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Bioaerosol Management in Transport: A Review of Infection Control for High-Risk Pathogens in Ground and Air Ambulances

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Abstract

Background: The mobile environment of ground and air ambulances poses significant challenges for infection control, acting as potential transmitters of airborne and droplet-borne pathogens such as Tuberculosis, COVID-19, and measles. Existing decontamination protocols are often inconsistent and poorly integrated with hospital infection prevention strategies, thereby increasing risks for EMS personnel and patients.
Aim: This narrative review aims to systematically synthesize the current evidence on bioaerosol contamination risks within medical transport vehicles and to evaluate the efficacy of existing decontamination protocols.
Methods: A comprehensive literature search was conducted using PubMed, Scopus, CINAHL, and EMBASE databases for studies published between 2010 and 2024.
Results: The review highlights that current practices in pathogen management are reactive and inconsistent, particularly concerning high-touch surfaces and ambulance cabin air. It advocates for a multi-modal framework comprising: 1) Pre-transport risk assessment and notification, 2) In-transit source control with advanced respiratory measures, and 3) Post-transport decontamination through thorough cleaning and improved air exchange. Additionally, it emphasizes the need for surface sampling for quality assurance and the inclusion of pharmacy in the disinfectant selection process, both of which are often lacking.
Conclusion: Effective bioaerosol management in medical transport necessitates a shift to a systems-based approach, emphasizing coordinated protocols across dispatch, clinical care, and environmental decontamination. Standardization of these protocols is crucial to safeguard EMS workforce health and disrupt community transmission chains.
Keywords: Ambulance Decontamination, Airborne Transmission, Infection Control, Emergency Medical Services, Bioaerosol.

Introduction

The ambulance, whether terrestrial or aerial, represents one of the most vulnerable yet overlooked frontiers in the chain of infection control. Unlike static hospital rooms with engineered negative pressure, controlled air exchanges, and dedicated cleaning teams, medical transport vehicles are dynamic, densely equipped, and operate under severe time constraints (Casanova et al., 2018; Novas et al., 2022). These confined spaces become temporary bioaerosol chambers when transporting patients with active pulmonary tuberculosis, measles, COVID-19, varicella, or other airborne/droplet pathogens. The risk is not hypothetical; numerous outbreak investigations have traced the transmission of diseases like severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), and COVID-19 directly to exposures within ambulances and during patient transport (Alhazzani et al., 2021). The consequences are twofold: first, the infection and subsequent quarantine of highly trained EMS personnel, depleting an already strained workforce during crises. Second, the iatrogenic infection of subsequent patients, particularly those who may be

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immunocompromised, transforms the ambulance from a vehicle of rescue to one of transmission (Amro et al., 2022).

Despite this clear and present danger, protocols for managing high-risk pathogen transport and subsequent vehicle decontamination remain startlingly heterogeneous, often based on tradition rather than evidence, and siloed from the broader infection prevention expertise found in hospital settings. This narrative review seeks to illuminate the specific bioaerosol risks inherent to medical transport, critically appraise the current state of decontamination science and practice, and propose a unified, interdisciplinary framework that draws essential knowledge from fields including heating, ventilation, and air conditioning (HVAC) engineering, clinical microbiology, respiratory therapy, and pharmacy. The ultimate value of this synthesis is to provide a crucial, evidence-based guideline for protecting those who serve on the very front lines of public health emergencies.

Surface and Airborne Risks in a Confined Space

Understanding the specific contamination vectors within an ambulance is the first step toward effective control (Table 1). The risk environment is dual-faceted: persistent surface contamination and suspended bioaerosols. High-touch surfaces within the patient compartment—such as cardiac monitor buttons, stretcher rails, door handles, oxygen regulators, and radio equipment—are frequently contaminated with pathogens following patient care, even during routine transports (Tahir et al., 2023). Studies using adenosine triphosphate (ATP) bioluminescence and microbial cultures have consistently demonstrated inadequate cleaning of these critical points, with contamination levels often exceeding accepted benchmarks from hospital settings (Youssef et al., 2023). For airborne pathogens, the confined volume of an ambulance cabin (often less than 15 cubic meters in a ground unit) drastically reduces the dilution effect seen in larger rooms.

Aerosols generated by a coughing or breathing patient can remain suspended for extended periods and distribute widely throughout the cabin (Cox et al., 2023). Computational fluid dynamics models have shown that airflow patterns within an ambulance, driven by the vehicle's HVAC system and movement, can actively spread contaminants from the patient area to the driver's compartment, even with a partition present (Atiyani et al., 2021). This is exacerbated during aerosol-generating procedures (AGPs) such as bag-valve-mask ventilation, suctioning, or intubation, which can create concentrated plumes of infectious particles. The materials used in ambulance interiors—often textured plastics, fabrics, and crevices in complex equipment—further complicate decontamination, as they can harbor organic matter that shields pathogens from disinfectants (Bielawska-Drozd et al., 2017). This combination of high-touch fomites, suspended aerosols, and difficult-to-clean surfaces creates a uniquely challenging environment that demands a tailored and rigorous response (Obenza et al., 2022). Figure 1 integrates risk stratification, PPE escalation, ventilation controls, surface decontamination, and verification processes, emphasizing interdisciplinary collaboration.

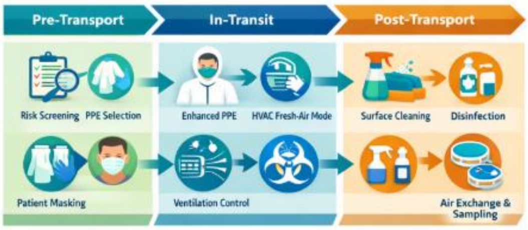

Figure 1. Tiered Risk-Based Bioaerosol Management Framework for Medical Transport

Risk Stratification, PPE, and Crew Safety

The foundation of effective bioaerosol management is preventing contamination at the source, which begins with risk-aware practices by the EMS crew. A critical failure point is the frequent lack of definitive diagnosis at the time of dispatch; crews often respond to patients with undifferentiated respiratory distress, making universal precautions and a high index of suspicion paramount (Cunha & Cunha, 2017). Implementing a robust pre-transport screening protocol, even if based solely on symptoms and epidemiology (e.g., fever and cough during a known measles outbreak), can trigger advanced preparation. When a high-risk pathogen is suspected or confirmed, the immediate application of appropriate personal protective equipment (PPE) is the most effective intervention to protect crew and prevent environmental seeding (Brachmann et al., 2023).

For true airborne pathogens like tuberculosis and measles, this necessitates the use of a fit-tested N95 respirator or equivalent (e.g., FFP2), or a powered air-purifying respirator (PAPR) for prolonged transports or during AGPs (CDC, 2020). The expertise of Respiratory Therapists (RTs) is invaluable here; RTs are specialists in airborne precautions and the management of AGPs. Their knowledge can be leveraged to train EMS personnel on respirator fit, the hierarchy of respiratory protection, and safe techniques for airway management that minimize aerosol spread, such as using in-line viral filters on ventilation circuits (Wax & Christian, 2020). Furthermore, crew behavior post-call is crucial. The disciplined doffing of PPE before entering the driver's compartment or clean areas, and the safe containment of used PPE, prevent cross-contamination. Education must emphasize that PPE is the primary personal defense, but it does not replace the need for subsequent environmental decontamination (Boiano & Steege, 2016).

The Role of Ventilation and HVAC Systems

While PPE protects the individual, engineering controls are designed to protect the shared environment. The ambulance's HVAC system is the single most important engineering control for managing bioaerosols, yet its potential is frequently underutilized. The default recirculation mode, which cools or heats cabin air efficiently, is precisely the wrong setting for infection control, as it continuously recirculates contaminated air (Hobday & Dancer, 2013; Fageha & Alaidroos, 2022). The primary intervention is to maximize fresh air intake and exhaust. For modern ambulances, this means setting the HVAC to "non-recirculating" or "fresh air" mode at the highest fan speed possible during and after transport of a suspected case. This creates a constant flow of air from outside, through the cabin, and out, providing dilution and removal of airborne contaminants. Where feasible, opening windows further enhances this effect (Waheeb & Hemeida, 2022).

For air medical transports, where opening windows is impossible, the aircraft's ventilation system, which typically uses High-Efficiency Particulate Air (HEPA) filtration and has high air exchange rates, becomes a critical asset (Bielecki et al., 2020). Some advanced systems are exploring the incorporation of upper-room ultraviolet germicidal irradiation (UVGI) or portable HEPA filtration units that can be placed in the patient compartment. These technologies, common in tuberculosis clinics, actively inactivate airborne pathogens and could be adapted for use in larger mobile intensive care units or during prolonged standby periods (Mphaphlele et al., 2015; Mamahlodi, 2019). A systems-based approach requires that EMS agencies, in collaboration with vehicle manufacturers and HVAC engineers, specify and maintain these ventilation features, and that crews are trained to use them as a standard infection control practice (Sotomayor-Castillo et al., 2021).

The Decontamination Cascade in Cleaning, Disinfection, and Verification

Once the patient is transferred and the crew is safely doffed, the focus shifts to environmental decontamination. This process must be a structured cascade, not a single wipe-down. The first, non-negotiable step is thorough cleaning—the physical removal of organic debris and soil using a detergent and water. Disinfectants cannot penetrate layers of blood, mucus, or vomit; applying them to a dirty surface is ineffective (Rutala & Weber, 2019). All surfaces, with particular attention to high-touch areas, must be meticulously wiped clean. This is followed by disinfection—the chemical inactivation of remaining pathogens. Here, the selection of the disinfectant agent is a decision that should involve Pharmacy expertise. Pharmacists, with their knowledge of chemical efficacy, material compatibility, and occupational safety, are ideally positioned to guide EMS agencies in selecting Environmental Protection Agency (EPA)-registered disinfectants approved for use against emerging pathogens (e.g., those on List N for COVID-19) (Okidi et al., 2022). They can advise on appropriate contact times (the wet dwell time required to kill pathogens), which are often neglected in practice, and on the safety of agents for sensitive equipment like monitors and ventilators (Vuppu et al., 2023).

The use of hydrogen peroxide vapor or ultraviolet-C (UVC) robots represents an advanced tier of terminal decontamination. These technologies can achieve a high level of sterilization for the entire cabin air and surfaces, but they require significant capital investment, dedicated time, and safety protocols (Otter et al., 2013). Finally, a program of verification through environmental sampling is essential for quality assurance. This is the domain of the Medical Laboratory. Periodic surface sampling using swabs for culture or PCR, or ATP bioluminescence to measure organic residue, provides objective data on cleaning efficacy. This feedback loop is critical for identifying missed hotspots, validating new procedures, and ensuring that the decontamination protocol is not just performed, but is effective (Suleyman et al., 2018). Figure 2 illustrates patient-generated aerosols, HVAC-driven airflow patterns, migration toward the driver cabin, and mitigation strategies including fresh-air intake, HEPA filtration, and source control via masking.

Table 1: Interdisciplinary Roles in Ambulance Bioaerosol Management

Discipline/ Role	Key Responsibilities	Contributions to the Framework
EMS Leadership/ Operations	Develop & enforce policy; manage fleet logistics & downtime; secure resources.	Creates the operational structure and accountability for protocol implementation.
Infection Prevention & Control (IPC)	Risk assessment; protocol development based on latest evidence; outbreak liaison.	Provides the scientific foundation and links transport protocols to hospital-based standards.
Respiratory Therapy (RT)	Expertise in airborne precautions, AGPs, and respirator use.	Trains EMS on advanced respiratory protection and safe airway management to reduce source aerosols.
Pharmacy	Evaluate and recommend disinfectants for efficacy, material compatibility, and staff safety.	Ensures the chemical means of decontamination are both effective and practical for the unique ambulance environment.

Medical Laboratory	Conduct environmental surface sampling (ATP, cultures); interpret results for quality assurance.	Provides objective data to verify cleaning efficacy and drive continuous protocol improvement.
Facilities/ Fleet Engineering	Specify and maintain vehicle HVAC systems for optimal fresh air exchange; integrate new technologies (UVGI, HEPA).	Designs and maintains the engineering controls that manage airborne risks.
EMS Field Personnel	Execute risk screening, PPE use, in-transit precautions, and cleaning/disinfection procedures.	The ultimate end-users; their adherence and feedback determine real-world protocol success.

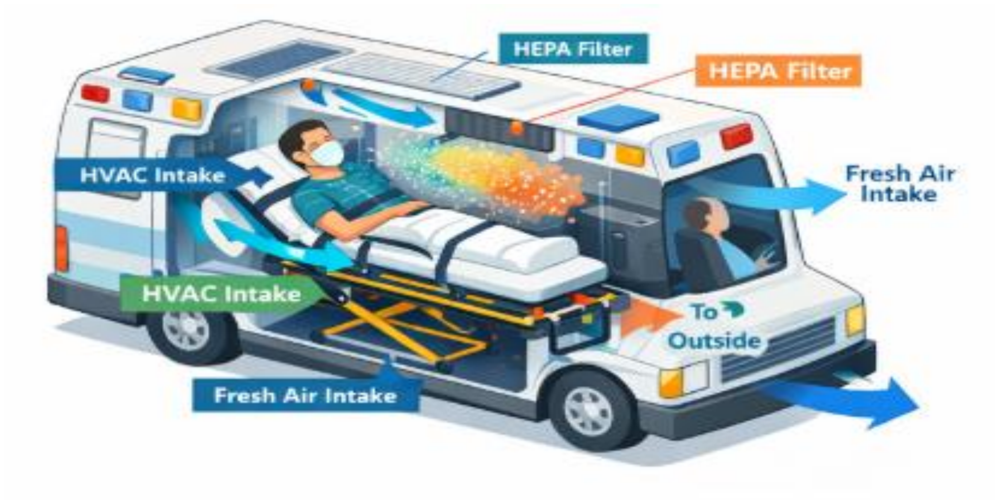

Figure 2. Airflow and Bioaerosol Dispersion in a Ground Ambulance

Operational and Logistical Challenges

Implementing a rigorous bioaerosol management protocol confronts significant operational realities (Table 2). The most salient is downtime—the period a vehicle is out of service for decontamination. In high-volume urban systems, taking an ambulance offline for the 10-15 minutes required for a basic clean versus the 45-60 minutes needed for a full terminal decontamination after a high-risk call has major implications for system capacity and response times (Rosiello et al., 2020). Agencies must develop tiered response plans, where the level of decontamination is matched to the assessed risk, and have backup vehicles or flexible staffing to manage downtime. This requires a clear policy at the administrative level. Policies must unambiguously define high-risk transports, specify PPE requirements, detail the step-by-step decontamination procedure, and outline responsibilities (Baldovin et al., 2022).

Such policies cannot be created in a vacuum; they necessitate interdisciplinary input from infection preventionists, occupational health, fleet managers, and clinical leadership. Sustained success hinges on continuous training (Soleman et al., 2023). One-time lectures are insufficient. Training must include hands-on drills for donning/doffing PPE, practicing decontamination procedures on mock vehicles, and incorporating lessons from verification sampling (Jafari et al., 2022). Culture change is required to elevate infection control to the same level of importance as clinical skills like intubation or cardiac arrest management.

Table 2: Tiered Risk-Based Decontamination Protocol for Medical Transport Vehicles

Risk Tier & Example Pathogens	In-Transit Precautions	Post-Transport Decontamination Protocol	Estimated Downtime
Tier 1: Routine (No suspected respiratory infection)	Standard Precautions.	1. Routine cleaning of stretcher and high-touch surfaces with hospital-grade detergent/disinfectant. 2. Restock supplies. 3. Empty trash.	10-15 minutes
Tier 2: Droplet/Airborne Suspected (e.g., Influenza, COVID-19*, Pertussis)	Crew: N95 respirator, eye protection, gown, gloves.	1. All Tier 1 steps. 2. Enhanced disinfection of all cabin surfaces (walls, ceiling, floor) with EPA-registered disinfectant,	30-45 minutes

	Patient: Surgical mask if tolerated. Vehicle: HVAC on full fresh-air mode.	observing full contact time. 3. Focus on all equipment surfaces. 4. Cabin air exchange (open doors, run HVAC) for 20+ minutes.	
Tier 3: High-Consequence Airborne (e.g., Active TB, Measles, Varicella)	Crew: PAPR or fit-tested N95 for duration. Patient: Surgical mask if possible. Vehicle: Full fresh-air mode; consider portable HEPA if available.	1. All Tier 2 steps performed by trained personnel in appropriate PPE. 2. **Terminal Decontamination:** Use of advanced method (e.g., hydrogen peroxide vapor, UVC robot) if available and practicable. 3. Mandatory verification sampling (ATP or microbiological) before returning to service.	60+ minutes (or until verification passed)
***Note: COVID-19 is primarily airborne; its placement here reflects common EMS operational categorization based on PPE needs.**			

Synthesis and Proposed Framework

The evidence compels a move from fragmented, reactive practices to an integrated, systems-based framework for bioaerosol management in medical transport. This framework operates across three temporal phases: Pre-Transport, In-Transit, and Post-Transport, with continuous feedback loops. In the Pre-Transport phase, dispatch and crew utilize screening tools to stratify risk, triggering specific preparedness actions (e.g., donning advanced PPE before patient contact, pre-setting vehicle ventilation). The In-Transit phase focuses on source control: effective respiratory source control from the patient (e.g., masking), strict adherence to PPE by the crew, and maximizing cabin air dilution through tactical HVAC use. The Post-Transport phase is where the multidisciplinary model fully converges.

A tiered decontamination protocol, informed by the transport risk level, is executed. This protocol is guided by pharmacy-vetted disinfectants, targets surfaces identified through laboratory sampling as high-risk, and employs engineering controls like extended air flushing. Verification sampling, analyzed by the laboratory, closes the loop, confirming efficacy and informing protocol refinement. This entire process must be underpinned by robust policies, recurrent multidisciplinary training, and a culture of safety that prioritizes infection control as a core component of EMS professionalism. Such an approach recognizes that the ambulance is an extension of the healthcare facility and must be governed by the same rigorous standards of environmental hygiene.

Conclusion

The management of bioaerosols in ground and air ambulances is a complex but non-negotiable component of modern infection prevention and health security. The enclosed, mobile nature of these vehicles creates a high-risk environment for the transmission of serious pathogens, threatening the health of the essential EMS workforce and the patients they serve. Current practices are too often inadequate, inconsistent, and divorced from the wealth of relevant expertise in fields like ventilation engineering, microbiology, and disinfectant science. This review argues that effective protection requires an interdisciplinary, systems-based framework. By integrating strategic risk stratification, in-transit engineering controls, a tiered decontamination cascade informed by pharmacy and laboratory science, and rigorous operational policies, EMS agencies can transform their vehicles from potential vectors into secure environments of care. Investing in this integrated approach is an investment in workforce protection, patient safety, and community resilience against current and future airborne threats. The time to standardize and optimize bioaerosol management in transport is now, before the next pandemic reveals this vulnerability once more.

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