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Major Article

Mathematical modeling and simulation of bacterial distribution in an aerobiology chamber using computational fluid dynamics

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Key Words:
Airborne spread of infectious agents
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Predictive modeling of bacterial distribution in an aerobiology chamber

Background: Computer-aided design and draft, along with computer-aided engineering software, are used widely in different fields to create, modify, analyze, and optimize designs.
Methods: We used computer-aided design and draft software to create a 3-dimensional model of an aerobiology chamber built in accordance with the specifications of the 2012 guideline from the Environmental Protection Agency for studies on survival and inactivation of microbial pathogens in indoor air. The model was used to optimize the chamber's airflow design and the distribution of aerosolized bacteria inside it.
Results: The findings led to the identification of an appropriate fan and its location inside the chamber for uniform distribution of microbes introduced into the air, suitability of air sample collection from the center of the chamber alone as representative of its bacterial content, and determination of the influence of room furnishings on airflow patterns inside the chamber.
Conclusions: The incorporation of this modeling study's findings could further improve the design of the chamber and the predictive value of the experimental data using it. Further, it could make data generation faster and more economical by eliminating the need for collecting air samples from multiple sites in the chamber.

INTRODUCTION

Prediction of particle transport in turbulent flow is essential in different fields, such as dispersion of passive or reactive particles in turbulent media and in studying air pollution.[1] For example, we are exposed to airborne particulates in workplaces, homes, and other indoor settings.[2] The fate and deposition of such particulates indoors have substantial implications for human and animal health, clean rooms, and air decontamination.[3-5] Therefore, a good understanding of the particle-laden turbulent flow is important in addressing indoor air quality issues and in controlling particle dispersion.

Mitigating the spread of microbial contaminants by indoor air is an essential design consideration for homes, biomedical and health care facilities, and other public settings. Once airborne, the movement of microbes is difficult to control because they may become rapidly dispersed by air movement or adhere to other surfaces for travel with them.[6,7] Ventilation, either natural or mechanical, can provide adequate air exchanges to reduce the risk for airborne microbial spread; however, mechanical ventilation, particularly with conditioning, can be expensive.[8] According to the *Guidelines for Design and Construction of Hospital and Health Care Facilities*,[9] 6-15 air changes per hour are needed to maintain a healthful environment while reducing exposure to harmful chemicals and microbes. This

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requires ventilation system engineers to understand microbial behavior in air to design more efficient and economical means of treating and supplying indoor air.[10]

In general, particles with a mass median aerodynamic diameter of 10 µm or less can remain airborne.[11] Memarzadeh and Xu[12] emphasized the importance of particle size in the airborne transmission of infections by transport of pathogen-laden particles to the mucosal surface of a susceptible host.[12]

Available information shows that ventilation systems can influence the spread of airborne pathogens indoors,[13,14] airflow patterns may contribute directly to such spread,[15] and airflow rates can influence the transport and removal of human expiratory droplets.[5,16-18] Assessing the risk of transmission of infections via air is more difficult than predicting reductions in concentrations of harmful gases with ventilation. Also, and unlike inhaled gases, it may take only a few infectious units of a given pathogen to infect a susceptible host, which, in turn, can amplify the level of the pathogen many-fold for further dissemination.

Increasing the air exchange rate alone is often inadequate for reducing the risk of spread of airborne infections everywhere within a given room. For optimal safety, the entire ventilation system should be analyzed to determine the likely path of pathogen-laden particulates within the occupied zones and the required corrective action.[19]

The 2 major approaches to study of the dispersion of particles in indoor air are physical modeling and numerical simulation with computational fluid dynamics (CFD). Empirical data are useful for CFD validation of air and movement of particulates in indoor environments and health care facilities. CFD modeling is also much more economical to perform than full-scale experimentation with actual pathogens or their surrogates.[20] Thus, with the ready availability and greater sophistication of CFD, it is increasingly being applied to predict room air movement in various types of health care settings.[21] However, this approach has not been adequately applied to other types of indoor settings and validated with experimental data[22]; when applied to predict airflow patterns in buildings, it was a flexible alternative to physical models.[22-24]

This study applies CFD to optimize and validate the performance of an aerobiology chamber that was designed based on Environmental Protection Agency guidelines.[25] The best location, angle, and speed of a muffin fan for producing uniform bacterial distribution were determined. The number of air sampling sites required for characterizing the distribution of the nebulized bacteria in the chamber was investigated. The stabilization time required to produce a uniform distribution of the bacteria was determined, and the effect of furniture on bacterial distribution also was studied.

METHODS

The dimensions of the studied aerobiology chamber were 320 cm × 360 cm × 210 cm.[26] The chamber was designed based on Environmental Protection Agency guidelines[25] and then used to study bacteria survival in air (Fig 1).[26] A 6-jet nebulizer was used to aerosolize bacterial suspensions into the chamber through a pipe with a 3.8-cm diameter. The air was sampled from the center of the chamber using a slit-to-agar machine via a 5.0-cm pipe. A muffin fan (Nidec Alpha V, TA300, Model A31022-20, P/N: 933314 3.0-inch/7.62-cm diameter; output 30 CFM; Nidec Corp., Braintree, MA) placed on the floor of the chamber directly beneath the nebulizer inlet pipe was actuated from the outside for continuous operation during nebulization and testing to ensure uniform distribution of the aerosolized particles and/or any treatment introduced. The procedure of the experiment was as follows:

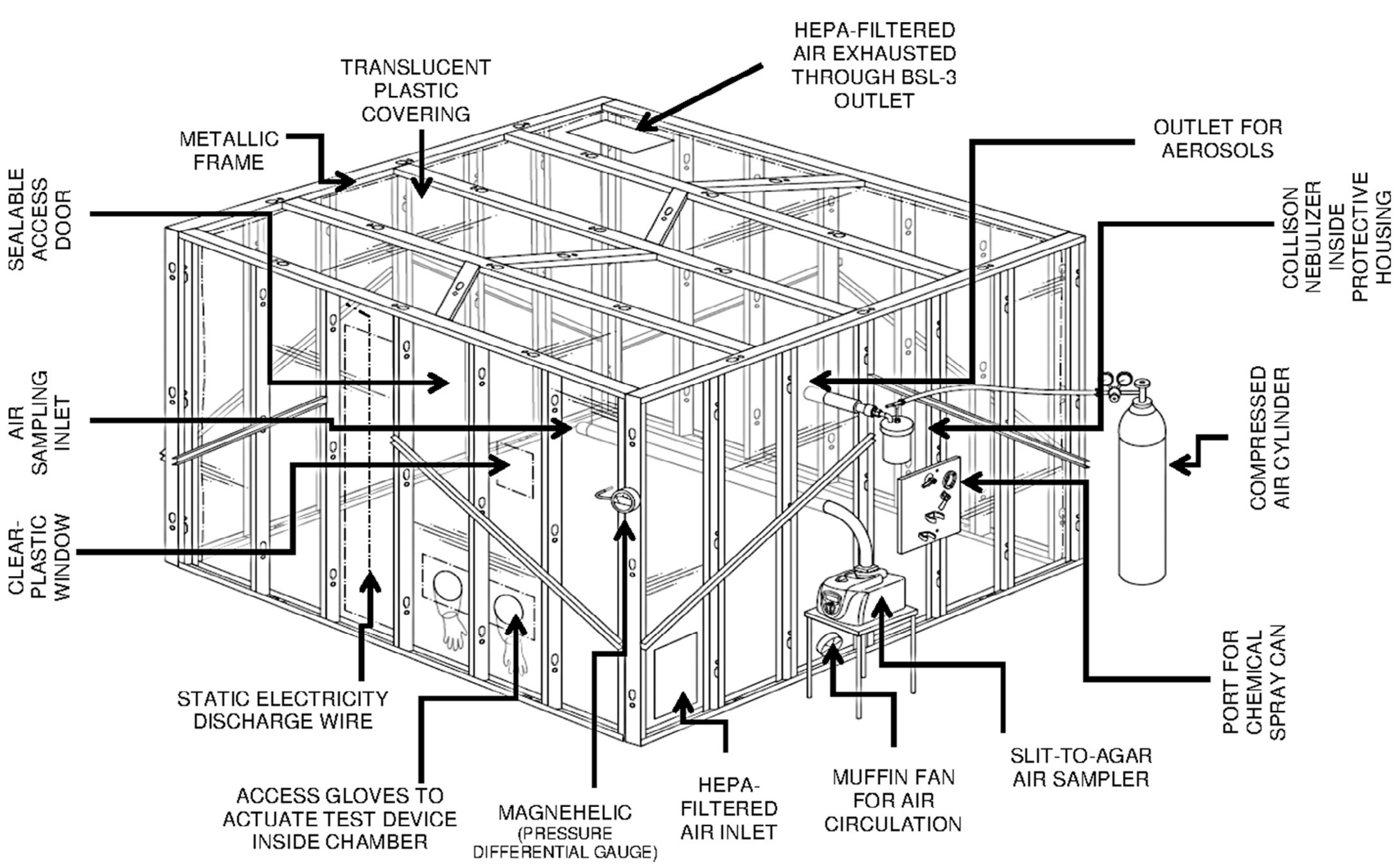

Fig 1. Aerobiology chamber designed based on Environmental Protection Agency guidelines.[25] Reprinted with permission.