

Chlorine Dioxide as an Effective Agent for Bioaerosol Mitigation in Critical Facilities

Sohil Purohit, Marie Bourgeois, George Lukasik, Raymond Harbison*

Center for Environmental and Occupational Risk Analysis and Management, College of Public Health, University of South Florida, Tampa, FL, USA

Email: *rharbiso@ix.netcom.com

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Abstract

Chlorine dioxide (ClO₂) gas is a well-established antimicrobial agent with broad-spectrum efficacy against bacteria, fungi, and viruses. In clinical settings, especially operating rooms and dental clinics, bioaerosol transmission of infectious agents poses significant risks. This study evaluates the effectiveness of ClO₂ gas in mitigating airborne microbial contaminants using data from experimental setups, including HEPA filter environments, chlorine dioxide filters, and controlled laboratory conditions. Supported by empirical findings and our previously published studies, this study's results demonstrate over 99% reduction in airborne pathogens, confirming ClO₂'s potential as a critical disinfection strategy in healthcare facilities.

Keywords

Chlorine Dioxide, Bioaerosol Mitigation, Critical Facilities, Antimicrobial Efficacy

1. Introduction

1.1. The Need for Bioaerosol Mitigation in Clinical Settings

Bioaerosols are airborne particles that contain or originate from living organisms and can include bacteria, fungi, and viruses. In healthcare environments, particularly dental clinics and operating rooms, these particles can lead to airborne transmission of infectious diseases [1] [2]. Procedures such as drilling, ultrasonic scaling, or surgery contribute to bioaerosol generation, increasing risks for healthcare workers and patients [3]. Mitigation strategies are essential for maintaining indoor air quality and preventing nosocomial infections [4].

1.2. Why Chlorine Dioxide

Chlorine dioxide is a volatile, highly water-soluble gas known for its oxidative capabilities, allowing it to inactivate microorganisms by disrupting cellular membranes and proteins [5]. Chlorine dioxide rapidly transfers from the gas phase to liquid in droplets or on surfaces. This characteristic makes it a more effective gaseous disinfectant than other oxidizers, such as ozone or vaporized hydrogen peroxide. It is highly effective in both surface and air disinfection, does not leave harmful residues, and degrades into non-toxic byproducts [6]. Unlike liquid disinfectants, ClO₂ gas can penetrate crevices and inaccessible areas, making it suitable for comprehensive disinfection in clinical settings. The EPA and FDA have approved ClO₂ for potable water treatment, food sanitization, and hospital sterilization [7] [8].

1.3. Background and Uses of Chlorine Dioxide

Chlorine dioxide has been used since the early 20th century in water treatment, food processing, medical device sterilization, and industrial bleaching. In recent decades, it has gained popularity in environmental and healthcare disinfection due to its gaseous nature, simpler delivery technology and broad-spectrum efficacy [5]. ClO₂ gas can destroy a wide range of microbial contaminants, including *Staphylococcus aureus*, *Escherichia coli*, fungal spores, and viruses like human coronavirus OC43 [7] [9]. Its integration in air filtration systems enhances its utility in indoor air quality control [6].

1.4. Safety of Chlorine Dioxide

The U.S. OSHA sets the permissible exposure limit for ClO₂ at 0.1 ppm TWA and 0.3 ppm STEL. Long-term animal studies have demonstrated no toxic effects at or below these levels [10]. ClO₂ is rapidly consumed in ambient environments and leaves minimal residuals on surfaces or air, offering a high margin of safety [11] in a variety of applications. Furthermore, regulatory guidelines such as those from NIOSH and OSHA support its safe use in controlled environments [10] [11].

1.5. Aerosol Transmission and the Role of ClO₂

Aerosol and droplet transmission is a major vector for infectious diseases in healthcare settings. Bioaerosols can remain airborne for prolonged periods and pose persistent exposure risks [1]. Traditional cleaning methods often overlook airborne pathogens or difficult-to-access spaces. Chlorine dioxide, introduced as a dry gas into spaces or air flows, offers superior coverage and air disinfection even at relatively low concentrations [7]. Previous studies demonstrated > 99% reduction in viable microorganisms in dental clinics and cafeterias following ClO₂ application [6] [12].

2. Materials and Methods

2.1. Study Design

This study evaluated the bioaerosol mitigation potential of chlorine dioxide gas

when integrated with air filtration systems under controlled laboratory conditions. The aim was to assess its efficacy against three representative microorganisms: *Aspergillus versicolor*, *Staphylococcus epidermidis*, and *Bacillus atrophaeus* endospores. The experimental setup focused on quantifying decay rates and evaluating the comparative performance of chlorine dioxide-integrated filtration media and HEPA filters over time.

2.2. Bioaerosol and Chamber Conditions

The experiments were conducted in a sealed environmental exposure chamber with a volume of 742 cubic feet. Conditions within the chamber were consistently maintained at 24°C - 26°C temperature and 40% - 50% relative humidity.

Bioaerosols were generated using a single-jet Collision atomizer 9302 (TSI Inc., USA) operated at a pressure of 35 PSI. The atomizer aerosolized suspensions of each test organism for 75 minutes, ensuring a stable airborne concentration. The organisms tested included *Aspergillus versicolor* (fungal spores), *Staphylococcus epidermidis* (Gram-positive cocci), and *Bacillus atrophaeus* endospores (ATCC® 9372™, used as a surrogate for agent *Bacillus anthracis*).

2.3. Filters and Application

Three chlorine dioxide-based filtration approaches were evaluated under controlled environmental conditions. The first involved the use of the ICA Tri-Nova Air Mover with a HEPA filter, centrally positioned in a sealed 742-cubic-foot chamber to assess physical air filtration performance. The second method utilized the ICA Tri-Nova Air Mover with chlorine dioxide-infused media, designed to release low levels of chlorine dioxide gas during active airflow, positioned in the Air Mover as a filtering element. Third, the Z-Series UltraShok system (ICA Tri-nova, USA), consisting of 40 grams each of UltraShok Part A (precursor) and Part B (acid activator), was used to generate active chlorine dioxide gas, and tested in combination with ICA Tri-Nova Air Mover with a HEPA filter.

2.4. Air Sampling and Calculation

Air samples were collected at defined intervals: 0 (T0 baseline), 30, 60, 90, 120, and 180 minutes post-aerosolization with a National Institute of Standards and Technology (NIST) timer.

Sampling was performed using BioSampler® Liquid Impingers (SKC Ltd.), which pulled 120 liters of sample air from the chamber. Each sampler containing 20 mL of sterile phosphate-buffered saline (PBS) was supplemented with 0.01% sodium thiosulfate. Immediately after the T0 sample, subsequent air samples were collected at predefined time intervals. Quality control measures included a positive control (PBS inoculated with the test organism) and a negative control (uninoculated PBS), both prepared with 0.01% sodium thiosulfate and processed identically to the test samples. All samples were analyzed on the same day following ISO 17025:2017 laboratory standards.

3. Results

The use of chlorine dioxide-integrated filtration systems led to substantial reductions in airborne microbial concentrations. *Aspergillus versicolor* bioaerosols were reduced by over 98.95% within just 30 minutes, maintaining a 99.99% reduction through 180 minutes (Figure 1). *Staphylococcus epidermidis* showed similar responsiveness, with reductions exceeding 99.99% achieved within 90 minutes and sustained throughout the exposure period (Figure 2). For *Bacillus atrophaeus* endospores, a 99.91% reduction was observed at 120 minutes, improving to 99.99% by 180 minutes (Figure 3). Comparatively, HEPA filtration achieved a 99.9% reduction over the same duration. These results demonstrate that chlorine dioxide is highly effective across different microbial types, including resilient endospores and performs on par with or better than traditional HEPA systems within a shorter operational window.

In the filter-only cases (Figure 1 and Figure 2), the working gas concentration remained below the 0.1 ppmv safety threshold throughout the experiments. The observed reductions in bioaerosol are therefore attributed to the action of the ClO₂-infused filter media, which physically captures bioaerosol particles and provides an oxidizing environment lethal to the pathogens trapped within the filter bed.

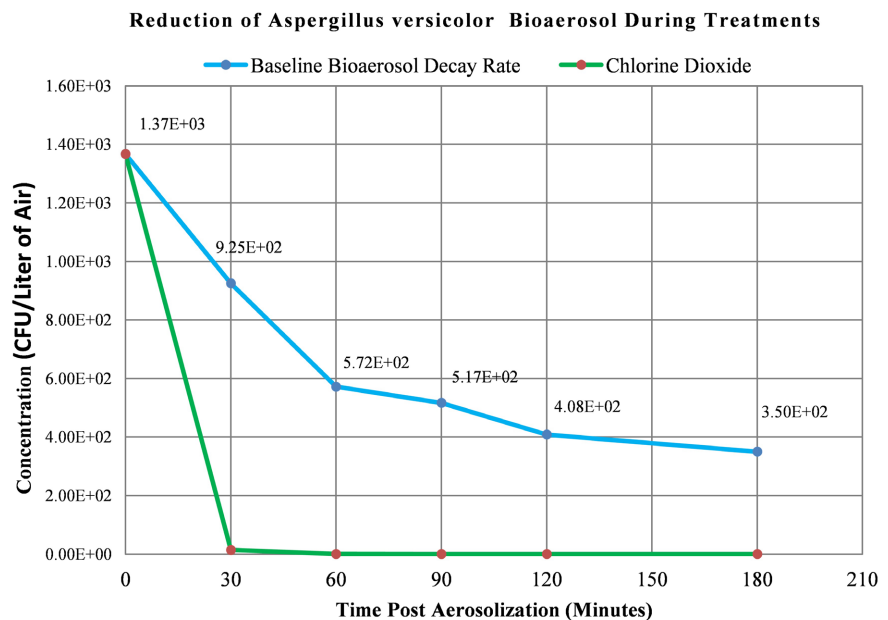


Figure 1. Performance of ClO₂ filter media.

In contrast, in the ClO₂ gas pulse condition (Figure 3), the working gas concentration peaked at 25 ppmv and remained effectively constant over the sampling period. Although both approaches employ chlorine dioxide, they operate at very different concentrations. Notably, the decay curves for the ClO₂ gas pulse and HEPA filtration reached similar endpoints within the same timeframe. This ob-

ervation reinforces the concept that ClO₂ gas rapidly transfers to airborne bioaerosol particles, achieving lethal concentrations quickly, even at relatively low concentrations that are compatible with human occupancy.

These findings highlight two distinct bioaerosol mitigation strategies: a rapid decontamination approach using high-concentration ClO₂ gas pulses (25 ppmv), which must be performed in unoccupied spaces, and a preventative approach using filter media that maintain ClO₂ levels below established safety thresholds during normal operations.

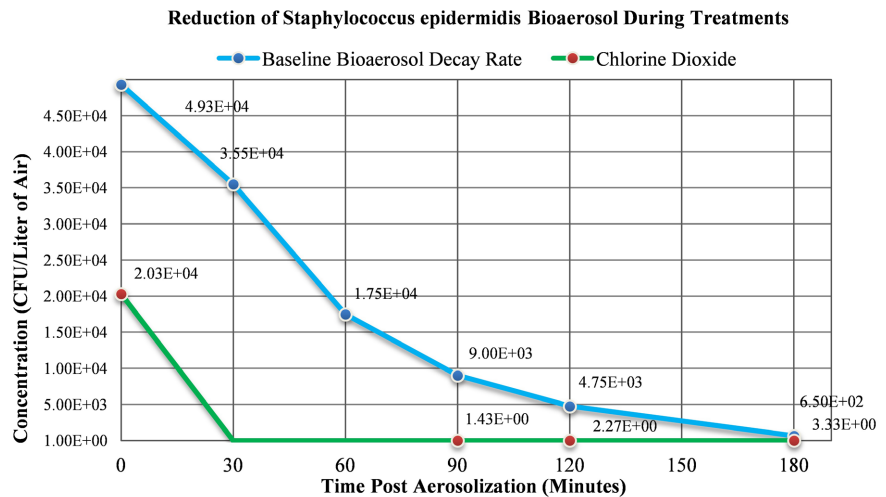


Figure 2. Performance of ClO₂ filter media.

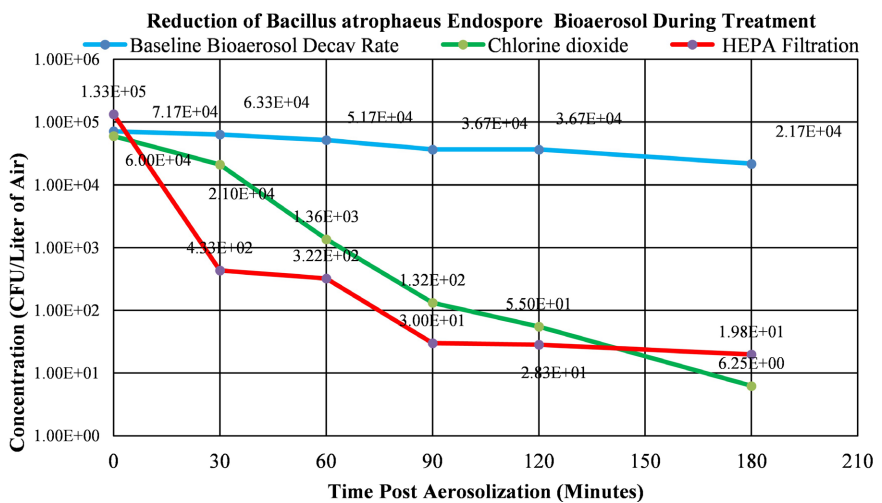


Figure 3. Performance of ClO₂ gas pulse (25 ppmv) vs HEPA alone.

4. Conclusion

This study demonstrates that chlorine dioxide is a highly effective agent for mitigating airborne microbial contamination in controlled environments. Across all tested organisms, *Aspergillus versicolor*, *Staphylococcus epidermidis*, and *Bacillus atrophaeus* endospores chlorine dioxide filtration achieved greater than 99.9%

reduction within 90 to 180 minutes. These results highlight its broad-spectrum efficacy, including against resilient spores, and its potential to perform as well as or better than HEPA filtration. Given its non-carcinogenic properties, shorter disinfection cycle, and compatibility with existing air handling systems, chlorine dioxide offers a practical and powerful alternative for enhancing bioaerosol control in critical facilities such as operating rooms, laboratories, and large sterilization areas. Its adoption could significantly improve indoor air safety and reduce infection risks in high-stakes healthcare and research settings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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