ARTICLES—GENERAL

Source, Significance, and Control of Indoor Microbial Aerosols: Human Health Aspects

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SYNOPSIS ....

The usual profile of indoor microbial aerosols probably has little meaning to healthy people. However, hazardous microbial aerosols can penetrate buildings or be generated within them; in either case, they can have significant adverse effects on human health. These aerosols can be controlled to some extent by eliminating or reducing their sources. In this regard, careful consideration should be given in building construction to the design of ventilation and air-conditioning systems and to the flooring material, so that these systems and the flooring material will not act as microbial reservoirs.

It is evident that in spite of the considerable body of data available on indoor microbial aerosols, little is known of their true significance to human health except in terms of overt epidemic disease. Continued research is needed in this area, particularly in respect to situations of high risk in such locations as hospitals and schools for young children.

THERE IS LITTLE DOUBT that the pollution caused by microbial aerosols inside of dwellings, hospitals, and various other buildings and enclosures presents specific hazards to the human occupants. Examples of respiratory disease resulting from aerosols of infectious micro-organisms range from episodes of inhalation anthrax in textile mill workers to the long and well-documented history of nosocomial infections. Although considerable attention has been given to aerosols out of doors, it has become increasingly apparent that indoor aerosols place human occupants at greater risk because an enclosed space confines and protects the aerosol, which thus can dose the occupant for an extended period. Riley (1) stated that the atmosphere of a building along with its occupants constitutes an ecological unit throughout which aerosols from various sources move on air currents. The principal source of these aerosols, of course, is man himself, who by various means such as coughing or even talking, expels droplets, which form droplet nuclei (1–5 µm) capable both of remaining suspended for long periods and of penetrating the deep recesses of the human lung. Other hazardous aerosol sources include materials of animal origin that are brought indoors for manufacturing activities; indoor aerosols also may result from penetration into structures from external sources or from saprophytic growth within the structure (2).

Most studies of indoor microbial aerosols to date have focused on determining the sources of specific illness episodes in institutions such as hospitals and schools. Nosocomial airborne infection, for example, has received particular attention because hospitals contain both hypersusceptible and hyperinfectious people (1). Schools with young children represent another particularly unique opportunity for airborne infection, and classic studies of airborne disease epidemiology have been done in such schools (3).

However, although considerable interest has been shown in specific episodes involving aerosols, the subject generally has been somewhat overshadowed, during the past decade particularly, by interest in outdoor air pollution and, more recently, by indoor chemical pollution. The principal purpose of this review is to put the whole question of indoor microbial aerosols into perspective as it relates to present aerosol technology. In this review, we examine (a) the characteristics of various indoor microbial aerosol sources, (b) the significance of these aero-

sols to the health of the human occupants of these indoor areas, and (c) the state-of-the-art methodology for their control.

Known Sources and Affected Environments

Animate sources. Animate sources, for this discussion, include microbial aerosols that arise from living entities, plant or animal, or products derived from them. The discussion of these sources is not meant to be all encompassing but only to illustrate various conditions.

Human sources. The most important animate source of indoor microbial aerosols for man is man himself. Aerosol particulates from the human body arise principally from two sources: (a) droplet nuclei formed from droplets expelled from the nose and mouth and (b) small fragments of desquamated skin that arise as a result of body motion and various activities (4). In addition, some aerosols may result from toilet-flushing (discussed later in subsection on "Inanimate aerosol sources," page 236).

Droplet nuclei. Talking, coughing, or sneezing may result in air velocities in the respiratory tract that reach 100 meters per second in the mucous-membrane-lined passages (5). The surface energy created by this high air velocity causes small amounts of mucous secretions to be expelled as fine droplets, from which droplet nuclei are formed from the nose and mouth. Indeed, Jennison (6) showed by high-speed photography that up to 40,000 droplets (80 percent less than 100 μm in diameter) were expelled during a violent sneeze, whereas a cough produced only a few hundred such droplets. These expelled droplets rapidly come to equilibrium with ambient humidity, forming droplet nuclei. Duguid (7) showed that 97 percent of these droplet nuclei were in the range of 0.5 to 12 μm in diameter, the majority of these being from 1.0 to 2.0 μm in diameter. These small particles can remain suspended in room air for more than 90 minutes. Particles of this size are deposited in the upper respiratory tract, and some reach the deepest recesses of the lungs, where contained pathogens have the greatest chance to initiate infection. Using bacterial spores and bacteriophages as tracers, Buckland and Tyrell (8) observed that sneezing and blowing the nose were more than 1,000 times more efficient than coughing in producing infectious aerosols from nasal secretions. These results confirmed Jennison's earlier work comparing coughing and sneezing (6). A

question exists, however, regarding the contribution that indoor aerosols formed by coughing and sneezing make to human disease. Gwaltney (9), for example, showed that infections caused by rhino viruses are not generally airborne. He reported that virus could be recovered from only 1 in 13 infected volunteers as a result of sneezing and only 1 in 12 as a result of coughing. These data indicate that infected people are not necessarily disseminators of the common cold virus.

Desquamated skin. Aerosolized particulates resulting from desquamated skin have been investigated, primarily in hospitals, as sources of *Staphylococcus* aerosols. Staphylococci and various other organisms are found on these skin particles, which, according to Noble (10), have a mean equivalent diameter of 13.5 μm. Lidwell and associates (11) demonstrated that these airborne particles, assumed to be largely skin scales, average four viable *Staphylococcus aureus* cocci per scale. Pinkus (12) indicated that a complete covering of skin is shed every 1 or 2 days, depending on individual and regional differences. On the basis of the work of Noble (10) and Pinkus (12), Clark and Cox (13) calculated that on the order of 7 million skin scales per minute are liberated from the human body. Although the average size is about 13 μm in diameter, it should be noted that substantial numbers of these skin particles are of a size (less than 10 μm in diameter) that would allow them to remain suspended for prolonged periods. Noble (10) showed that about 30 percent of the particles carrying staphylococci are less than 10 μm in equivalent diameter. Using a high-volume (730 liters per minute) slit sampler and a glass cyclone sampler, May and Pomeroy (14) were able to sample up to 17,651 colony-forming particles per minute from a naked man.

Skin particles detach themselves through the abrasive action of fabrics (13,15) such as bedding and clothing. Consequently, bed-making has been shown to contaminate the air of hospital wards (4), and the abrasive action of clothing seems to dominate as a method of detaching particles from the skin (13). The bellows action of clothing caused by movement pumps large quantities of air, and this pumping action carries skin particles through the openings. Particles shed from the surgeons' body, for example, can penetrate gown fabrics or escape through leg, arm, and neck openings of the gown (4,16). The natural convective boundary layer around the warm human body has air velocities cap-

able of transporting particles of greater than 50 μm diameter upwards (*13*). These aerosols can be controlled somewhat by wearing tightly woven fabric and by sealing openings around trouser bottoms and the wrist and neck.

It is interesting to note that men appear to be more profuse disseminators of bacterial aerosols than women (*14,15,17*). Hill and associates (*17*), for example, showed that significantly more men shed *S. aureus* organisms than women, and that the shedding increased with friction of clothing against the skin. The main site of shedding for men was found to be the perineal area. May and Pomeroy (*14*) also observed higher bacterial aerosol dissemination rates for men, particularly naked men. Their results are summarized in table 1. As noted in the table, the highest total output of colony-forming particles per minute was 17,651 from a naked male and the lowest, 237 from a clothed female. These particles contained a wide variety of micro-organisms, most of which were staphylococci and fungi. Males showed a marked increase of shedding when naked compared to when clothed. Clothing apparently acted as a particle absorber.

To determine the effects of showering and subsequent dressing on the production of bacterial aerosols in a communal high school shower, Adams and associates (*18*) took air samples before and after two shower periods of a boys' gym class (12 to 18 boys each). During the regular procedures of dressing for gym class, undressing after class, showering, and changing to street clothes, a rise and fall of airborne bacterial concentration, as shown in figure 1, was observed. Although significant numbers of aerosolized bacteria resulted from dressing and undressing, the highest numbers were associated with showering. About 51 percent of the aerosolized particles were in the respirable size range (less than 5 μm), and the majority of the organisms were found to be staphylococci. The aerosols did not have a long residual time, probably because of the decay of viability, physical removal by ventilation, or both. Showering can increase the rate of shedding of microbial aerosol particles for up to 1 hour afterwards (*19*).

Animal sources. It is reasonable to assume that animals shed aerosol particles in a fashion similar to man, that is, through respiration and shedding from the hide. In addition, fecal droppings and urination can be sources of microbial aerosols. The significance of these aerosols to human health, of course, depends partly upon the kind of organisms

Table 1. Total output per minute of colony-forming particles by male and female subjects, clothed and unclothed

Number, sex, and state of subjects	Mean total output	Ratio (95 percent limits)	Ratio unclothed to clothed
17 males:			
Clothed	1,008	+ 238 ⎫	
Unclothed ...	4,247	+2,087 ⎭	4.21
11 females:			
Unclothed ...	810	+ 551 ⎫	
Clothed	753	+ 649 ⎭	−1.08

NOTE: The male-to-female ratio was 1.34 clothed and 5.2 unclothed.
SOURCE: Adapted from table in reference 14, page 430.

Figure 1. Microbial aerosols from showering and dressing in a high school boys gym class
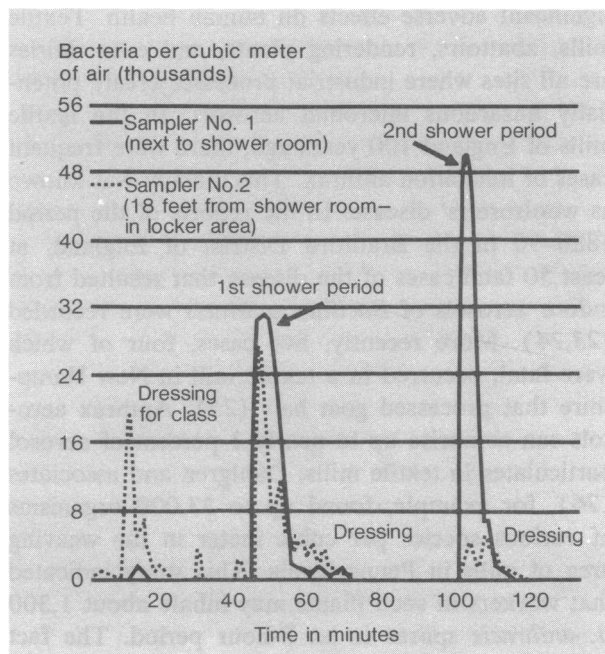
found in the resulting aerosol particles. Viruses such as rabies, for example, were isolated from the air of natural caves frequented by bats (*20*), and the transmission of the resulting disease to human beings via the aerosol route was indicated (*21*).

Indoor transmission of disease between animals by aerosols is well established for Newcastle disease, Rift Valley fever, Venezuelan equine encephalitis, yellow fever, and similar diseases (*22*). Zoonotic infection by aerosol is also conceivable for any micro-organism to which both man and animals are susceptible. A more exhaustive review of this subject should provide numerous other examples of disease transmission to human beings from aerosols arising from animals kept indoors.

'... men appear to be more profuse disseminators of bacterial aerosols than women ... significantly more men shed S. aureus *organisms than women and ... the shedding increased with friction of clothing against the skin.'*

Likewise, indoor processing of animal products can generate high concentrations of microbial aerosols that may contain organisms with potentially significant adverse effects on human health. Textile mills, abattoirs, rendering plants, and even dairies are all sites where industrial processes create potentially hazardous microbial aerosols. In the textile mills of England 100 years ago, there were frequent cases of inhalation anthrax. This malady was known as woolsorters' disease. In the reports of the period 1880–90 in the Bradford District of England, at least 50 fatal cases of the disease that resulted from indoor aerosols of *Bacillus anthracis* were recorded (23,24). More recently, five cases, four of which were fatal, occurred in a textile mill in New Hampshire that processed goat hair (25). Anthrax aerosols can comprise up to nearly 1 percent of aerosol particulates in textile mills. Dahlgren and associates (26), for example, found up to 33,000 organisms of various species per cubic meter in the weaving area of mills in Pennsylvania. This study indicated that workers in such plants may inhale about 1,300 *B. anthracis* spores in an 8-hour period. The fact that no cases of inhalation anthrax were recorded from these mills shows that apparently a higher dose of *B. anthracis* is needed to initiate infection.

Q fever can also be contracted through exposure to aerosols produced in textile mills and other factories that handle animal hides and hair (such as furniture manufacturing plants). In Pennsylvania, a sizable outbreak of this disease was reported by Sigel and associates (27) in a wool- and hair-processing plant that used unscoured wool from several countries. Gutscher and Niefer (28) reported a series of Q fever cases in personnel employed by a furniture manufacturing firm in Switzerland, in which the attack rate reached 55 percent. Textile mill activities produce aerosolized dust particles of small size that can remain suspended for long periods, especially in poorly ventilated areas, and allow exposure of plant personnel to large doses of microbial aerosol. In many cases, improved ventilation would substantially reduce the risk of infection.

Other frequent sources of infection from the aerosols that cause Q fever are abattoirs and rendering plants that process infected animals. Historically, Q fever is a disease of abattoir workers and is sometimes called "abattoir fever." Aerosol infections in abattoirs occur in virtually every major country in the world. In Australia, Dyer (29) reported aerosol infection to be widespread not only in abattoirs but also in dairies. Sporadic cases of Q fever of apparent aerosol origin occur not only in rendering plants (30,31), but also in tanneries (30).

Both abattoir and rendering plants are often sources of aerosols that cause disease among employees. Increased risks occur when farm and ranch livestock begin to show signs of epizootic disease and the owner hastens them to market to avoid large economic losses. Processing infected animals can result in infectious aerosols that diffuse throughout the plant. Additionally, animals already dead at the farm may be offered or sold to rendering plants for salvage for hides, fat, and protein products. Such a situation occurred in an ornithosis (psittacosis) outbreak in turkeys on ranches near Portland, Oregon, in 1956. As reported by Holmes and Osgood (32) and Spendlove (33), live turkeys with inapparent disease were processed by a local abattoir; dead birds were processed by a rendering plant. Aerosols resulting from processing caused human disease in the employees of both plants. An ornithosis incidence rate of 75 percent occurred among the 32 rendering plant employees. Results of a subsequent investigation by Spendlove (33) with tracer organisms indicated that the rendering process produced aerosols that diffused throughout the plant, even to exterior downwind areas.

Brucellosis from aerosol transmission is another disease frequently found in abattoirs. Hendricks and associates (34) reported a widespread brucellosis epidemic in an abattoir that was transmitted by aerosols. Here, differences in attack rates among workers doing comparable work on different floors were thought to be related to different levels of exposure to the aerosols generated in the kill department. In six separate plants, Kaufman and associates (35) found that the largest incidence of brucellosis occurred in the kill department, but they also noted that in many cases the diseased person had no direct contact with animal material, a result indicating aerosol transmission. Complete separation of the other units of the abattoir from the kill area, which

Table 2. Prevalence of byssinotic symptoms

Workplace	Number of workers employed	Number of workers interviewed	Percentage prevalence of byssinotic symptoms	Endo agar bacteria [1]	Nutrient agar bacteria [1]	Fungi [1]	Endo- toxins
Cotton spinning mill:							
1	40	36	33	2,800	26,200	7,100	0.62
2	55	48	40	3,500	76,900	5,600	.93
3	27	22	7	335	7,600	11,500	.32
4	77	69	28	3,100	16,400	1,500	1.60
5	72	71	21	2,900	16,100	3,800	.80
6	46	46	17	1,950	17,600	9,600	.80
7	97	91	12	1,550	9,700	4,400	.20
Cotton waste mill:							
1	58	57	12	1,500	4,600	1,750	1.24
2	56	52	0	710	850	1,450	.80
Willowing mills	59	59	5	1,100	7,700	22,500	.40
Wool mill	44	42	0	180	14,800	2,500	.00
Tea-packing factory .	89	85	0	300	800	5,200	.00
Pipe tobacco factory .	..	..	0	490	2,100	950	.00

[1] Number per cubic meter.   NOTE: Italicized numbers are mean values for 2 observations.   SOURCE: Based on reference 38.

was operated under negative air pressure, reduced the risk of infection.

In the Mississippi River Valley, various kinds of structures can be significant sources of infectious aerosols of *Histoplasma capsulatum,* the causative agent of histoplasmosis. Infectious aerosols of this agent can be generated by cleaning such structures as chicken coops and other areas that are frequented by birds. The majority of the numerous epidemics of histoplasmosis reported have been traced to aerosol dust exposure (*36,37*).

Plant sources. The human health consequences of exposure to aerosols from plant sources are generally less important than the consequences of exposure to aerosols caused by animal sources and animal products. The reason is simply that microorganisms associated with plants are less frequently pathogenic to man. Aerosols associated with the handling of plants and their products can, nevertheless, adversely affect human health. Microbial aerosol associated with cotton dust, for example, produces byssinnosis among workers in cotton mills. Cinkotai and associates (*38*) studied the concentration of microbial aerosols and their endotoxins in relation to the prevalence of byssinotic symptoms among workers in the cardrooms of seven cotton spinning mills, a wool spinning mill, and two cotton waste mills. In addition, they examined aerosols in a tea packing plant and a pipe tobacco factory. Their results are shown in table 2. The concentration of organisms cultured on endo agar plates correlated

with the prevalence of byssinosis to a high degree of confidence. Those organisms cultured on nutrient agar had high concentrations of colony-forming units, up to 76,900 per cubic meter, but they showed less correlation with byssinosis prevalence; the fungi and endotoxins demonstrated no significant correlation. Cinkotai and associates concluded that gram-negative bacteria were closely linked with the prevalence of byssinosis.

Industrial plants that process vegetables for freezing can also produce significant quantities of microbial aerosols. Mundt and associates (*39*), for example, found aerosols of *Leuconostoc* and *Aerococcus* along with many different species of streptococci, particularly *Streptococcus faecalis,* in such plants.

Laboratory sources. Microbial aerosols arising from various laboratory procedures are well known. Studies with lengthy lists of laboratory-acquired infections (*40–42*) exist that document many aerosol-transmitted diseases. In addition to the time lost from work due to these infections, Hanson and associates (*40*) noted that 4 percent of 428 laboratory-acquired arbovirus infections reported up to 1967 were fatal. Most of these infections were associated with a nonspecific incident in which the likelihood of aerosol production occurred during routine laboratory procedures. Among the most frequently reported laboratory-acquired viral infections are infectious hepatitis, Venezuelan equine encephalitis, and Newcastle disease (*43*). There is also evidence

that Epstein-Barr virus can be transmitted in aerosols from blood and result in infectious mononucleosis among hospital laboratory technicians (44). Transmission of a number of diseases between adjacently caged, experimentally infected laboratory animals has been demonstrated, such as herpesvirus simiae infection, Newcastle disease, Rift Valley fever, Q fever, tuberculosis, brucellosis, histoplasmosis, and psittacosis. Aerosols have been controlled by combinations of air-washing aerosol-exposed animals and placing filter tops or ultraviolet irradiation over their cages (45).

Pike (42) indicated that among 37 bacterial species implicated in laboratory infections, those causing brucellosis, typhoid fever, tularemia, and tuberculosis accounted for 64 percent of these infections. A large portion of these can be traced to indoor aerosols. The largest recorded laboratory epidemic of brucellosis occurred in Michigan and resulted in 45 clinical cases (including 1 fatal case) and 49 subclinical cases from December 1938 to February 1939 (46). In this incident, the majority of those affected were students in a class on the second and third floor of a building with a brucellosis laboratory in the basement. In this case, all modes of transmission of the disease except aerosol were eliminated by the investigators.

Ventilation, Air-conditioning, and Penetration

Ventilation and air-conditioning systems can be sources of microbial aerosols either from contaminated air entering the system or directly from microbial growth within the system. Air entering the system comes either from a source external to the structure or from recirculated air from the inside. If air comes from an external source, outside aerosols penetrate the structure through air-intake plenums, whereas if the air is recirculated from inside, aerosols from various inside sources are transported and disseminated throughout the structure by the ventilation or air-conditioning system. For these reasons, care must be taken in ventilation- and air-conditioning design to ensure that microbial aerosols from these sources are minimized. Particular care must be taken in placing the intake plenum so that it does not draw aerosols from sewer vents, cooling towers, and various other obvious outside sources. When all or most of the air is recirculated from the inside, inside sources of microbial aerosols must be considered in the design of the system. In this regard, closed environments such as submarines, ships, and other structures in which virtually all the inside air is recirculated can present particular problems. Houk (47), for example, reported an extensive epidemic of tuberculosis in a naval ship that probably resulted from a single person's disseminating aerosol by coughing, singing, and talking—aerosol that was "evenly spread" throughout the vessel by the ventilation system.

The role of the ventilation system in the spread of measles in an elementary school was documented by Riley (48). In this case, 60 children in kindergarten through first grade in a modern elementary school were affected. The means of spread was shown to be directly related to the ventilation system. Ventilation within hospitals has special significance for the occupants of these structures because of the nosocomial infections that occur from this source. Walter (49) stated that unfortunately comfort, rather than hygiene, is usually the objective of hospital ventilation systems. He pointed out that airborne disease transmission through these systems occurs by means of such vehicles as dust, droplets, and droplet nuclei. The dust that is transmitted includes fragments of dried excrement, excretion discharges, contaminated lint, or desquamating epithelium, as previously noted. Droplets and droplet nuclei generally arise from human vocal activities. In this regard, Walter (49) noted that people who are carriers lend both ubiquity and continuity to the dissemination process.

Aerosols laden with S. aureus are of considerable importance in disease production, particularly in hospital environments. Shaffer and McDade (50) reported the spread of this organism from an active patient ward to an empty ward. Recirculation of the inside air by the air-conditioning system was responsible for the aerosols' spread; the problem was eliminated by thorough cleaning and chemical disinfection. The spread of S. aureus and other organisms by air movement is of major concern in operating rooms. To reduce the potential risk of infections caused by these aerosols, various modes of air movement from the ventilation system, such as "laminar air" flow, have been used to attempt to control aerosol contamination of open surgical wounds.

Gunderman (51) indicated that microbial growth within ventilation systems may occur at any time when the air comes in contact with water, when water is present in the system, or when the relative humidity exceeds 97 percent. Pseudomonas species are common organisms found to grow and disseminate in aerosols from ventilation systems. For example, Anderson (52) reported that Pseudomonas

pyocyanae (*Pseudomonas aeruginosa*) was spread from water in the cooling unit of a ventilation system. Gunderman (*51*) isolated both *Klebsiella* and *Pseudomonas* species, as well as sporeforming bacteria and mold fungi.

Overwhelming evidence has accumulated indicating that *Legionella* species grow within air-conditioning cooling towers. Aerosols formed by these units, if located near intake plenums of ventilation systems, can be drawn into the systems and disseminated throughout the affected buildings, where they can result in human infection. An explosive outbreak of the Pontiac fever form of legionellosis in 1968 was shown to be spread by the air-conditioning system of the office of the Pontiac County (Michigan) Health Department (*53*). In this case, 95 of 100 employees and 49 of 170 visitors to the building over a 5-week period were infected. Another epidemic of legionellosis in which a ventilation system was involved occurred in a Memphis, Tenn., hospital in 1978 (*54*). Again, a cooling tower near an air intake was involved. In this case, 44 people were affected. Cooling towers use large volumes of water, which continuously pass through evaporative condensors in which refrigerant gas is condensed. Mallison (*55*) stated that although cooling towers are not a natural reservoir for *Legionella,* and these organisms may originally come from the soil or natural bodies of water, wind may spread them from these sources to the cooling towers. There they are scrubbed out by the action of the water spray and grow to be disseminated as aerosols created by operation of the cooling towers. Ventilator intakes located nearby then disseminate these aerosols throughout the structure.

Unless special precautions are taken, outside aerosols that are potentially hazardous also penetrate structures by natural ventilation, through windows, doors, and other openings. Spendlove (*56*) showed that a variety of potentially hazardous aerosols are available to pentrate residences and other structures. These aerosols arise from industrial activities in rendering plants, abattoirs, and textile mills, from sewage treatment facilities, and from agricultural activities. The study indicated that from both empirical and theoretical standpoints, residential dwellings offer little resistance to penetration by these aerosols. Factories, hospitals, and public buildings with closed doors and windows offer some resistance, but penetration by natural ventilation also occurs in these structures. Air-conditioning, on the other hand, tends to significantly reduce penetration. The condensation of aerosols on the cooling coils probably acts somewhat as a filter, thus reducing penetration. As a result, the air-conditioner exerts a slight positive pressure on the building if the windows and doors are kept closed, and penetration of aerosols is reduced by natural ventilation processes.

Humidifiers and Inhalation Therapy Equipment

Humidifiers are potential sources of airborne micro-organisms that cause both respiratory infections and immune reactions in sensitized persons. A study of respiratory tract infections caused by *P. aeruginosa* by Grieble and associates (*57*) demonstrated that unheated, uncovered room humidifiers were a source of hospital-acquired *Pseudomonas* pneumonia. *Acinetobacter calcoaceticus* was reported by Smith and Massanori (*58*) to be the source of several systemic infections. These authors suggested that the organism may have spread from the humidifier to the skin and finally to the blood by an intravenous catheter, since entry into the blood via the respiratory tract appeared unlikely. Smith and Massanori emphasized the dangers of cold-air humidifiers in an inpatient setting.

Pathogens isolated from home humidifiers in the United States are principally thermophilic actinomycetes of the *Thermoactinomycetes* genus (*59*). These organisms are rich sources of antigens in several types of hypersensitivity pneumonitis induced by organic dust. Hypersensitivity pneumonitis is an example of an immune complex in sensitized persons following their repeated inhalation of these antigens (*60*). This disease, sometimes called humidifier fever, is similar to farmer's lung disease (*61*). Describing an outbreak of hypersensitivity pneumonitis in a husband and wife as a result of using a cold-mist vaporizer, Richerson (*62*) emphasized the subtle presentations of allergic alveolar diseases and the difficulties in arriving at a definitive diagnosis. Kohler and associates (*63*) determined that thermotolerant bacteria found in patients' home humidifiers (bacteria with enhanced growth at 56° C) were the cause of hypersensitivity pneumonitis. In England, various amoebae, including *Naegleria gruberi,* have also been associated with humidifier fever (*61*).

Seabury and associates (*59*) isolated a large number of sporeforming and nonsporeforming thermotolerant bacteria of undetermined disease significance, along with the *Thermoactinomycetes* genus, from virtually every home-humidifier water sample they analyzed. Covelli and associates (*64*) showed

that 70 percent of the fine-particle humidifiers studied disseminated at least 480 viable particles per hour and that 30 percent of these devices emitted more than 12,000 viable particles per hour. Vapor-type humidifiers were also shown to be a potential source of airborne microbial contamination.

Studies by Burge and associates (65), however, indicated that humidifiers do not significantly contribute thermophilic actinomycetes to the air. Although these organisms were recovered from 6 percent of the humidifiers studied, they were found in the air in 100 percent of the homes studied. In those homes, furnace humidifiers were more frequently free of micro-organisms than the console type of humidifiers. Based upon their observations, these authors concluded that the risks of air contamination are not clear and are not great enough to warrant discontinuing use of humidifiers.

Studies of inhalation therapy equipment by Reinarz and associates (66) demonstrated that those instruments with reservoir nebulizer assemblies generated aerosols containing large numbers of gram-negative bacilli, namely, Pseudomonas species, Flavobacteria species, Herella species, Alcaligenes faecalis, and Achromobacter species. They reported a tenfold increase in the incidence of acute gram-negative necrotizing pneumonias in a hospital following the introduction and widespread use of such inhalation therapy equipment. Pseudomonas and Alcaligenes were the most commonly isolated organisms in a 2-year study (67) of the fluid from heated nebulizers. Castle and associates (68) reported that intubation and continuous ventilating assistance were significantly associated with A. calcoaceticus infections among patients in a surgical intensive care unit.

Inanimate aerosol sources. Inanimate reservoirs of potentially infectious micro-organisms can, if disturbed, become sources of microbial aerosols. Although our environment is not sterile, gross contamination of objects that can produce microbial aerosols in structures such as hospitals, in which there are high densities of immunologically depressed persons, should arouse public health concerns.

Floor covering material is one such potential source of airborne micro-organisms. Walter (49), for example, noted that the floor is the largest and most persistent secondary bacterial aerosol reservoir in the hospital environment. Bacteria were shown by Ayliffe and associates (69) to accumulate rapidly on hospital floors, reaching a fluctuating equilibrium

concentration after about 24 hours and then reaching a higher level after about 14 days. Using a plug sampling technique, Anderson (70) found evidence of high levels of carpet contamination in patient care areas. The microbial concentrations on carpeted floors were found to be up to 100 million organisms per square meter (10 million per square foot), which were about 4 orders of magnitude higher than those observed on uncarpeted floors. Redispersion of these organisms into the air was found, however, to be more heavily influenced by the floor traffic than by the type of floor covering (71). Walking on floors was shown by Hambreeus and associates (72) to redisperse S. aureus from contaminated floors about three times more readily than direct blowing air and about 17 times more readily than mopping. It was noted that walking can produce air currents that effectively move particles upward. The degree of dispersion expected was determined by a redispersion factor (Ne):

$$Ne = B/(R + S) \qquad (1)$$

Where B is the rate of dispersal,
R is the rate of ventilation, and
S is the rate of sedimentation.

Redispersion was determined to be inversely proportional to the rate of removal and could be effectively reduced by increasing the ventilation rate. Since vacuuming and shampooing did not effectively reduce micro-organism contamination from carpets, Anderson (70) recommended the use of hard-surface floors in hospitals. Walter (49), however, recommended that these floors be designed to withstand flooding.

Other studies of the influence of carpeting on microbial aerosols have, on the other hand, failed to demonstrate higher concentrations in carpeted versus noncarpeted areas (73). In preliminary studies, Shaffer (74) and Shaffer and Key (75) also found no evidence that hopital carpeting produced any infectious hazard in terms of increased microbial content in the air. They did, however, recommend that similar studies be conducted in a variety of institutions over extended periods.

In addition to floors as aerosol sources, such aerosols can be created from numerous other activities and materials in hospitals. For example, Aisner and associates (76) implicated a fireproofing material sprayed onto beams during construction as a source of Aspergillus respiratory infections in cancer patients. They recommended avoiding the use of materials that might be the source of high concentrations of Aspergillus spores in hospitals. Using an MSI (multi-stage impactor) large-volume air sampler,

Table 3. Examples of epidemic disease resulting from indoor aerosols

Disease	Source	Type of structure	Numbers affected	Percent attack rate	Reference numbers
Influenza	Infected person.	Commercial aircraft.	38	72	82
Inhalation anthrax	Wool, rags.	Textile factory.	50 (fatalities)	. . .	23, 24
Inhalation anthrax	Goat hair.	Textile factory.	5 (4 fatalities)	. . .	25
Ornithosis	Infected turkeys.	Rendering plant.	27	75	32, 33
Psittacosis	Infected turkeys.	Abattoir.	28	[1] 49	83
Brucellosis	Slaughtered animals.	Abattoir.	387	[2] 1–11	35
Brucellosis	Brucella laboratory.	School building.	45	. . .	46
Byssinosis associated with gram-negative organisms.	Cotton spinning.	Cotton mill.	86	33	38
Hemorrhagic fever	Animal excreta.	Laboratory.	113	. . .	84
Tuberculosis	Infected person.	U.S. naval vessel.	140 TU tuberculin reactions.	45.5	47
			7 active cases.	[1] 2.3	. . .
Measles	Infected person or ventilation system.	Grade school.	60 children.	6.9	3, 48
Legionellosis (Pontiac fever).	Air-conditioning system.	Public building.	135	[2] 29–95	53
Legionellosis	Ventilation system.	Hospital.	39	[2] 1.7–3.4	54

[1] Calculated.   [2] Depending on location or length of exposure.   NOTE: Leaders (. . .) indicate no data.

Litsky and Litsky (77) found that reusable bed linen generated viable microbial particles in concentrations about 10 to 35 times higher than those generated by disposables. They suggested that disposable linen produces less lint and traps more micro-organisms because of its smaller pores.

Floor drains and waste disposal systems can represent a significant potential microbial aerosol source throughout a community. Floor drains in dairy processing plants were shown by Heldman and associates (78) to be a source of airborne microbial contamination.

The flushing of a water closet was shown by Darlow and Bale (79) to produce locally high concentrations of bacterial aerosols. Closing the toilet lid before flushing effectively reduced the airborne concentrations of large particles, but smaller droplets remain airborne for potential access to the respiratory tract. Gerba and associates (80) confirmed earlier studies showing that bacterial aerosols are generated by flushing toilets. They demonstrated that virus aerosols can also be produced from water in toilet bowls seeded with virus; these viruses were found to settle on surfaces throughout the bathroom.

Health Significance

The consequences of indoor microbial aerosols, in terms of human health, depend upon the number and kinds of organisms, their pathogenicity, and the overall susceptibility of the exposed occupants of the building. In a comprehensive study of primary school classrooms, Williams and associates (81) found only relatively small numbers of a few species that could be classed as pathogenic. Their investigation yielded an average count of 2,470 organisms per cubic meter of air (70 organisms per cubic foot). Most of the organisms isolated from air samples (81.6 percent) were normally nonpathogenic species of micrococci. The other groups included diphtheroids, coliforms, and aerobic spore-forming organisms, all of which were found in small numbers (only 1.0 to 6.8 percent of the organisms isolated). Streptococci comprised 3.1 percent of the organisms isolated; of these, only 2.6 percent were of the 6-hemolytic type. The majority of these organisms were of the viridian type (44.7 percent) and the salivarius type (25.5 percent). The percentage of the salivarius type isolated correlated with the amount of talking done, an indication that the organisms arose primarily from the human respiratory tract. Surprisingly, S. aureus comprised only 0.39 percent of the total organisms isolated. Although this species profile would certainly change with environmental and epidemiologic conditions, it is probably typical for an inside environment with a moderate number of people.

High concentrations of pathogenic micro-organisms in indoor aerosols are not necessarily associated with the production of disease. Dahlgren

'The consequences of indoor microbial aerosols, in terms of human health, depend upon the number and kinds of organisms, their pathogenicity, and the overall susceptibility of the exposed occupants of the building.'

and associates (26), for example, showed that in an 8-hour day, workers in textile mills may inhale as many as 1,300 anthrax spores without evidence of apparent disease. The high individual dose-response requirement and the relatively low virulence of the organism probably account for the lack of overt disease.

However, large percentages of susceptible persons exposed to indoor aerosols do exhibit overt disease when exposed to high concentrations of virulent organisms. Table 3 lists examples of a variety of aerosol sources and structures that have resulted in significant numbers of human infections following exposure to indoor aerosols. Moser and associates (82) reported 38 cases of influenza aboard a commercial airliner, with an attack rate of 72 percent, resulting from one infected passenger. As the table indicates, inhalation anthrax was a frequent cause of death in textile mills in the Bradford District of England between 1880 and 1890 (24) and even occurred in the United States in 1957 (25). Persons exposed to aerosols of *Chlamydia psittaci* have experienced high attack rates of psittacosis (32,33,83). Brucellosis and Q fever have been recorded as causes of infection via aerosols in abattoirs and rendering plants, and Q fever has been recorded as the cause of infection in textile mills (37). Byssinosis, listed in table 3, is not an infection but rather a form of pneumoconiosis that has been found to be related to aerosols of gram-negative organisms associated with cotton dust (38). The example in the table of hemorrhagic fever arising from laboratory animal excreta indicates the need to control the aerosols from this source by such means as properly ventilated cages (84). Disease transmission associated with the closed recirculated-air environments of seagoing vessels is exemplified by a series of tuberculosis cases and positive tuberculin reactions arising from one infected person on a naval vessel (47). The susceptibility of school chil-

dren to disease from inside aerosols is exemplified by a large series of cases of measles reported by Riley and associates (3). Finally, recent cases of legionellosis arising from the indoor aerosols of *Legionella pneumophilia* were reported by Glick and associates (53) and Dondero and associates (54). In the case of this organism, the attack rate is extremely variable, as indicated in table 3, and is probably related to the organism's virulence, size of the aerosol particle, length of exposure, concentration of the organisms per volume of air, and susceptibility factors.

The significance of aerosols in nosocomial infection involving open wound surgery has been questioned by some investigators. In the judgment of Dixon (85), "Aerosol transmission is not a major factor in the acquisition of these infections, and for many operative procedures it plays an insignificant role." Although data directly implicating aerosol infection is sparse, the ultimate test may be the health benefit derived from aerosol control measures. Charnley (86), for example, reported that the incidence of infection following total hip replacement fell from 7 to 0.5 percent between 1960 and the end of 1970, largely as a result of various control procedures that resulted in cleaner air. These procedures included measures taken to reduce bacterial penetration of the surgeon's gown. Likewise, Lowell and associates (87) reported the reduction of deep wound infection following hip and knee arthroplasty. Reductions in the infection rate from 3.06 to 0.53 percent for hips and from 10.3 to 0.79 percent for knees were attributed to the use of ultraviolet irradiation, although earlier work by Howard and associates (88) showed little effect of ultraviolet irradiation on operating room infection rates. Since aerosol control meaures appear to result in such dramatic reductions in open wound infection, there is little doubt about the significance of aerosols in producing infection.

The contribution of inhalation therapy equipment and room humidifiers to respiratory infection is well documented. An example of infection from such equipment was given by Reinarz and associates (66), who reported pulmonary disorders, including various forms of pneumonia, caused by *Herella* species, *Acinetobacter, Pseudomonas* species, and *Achromobacter*. Smith and Massanari (89) reported a series of systemic infections with *A. calcoaceticus* from unheated room humidifiers at patients' bedsides, infections that subsided when the humidifiers were removed. Hypersensitivity pneumonitis was reported by Banaszak and associates (90), which ap-

Table 4. Health significance of various sources of indoor aerosols.

Sources	Activities creating aerosols	Examples of organisms of health significance	Potential risk to human health
Human:			
Desquamated skin	Motion (clothed and unclothed), showering, bed-making.	Staphylococci.	Low.
Respiratory tract	Talking, coughing, sneezing, blowing nose.	Staphylococci, streptococci, respiratory viruses, *Mycobacterium tuberculosis, Yersinia pestis, Haemophilus pertussis.*	Moderate to high.
Gastrointestinal tract	Toilet.	*Escherichia coli,* enteroviruses.	Low.
Ventilation:			
Penetration from exterior ..	Air movement from cooling towers and other exterior aerosols.	*Legionella* species, *Bacillus anthracis,* and various others.	Low to high.
Interior systems	Operation.	*Pseudomonas* species, staphylococci fungi.	Low.
Humidifiers	Operation.	*Pseudomonas* species, *Acinetobacter* species, *Serratia* species, *Actinomycetes* species.	Moderate.
Industrial:			
Wool, goat hair, cotton, and so forth.	Textile and furniture manufacture.	*B. anthracis, Coxiella burnetii,* gram-negative organism.	High.
Slaughtered animals and birds.	Meat packing and rendering plants.	*C. burnetii, Brucella* species, *Chlamydia psittaci.*	High.
Vegetables	Freezing, canning, drying.	*Streptococcus* species.	Low.
Dairies	Milk processing.	*C. burnetii,* streptococci.	Low to high.

parently arose from contamination of an air-conditioning system by thermophilic actinomycetes.

Based upon reported disease production from various aerosol sources, table 4 gives examples of the health significance of specific organisms that arise from those indoor sources and provides an evaluation of the potential health risk that they pose. From the wide variety of sources listed, it can be seen that the highest risk to health results from the following three sources: (*a*) diseased animals and animal products brought indoors for processing, (*b*) the penetration of pathogen-laden aerosols from out of doors, and (*c*) the aerosols generated by human activity indoors. Generally, although infection is possible from desquamated skin and toilet flushing, the risk from these sources is probably low. Humidifiers, of course, can cause pneumonitis hypersensitivity, but ventilation systems by and large simply transport aerosols from primary sources throughout a structure.

Control of Microbial Aerosols

Effective control of indoor microbial aerosols can be achieved by eliminating their many sources when such elimination is practical by various physical and chemical means. These mitigating measures can be directed at the aerosols' source or at the aerosols themselves once they are formed, or at both.

Aerosol reduction at source. Aerosols can be most effectively controlled by elimination or reduction of their sources.

Human shedding. Reduction of aerosols from human sources can be achieved, for example, by covering the nose while sneezing, a practice that has been reported to reduce aerosol production by a full log (8). Aerosols produced by human shedding can be reduced by controlling the number of people in a room, by modifying their activity in that particular environment, or by both measures. In this regard, airborne microbial contamination in operating rooms can be reduced by controlling the number of operating personnel present during surgery and their activity (91). Unidirectional horizontal airflow significantly reduces the contamination produced by operating room personnel (92). The amount of microbial aerosols caused by human shedding also depends on the kind of clothing worn (14). The main site of shedding by men is from the perineal area, and this shedding can be controlled by wearing ventile, closely woven textile underpants (17). The use of ventile gowns is one method of reducing

micro-organism shedding from the surgeon's body in the operating room (16). Surgical masks must also be carefully selected and carefully worn if they are to reduce microbial aerosol penetration in the operating room (93).

Speers and associates (19) found that aerosol dissemination of skin organisms caused by showering could be somewhat controlled by repeated use of pHisoHex (a mixture of 3 percent hexachlorophene, detergent, and various skin conditioners, including lanolin) during showering. They concluded that although a reduction in bacterial shedding was evident, the effect was not consistent.

Humidifiers and nebulizers. Control of microbial aerosol dissemination by humidifiers and respiratory treatment equipment requires careful examination and decontamination of all potentially contaminating components of the system. For example, Grieble and associates (57) found that the humidifier motor, as well as the reservoir, required sterilization. These authors recommended use of only sterile distilled water in the reservoirs. They further observed that removal of humidifiers from a hospital setting eliminated gross environmental contamination by *Pseudomonas* species.

Airoldi and Litsky (94) found that the usually followed routine in humidifier cleaning of washing the reservoir and all accessible parts with a soap solution, followed by a tap-water rinse, wiping, and spraying with a commercial disinfectant-deodorant was not an effective means of decontamination. They were, however, able to decontaminate the system effectively with ethylene oxide. Burge and associates (65) noted that antifoulants were not effective in decreasing micro-organism concentrations in humidifiers. Reinarz and associates (66) indicated that brief daily nebulization of a 0.25 percent acid solution could effectively decontaminate inhalation therapy equipment incorporating nebulizers. The discrepancy in the effectiveness of various decontamination techniques may be due to the varying degrees of thoroughness with which the operators cleaned the systems before applying these techniques. For example, Cartwright and Hargrave (95) found that scale on ventilators was a source of *P. aeruginosa.* They noted that such ventilators could not be properly disinfected by chemical means until all the scale had been removed. Furthermore, Spaepen and associates (67) emphasized that heated, steam-type nebulizers should be selected to reduce the risk of microbial contamination.

Carpets and floors. Anderson (70) found that vacuuming and shampooing carpets did not effectively reduce micro-organism contamination and therefore recommended hard-surface floors in hospitals. Walter (49) recommended that hospital floors be designed to withstand flooding. A recent study has shown that aerosol concentrations were twice as high above carpeted areas as above bare tile (96). Other studies on the influence of carpeting on microbial aerosols have, on the other hand, failed to demonstrate higher microbial aerosol concentrations in carpeted versus noncarpeted areas (71,73). In preliminary studies by Shaffer (74) and Shaffer and Key (75), no evidence was found that hospital carpeting produced any infectious hazard in terms of increased bacteria. Although Anderson and associates (96) found many types of potentially infectious organisms in aerosols above carpeted areas and were able to isolate typable organisms—which were also found in the carpet—from patients, they did not find any frank disease in patients that was caused by these organisms. During the flooding of floor drains, bacterial aerosol concentrations were shown to increase more than tenfold (74, 75). Continuous intermittent flooding reduced microbial aerosols, as did the use of a chlorine disinfectant (73). Flooding floors with a germicidal detergent, followed by wet pickup of the slurry, has been demonstrated to be effective in reducing airborne microbial contamination (97).

Reduction of aerosol concentration. After micro-organisms have become aerosolized, concentrations of viable micro-organisms can be reduced by disinfection (chemical or physical), by dilution, or by precipitation or filtration (physical or electrostatic).

Disinfection. Disinfection by ultraviolet (UV) irradiation was reported by Wells and associates (98) to reduce the spread of certain communicable childhood diseases. Perkins and associates (99) also indicated that the spread of measles in classrooms was modified by using ultraviolet light irradiation. They did not, however, recommend the routine installation of UV lights. A review by Decker and associates (100), indicated that the ultraviolet lights tested were not efficient in reducing microbial aerosol concentrations. In a series of papers (101–104), Riley and associates emphasized the importance of the location of UV lights and air mixing in achieving effective sterilization. Ultraviolet light irradiation was shown to be more than twice as effective in reducing airborne *Serratia marcescens*

when cold air entered at the ceiling, near the UV source, as when hot air entered in this region. This effect was mainly attributed to vertical air mixing, which occurred at rates up to 15 times greater when cold air entered near the ceiling than when hot air did. Processes to maximize air movement past the UV source improved the effectiveness of sterilization. Temperature gradients and lower ceilings contributed to adequate UV disinfection. In a review of the spread of respiratory viruses by air-conditioning systems, Zeterberg (105) emphasized that UV irradiation for aerosol decontamination was effective under controlled conditions, such as in a laboratory, but it was considerably less effective in practical applications. He referenced such difficulties with UV in the field studies as viral aggregate formation, weak field strength, insufficient exposure time, nonuniformity of radiation absorption, and a tendency of UV sources to accumulate dust. In addition, UV disinfection is most effective at relative humidity levels below 60 percent (97). Zeterberg (105) suggested that the only practical way to prevent the spread of submicron infective and antigenic material was by adequate filtration of the building's circulating air volume.

Dilution. The most important and practical technology for the control of indoor aerosol contamination is ventilation and filtration. McNall (106) examined indoor aerosol contamination and studied the application of predictive equations for evaluating the influence of several parameters on inside contamination concentrations. For aerosol particles of less than 10 μm in size from a source within a space, he described the following equation:

$$C_s = \frac{V_o\, C_o + N_p}{V_r\, E + V_o} \qquad (2)$$

where

C_s = steady state inside contaminant concentration,
C_o = outside contaminant concentration,
V_o = infiltration of outside air through cracks and other leaks (cubic meters per second),
N_p = rate of contaminant production in the space,
V_r = ventilation system recirculation rate (cubic meters per second), and
E = filter efficiency (percent in unit time).

Figure 2. Diagram of typical interior-space ventilating system and contaminant production
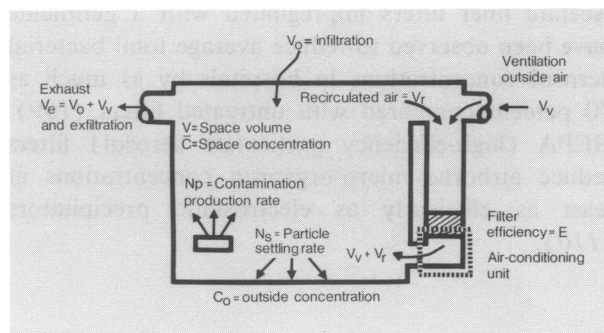
SOURCE: Reference 106, page 553.

The parameters of this equation are illustrated in figure 2. The equation shows that indoor microbial aerosol concentrations, whether originating from outdoor air that has penetrated the structure or originating from within the structure, can be reduced by increasing the filter efficiency or the rate of the air recirculation with filtration or by increasing the air infiltration. As filter efficiency increases, there is a diminishing return for any V_r/V_o. This equation, however, does not take into account the die-off that occurs with viable microbial aerosols.

Precipitation or filtration. Energy conservation measures encourage the reduction of V_o (infiltration from the outside air) and consequently result in a greater need for more efficient air disinfection or filtration systems. Biological air-cleaning filters were divided by Decker and associates (100) into the following four categories: (a) roughing filters, (b) medium-efficiency filters, (c) high-efficiency filters, and (d) ultrahigh-efficiency filters. Both mechanical and electronic air filters are in wide use. Electrostatic precipitators are effective, but under actual operating conditions, they only perform satisfactorily when they receive good maintenance. When performing improperly under high relative humidity, these electronic filters can emit varying concentrations of ozone, which can enhance the susceptibility of a building's residents to respiratory infections from aerosols, but which also may have a deleterious effect upon aerosolized micro-organisms. Media filters remove aerosol particles by passing particulate-containing air through randomly oriented filter fibers. As the air continually changes direction, the aerosols are impacted onto the fibers by inertial forces. Electrostatic charges of the filter media can either increase or decrease filter efficiency (107). Media filters impregnated with a germicide have been

reported to significantly reduce bacterial aerosol concentrations in air-conditioned homes (*108*). Acetate fiber filters impregnated with a germicide have been observed to reduce average total bacterial aerosol concentrations in hospitals by as much as 70 percent compared with untreated filters (*109*). HEPA (high-efficiency particulate aerosol) filters reduce airborne micro-organism concentrations at least as efficiently as electrostatic precipitators (*110*).

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