiologies of carbapenem-resistant *Acinetobacter baumannii* (CRAB) and carbapenem-resistant Pseudomonas aeruginosa (CRPA) infection outbreaks in the PICU and develop targeted prevention and control strategies using the root cause analysis (RCA) approach.

Methods: A retrospective analysis was conducted on five cases (n=5) of MDR infection clusters admitted to the PICU of a large comprehensive hospital from January to February 2024. RCA was applied to identify underlying causes, develop targeted interventions, and evaluate their effectiveness.

Results: From 31 January to 18 February 2024, four CRAB strains and three CRPA strains were detected among five patients (n = 5). Environmental sampling (145 specimens) revealed CRAB in four sites (crane tower, handwashing basin wall, healthcare workers' hands, and PDA devices) and CRPA in two sites (fiberoptic bronchoscopes and healthcare workers' hands). Post-intervention, no further MDR clusters were observed in 2024, indicating effective control.

Conclusion: RCA facilitates systematic identification of root causes for MDR outbreaks, enabling targeted interventions to curb transmission and strengthen infection control practices.

Keywords: root cause analysis, pediatric intensive care unit, multidrug-resistant bacteria, carbapenem-resistant *Acinetobacter baumannii*, carbapenem-resistant *Pseudomonas aeruginosa*, outbreak

Introduction

Children admitted to the Pediatric Intensive Care Unit (PICU) are particularly vulnerable to multidrug-resistant (MDR) bacterial infections due to severe underlying conditions, immature immune systems, frequent invasive procedures, and extensive antibiotic exposure.[1,2] Among these pathogens, carbapenem-resistant *Acinetobacter baumannii* (CRAB) and carbapenem-resistant Pseudomonas aeruginosa (CRPA) represent the most clinically significant MDR Gram-negative organisms within PICU. These pathogens are associated with life-threatening conditions including lower respiratory tract infections, bloodstream infections, and disseminated disease. Their extensive resistance profiles drastically limit therapeutic options for critically ill pediatric patients, consequently elevating mortality risks and escalating healthcare expenditures.[3,4] CRAB demonstrates exceptional environmental persistence, whereas CRPA transmission frequently correlates with contaminated medical equipment and aqueous reservoirs. Both organisms disseminate efficiently via healthcare workers' hands, fomites, and environmental surfaces, often precipitating nosocomial clusters and outbreaks that impose substantial clinical burdens and operational challenges on healthcare systems.[5]

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Root Cause Analysis (RCA) is a structured, retrospective approach to investigating adverse events, aiming to identify fundamental causes and implement preventive measures. This method focuses on exploring fundamental and systemic causes rather than simply attributing problems to individuals. By revealing potential management loopholes and process deficiencies, it helps formulate targeted and sustainable interventions to prevent the recurrence of similar incidents.[6] Accordingly, RCA has been increasingly applied in the investigation and control of nosocomial infection outbreaks in recent years. It can assist medical institutions in identifying key transmission links, optimizing infection prevention and control protocols, and effectively blocking pathogen transmission.[7,8] However, studies that apply a complete RCA framework specifically to the investigation and control of concurrent outbreaks of CRAB and CRPA in PICU remain relatively limited.

This study used RCA to explore the causes of CRAB and CRPA infection outbreaks in the PICU. Targeted interventions were implemented to block pathogen transmission and prevent recurrence. We aimed to provide practical references for the investigation and control of MDR outbreaks in clinical practice.

Methods

Study Population

The study was conducted in the PICU of a large comprehensive hospital in Wuhan, China. Five clustered cases of MDR infections occurring between 31 January and 18 February 2024, were included. The study was approved by the Ethics Committee of Tongji Hospital (TJ-IRB202410013). Given the retrospective nature of the study, the requirement for written informed consent was waived by the Ethics Committee. Strict confidentiality was maintained for all patient data, and all personal identifiers were protected to ensure privacy. The verbal informed consent procedure obtained from the legal guardians of pediatric patients was also reviewed and approved by the Ethics Committee. All research procedures were conducted in accordance with the Declaration of Helsinki.

Epidemiological Investigation

A retrospective analysis was performed, with data retrieved from the Xinglin Hospital Infection Real-time Monitoring System, Hospital Information System (HIS), and Laboratory Information Management System (LIS), and supplemented by on-site verification. The collected data encompassed four core dimensions: demographic characteristics (age and sex) of participants; clinical profiles including admission diagnoses, invasive procedures performed, and antimicrobial administration details; microbiological findings covering specimen types, pathogen identification results, and antimicrobial susceptibility test outcomes; and clinical outcomes (treatment efficacy and prognosis).

Environmental Sampling and Microbiological Testing

The hospital infection control department conducted environmental hygiene monitoring of the PICU. The high-touch surfaces (bed rails, monitors, infusion pumps, handwashing basins), healthcare workers' hands, medical equipment (fiberoptic bronchoscopes, ventilator components), air and water sources, etc., are sampled with reference to the corresponding norms, and then inoculated on ordinary nutrient agar dishes to detect the number of bacterial colonies. For detection of MDR, samples were inoculated onto CHROMagar selective media for CRAB and carbapenem-resistant *Klebsiella pneumoniae* (CRKP). Since *Pseudomonas aeruginosa* can grow on this selective medium and a dedicated selective medium for CRPA was not available in our laboratory, we used the above CRAB/CRKP medium for CRPA screening to ensure comprehensive detection of the three major carbapenem-resistant Gram-negative pathogens. All samples were inoculated within 4 hours after sampling and incubated at 36±1°C for 48 hours. Target colonies were screened according to colony morphology, and culture-positive specimens were identified using the VITEK 2-Compact fully automatic microbiological identifier (bioMérieux, France). Antimicrobial susceptibility testing was performed using the Kirby–Bauer disk diffusion method, with results interpreted according to CLSI 2014 guidelines.[9]

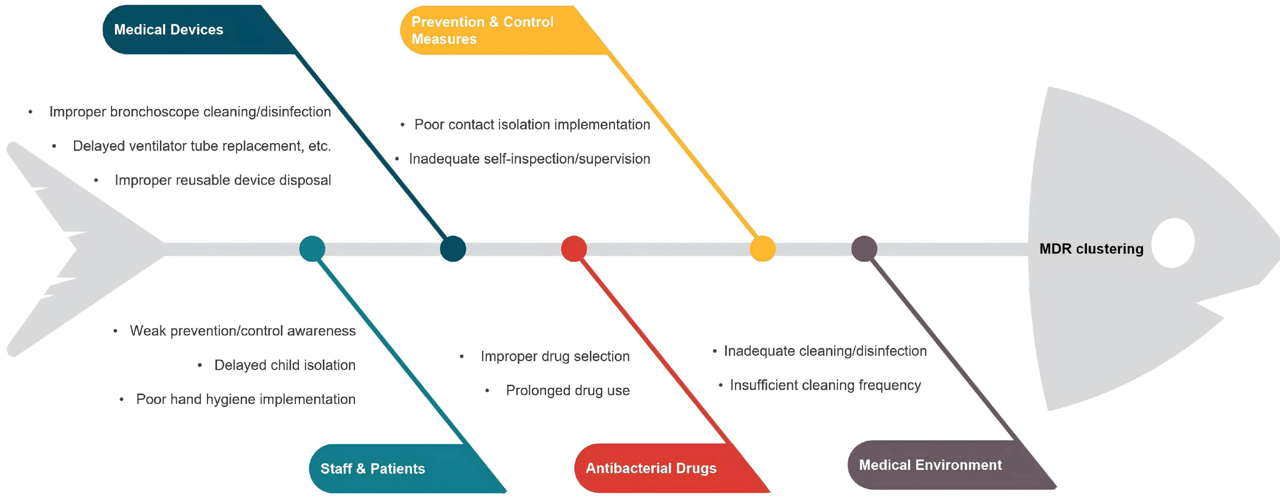

Figure 1 Fishbone diagram of root cause analysis (RCA) for CRAB and CRPA clustered infection outbreaks in the PICU. Root causes were systematically analyzed in accordance with the standard framework (Staff & Patients, Medical Devices, Antibacterial Drugs, Prevention & Control Measures, Medical Environment), so as to identify root causes of MDR bacterial clustering transmission.

Root Cause Analysis

The RCA team was a multidisciplinary group consisting of infectious disease physicians, microbiologists, infection control specialists, ward medical staff, medical and nursing department managers, and logistics staff. All members received standardized RCA training. The RCA team constructed a timeline and investigated from the dimensions of "person–machine–material–method–environment". Discrepancies with MDR prevention and control protocols were defined as direct causes. Direct causes were analyzed stepwise to determine root causes, presented in a fishbone diagram (Figure 1). The 5W1H framework (What, Why, Who, When, Where, How) was used to structure the RCA and intervention design.

Statistical Analysis

Categorical variables are presented as frequencies and percentages. This study mainly adopted descriptive statistics. The limited number of outbreak cases restricted statistical power, which is common and understandable in investigations of single infectious disease outbreaks. This limitation is clearly stated in the Discussion section.

Results

Outbreak Identification

Between January 31 and February 18, 2024, five patients tested positive for MDR bacteria: four with CRAB and three with CRPA (one patient had concurrent CRAB and CRPA), and the antimicrobial susceptibility profiles of the same type of bacteria detected in different patients are completely consistent. All cases were classified as Hospital Acquired Infections (HAI) except one suspected colonization, which was classified as a Class II medical safety adverse event, defined as an event that has caused actual harm or potential risk to patients and requires intervention to prevent adverse outcomes. Clinical details are summarized in Table 1.

Epidemiological Investigation

Population Distribution

Among the five patients with detected MDR, 2 are boys and 3 are girls, with a mean age of 1.28 years. All five patients had been hospitalized in the PICU for over 10 days prior to MDR detection; 4 had undergone fiberoptic bronchoscopy, and 3 had received carbapenem antibiotics before detection. All patients were discharged after treatment.

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Table 1 Clinical Characteristics of 5 Patients with MDR Infections in PICU

No.	Bed No.	Age	Gender	Specimen Type	MDR Type	Detection Date	ICU Admission Days Before Detection	Intubation	Ventilator Use (Days)	Fiberoptic Use	Carbapenem Exposure	Diagnosis	Outcome
1	17	4y	Female	Sputum	CRAB	Jan 31	23	Yes	21	No	Yes	HAI	Improved
1	13	4y	Female	Bronchial Lavage	CRPA	Feb 18	41	Yes	39	Yes	Yes	HAI	Improved
2	12	3m	Male	Bronchial Lavage	CRPA	Feb 04	14	Yes	10	Yes	No	HAI	Improved
3	11	1m	Male	Sputum	CRAB	Feb 08	10	Yes	8	No	No	HAI	Improved
4	7	2y	Female	Bronchial Lavage	CRAB/ CRPA	Feb 17	11	Yes	11	Yes	Yes	HAI	Improved
5	17	1m	Female	Bronchial Lavage	CRAB	Feb 18	17	Yes	16	Yes	Yes	Colonization	Improved

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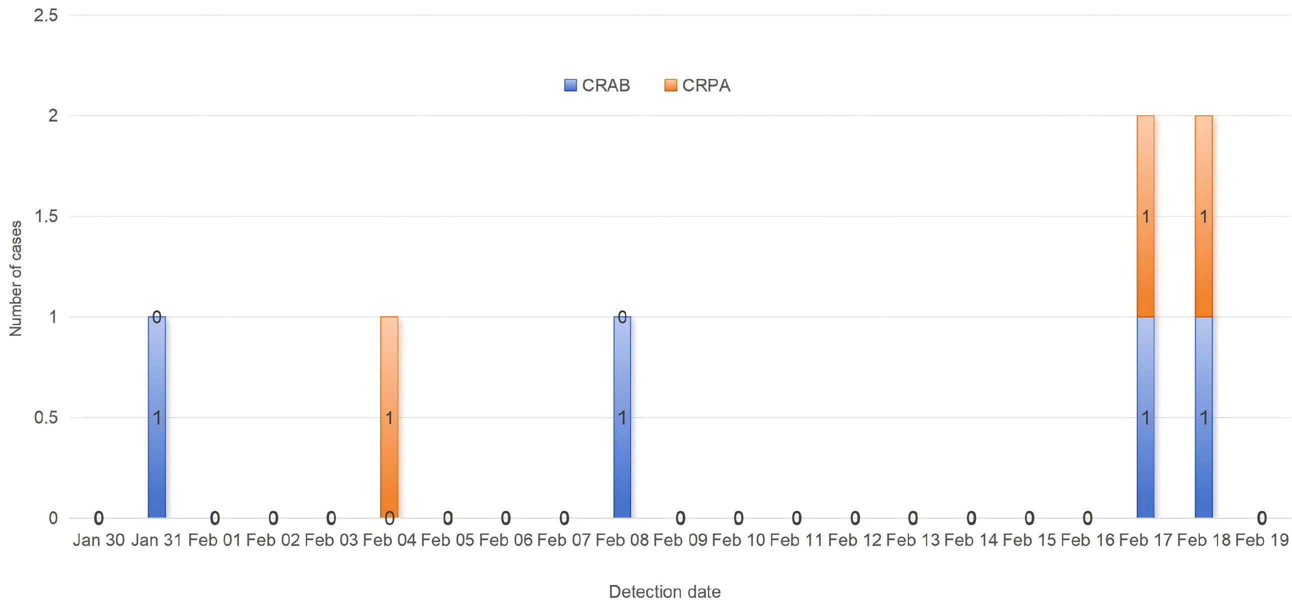

Figure 2 Temporal distribution of CRAB and CRPA detection cases during the outbreak investigation period (January 31 to February 18, 2024). Blue bars represent CRAB positive cases, Orange bars represent CRPA positive cases. The vertical axis indicates the number of daily detected cases.

Temporal Distribution

The first CRAB case was detected on January 31, 2024, followed by CRPA on February 4, 2024, with sporadic cases until February 17, 2024 (Figure 2).

Spatial Distribution

CRAB cases were dispersed, while CRPA cases clustered in adjacent beds (Figure 3).

Device Association

Four patients underwent fiberoptic bronchoscopy. Shared bronchoscopes showed CRPA in rinsing fluid, with matching antimicrobial profiles.

Environmental Hygiene Testing

Environmental hygiene sampling was carried out on February 21,2024, and of 145 environmental samples, 4 (2.76%) tested positive for CRAB and 2 (1.38%) for CRPA (Table 2). Contaminated sites included: CRAB: Crane tower (20.0%), Personal Digital Assistant (PDA, 20.0%), handwashing basin wall (12.5%), healthcare workers' hands (10.0%); CRPA: Fiberoptic bronchoscopes (25.0%), healthcare workers' hands (10.0%).

Interventions and Outcomes

Based on RCA findings, targeted interventions were formulated by the 5W1H principle, as summarized below:

Enhanced Isolation

Cluster patients in dedicated isolation wards, and the bedside isolation measures are strictly implemented; MDR-infected patients are strictly under the care of specialists; restrict visitor access, and the medical staff entering and exiting the ward are strictly implementing the contact and isolation measures.

Hand Hygiene and Training

Mandatory education on MDR transmission for medical staff; real-time supervision of hand hygiene compliance.

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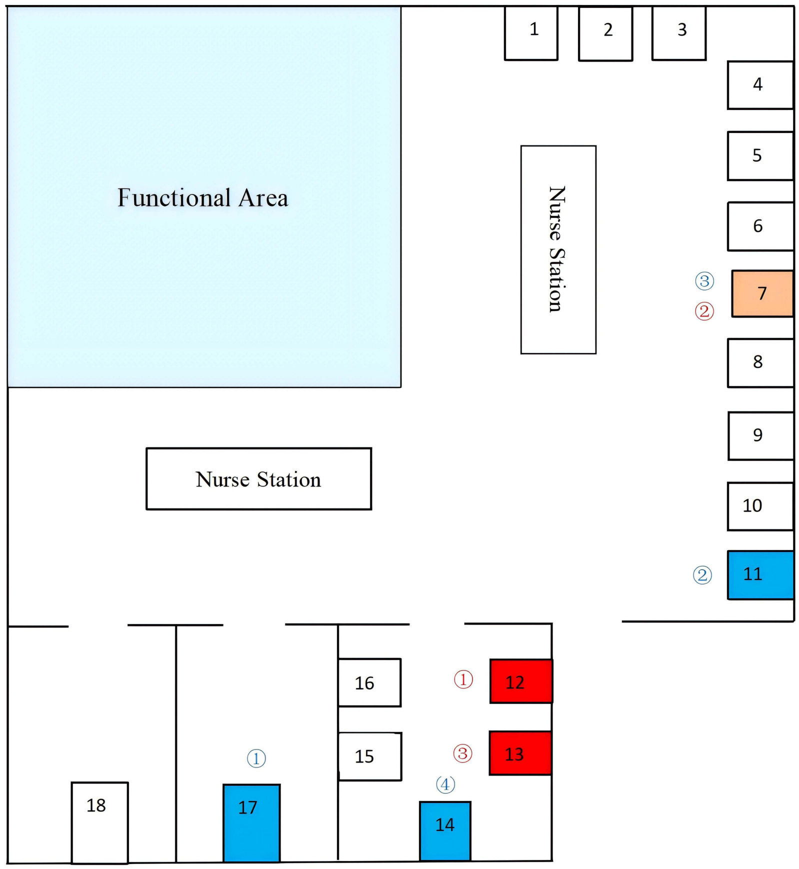

Figure 3 Blue marking for patients with CRAB detection, red marking for patients with CRPA detection; Orange marking for double detection; of which, bed 17 and bed 13 are the same patient was detected at different time points: after CRAB became negative, it was transferred to bed 13 and then CRPA was detected; blue ①~④ is the order of CRAB detection, and red ①~③ is the order of CRPA detection.

Environmental Disinfection

Quaternary ammonium wipes for high-touch surfaces and strictly "one wipe per surface"; cleaning staff using 500 mg/L chlorine for patient zones; 1,000 mg/L chlorine for handwashing basins; and the air-conditioning vents are cleaned and disinfected by the property staff.

Table 2 Environmental Surveillance Results in the PICU

Sampling Site	Sample Condition	No. of Samples	CRAB Positive	CRAB Rate (%)	CRPA Positive	CRPA Rate (%)
Crane tower	In use	5	1	20.00	0	0.00
Bedrail	In use	5	0	0.00	0	0.00
Infusion pump	In use	5	0	0.00	0	0.00
Ventilator panel	In use	5	0	0.00	0	0.00
Monitor panel	In use	5	0	0.00	0	0.00
Treatment vehicle	In use	5	0	0.00	0	0.00
PDA	In use	5	1	20.00	0	0.00
Floor around the bed	In use	5	0	0.00	0	0.00
Serving platter	In use	5	0	0.00	0	0.00
Stethoscope	In use	5	0	0.00	0	0.00
Bedside cupboard	In use	5	0	0.00	0	0.00
Computer keyboard	In use	5	0	0.00	0	0.00

(*Continued*)

Table 2 (Continued).

Sampling Site	Sample Condition	No. of Samples	CRAB Positive	CRAB Rate (%)	CRPA Positive	CRPA Rate (%)
Handwashing basin wall	In use	8	1	12.50	0	0.00
Nurse's platform surface	In use	2	0	0.00	0	0.00
Shared instruments and equipment	In use	6	0	0.00	0	0.00
Decontamination tank	In use	2	0	0.00	0	0.00
Bronchoscopic storage cabinet	In use	1	0	0.00	0	0.00
Healthcare workers' hands	Working	10	1	10.00	1	10.00
Ventilator tubing	Before opening	12	0	0.00	0	0.00
Ventilator parts	Before opening	12	0	0.00	0	0.00
Air	Before disinfection	24	0	0.00	0	0.00
Fiberoptic bronchoscopes	After disinfection	4	0	0.00	1	25.00
Pure water in the bronchoscopy room	In use	4	0	0.00	0	0.00
Total	–	145	4	2.76	2	1.38

Equipment Management

Strictly implement the process of cleaning and disinfection of fibrilloscopes, and then send four fibrilloscopes to the Disinfection and Supply Center for sterilisation and treatment before fixing one fibrilloscope for the exclusive use of MDR patients, and replace the disinfectant from glutaraldehyde to o-phthalaldehyde (OPA). Contact the ventilator manufacturer to clean and sterilise the relevant intraventilator tubes of positively detected patients.

Antimicrobial Stewardship

Pharmacy-led prescription reviews were performed, and an approval mechanism for special-grade and restricted antibiotics was adopted to standardize and appropriately restrict carbapenem use in the PICU.

After the implementation of the above measures, the implementation status and effectiveness of each measure were continuously tracked. From February 21 to March 6, there were no new patients with multidrug-resistant (MDR) bacterial infections in the PICU, and the outbreak was terminated. By December 31, 2024, no MDR clustering events had occurred in the PICU, confirming that the intervention and control measures were effective.

Discussion

Our key findings confirm RCA's value in managing PICU MDR outbreaks. A cluster of 5 CRAB/CRPA HAI/colonization cases (Jan 31–Feb 18, 2024) involved transmission via healthcare workers' hands, poorly reprocessed bronchoscopes, and high-touch surfaces. Targeted interventions rapidly halted the outbreak with no 2024 recurrence, highlighting RCA's role in addressing infection control gaps.

Consistent with previous studies,[10,11] reinforcing standard infection prevention and control measures (eg., hand hygiene, contact isolation, environmental cleaning and disinfection) proved critical for controlling MDR spread in the PICU. Healthcare workers' hands are well-documented as a major vector for cross-transmission of MDR bacteria in ICUs,[12] and improved hand hygiene compliance significantly reduces transmission risk via contaminated hands. Environmental surfaces in ICUs are another important medium for transient and cross-transmission of MDR bacteria, as their physicochemical properties allow pathogens such as CRAB to survive for days to months.[10] Intensive cleaning and disinfection of these surfaces effectively reduces environmental pathogen load, thereby decreasing MDR colonization and spread.[13] Early single-room or centralized isolation of MDR patients with dedicated nursing care further interrupts transmission chains,[14,15] and these standardized preventive measures are both effective and cost-effective for MDR control.[16] Their effectiveness in our PICU may be attributed to the relatively low baseline MDR prevalence.[17]

Fiberoptic bronchoscopy is widely used clinically for treating lung infections, as it facilitates the timely removal of infectious agents, improves lung ventilation, and reduces inflammation.[18,19] However, our study identified fiberoptic bronchoscopes as a critical transmission vector, with CRPA detected in disinfected devices—consistent with reports of inadequate reprocessing enabling cross-infection.[20,21] Switching to OPA (a more effective disinfectant for endoscopes) and designating dedicated bronchoscopes for MDR patients eliminated this risk, highlighting the need for rigorous reprocessing protocols and dedicated equipment for high-risk patients.

CRAB was also detected on the walls of bedside handwashing basins, suggesting that contaminated handwashing facilities may serve as MDR transmission vectors. Consistent with relevant studies and guidelines,[22,23] this finding supports the need to strengthen disinfection of handwashing sinks or remove unnecessary sinks in critical care settings. Additionally, irrational antimicrobial use is a well-established root cause of MDR infections. Several studies have shown that CRPA is highly likely to be induced by carbapenem use (eg., meropenem) in PICU patients, and the benefits of meropenem administration may not outweigh the risk of inducing CRPA.[24,25] Clinicians should therefore exercise caution when prescribing carbapenems in the PICU.

Determining the cause of an outbreak is one of the most difficult aspects of the investigation and disposition of previous hospital infection outbreaks, and often the source cannot be identified even until the outbreak is over. Conventional epidemiological investigations are often limited by the level of the investigator and are unable to comprehensively and accurately reveal the cause of the outbreak, and some studies have shown that less than half of the outbreaks have found the source of the outbreak.[26] Through the application of root cause analysis, the root cause of adverse events such as similar nosocomial outbreaks can be identified in a timely and comprehensive manner with the help of a multidisciplinary team and scientific methods, so that the proliferation of outbreaks can be controlled as soon as possible, and the risk of the reoccurrence of such events can be effectively reduced,[27,28] which is crucial for the investigation and disposal of outbreaks.

Despite its contributions, this study has several limitations. First, it employed a single-center design, which may limit the generalizability of findings to other PICU with different patient populations, resource availability, or infection control practices. Second, whole-genome sequencing (WGS) was not performed to confirm the genetic relatedness of clinical and environmental isolates, which would have strengthened causal links between environmental contamination and patient infections.[29] Third, no quantitative data on healthcare worker compliance with infection control measures (eg., hand hygiene adherence rates pre- and post-intervention) were collected, making it difficult to directly link changes in compliance to outbreak control. Fourth, only one round of environmental sampling was conducted on February 21, 2024, which may not reflect the dynamic changes in environmental contamination during the entire outbreak. Fifth, this study mainly used descriptive statistics, and the limited number of cases (n=5) restricted statistical power. Although these constraints are common and understandable in outbreak investigations, they should be noted as limitations.

Conclusion

RCA facilitates systematic identification of root causes for CRAB and CRPA outbreaks in the PICU, enabling targeted interventions to curb transmission and strengthen infection control practices. Although this study is limited by its single-center design and small sample size, the RCA approach shows broad applicability and practical value in the investigation and control of MDR bacterial outbreaks, and can provide a useful reference for infection control management in similar pediatric intensive care settings.

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Disclosure

The authors report no conflicts of interest in this work.

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