

ORIGINAL RESEARCH ARTICLE

Investigation of a carbapenem-resistant *Acinetobacter baumannii* outbreak in the surgical unit of a cardiac care center in Karachi, Pakistan

Moiz Ahmed Khan^{1,2*}, Ahson Memon³, Khudabaksh Shaikh³, Victor Basheer², Margaret Palous², Abeer Salim Habib⁴, Wajid Ali Khan¹, Nassim Sheraz², Arsalan Ilyas³, and Sohail Abrar Khan⁵

¹Department of Clinical Laboratory, Tabba Heart Institute, Karachi, Pakistan

²Department of Infection Control, Tabba Heart Institute, Karachi, Pakistan

³Department of Cardiothoracic Surgery, Tabba Heart Institute, Karachi, Pakistan

⁴Department of Patient Safety and Quality Assurance, Tabba Heart Institute, Karachi, Pakistan

⁵Department of Cardiology, Tabba Heart Institute, Karachi, Pakistan

Abstract

Carbapenem-resistant *Acinetobacter baumannii* (CRAB) poses a significant threat in cardiac surgical units due to its ability to survive on surfaces, intrinsic multidrug resistance, and association with high morbidity and mortality. Between June 15 and June 30, 2025, a tertiary cardiac care center in Karachi, Pakistan, identified an unusual cluster of CRAB infections among post-operative cardiac surgery patients, prompting a systematic outbreak investigation. A multidisciplinary outbreak response team conducted an investigation on July 1 and July 2, 2025. Cases were defined as patients developing laboratory-confirmed CRAB infections with onset ≥ 48 h after hospital admission and within 30 days of cardiac surgery. Active case finding included medical record review and surveillance cultures. Direct observations assessed hand hygiene compliance, personal protective equipment (PPE) use, and environmental cleaning using standardized checklists. Environmental surveillance cultures were obtained from high-touch surfaces in operating rooms (ORs) and intensive care units. Fingerprint cultures from 10 healthcare workers (five from each setting) were screened for CRAB colonization. Seven patients developed CRAB infections: four ventilator-associated pneumonias (VAPs), two central line-associated bloodstream infections (CLABSIs), and one surgical site infection. The median age was 67 years (range 58–74), and the male-to-female ratio was 6:1. Four patients (57.1%) died, of whom two had VAP and two had CLABSI. All isolates demonstrated identical resistance profiles, including resistance to carbapenems, β -lactams, fluoroquinolones, aminoglycosides, and trimethoprim-sulfamethoxazole, with susceptibility to tigecycline and minocycline. Environmental cultures were negative. Fingerprint cultures identified CRAB colonization on one OR technician's hands, with a susceptibility profile matching patient isolates. Observational audits revealed suboptimal hand hygiene, inadequate environmental cleaning between procedures, and inadequate compliance with PPE protocols. Our investigation revealed healthcare worker hand colonization and lapses in infection control practices as the primary drivers of CRAB transmission and underscored the critical need for sustained, resource-appropriate infection control interventions and continuous vigilance to prevent multidrug-resistant organism outbreaks in similar healthcare environments.

*Corresponding author:

Moiz Ahmed Khan
(moiz.khan@tabbaheart.org)

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1. Introduction

Carbapenem-resistant *Acinetobacter baumannii* (CRAB) has emerged as a critical healthcare-associated pathogen, designated by the World Health Organization (WHO) as a priority pathogen requiring urgent research and development of new antimicrobials.¹ CRAB infections are associated with high mortality rates, prolonged hospital stays, and substantial healthcare costs, with mortality rates ranging from 40% to 70% in critically ill patients.^{2,3} The organism's ability to survive on environmental surfaces for extended periods, coupled with its intrinsic resistance to several antimicrobials, makes CRAB particularly challenging to control in healthcare settings.^{4,5}

Healthcare-associated outbreaks of CRAB have been increasingly reported worldwide, particularly in intensive care units (ICUs) and surgical settings.⁶ The global emergence of CRAB during the COVID-19 pandemic has further complicated infection control efforts, with several studies reporting increased rates of CRAB infections in hospitals managing COVID-19 patients.⁵ These outbreaks highlight critical gaps in infection prevention and control practices that require systematic investigation and intervention.

Healthcare workers serve as critical vectors for CRAB transmission within healthcare facilities, with their hands representing the most direct route of pathogen transmission to vulnerable patients. Cross-transmission via the hands of healthcare workers, which have become contaminated either directly from patient contact or indirectly by touching contaminated environmental surfaces, has been implicated in 20–40% of healthcare-associated infections globally.⁷ This colonization is particularly concerning in high-acuity cardiac surgery units where staff members engage in frequent patient contact, perform multiple invasive procedures, and transition between numerous patients throughout their shift. The identification of colonized healthcare workers as outbreak sources has been documented in several CRAB outbreaks, yet targeted surveillance of healthcare worker hand colonization remains inconsistently implemented across many institutions, particularly in resource-limited settings. Furthermore, the transient nature of hand colonization means that a single episode of contamination can lead to multiple secondary transmissions if effective hand hygiene is not rigorously maintained between patient contacts.

Cardiac surgery patients represent a particularly vulnerable population due to multiple risk factors, including invasive procedures, prolonged hospitalization, use of mechanical ventilation, and presence of indwelling devices.⁸ The complex nature of cardiac surgical procedures

often requires extended operative times, multiple healthcare worker interactions, and intensive post-operative care, all of which can contribute to increased transmission risk if proper infection control measures are not maintained. Existing comorbidities, such as poorly controlled diabetes mellitus, may be associated with prolonged hospital stay after cardiac surgical procedures.

The environmental persistence of CRAB and its capacity for widespread surface contamination present unique challenges in high-touch, high-traffic areas, such as cardiac operating rooms (ORs). Environmental contamination with CRAB is highly variable across outbreak scenarios and is influenced by multiple factors, including the intensity of patient shedding, adherence to environmental cleaning protocols, and the specific characteristics of hospital surfaces. In prospective environmental surveillance studies, approximately 48% of patient rooms housing individuals colonized or infected with CRAB demonstrated environmental contamination at one or more sites, with high-touch surfaces most commonly affected.⁹ Supply cart drawer handles, infusion pumps, ventilator touch pads, and bed rails represent particular reservoirs of environmental CRAB, as multiple healthcare workers frequently come into contact with these surfaces during routine patient care activities. The OR environment in cardiac surgery units presents additional complexity due to the extended duration of procedures, the spatial constraints of the operating suite, and the circulation of multiple surgical personnel. The presence of visible contamination, such as blood splashes on environmental surfaces, equipment trolleys, and floor areas, indicates that routine environmental cleaning protocols may be inadequate to prevent pathogen persistence, particularly when cleaning procedures do not employ sufficient contact times for disinfectant application or when high-touch surfaces are overlooked during terminal cleaning procedures.

Systematic outbreak investigation is essential for identifying sources of transmission, understanding contributing factors, and implementing targeted control measures. The traditional approach to outbreak investigation involves epidemiological analysis, environmental assessment, and microbiological investigation, followed by implementation of control measures tailored to the specific outbreak circumstances.¹⁰ Recent advances in molecular epidemiology, including whole-genome sequencing, have enhanced our ability to understand transmission patterns and guide infection control interventions.¹¹

While outbreak investigations of CRAB have been conducted in various healthcare settings, the

epidemiological and infection control response literature predominantly focuses on general ICU environments and multidisciplinary surgical centers. The specific vulnerabilities and transmission dynamics of CRAB outbreaks in specialized cardiac surgery units, where the confluence of prolonged operative times, extensive healthcare worker–patient interactions, multiple invasive devices, and intensive post-operative care requirements creates a unique epidemiological landscape, remains underexplored. Furthermore, documented outbreak investigations in resource-limited healthcare settings, particularly in South Asia, are limited. The knowledge gap addressed by this investigation concerns the systematic characterization of outbreak source identification and transmission pathways specific to cardiac surgical populations, with particular emphasis on the role of healthcare worker-mediated transmission and the efficacy of targeted infection control interventions in this high-risk, resource-constrained environment. This investigation fills this gap by providing detailed epidemiological and microbiological findings that elucidate transmission mechanisms specific to cardiac surgery units and demonstrate a systematic outbreak response framework applicable to similar healthcare settings.

The objective of this study is to investigate a CRAB outbreak that occurred in the cardiac surgery unit of a cardiac tertiary care hospital, identify the source and contributing factors, and evaluate the effectiveness of the implemented control measures. This investigation provides valuable insights into infection control challenges in high-risk surgical environments and demonstrates the importance of comprehensive outbreak response.

2. Methods

2.1. Study setting and background

This outbreak investigation was conducted at a 150-bed specialized cardiac tertiary care center in Karachi, Pakistan. The hospital operates three cardiac ORs and two ICUs with a total capacity of 24 ICU beds. The facility performs approximately 1,200 cardiac surgical procedures annually, primarily coronary artery bypass grafting, valve replacements, and congenital heart surgeries.

The hospital's Infection Control Department identified an unusual cluster of CRAB infections in patients who had undergone cardiac surgery between June 15 and June 30, 2025. A case was defined as any patient who developed a healthcare-associated infection caused by CRAB, confirmed by microbiological culture, with onset ≥ 48 h after hospital admission and within 30 days of cardiac surgery. Cases were classified as ventilator-associated pneumonia (VAP), central line-associated bloodstream infection (CLABSI),

or surgical site infection (SSI) according to standard definitions in the National Healthcare Safety Network guidelines.^{12–14}

An outbreak investigation team comprising infection control practitioners, clinical microbiologists, cardiac surgeons, anesthesiologists, and nursing supervisors was assembled. The investigation was conducted from July 1 to July 2, 2025, with immediate implementation of enhanced infection control measures. Follow-up surveillance continued for 90 days after the outbreak to confirm sustained control.

Active case finding was chosen as the primary surveillance strategy, as routine passive surveillance systems in resource-limited healthcare settings often underestimate outbreak magnitude and may result in delayed outbreak recognition.¹⁵ Given the high-acuity nature of post-operative cardiac patients and the potential for rapid clinical deterioration, a comprehensive review of medical records was supplemented with targeted questioning of clinical staff regarding any unusual patterns of infection or clinical deterioration in recently operated patients. The case finding process included a systematic examination of microbiology laboratory records for all bacterial isolates recovered from cardiac surgery patients during the outbreak period, with particular attention to Gram-negative organisms that demonstrated resistance to antimicrobial agents. This dual approach of laboratory-directed surveillance combined with medical record review permitted the identification of both clinically evident infections and episodes of colonization without clinical manifestations, thereby providing a more complete understanding of outbreak magnitude and transmission patterns. For confirmed cases, detailed clinical information was extracted, including comorbid medical conditions, type and duration of mechanical ventilation, management of invasive devices, and temporal relationship to surgical procedures, to enable a more detailed epidemiological characterization that would not be possible through passive surveillance mechanisms alone. Furthermore, an epidemic curve was constructed to visualize the temporal distribution of cases.

2.2. Outbreak investigation

Comprehensive environmental sampling was conducted throughout the ORs and ICU areas. Surface swab cultures were obtained from high-touch surfaces, including bed rails, monitors, infusion pumps, ventilator controls, door handles, and medical equipment. Environmental samples were collected using sterile swabs moistened with sterile saline and inoculated on MacConkey agar and 5% sheep blood agar plates. Plates were incubated at 37°C for 24–48 h

before examination.

Microbial surveillance of healthcare workers was performed through fingerprint cultures. A representative sample of 10 healthcare workers (five from the ORs and five from the ICUs) was screened. Fingerprint cultures were obtained by pressing the fingers of both hands onto blood agar plates for five seconds. Plates were incubated at 37°C for 24–48 h, and suspicious colonies were further characterized using standard microbiological methods.

All clinical specimens were processed for bacterial culture according to standard protocols. Bacterial identification was performed using conventional biochemical methods and confirmed using API® ID strips and APIWEB™ database (bioMérieux, France). Antimicrobial susceptibility testing was conducted using the Kirby–Bauer disk diffusion method according to Clinical and Laboratory Standards Institute M100 guidelines.¹⁶

Structured observations of infection control practices were conducted using standardized checklists. Observations included hand hygiene compliance, personal protective equipment (PPE) use, environmental cleaning procedures, and adherence to aseptic techniques during patient care activities. Observations were conducted by trained infection control nurses during different shifts to capture variations in practice patterns. Data were collected using standardized forms and entered into a secure database. Descriptive statistics were used to characterize cases.

3. Results

3.1. Outbreak description

Seven patients who underwent cardiac surgery between June 15 and June 30, 2025, subsequently developed culture-confirmed CRAB infections (Figure 1). The outbreak included four cases of VAP (57.1%), two cases of CLABSI (28.6%), and one SSI (14.3%). The median age of affected patients was 67 years (range: 58–74 years), with six males

and one female. The median time from surgery to infection onset was 4 days (range: 3–7 days) (Table 1).

Four patients (57.1%) died during hospitalization, including two patients with VAP and two patients with CLABSI. The case fatality rate was 50% (2/4) for VAP cases and 100% (2/2) for CLABSI cases. The patient with SSI recovered following appropriate treatment and was discharged (Table 2).

All seven CRAB isolates demonstrated identical antimicrobial susceptibility patterns. The isolates were resistant to all tested β -lactam antimicrobials, including imipenem, meropenem, ertapenem, doripenem, piperacillin–tazobactam, and ceftazidime. Resistance was also observed to fluoroquinolones (ciprofloxacin and levofloxacin), aminoglycosides (amikacin and gentamicin), and trimethoprim–sulfamethoxazole. Notably, all isolates were susceptible to tigecycline and minocycline. Due to the unavailability of minocycline in the hospital and the local supply chain, all patients were treated with tigecycline monotherapy.

The epidemic curve constructed from the line-list data illustrated a point-source outbreak, with initial onset occurring on day 3 with one case, peaking on day 4 with three cases, and then declining sharply to 1 case/day on days 5–7. The brief, single-peaked distribution of cases over 5 days suggests exposure to a common source occurring shortly before day 3, followed by a rapid decrease in incident cases (Figure 2).

The point-source pattern observed in this outbreak is characteristic of a discrete, time-limited exposure event followed by rapid implementation of effective control measures, rather than a pattern of continuous or propagated transmission. Point-source epidemics typically demonstrate a sharp rise in cases as susceptible individuals are exposed to a common source during a defined time window, followed by an equally sharp decline once the source is removed or exposure is interrupted.¹⁷ The temporal clustering of cases on days 3–4 of the outbreak

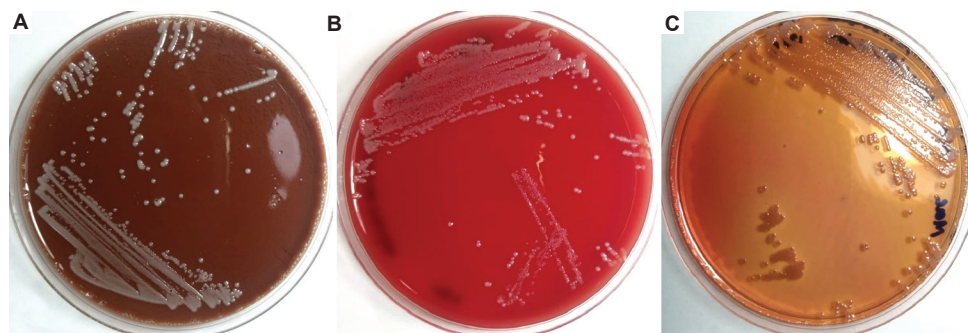


Figure 1. Colony morphology of *Acinetobacter baumannii*. (A) Chocolate agar, (B) 5% sheep blood agar, and (C) MacConkey agar.

Table 1. Outbreak summary statistics

Characteristic	Value
Total cases (n)	7
Ventilator-associated pneumonia	4 (57.1%)
Central line-associated bloodstream infection	2 (28.6%)
Surgical site infection	1 (14.3%)
Overall mortality rate	4/7 (57.1%)
VAP mortality rate	2/4 (50.0%)
CLABSI mortality rate	2/2 (100.0%)
SSI mortality rate	0/1 (0.0%)
Age (years), median (range)	67 (58–74)
Gender distribution (male: female)	6:1
Time from surgery to infection onset (days), median (range)	4 (3–7)

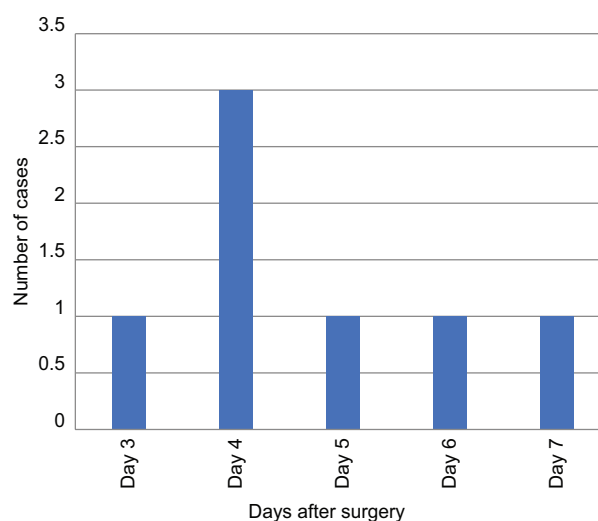
Note: Data presented as n (%), unless stated otherwise.

Table 2. Individual case characteristics and outcomes

Case ID	Infection type	Days from surgery to onset	Outcome
Case 1	VAP	3	Death
Case 2	VAP	4	Death
Case 3	VAP	4	Discharged
Case 4	VAP	5	Discharged
Case 5	CLABSI	4	Death
Case 6	CLABSI	6	Death
Case 7	SSI	7	Discharged

Abbreviations: CLABSI: Central line-associated bloodstream infection; SSI: Surgical site infection; VAP: Ventilator-associated pneumonia.

with a rapid decline thereafter suggests that the primary exposure event occurred on a single occasion or over a very brief period, with symptomatic disease appearing 3–7 days post-exposure as bacterial multiplication within the host reached sufficient levels to trigger clinical manifestations and isolation of organisms on culture. This pattern contrasts markedly with propagated outbreaks involving person-to-person transmission, which typically demonstrate multiple waves of cases, prolonged case distribution over many weeks or months, and a gradual decline in case incidence even without explicit control interventions.¹⁷ The immediate sharp decline in case numbers following outbreak identification and implementation of enhanced infection control measures on July 2, 2025, provides temporal evidence supporting the effectiveness of implemented interventions, suggesting that the brief exposure window during a specific operational period, rather than an ongoing environmental reservoir, was the primary source of CRAB transmission.

**Figure 2.** Epidemic curve of the carbapenem-resistant *Acinetobacter baumannii* outbreak

3.2. Outbreak investigation results

Extensive environmental sampling of OR and ICU areas yielded negative results for CRAB. Surface samples were collected from high-touch surfaces, including patient bed areas, medical equipment, and common areas. All environmental cultures were negative for pathogenic organisms, including CRAB, after 48 h of incubation. This finding suggested that environmental contamination was not the primary source of transmission during the investigation period.

Microbial surveillance through fingerprint cultures of 10 healthcare workers, five each from OR and ICU, revealed CRAB from the fingerprint culture of one OR staff member. This individual was an OR technician who had been working in all three cardiac ORs during the outbreak period. The CRAB isolate from the staff member's fingerprint culture showed an identical antimicrobial susceptibility pattern to the patient isolates, suggesting a common source or transmission pathway. The colonized staff member was temporarily removed from patient care activities.

Direct observation of infection control practices revealed several critical breaches across the OR and ICU areas (Figure 3). Hand hygiene compliance was suboptimal, with healthcare workers frequently failing to perform hand sanitization between patient care tasks and before entering sterile areas. Environmental cleaning protocols were inadequate, with visible blood splashes observed on floors and equipment trolleys, indicating insufficient cleaning between procedures. One of the healthcare workers in the OR was observed wearing jewelry and accessories during

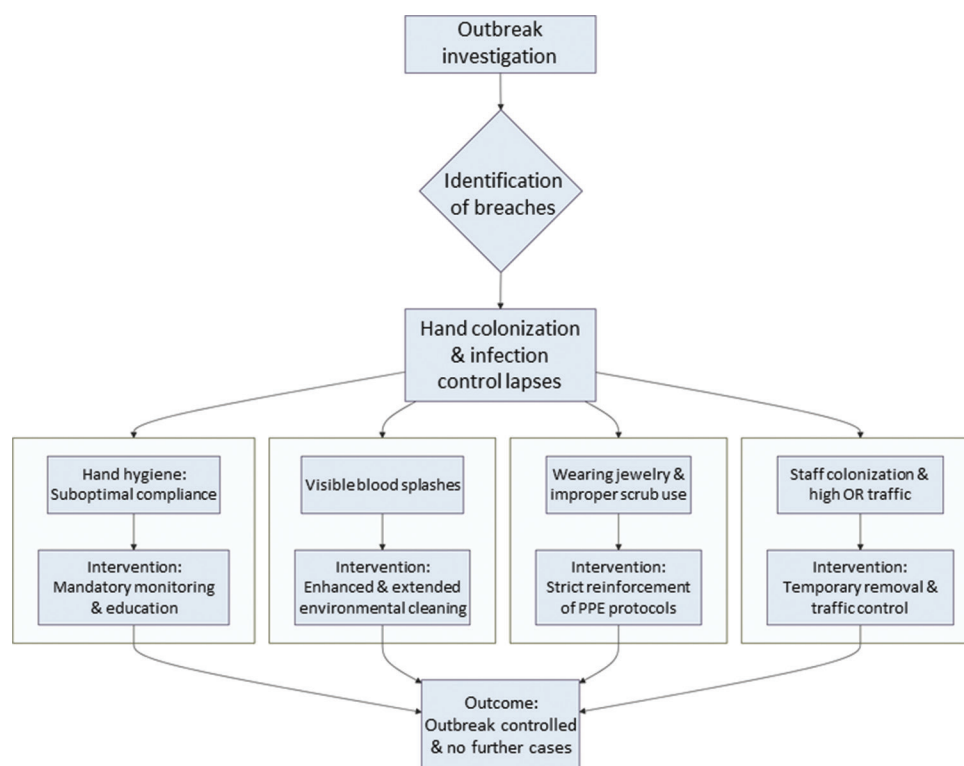


Figure 3. Summary of identified infection control breaches and implemented interventions during the carbapenem-resistant *Acinetobacter baumannii* outbreak

Abbreviations: OR: Operating room; PPE: Personal protective equipment.

procedures, contrary to established surgical protocols. Additionally, staff members were observed leaving the hospital premises while still wearing scrubs, contrary to the facility's uniform-change policy.

3.3. Limitations of molecular characterization

While recent advances in molecular epidemiology, particularly whole-genome sequencing, have enhanced outbreak investigation capabilities, this investigation was conducted with limited molecular typing resources. Molecular characterization through whole-genome sequencing was considered for definitive confirmation of clonal relatedness among the outbreak isolates; however, this analysis was deemed infeasible due to resource constraints, including the unavailability of sequencing infrastructure within our institution and associated financial limitations. Consequently, outbreak investigation relied on conventional antimicrobial susceptibility testing as the primary method for presumptive strain characterization. The identical susceptibility profiles across all seven patient isolates and the matching profile of the staff member's isolate provided presumptive microbiological linkage, although definitive genomic confirmation of clonal identity could not be established.

Despite this limitation, the epidemiological integration of identical antimicrobial susceptibility patterns with the identification of CRAB colonization in a healthcare worker, combined with infection control breaches documented through direct observation, provided sufficient evidence to establish likely transmission pathways and implement effective outbreak control measures.

3.4. Implementation of control measures

Based on the investigation findings, comprehensive infection control measures were immediately implemented (Figure 3). These included mandatory hand hygiene compliance monitoring with improved direct observation protocols, enhanced environmental cleaning between OR procedures with extended contact times, strict reinforcement of dress code policies requiring removal of all jewelry and accessories before entering clinical areas, implementation of OR traffic control measures to minimize unnecessary personnel movement, and comprehensive staff education programs focusing on CRAB transmission and prevention strategies.

The comprehensive staff education programs were implemented across all shifts and targeted all healthcare personnel involved in patient care within the cardiac

surgical units, including resident medical officers, residents, fellows, nursing staff, OR technicians, and housekeeping personnel. The education was delivered through a combination of interactive classroom-style sessions and mandatory, hands-on demonstrations in the unit, based on the formal curriculum of the hospital's Infection Prevention and Biosafety Assessment Initiative. The content was specifically tailored to the outbreak's findings, with a strong focus on the pillars of infection control, including the critical role of hand hygiene—reinforcing the five moments and seven steps of hand hygiene—the correct sequence for donning and doffing PPE, and the principles of environmental cleaning and decontamination. The training also emphasized the care bundle-based approach for VAP and CLABSI prevention and integrated key concepts from antimicrobial stewardship. This educational intervention was strategically designed using the Pareto principle (80/20 rule), focusing the majority of effort on the 20% of practices, such as hand hygiene and PPE use that would yield 80% of the results in mitigating CRAB transmission.

The temporal pattern of case distribution, as demonstrated by the epidemic curve, is consistent with a discrete exposure event rather than continuous or propagated transmission, indicating that control measures implemented immediately after identification of the peak may have effectively curtailed further spread (Figure 2).

Following implementation of enhanced infection control measures, no additional CRAB cases were identified in the 90-day surveillance period. Furthermore, hand hygiene compliance improved from an estimated baseline of 60% to >90% during the post-intervention period.

4. Discussion

This investigation of a CRAB outbreak in a cardiac surgical unit demonstrates the complex interplay of factors that contribute to healthcare-associated transmission of multidrug-resistant organisms. CRAB detected in an OR staff member's hand culture, combined with multiple infection control breaches, highlights the critical importance of adherence to established protocols in high-risk environments.

The finding of CRAB colonization in a healthcare worker's hands, while environmental cultures remained negative, suggests person-to-person transmission as the primary mode of spread during this outbreak.^{4,18} This pattern is consistent with previous reports demonstrating that healthcare workers' hands serve as the principal vehicle for CRAB transmission in healthcare settings.^{5,19} The identical antimicrobial susceptibility patterns observed in all isolates, including the staff isolate, further support this

transmission hypothesis.

The high mortality rate observed in this outbreak (57.1%) reflects the severe clinical impact of CRAB infections in cardiac surgery patients. Patients with VAP and CLABSI had particularly poor outcomes, which aligns with published literature reporting mortality rates of 40–70% for CRAB infections in critically ill patients.^{2,3} The exclusive susceptibility to tigecycline and minocycline observed in our isolates is consistent with global trends showing limited therapeutic options for CRAB infections.^{20,21} The unavailability of minocycline in our setting highlights the challenges of managing CRAB infections in resource-limited environments.

Although all outbreak isolates demonstrated susceptibility to tigecycline during *in vitro* testing, the clinical implications of this finding warrant careful consideration, given emerging evidence of tigecycline resistance development during prolonged therapy and suboptimal pharmacokinetics in certain infection types.^{21,22} Tigecycline resistance mediated by upregulation of the AdeABC efflux pump has been documented in multiple case reports of treatment failures during prolonged tigecycline monotherapy, particularly in patients with VAP or bacteremia. In this outbreak, four patients presented with VAP and two with CLABSI, both infection types where tigecycline pharmacokinetics and clinical efficacy have been questioned in published literature. The monotherapy approach with tigecycline employed in this outbreak, while justified by the unavailability of alternative agents, including minocycline, colistin, and polymyxin B, may have contributed to treatment failures and high mortality in CLABSI patients. Published data from antimicrobial stewardship programs suggest that restricting tigecycline to United States Food and Drug Administration-approved indications (complicated intra-abdominal infections and complicated skin and soft tissue infections) while reserving alternative agents for severe infections associated with mechanical ventilation and bacteremia produces superior clinical outcomes and reduces the selective pressure for resistance development. The global shortage of minocycline in pharmaceutical supply chains, as encountered in this institution, represents a critical resource limitation for managing CRAB infections in resource-constrained healthcare settings and underscores the urgent need for the development of novel antimicrobial agents with improved pharmacokinetics and reduced propensity for resistance development during therapy.

The multiple sequential breaches in infection control practices documented during direct observation audits suggest systemic rather than isolated lapses in protocol adherence. Hand hygiene compliance observed at

estimated baseline levels of 60% indicates that a substantial proportion of patient care activities were occurring without appropriate hand hygiene, creating numerous opportunities for CRAB transmission throughout the healthcare worker's shift. The presence of jewelry and accessories during operative procedures represents a violation of surgical asepsis principles, as such personal items create microbial biofilms and can harbor pathogens for extended periods, effectively creating portable reservoirs of contamination that persist despite routine hand hygiene efforts. Inadequate environmental cleaning between operative procedures, evidenced by the observation of visible blood splashes remaining on floors and equipment trolleys, indicates that mechanical action and contact time for disinfectant agents were insufficient to achieve the target reduction in surface microbial contamination.^{23,24} The convergence of these multiple deficiencies, such as suboptimal hand hygiene, inadequate environmental disinfection, and protocol violations regarding PPE and dress code, created a high-risk scenario where CRAB was easily transmitted from the colonized healthcare worker to successive groups of susceptible patients over a brief exposure window. These findings align with international evidence demonstrating that outbreaks rarely result from a single protocol violation but rather from the confluence of multiple small gaps that collectively exceed the threshold for outbreak propagation.

The negative environmental cultures despite visible contamination suggest that routine environmental sampling may have limited utility during active outbreak investigation. This finding, despite identifying a colonized healthcare worker and observing visible lapses in cleaning, aligns with several published outbreak reports. Some investigations have similarly failed to recover CRAB from the environment despite strong epidemiological evidence of environmental transmission or ongoing transmission from human reservoirs, highlighting the challenges of intermittent contamination and the limitations of one-time environmental sampling.^{11,25} Conversely, this finding contrasts with other well-documented CRAB outbreaks where extensive environmental contamination of high-touch surfaces and equipment was a central feature of sustained transmission.^{4,23} This divergence underscores that the role of the environment can be highly variable across outbreaks. In our context, the evidence suggests that the primary mode of transmission was likely rapid, person-to-person spread via the colonized healthcare worker's hands, with environmental surfaces playing a less critical or more transient role that was not captured by our sampling. This reinforces the recommendation that during an active outbreak, a negative environmental screen should not preclude a simultaneous and rigorous focus on staff surveillance and adherence to hand hygiene.^{19,25}

The successful control of this outbreak through enhanced infection control measures demonstrated the effectiveness of systematic intervention strategies. The implementation of direct hand hygiene monitoring, enhanced cleaning protocols, and staff education resulted in sustained outbreak control.^{4,5} These interventions align with WHO guidelines for preventing and controlling carbapenem-resistant organisms in healthcare facilities.²⁶ Furthermore, the design of the comprehensive staff education program using the Pareto principle (80/20 rule) reflects a rational approach to resource allocation within settings where training time, personnel availability, and educational materials represent limited resources. Application of the Pareto principle to infection control prioritizes the 20% of practices that are responsible for the vast majority (80%) of disease transmission and focuses intensive intervention efforts on these high-yield areas rather than attempting comprehensive redesign of all hospital processes simultaneously. In the context of CRAB outbreak prevention, hand hygiene and appropriate use of PPE represent the most critical interventions with the greatest impact on transmission interruption, as healthcare workers' hands represent the primary transmission vehicle in many outbreak scenarios. By concentrating educational resources on reinforcing the five steps of hand hygiene and the correct sequence for donning and doffing PPE, and deliberately emphasizing these practices at the beginning and throughout the education program, the intervention maximized the likelihood of behavior change with limited resources. The integration of VAP and CLABSI care bundles into the education program extended the scope of infection prevention beyond hand hygiene to include other high-yield practices specifically relevant to the infection types observed in this outbreak. This focused, principle-based approach to designing interventions in resource-limited settings allows healthcare facilities to achieve substantial improvements in infection prevention outcomes despite chronic under-resourcing, by strategically concentrating effort and resources on the practices with the greatest epidemiological impact rather than attempting to address all deficiencies in infection control infrastructure simultaneously.

While our immediate intervention successfully contained the outbreak, the long-term sustainability of such enhanced infection control measures in resource-limited settings remains a critical challenge. Maintaining the high levels of hand hygiene compliance and rigorous environmental cleaning achieved post-intervention requires continuous monitoring, persistent staff education, and strong institutional commitment, all of which can be difficult to uphold once the immediate threat of an outbreak subsides.^{5,26} Strategies for sustainability must include the

integration of these practices into daily quality assurance metrics, periodic refresher training sessions to combat complacency, and empowering frontline staff as infection control champions. Furthermore, fostering an institutional safety culture where adherence to protocols is valued and recognized is paramount. Future efforts should focus on developing cost-effective, context-appropriate models for sustaining these gains without relying on the heightened alertness triggered by an active outbreak, thereby creating a more resilient defense against future transmissions of multidrug-resistant organisms.^{4,26}

Healthcare facilities in resource-limited settings such as Pakistan face formidable structural barriers to implementing and sustaining optimal infection prevention and control practices, a reality that contextualizes both the strengths and limitations of this outbreak investigation.^{27,28} Low- and middle-income countries typically allocate only 1–2% of healthcare budgets to infection prevention initiatives, creating chronic shortages of trained infection control personnel, surveillance systems, and essential supplies such as alcohol-based hand rubs and PPE. Pakistan's infectious disease surveillance infrastructure historically operated on passive surveillance models with substantial underreporting of healthcare-associated infections, and many facilities lack centralized infection control programs with dedicated leadership, documented policies, or standardized protocols.^{15,27} The implementation of comprehensive outbreak investigation in this facility required mobilization of multidisciplinary expertise, coordination across departmental boundaries, and temporary reallocation of resources, efforts that are sustainable during acute outbreak response but challenge continuity of enhanced practices in routine operations. This investigation nevertheless demonstrates that even within significant resource constraints, systematic outbreak investigation using established epidemiological principles and conventional microbiological methods can successfully identify transmission sources, guide targeted control measures, and produce dramatic reductions in CRAB transmission. The finding that negative environmental cultures were obtained despite obvious contamination and ongoing transmission suggests that, in resource-limited settings, direct observation of healthcare worker practices and targeted surveillance of healthcare worker colonization may be more cost-effective and informative approaches than extensive environmental sampling, thereby allowing efficient allocation of limited laboratory and personnel resources toward interventions most likely to interrupt transmission pathways specific to cardiac surgical environments.

Several limitations of this investigation should be acknowledged. The lack of molecular typing prevented

definitive confirmation of clonal relatedness among isolates, although identical susceptibility patterns strongly suggest a common source. The retrospective nature of some data collection may have introduced recall bias in characterizing infection control practices. Additionally, this was a single-center outbreak investigation and thus, its generalizability may be limited to other healthcare settings due to localized nuances.

The implications of this investigation extend beyond the immediate outbreak response. The findings highlight the vulnerability of cardiac surgery patients to CRAB infections and the critical importance of maintaining rigorous infection control standards in these high-risk environments. Furthermore, the outbreak investigation methodology described here can serve as a model for similar investigations in healthcare settings worldwide. Future research should focus on developing rapid diagnostic methods for outbreak investigation, optimizing staff surveillance strategies, and evaluating the long-term sustainability of enhanced infection control interventions. Additionally, the development of novel therapeutic options for CRAB infections remains a critical priority given the limited antimicrobial susceptibility observed in the outbreak strains.

5. Conclusion

This systematic investigation of a CRAB outbreak in a cardiac surgical unit identified healthcare worker hand colonization as the likely source of transmission, in the context of multiple infection control failures. The investigation demonstrated that comprehensive outbreak response, including environmental assessment, staff surveillance, and direct observation of practices, is essential for identifying transmission sources and implementing effective control measures. The successful control of this outbreak through enhanced infection control protocols emphasizes the critical importance of sustained adherence to established standards in high-risk healthcare environments. These findings provide valuable insights for infection prevention practitioners managing similar outbreaks and reinforce the need for continuous vigilance in preventing healthcare-associated infections caused by multidrug-resistant organisms. Moving forward, we recommend the institutionalization of enhanced, periodic hand hygiene and environmental cleaning audits, alongside targeted staff screening during future outbreaks. At a national level, these findings underscore the urgent need for developing and funding robust antimicrobial resistance surveillance networks and standardized outbreak response protocols for cardiac care centers, to enable early detection and coordinated containment of multidrug-resistant organisms.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Moiz Ahmed Khan, Ahson Memon, Khudabaksh Shaikh

Data curation: Victor Basheer, Margaret Palous, Wajid Ali Khan, Nassim Sheraz

Formal analysis: Moiz Ahmed Khan, Victor Basheer, Margaret Palous

Investigation: Victor Basheer, Margaret Palous

Methodology: Moiz Ahmed Khan

Project administration: Moiz Ahmed Khan, Ahson Memon, Khudabaksh Shaikh, Abeer Salim Habib, Sohail Abrar Khan

Supervision: Moiz Ahmed Khan, Arsalan Ilyas

Validation: Moiz Ahmed Khan, Victor Basheer, Margaret Palous

Visualization: Moiz Ahmed Khan

Writing–original draft: Moiz Ahmed Khan

Writing–review & editing: Moiz Ahmed Khan, Abeer Salim Habib

Ethics approval and consent to participate

Ethical approval was not required for this outbreak investigation as it constituted routine public health surveillance activities conducted by the institutional Department of Infection Control for immediate outbreak response and infection control purposes. The investigation was conducted in accordance with standard infection control protocols and institutional guidelines. All patient data were handled confidentially and in compliance with institutional policies for outbreak investigation and reporting.

Consent for publication

Written informed consent for publication was not obtained from individual patients, as this investigation constituted a public health surveillance activity conducted for immediate outbreak control and infection prevention purposes. All data presented have been rigorously de-identified and aggregated to ensure complete patient anonymity, with no personal identifiers, protected health information, or identifiable clinical details included in the manuscript. This approach is in accordance with established ethical

guidelines for public health practice and outbreak reporting, where the imperative for timely dissemination of findings to protect public health outweighs the requirement for individual consent, provided confidentiality is strictly maintained. The investigation was performed under the authority of the institutional Department of Infection Control and adhered to internal protocols for outbreak management and data reporting.

Availability of data

All data generated during the course of this project are included in the published article.

Further disclosure

The complete findings of this outbreak investigation were presented in full at the Medical Microbiology and Infectious Diseases Society of Pakistan scientific session during the 46th Annual Conference of the Pakistan Association of Pathologists. This manuscript has not been previously published, nor has it been uploaded to any preprint server.

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