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STATE OF THE SCIENCE

Characterization of infectious aerosols in health care facilities: An aid to effective engineering controls and preventive strategies

Eugene C. Cole, DrPH
Carl E. Cook, MS
Durham, North Carolina

Assessment of strategies for engineering controls for the prevention of airborne infectious disease transmission to patients and to health care and related workers requires consideration of the factors relevant to aerosol characterization. These factors include aerosol generation, particle sizes and concentrations, organism viability, infectivity and virulence, air-flow and climate, and environmental sampling and analysis. The major focus on attention to engineering controls comes from recent increases in tuberculosis, particularly the multidrug-resistant varieties in the general hospital population, the severely immunocompromised, and those in at-risk and confined environments such as prisons, long-term care facilities, and shelters for the homeless. Many workers are in close contact with persons who have active, undiagnosed, or insufficiently treated tuberculosis. Additionally, patients and health care workers may be exposed to a variety of pathogenic human viruses, opportunistic fungi, and bacteria. This report therefore focuses on the nature of infectious aerosol transmission in an attempt to determine which factors can be systematically addressed to result in proven, applied engineering approaches to the control of infectious aerosols in hospital and health care facility environments. The infectious aerosols of consideration are those that are generated as particles of respirable size by both human and environmental sources and that have the capability of remaining viable and airborne for extended periods in the indoor environment. This definition precludes skin and mucous membrane exposures occurring from splashes (rather than true aerosols) of blood or body fluids containing infectious disease agents. There are no epidemiologic or laboratory studies documenting the transmission of bloodborne virus by way of aerosols. (AJIC Am J Infect Control 1998;26:453-64)

During 1996, a total of 21,337 cases (8.0 cases/100,000 population) of tuberculosis (TB) were reported to the Centers for Disease Control and Prevention (CDC) from the 50 states, District of Columbia, and New York City, and this total represents a 6.7% decrease from 1995 (8.7 cases/100,000 population).¹ Although the number of TB cases has decreased for 4 consecutive years, the TB incidence for 1996 exceeded the national

goal of TB elimination. The prevalence of TB infection remains higher for foreign-born persons and minority groups, and it remains a significant public health problem.

Additionally, infected persons who have failed to complete their TB treatment have fostered the development of multidrug-resistant strains of the primary causative agent, *Mycobacterium tuberculosis*. According to the CDC, virtually all new infections in the country today are contracted through the aerosol route from infected patients who are coughing and dispersing infective droplet nuclei into the air.² Health care and other workers exposed to confined and TB-prevalent populations are at great risk for infection. Before 1990, outbreaks of multidrug-resistant TB were uncommon³; since then, more than 10 outbreaks have been reported, all in hospitals and prisons in the

From DynCorp Health Research Services, Durham.

Reprint requests: Eugene C. Cole, DrPH, DynCorp Health Research Services, 4815 Emperor Blvd, Suite 300, Durham, NC 27703.

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eastern United States.⁴⁻⁸ The presence of patients with active TB near immunocompromised patients in HIV-dedicated wards has led to infection of patients with HIV and multidrug-resistant TB, whose TB cases often go unrecognized. A nosocomial outbreak of multidrug-resistant *M tuberculosis* in Spain during a 45-month period infected both patients and health care workers.⁹

In an intensive care unit, 31% of hospital staff (14/45) who were exposed to an active, undiagnosed TB case during a 5-day period were infected,¹⁰ and a prison guard receiving immunosuppressive therapy acquired a fulminant and fatal case of TB from HIV-infected inmates.¹¹ TB has been declared an endemic and nosocomial infection in nursing homes.¹²

TB is a severe infectious disease, predominantly pulmonary, that is caused by *M tuberculosis* and *Mycobacterium africanum* primarily from human beings and *Mycobacterium bovis* primarily from cattle.¹³ Those infected with HIV are also predisposed toward infection with other mycobacteria, including *Mycobacterium avium*, *Mycobacterium intracellulare*, and *Mycobacterium scrofulaceum*.¹⁴ TB occurs when airborne droplet nuclei containing few or even single infectious units bypass the bronchial mucociliary apparatus to reach and multiply in the terminal air space.¹⁵ Infection in the lungs commonly begins in the lower division of the lower lobe, the middle lobe, the lingula, and the anterior portion of the upper lobes; in most cases there is a single initial focus, but one fourth or more of cases show multiple foci.¹⁵ Bacilli are ingested by alveolar macrophages, continue to multiply, and spread to regional lymph nodes, where progressive disease may occur rapidly or after many years. In children and elderly persons, the primary focus may become an area of advancing pneumonia.¹⁵

In addition to TB, hospital patients and health care and related workers remain at risk for contracting other infectious airborne diseases in the indoor environment, to include viral (influenza, measles, chickenpox), chlamydial (psittacosis), bacterial (legionnaires' disease), and fungal (aspergillosis) infections. The extreme infectiousness of airborne measles was demonstrated in an outbreak in a private pediatric practice, where a 12-year-old boy with measles was subject to vigorous coughing.¹⁶ Seven secondary cases occurred. Four patients had had transient contact with the patient as he entered or exited, whereas 3 had entered the office as long as 1 hour after the patient was gone. Airflow studies subsequently

showed that droplet nuclei were generated throughout the entire office suite. Personnel involved in the direct care of patients with respiratory diseases such as psittacosis from *Chlamydia psittaci* or pneumonia from *Chlamydia pneumoniae* are at risk of infection by the aerosol route.¹⁷ During a psittacosis epidemic in Louisiana in 1943, there were 8 deaths among 19 diagnosed infections in nursing attendants.¹⁸

The epidemiology of nosocomial legionnaires' disease has not been well elucidated. It is estimated that 10,000 to 15,000 persons get legionnaires' disease in the United States each year.¹⁹ An additional unknown number of people are infected and have mild symptoms or no illness at all. About 5% to 15% of known cases of legionnaires' disease have been fatal. Of 196 cases of nosocomial legionnaires' disease reported in England and Wales during 1980 to 1992, 69% occurred during 22 nosocomial outbreaks.²⁰ Nine percent of cases occurred at least 6 months before or after a hospital outbreak. Another 13% were in hospitals where other sporadic cases (but no outbreaks) were identified. Only 9% occurred at institutions where no outbreaks or additional sporadic cases were identified.

The overall proportion of nosocomial pneumonias caused by *Legionella* species in North America has not been determined, although individual hospitals have reported ranges of 0% to 14%.²⁰ Because diagnostic tests for *Legionella* species infection are not routinely performed on all patients with hospital-acquired pneumonia in most US hospitals, these ranges probably underestimate the incidence of legionnaires' disease.

An 850-bed, tertiary-care, university-based hospital was monitored during a period of hospital construction for the epidemiology of invasive aspergillosis.²¹ A sample of 153 patients was monitored by *Aspergillus* antigen testing and culture, and 24 cases were found during a 1-year period; of those, 7 were determined to be nosocomial.

AEROSOL CHARACTERIZATION

An assessment of airborne infectious entities requires investigation into their generation and also their particle sizes, aerodynamic properties, concentrations, infectivity and virulence, and viability with respect to climate factors (temperature, relative humidity).

Bioaerosol generation

Human source. Most respiratory infections (mycobacterial, viral) are transmitted by the air-

borne route from human sources through the inhalation of droplet nuclei. Such droplet nuclei are small ($<6\ \mu\text{m}$) infectious particles of respiratory secretions that are aerosolized by coughing, sneezing, talking, or singing. The CDC estimates that the size of the droplet nuclei carrying the TB bacilli is between 1 and $5\ \mu\text{m}$.²²

A cough can generate some 3000 droplet nuclei, as can talking for 5 minutes.¹⁵ A sneeze can generate as many as 40,000 droplets, which can evaporate to particles in the 0.5 to $12\ \mu\text{m}$ range.²³ The CDC states that the number of mycobacteria that are expelled into the air from a person with TB correlates with a number of factors, including the presence of cough or other forceful expirational maneuvers and the willingness or ability of the patient to cover his or her mouth when coughing.²⁴ Particles larger than droplet nuclei that settle out from the air can potentially be resuspended in the indoor air after decreased size from droplet evaporation, in combination with an aerosol-generating activity such as making a bed. Aerosol chamber studies have demonstrated the aerial dispersion of *Staphylococcus aureus* from the activity of a colonized operating room technician linked to wound infection in 11 patients.²⁵

Environmental source. Airborne opportunistic infectious disease microorganisms emanating from a variety of environmental sources have long been a concern with respect to nosocomial infection and hospital infection control practices. Susceptible health care and related workers are also at risk for infection with such agents.

Bacteria that have been implicated in airborne transmission in health care facilities include group A streptococci, *S aureus*, *Neisseria meningitidis*, and *Bordetella pertussis*.²⁶ An outbreak of methicillin-resistant *S aureus* in an intensive therapy unit was linked to the exhaust ducting of the adjacent isolation room ventilation system.²⁷ Legionnaires' disease has occurred from exposure to aerosols generated from contaminated cooling towers.²⁸ Additionally, the causative agent, *Legionella pneumophila*, has been isolated from aerosols produced by water faucets and shower heads,²⁹ by humidifiers and nebulizers,³⁰ and by squeezing manual ventilation bags.³¹

Fungi have long been involved in environmental source nosocomial infection. Sources of *Aspergillus* spores in health care facilities have been identified as outdoor construction,³² indoor construction and ceiling tile,³³ air conditioners,³⁴ and contaminated carpet.³⁵ Other potential environmental sources of a variety of *Aspergillus*

species are components of heating, ventilation, and air-conditioning systems, including contaminated filters, condensate, cooling coils, air intakes, and porous insulation in air ducts. In addition, aspergillosis in immunosuppressed patients at high risk has been associated with other hospital environmental reservoirs, including bird droppings in air ducts supplying high-risk patient areas³⁶ and contaminated fireproofing material or damp wood. The reported attributable mortality rates from invasive pulmonary aspergillosis vary, depending on the patient population studied. Rates have been as high as 95% among recipients of allogeneic bone-marrow transplants and patients with aplastic anemia, versus rates of 13% to 80% in patients with leukemia.³⁷

Microbial ecology. Every building has a microbial ecology, whose potential for human health effects can be minimized through proper design, construction, operation, maintenance, and cleaning. Of greatest importance are the extent and persistence of moisture in various structural, finishing, and furnishing materials. If relative humidity is uncontrolled, or if leaks, floods, or sewage backups are not readily and properly repaired, the result is an altered microbial ecology that permits the amplification (overgrowth) and dissemination of a number of fungal and bacterial species with potential for opportunistic nosocomial infection.³⁸

Microorganisms grow in moisture films on a variety of surfaces and within porous materials. The amount of free water available to them for growth on a substrate or microenvironment (such as wallboard, ceiling tile, carpet) is described as water activity (a_w), the ratio of the vapor pressure of water in the substrate to the vapor pressure of free water.³⁹ Increased a_w from high relative humidity, leaks, or floods, if allowed to persist more than 24 hours, changes the normal ecology of a microenvironment or entire building, with microbial competition resulting in the predominance of one or more organisms with potentially damaging effects upon materials and health.⁴⁰

Most fungi have a minimum requirement of a_w of at least 0.88. Some fungi have a lower limit of 0.66 to 0.70, however, which means that they require less water to germinate and amplify. These xerophilic fungi are best represented by the allergenic, toxigenic, and opportunistically infectious molds *Aspergillus* and *Penicillium*. Conversely, extremely wet microenvironments, particularly those with cellulose-based materials (such as dry-wall, wallpaper, and books), favor the growth of

fungi with high a_w , such as *Stachybotrys*, *Ulocladium*, and *Chaetomium*. *Stachybotrys* spores are known to contain tricothecene mycotoxins,⁴¹ and exposures have been associated with pulmonary hemorrhage in babies in contaminated home environments⁴² and with decreased immune function in workers in office buildings.⁴³

Bioaerosol size and aerodynamics

Infectious bioaerosol particles may exist as (1) single bacterial cells or spores, fungal spores, or viruses; (2) aggregates of several cells, spores, or viruses; or (3) biologic material carried by other, nonbiologic particles.⁴⁴ Microorganisms span wide size ranges. In general, infectious microorganisms range from 0.3 to 10 μm for bacterial cells and spores, 2.0 to 5.0 μm for fungal spores, and 0.02 to 0.30 μm for viruses. Specific pathogen sizes include 0.3 to 0.6 \times 1 to 4 μm for *M tuberculosis*;⁴⁵ 0.3 to 0.90 \times 2.0 to 20 μm for *L pneumophila*,⁴⁶ 2.5 to 3.0 μm for *Aspergillus fumigatus* spores⁴⁷; and 0.09 to 0.12 μm for influenza virus.⁴⁸ Most infectious particles generated from human respiratory sources occur primarily as droplet nuclei, 0.5 to 5.0 μm diameter.⁴⁹ As droplets are forcefully expelled from the respiratory tract, they begin to evaporate and thus change with respect to mass and aerodynamic diameter. On complete evaporation, the particles may be small enough to remain airborne in the indoor air flow. As pointed out almost 60 years ago, the size of droplet nuclei depends on the amount of solid matter contained in the evaporating droplet.⁵⁰

Microorganisms, however, are hygroscopic, and so the relative humidity of an indoor environment can have a dramatic effect on the particle's aerodynamic size, length of time airborne, and viability. The last is extremely important, because only a viable microorganism can initiate an infectious process. Gravitational, thermal, and electrostatic fields also affect the aerodynamic behavior.²³

Bioaerosol infectivity and virulence

The infectious disease process in an animal host is a function of microorganism concentration (infective dose) and virulence (disease promoting factors) that enable an agent to overcome the normal physical and immunologic defenses of the host. For human beings, the initiation of some microbial diseases requires only small infective doses because the agents have affinity for specific tissue and possess one or more potent virulence factors that render them resistant to inactivation. For example, infection with airborne *Francisella*

tularensis (the causative agent of tularemia) is reported to result from a single microorganism, whose virulence is associated with a cellular capsule.²³ Only a few cells of *M tuberculosis*, with its unique and resistant cell wall structure, are required to overcome normal lung clearance and inactivation mechanisms in a susceptible host. Susceptibility increases through long-term exposure and decreased immune function, which may result from a variety of natural or self-induced predisposing factors such as aging, crowded living conditions, heavy smoking, poor nutrition, and alcoholism. TB epidemics can occur among persons congregated in enclosed spaces, such as homeless shelters, nursing homes, hospitals, schools, prisons, and office buildings. Infectivity and the need for heating, ventilation, and air-conditioning engineering controls for TB were demonstrated more than 30 years ago. Experiments were conducted that exposed guinea pigs to air vented from a ward where patients with TB were receiving drug therapy. During a 2-year period, 71 of an average of 156 guinea pigs exposed continuously to the air from a 6-bed TB ward became infected.⁵¹ More recently, the contagiousness of *M tuberculosis* has been reviewed.⁵²

Viral infectivity and virulence are undoubtedly more readily noticeable to the general public. Each year, viral influenza epidemics sweep the globe, some with greater virulence than others. During major epidemics, influenza hospitalizations for persons at high risk may increase two to five times,⁵³ placing health care workers at increased risk for infection. Small infective doses are thought to be responsible because of the rapidity with which the disease spreads throughout a population. The natural airborne transmission of respiratory infection with the coxsackie A virus type 21 was investigated in 2 groups of adult volunteers. One was infected with the virus and the other, not infected and antibody free, was separated from the first by a double-walled, wire screen 4 feet wide.⁵⁴ Transmission of infection was demonstrated on day 6, as a wave of infection swept the previously uninfected group. Measles is a highly contagious viral disease that is spread by the airborne route. The infective dose is small, and as few as 4 doses per minute from an infected person can initiate an epidemic.⁵⁵ Additionally, rubella (German measles) and varicella (chickenpox) viruses can be readily spread by aerosols in indoor air.

Airborne fungi, most notably *A fumigatus* and other species, pose an extremely serious infectious disease threat to those who are immuno-

compromised as a result of immunosuppressive or cytotoxic therapy. Hospital outbreaks of pulmonary aspergillosis have occurred mainly among patients with granulocytopenia, especially in bone-marrow transplant units.⁵⁶ Although invasive aspergillosis has been reported in recipients of solid-organ (eg, heart) transplants,⁵⁷ the incidence of *Aspergillus* infections among these patients has been lower than among recipients of bone-marrow transplants, probably because granulocytopenia is less severe in solid-organ transplant recipients and the use of corticosteroids has decreased with the introduction of cyclosporine.⁵⁸

Inherent in the infection process initiated by the inhalation of infectious droplet nuclei is the area of deposition within the respiratory tract. Such deposition is influenced by hygroscopicity, which causes an increase in the size of inhaled aerosols through moisture take up as they move within the airways. Knight⁵⁹ estimates that a 1.5 μm hygroscopic particle—a common size in coughs and sneezes—increases to 2.0 μm in diameter when passing through the nose and to 4.0 μm in the saturated air of the nasopharynx and the lung. He further theorizes that the effect of hygroscopicity and the resultant particle size change increase retention in the tertiary bronchioles and alveolar ducts, an effect that may be significant for viral aerosols, which are highly infectious for that part of the lung.

Bioaerosol viability and climate factors

When pathogenic microorganisms leave their host and are aerosolized, they are potentially injured during the generation process. Additionally, once airborne they are outside of their natural habitat and, depending on a variety of environmental factors, are increasingly subject to loss of viability with time. Viability can be defined as the capability of a microorganism to reproduce. Even if a microorganism remains alive, if it cannot reproduce it can be considered nonviable because it has lost the ability to reestablish a population within a defined microenvironment. Factors influencing the survival of bioaerosols include their suspending medium, temperature, relative humidity, oxygen sensitivity, and exposure to UV or electromagnetic radiation. With a variety of bacteria, Wells and Stone⁶⁰ generated data indicating that microorganisms could remain viable in the airborne state for long enough to permit their wide dissemination. Once aerosolized in the indoor environment, microorganisms are subject to lethal desiccation, which

results from an interplay of organism morphology, physiology, oxygen sensitivity, and suspending medium, with varying levels of relative humidity and temperature, in addition to air movements, pressure fluctuations, air ions, and other airborne pollutants.²³ Thus the survival potential of any given microbial pathogen when aerosolized is unique to that organism under those specific conditions at that particular point in time. An assessment of environmental factors related to bacterial and viral survival in aerosols has been reviewed.⁶¹

Temperature and relative humidity. Temperature and relative humidity are important factors in aerosol survival. The effects of varied relative humidities can be studied only when temperature is controlled. In particular, many laboratory investigations have established that the effect of relative humidity on airborne microorganisms is an important but unpredictable factor. A study by Harper⁶² investigated the survival (for as long as 23 hours) of 4 viruses (vaccinia, influenza A, polio, and Venezuelan equine encephalomyelitis) aerosolized at varying temperatures and relative humidities in the dark. He found that in general viral survival at each relative humidity was better at lower temperature than at higher temperature. In addition, vaccinia, influenza, and Venezuelan equine encephalomyelitis viruses survived better at low relative humidity (17% to 25%), whereas polio viruses showed greatest survival at high relative humidity (80% to 81%). Another study⁶³ investigated the survival of 3 aerosolized human respiratory viruses (adenoviruses 4 and 7 and parainfluenza 3) in static chambers at 3 relative humidities (20%, 50%, 80%) and found that the adenoviruses survived better at 80% relative humidity, whereas the parainfluenza virus survived better at 20% relative humidity. The studies were carried out with aerosols with mass median diameters of about 2.0 μm . Davis et al,⁶⁴ conducting dynamic aerosol studies with adenovirus 12 at 28° to 30°C and 89%, 51%, and 32% relative humidity, found that survival increased as relative humidity increased and that the same relationship was present for the recovery of the virus from the lungs of exposed newborn hamsters. Schaffer et al⁶⁵ investigated effects of different means of virus propagation (cell cultures, egg cultures) on stability of influenza A virus at midrange relative humidity (50% to 80%) and showed varying survival to be related to method of propagation. More recently, Ijaz et al,⁶⁶ looking at survival of airborne human coronavirus 229E at different conditions of temperature (20°C and 6°C) and relative

humidity (30%, 50%, 80%), found that maximum survival of the aerosolized virus was extremely temperature dependent at 80% relative humidity. Theunissen et al⁶⁷ demonstrated efficient airborne survival of *Chlamydia pneumoniae* at 15° to 25°C and high relative humidity.

All these studies, as well as many others, indicate that the role of the environment in the survival of airborne microorganisms is extremely complex. For practical application to the control of airborne infectious agents, research must move from the laboratory test chamber to the actual indoor environment with previously developed standardized techniques and approaches.

ENVIRONMENTAL SAMPLING AND ANALYSIS

All existing methods of bioaerosol sampling are potentially applicable to the recovery of infectious disease agents from indoor air. Detailed reviews of bioaerosol sampling methods are available.^{23,68,69} Sampling focuses primarily on the recovery of viable microorganisms through methods of impingement, impaction, filtration, centrifugal separation, or electrostatic and thermal precipitation. All bioaerosol samplers fatally damage some portion of the total microorganisms collected. Such injury may occur through impaction onto culture media or other surfaces, or through sampler wall losses, turbulence in impingement fluid, or desiccation on filter media. Organism loss is also related to the rate of flow of air sampled. A filter method may sample at a rate of 4 L/min, whereas an all-glass impinger samples at a rate of 12.5 L/min, a sieve impactor at 28.3 L/min, a high-volume impactor at 180 L/min, and other high-volume samplers at hundreds or thousands of liters per minute. All samplers must be calibrated for flow rate before use, and their collection efficiencies must have been previously established as a function of particle size and shape.

Collection efficiencies are typically determined in controlled laboratory studies with particles of known size and shape under controlled conditions. A laboratory study of collection efficiencies of commonly used bioaerosol samplers was recently published⁷⁰; the physical factors affecting the performance of bioaerosol samplers, particularly with respect to the concept of stopping distance, have been intensively addressed.⁴⁴ Comparative sampler performance evaluations have also been conducted under field conditions with natural aerosols.⁷¹ Recent aerosol research has described the inlet sampling efficiencies of

several commercial bioaerosol samplers, as well as the design of a single-stage impactor that can be used to study different sampling and analysis variables that affect bioaerosol viability, such as relative humidity, sampling flow rate, and desiccation time.⁷² Such research can be critical in identifying sampling instruments and techniques to recover infectious agents that might be particularly sensitive to collection and are present only in small numbers in the indoor air, such as perhaps *M tuberculosis*. Efficient aerosol sampling methods and techniques for the collection of *M tuberculosis* from indoor air have not yet been described. Other airborne mycobacteria have been successfully recovered from the outdoor air, however, with impactor samplers with specified, enriched media.⁷³ A variety of aerosol sampling techniques and analysis procedures that have been used for the recovery of human viruses have been reviewed.^{69,74} The scope of the problem of sampling for airborne pathogens is exemplified by research results with natural aerosols of coxsackie A-21 virus.⁷⁵ It was found that if individuals harbored 10⁴ median tissue culture infectious dose of virus/ml oral secretions, sneezed 100 times in a closed room (70,000 L), and atomized 5.9 × 10⁻⁶ ml secretions with each sneeze, 12,000 L of air would have to be sampled to recover 1 median tissue culture infectious dose of virus.

Analysis of collected samples is no longer restricted to the collection of bioaerosols for viability culturing. New techniques commonly used in the clinical microbiology laboratory now have application to environmental monitoring, particularly when the goal is demonstration of airborne infectious agents. A variety of techniques, such as fluorescent antibody, monoclonal antibody, gene probe, and polymerase chain reaction, now afford other isolation and identification and confirmation options, particularly as rapid analysis and assessment of the indoor air becomes increasingly more important. Polymerase chain reaction in particular holds tremendous potential for the rapid and definitive assessment of airborne infectious agents not amenable to recovery by simple culture techniques, such as viruses, chlamydia, mycobacteria, and fungi such as *Histoplasma*.⁷⁶ Although bioaerosol recovery and rapid analysis methods and techniques have been addressed,⁷⁷ much research remains to be done to refine and standardize those optimal procedures that will prove effective with respect to the characterization of infectious disease aerosols.

RESEARCH NEEDS AND RECOMMENDATIONS

Model microorganism selection and use

Regardless of laboratory and aerosol test chamber data indicating the effectiveness of specific engineering controls, such potential applications must be eventually evaluated in actual indoor environments. Such studies in unoccupied buildings would require the aerosolization of one or more suitable model or indicator microorganisms. Such organisms would be required to be nonpathogenic to human beings, to be related to the target human pathogen, to possess similar aerosol and inactivation kinetics, and to be recoverable from the indoor air. The selection of such organisms would follow the determination from the literature of potential candidates, with subsequent chamber characterization in the aerosolized state, including assessment of potential recovery techniques. For example, *Mycobacterium phlei* would appear to be a candidate model organism for use in evaluating indoor engineering controls for preventing the airborne transmission of TB. *M phlei* is nonpathogenic for human beings, is a rapidly growing and pigmented environmental mycobacterium, and has been found to be 10 times more resistant to UV radiation than virulent *M tuberculosis*.⁷⁸ Its generation as an aerosol, perhaps in artificial sputum, would need to be assessed in the laboratory with respect to its resultant airborne characterization. Additionally, the appropriate collection medium and bioaerosol samplers would also need to be determined.

Similarly, model viruses and their recovery techniques could be selected for use in evaluating potential engineering controls in indoor environments. Aerosolized murine influenza viruses have been used as an infectious respiratory disease model,⁷⁹ and poliovirus type 1 and simian rotavirus SA11 have been used to assess germicidal effectiveness of UV light.⁸⁰ Bacteriophages have long served as excellent models for disinfection studies related to the inactivation of human viruses in water and waste water. Research is needed to determine which bacteriophages could serve as models of infectious human respiratory viruses in indoor air studies aimed at evaluating engineering controls.

Evaluation of existing engineering controls

Selected model microorganisms and sampling methods may be used to evaluate existing environmental engineering controls or combinations of controls for the prevention of airborne transmis-

sion of infectious agents in health care facilities. Three methods of air quality control are available: source control, removal control, and dilution control.⁸¹ Source control minimizes contamination within an occupied space, such as a laminar-flow bed providing local or source control for a patient with newly diagnosed TB. Removal control uses various air-cleaning devices to control particulates by either active or passive mechanisms. Active removal involves the use of devices with media filters or electronic air cleaners, such as the use of portable high-efficiency particulate air filtration units in the rooms of patients with TB, whereas passive removal involves mechanisms such as particle settling, ion diffusion charging, thermophoresis, and coalescence.⁸¹ Dilution control involves the reduction of airborne contaminants by the introduction of less contaminated air into the occupied space; this may occur through natural or mechanical ventilation.

Another air quality control that may be used in conjunction with other methods of particulate removal or dilution is UV air disinfection. The goal of this technique is to inactivate human pathogenic microorganisms in droplet nuclei in the air supplied to occupied spaces harboring potentially susceptible persons. Although it is recognized that different microorganisms vary in susceptibility to UV, the application of the technology to control airborne TB in health care and other work environments has been shown to be of value and is well described by Riley⁸² and Nardell.⁸³ The effectiveness of UV combined with a ventilation-filtration unit has been shown.⁸⁴

Evaluation of experimental engineering controls and devices

The research and development of experimental bioaerosol engineering control technologies may provide additional means of controlling infectious disease transmission in the indoor environment. For example, basic research on the use of pulsed high electric fields to inactivate microorganisms indicates the need for investigation of such a technique for potential applications to control airborne microbial contamination in air-handling systems.⁸⁵⁻⁸⁷

Although a variety of in situ optical techniques provide a powerful resource for the measurement of particle size distributions,⁸⁸ at present none can differentiate viable biologic particles from nonviable or nonbiologic ones. Dedicated research efforts aimed at the development of real-time devices to detect viable particles in nonviable or

nonbiologic airborne particulates could in the near future allow continuous monitoring and thus early warning detection or control systems in health care and other related facilities. Such devices would theoretically be designed to use light scattering or other physical means to detect only airborne microorganisms of certain pathogen groups, such as cells of mycobacteria, spores of *Aspergillus*, or perhaps even units of respiratory viruses. Further investigation is needed to demonstrate the feasibility of the concept of light scattering to differentiate viable biologic particles from nonviable or nonbiologic ones. Basic light scattering studies with an electrodynamic balance have been published.^{89,90}

RECOMMENDATIONS FOR PREVENTION OF TRANSMISSION OF INFECTIOUS AEROSOLS

An understanding of the factors affecting the generation, survival, and transmission of infectious aerosols in hospitals and other health care facilities is crucial to the task of preventing airborne-associated nosocomial infection. Ideally, the mechanisms for minimizing environmentally related infections should be addressed beforehand in every aspect of building design, construction, operation, and maintenance.

The entire indoor health care environment must be viewed as a distinct ecosystem, within which patients interact with a myriad of environmental occurrences on a continuing basis. To ensure that these occurrences present no increased risk of airborne transmission of infection, a series of basic environmental management strategies gleaned from the indoor environment research community are recommended. These include source management, activity management, design intervention, dilution intervention, and cleaning.

Source management

Every airborne infectious agent comes from a source, whether a human being, an animal, a material, or a surface. Sources can be managed either through removal, such as in the case of mold-contaminated building materials, or modification, such as by purging hot water systems to eliminate *Legionella* species. Patients with active TB can be housed in negative-pressure rooms, required to wear respirators, or placed in laminar-flow beds until shown to be noninfectious. Sources can also be managed through a program of building maintenance that ensures appropriate and routine inspection of potential sources, such as air intakes and filter banks; heating, ventila-

tion, and air-conditioning unit components; air ducts; cooling towers; and hot water systems. Environmental sources can also be managed through efficient and routine cleaning practices that remove potentially infectious particles and reduce pollutant source reservoirs, such as carpet and other dust-contaminated surfaces. Recent research on indoor pollutant sources and sinks showed positive correlations between airborne dust mass and airborne bacteria and fungi, carpet dust mass and carpet dust fungi, and carpet dust bacteria and airborne bacteria.⁹¹ One of the leading causes of nosocomial infectious aerosol transmission is fungal contamination generated by nearby construction and renovation. An excellent, proactive guide to dealing with dust control and containment from construction, *Infection Control Issues in Construction and Renovation*, was recently published.⁹²

Activity management

Activity management is the process of ensuring that the building is used for the activities that it was designed to accommodate. Sometimes when indoor air pollutants are encountered, it is the result of the building or section of the building being used for some other reason than that for which it was originally designed. Examples include laboratories in structures that were designed to be offices or living quarters, or offices in areas that were formerly laboratories. Use of a building in the way that was originally intended also facilitates and promotes a routine program of inspection, maintenance, and cleaning. Such a program can become an afterthought when a hospital is continually renovating the existing structure, constructing additions, or otherwise modifying the built environment.

Design intervention

Buildings and their furnishings need to be designed so that they can be effectively inspected, cleaned, and maintained. Design intervention is important when designing new buildings, as well as when remodeling an old structure for new use. Such interventions could include special exhaust ventilation or other airflow requirements or the removal and exclusion of certain building or furnishing materials that are particularly susceptible to microbial contamination, such as ceiling tile and carpet.

Dilution intervention

Dilution is the process used to make airborne pollutants less concentrated by replacing conta-

minated air with clean air. Infectious airborne particles may be moved by air and captured by air filters. For example, a study was conducted to investigate the effectiveness of in-room air filtration with dilution ventilation for control of TB infection.⁹³ Results showed that ventilation plus recirculating air filtration could achieve reductions of droplet nuclei concentrations with 30% to 90% effectiveness. This, in combination with source management controls such as treatment booths and respirators, could significantly lower transmission potential in high-risk settings. Similarly, in controlling nosocomial aspergillosis, high air-exchange rates are the most effective, particularly in combination with point-of-use filtration.⁹⁴ A guide to air exchanges per hour and the time required (in minutes) for removal efficiencies of 90%, 99%, and 99.9% has been published.⁹⁵ The figures of the guide are helpful but somewhat limited in value, because they assume perfect mixing of the air within the space and do not account for the resuspension of particles that have fallen out and are subsequently stirred up through activity. As previously mentioned, high air-exchange rates are most effective when combined with filtration.

Cleaning

Cleaning is the process of identifying, containing, removing, and properly disposing of contaminants from a surface or environment. It is the final defense in managing indoor environment contamination. Even if source management, activity management, design intervention, and dilution ventilation have all been optimally used to control infectious aerosols, cleaning is still necessary, although cleaning should become easier as each strategy is improved. The importance of cleaning was demonstrated in a year-long study of cleaning effectiveness in a multiuse building without evident problems.⁹⁶ The routine use of high-efficiency vacuum cleaners, damp dusting, and improved cleaning products, particularly in high-traffic areas, with attention to events such as leaks and spills, resulted in meaningful decreases in particulate and microbial contamination. After 7 months of improved cleaning practices and environmental monitoring, the data showed a significant decrease (50%) in airborne dust mass, a 61% decrease in airborne fungi, a 40% decrease in airborne bacteria and carpet dust fungi, an 84% decrease in carpet dust

bacteria, and a 72% reduction in carpet dust endotoxin.

SUMMARY

Control and prevention of the transmission of airborne infectious agents in the health care environment begin with an understanding of their origins, aerodynamics, survival, and infectivity so that appropriate engineering controls can be effectively implemented within an environmental management framework of preventive strategies that include source management, activity management, design intervention, dilution intervention, and cleaning. Such a total-environment concept is absolutely essential to reduce the risk of nosocomial airborne infection transmission to the lowest level possible. In particular, hospitals and other inpatient facilities should ensure that both infection control personnel and a certified industrial hygienist are involved both before and during any building renovation and construction.

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