

Engineering Control of Airborne Disease Transmission in Animal Laboratories

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We here present a review of the problem of controlling airborne disease transmission in animal research facilities, with emphasis on engineering design and air-treatment technologies. Dilution ventilation, pressurization control, source control, and air disinfection and removal systems are reviewed, and analytical studies on the effects of dilution ventilation, filtration, and ultraviolet germicidal irradiation are summarized. In addition, we discuss practical problems common to laboratory facilities and present a database of potential airborne pathogens and allergens that can be transmitted between humans and animals. We offer some conclusions regarding the design and selection of available technologies and components and provide cost estimates for various air-cleaning systems.

The potential for airborne disease transmission exists anywhere humans gather indoors, but the situation becomes an acute occupational hazard in laboratories where animals are used (1-3). Animal laboratories and animal facilities have the unique problem that zoonotic diseases can be transmitted not only between animals but also from animals to humans and vice versa (4, 5). In addition, humans can develop various allergies due to prolonged or chronic exposure to animals (6).

Many common human diseases have the potential to infect animals. This propensity partly is because of biological and physiological similarities between humans and animals. But the potential also is due to the fact that many human and animal diseases have common evolutionary origins. Tuberculosis, for example, dates to the beginning of animal husbandry (about 15,000 years ago) and apparently jumped species from cattle to humans (7).

Similarly, many types of animal diseases have the ability to affect humans. Whenever airborne transmission of disease from humans to animals (or vice versa) occurs, secondary transmissions are rare. Transmission of diseases from animals to humans, or from humans to animals, normally occurs through direct contact, but can potentially occur via airborne transmission also. Contact transmissions can be controlled through appropriate operating procedures, whereas the control of airborne transmission is best effected by engineered systems.

The most common and reliable technologies for keeping indoor or laboratory air free of microbes are dilution ventilation, filtration, and ultraviolet germicidal irradiation (UVGI). In addition, laboratories and animal facilities use air pressurization to isolate areas and thereby control the spread of airborne pathogens between zones. Each of these technologies has unique advantages and applications, and it is necessary to consider the strengths of each technology when designing air contamination-control systems. Each of these technologies will be addressed, but first it is necessary to identify the specific microbial threats and list their characteristics in a comprehensive database.

Airborne Pathogens in Animal Research Laboratories

Three broad categories of microbes are apparent from physical size—viruses, bacteria, and spores (which can be either fungal or bacterial). Because spores tend to be large and easily removed

by filters, it is not crucial to distinguish them by microbial group or species. Fungal and bacterial spores are uncommon contaminants in animal laboratory facilities, although these forms frequently occur in outdoor air.

In light of a review of the literature, Table 1 comprises all of the pathogens, allergens, and respiratory irritants (and their sources) that might conceivably occur in animal laboratories. Although it is intended to be comprehensive, some as-yet unidentified organisms, as well as some organisms that have not yet emerged as pathogens, may belong on this list.

Limits and Guidelines

The concentrations of airborne dust, allergens, and bacteria in animal laboratories and animal facilities can reach extraordinary levels, as shown in Table 2, which comprises data for unfiltered air. Although the actual conditions in animal houses may bear little similarity to those in animal laboratories, these test results provide good examples of the kinds of problems that can occur with air filtration. Poultry houses and swine houses are notorious for excessive airborne particle concentrations, and these numbers would seem to corroborate anecdotal reports. Most animal laboratories are unlikely to experience particle levels as high as those in the animal facilities shown here, but Table 2 highlights the potential for airborne disease transmission and allergic exposures.

Few upper limits for airborne particles, bacteria, or allergens have been proposed, but Table 2 includes one suggested limit for dander and allergens (6), above which the incidence of allergy to lab animals (ALA) increases. The fungal levels shown in Table 2 are in line with normal indoor levels for human dwellings, but this similarity is expected because most of the fungi probably arise from the outdoor air. To place these airborne concentrations in some perspective, the bacterial levels listed in Table 2 mostly are far beyond any limits that have been proposed for human dwellings. Suggested indoor levels of bacteria range from 500 to 1000 cfu/m³ (18). A well-kept laboratory, of course, would likely have levels far lower than even these human indoor limits.

The main problem with establishing limits for airborne microorganisms in animal facilities is the same as that for human habitats—few exposure limits are known with any certainty. Most available data reflect specific microbes and limited epidemiologic studies. As a result, few experts are willing to commit to upper limits on indoor airborne microorganisms that may cause undue concern or even legal problems. The upper limits used in the subsequent analyses here must be recognized for what

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Table 1. Airborne pathogens and allergens in animal laboratories

Airborne pathogen	Group	Source or species infected	Disease	Mean diameter (mm)
Avian adenovirus (FAV)	Virus	Birds	Respiratory disease, bronchitis	0.08
Bovine adenovirus	Virus	Bovines	Respiratory disease	0.08
Canine distemper virus (CDV)	Virus	Dogs	Canine distemper	0.14
Coxsackievirus	Virus	Humans, mice, rabbits, hamsters, swine, primates	Colds, acute respiratory disorder	0.03
Echovirus	Virus	Humans, mice, primates	Colds, meningitis	0.03
Equine rhinopneumonitis virus	Virus	Horses	Equine rhinopneumonitis	0.02
Feline picornavirus	Virus	Cats	Feline pneumonitis, upper respiratory disease	0.02
Guinea pig adenovirus	Virus	Guinea pigs	Respiratory disease	0.08
Hantaan virus	Virus	Rodents	Hemorrhagic fever, Korean hemorrhagic fever	0.10
Influenza A virus	Virus	Nosocomial; humans, birds, pigs	Flu, secondary pneumonia	0.10
Junin virus	Virus	Rodents	Hemorrhagic fever	0.12
Marburg virus	Virus	Humans, monkeys	Hemorrhagic fever	0.04
Measles virus	Virus	Humans, monkeys	Measles (rubeola)	0.16
Pneumonia virus of mice (PVM)	Virus	Mice	Pneumonia	0.20
Mumps virus	Virus	Humans, primates, rodents	Mumps, viral encephalitis	0.16
Newcastle disease virus (NDV)	Virus	Birds	Newcastle's disease	0.14
Parainfluenza virus	Virus	Humans, monkeys, dogs, rodents	Flu, colds, croup, pneumonia	0.19
Paravaccinia virus	Virus	Cattle, humans	Pseudocowpox	0.24
Poxviruses	Virus	Rabbits, sheep, swine, mice, horses, fowl, goats, cows	Mousepox, sheeppox, rabbitpox, swinepox, monkeypox, horsepox, fowlpox, goatpox, cowpox	0.24
Reovirus	Virus	Humans, birds, mice	colds, fever, pneumonia, rhinorrhea	0.08
Respiratory syncytial virus	Virus	Humans, chimpanzees	Pneumonia, bronchiolitis	0.19
Reston virus	Virus	Monkeys	Reston disease	0.04
Rubella virus	Virus	Humans, monkeys	Rubella (German measles)	0.06
Sendai virus	Virus	Rodents, hamsters	Sendai disease	0.14
Sialodacryoadenitis virus (SDAV)	Virus	Rats	Rat coronavirus disease	0.11
Simian adenovirus	Virus	Primates	Upper respiratory disease, enteritis	0.08
Theiler's virus	Virus	Mice	Encephalomyelitis	0.02
Vaccinia virus	Virus	Agricultural	Pox	0.22
Acinetobacter	Bacteria	Environment, soil, sewage, buildings; rats, swine	Opportunistic infections, sepsis, meningitis	1.22
Actinomyces bovis	Bacteria	Hamsters	Actinomycosis	0.90
Actinomyces israelii	Bacteria	Humans, cattle, rabbits, hamsters	Actinomycosis	0.90
Aerococcus viridans	Bacteria	Rodents, rabbits	Meningitis	1.41
Aeromonas spp.	Bacteria	Environment, soil; rodents	Nonrespiratory opportunistic infections, bacteremia	2.10
Alcaligenes spp.	Bacteria	Soil, water, buildings; humans, swine	Opportunistic infections	0.78
Bacteroides fragilis	Bacteria	Humans, rodents, rabbits	Opportunistic infections	3.16
Bordetella bronchiseptica	Bacteria	Rabbits, cats	Upper respiratory disease, pneumonia	0.32
Brucella	Bacteria	Goats, cattle, swine, dogs	Brucellosis, undulant fever	0.57
Burkholderia cepacia	Bacteria	Environment; rabbits	Opportunistic infections	0.71
Burkholderia mallei	Bacteria	Environment, nosocomial; horses, mules	Glanders, fever, opportunistic infections	0.67
Burkholderia pseudomallei	Bacteria	Environment, nosocomial, soil; rodents	Melioidosis, opportunistic infections	0.49
Chlamydia psittaci	Bacteria	Birds, fowl	Psittacosis/ornithosis, pneumonitis	0.28
Clostridium perfringens	Bacteria	Environment, soil; humans, animals	Sepsis, toxicosis, food poisoning	5.00
Corynebacterium bovis	Bacteria	Mice	Hyperkeratosis	0.70
Corynebacterium kutscheri	Bacteria	Mice	Pseudotuberculosis	0.70
Coxiella burnetii	Bacteria	Cattle, sheep	Q fever	0.28
Diplococcus pneumoniae	Bacteria	Monkeys	Pneumonia	0.71
Enterobacter cloacae	Bacteria	Humans, environment, rabbits	Opportunistic infections	1.41
Francisella tularensis	Bacteria	Animals, hamsters	Tularemia, pneumonia, fever	0.20
Haemophilus spp.	Bacteria	Rodents, guinea pigs, rabbits	Pneumonia, conjunctivitis, meningitis	1.00
Klebsiella orthinolytica	Bacteria	Rodents, rabbits	Pneumonia	0.67
Klebsiella oxytoca	Bacteria	Rodents, rabbits	Pneumonia	0.67
Klebsiella planticola	Bacteria	Rodents, rabbits	Pneumonia	0.67
Klebsiella pneumoniae	Bacteria	Environment, soil, humans, monkeys, mice, swine buildings	Opportunistic infections, pneumonia	0.67
Mycobacterium africanum	Bacteria	Monkeys	TB	0.90
Mycobacterium avium	Bacteria	Environment, water, mice	Cavitary pulmonary disease.	1.12
Mycobacterium bovis	Bacteria	Monkeys	TB-like infections	0.90
Mycobacterium lepraemurium	Bacteria	Rodents	Leprosy	0.90
Mycobacterium microti	Bacteria	Rodents	Tuberculosis	0.90
Mycobacterium tuberculosis	Bacteria	Humans, sewage, monkeys	Tuberculosis, TB	0.64
Mycoplasma pulmonis	Bacteria	Rats, mice	Chronic respiratory disease, murine mycoplasmosis	0.49
Pasteurella lepicseptica	Bacteria	Rabbits	Upper respiratory disease, pneumonia	0.24
Pasteurella multocida	Bacteria	Rabbits, rodents	Chronic respiratory disease, rhinitis, Otitis media, pneumonia	0.24
Pasteurella pneumotropica	Bacteria	Rodents	Rhinitis, sinusitis, otitis media	0.24
Pasteurella spp.	Bacteria	Monkeys	Pneumonia	0.24
Pneumococcus Type II	Bacteria	Rats, guinea pigs	Bacterial pneumonia	0.71
Pseudomonas aeruginosa	Bacteria	Environment, sewage, swine buildings	Pneumonia, toxins	0.49
Pseudomonas diminuta	Bacteria	Rats, guinea pigs	Rhinitis, conjunctivitis	0.49
Staphylococcus aureus	Bacteria	Humans, sewage, rodents	Staphylococcal pneumonia, opportunistic infections	0.87
Staphylococcus cohnii	Bacteria	Rats	Pneumonia, dermatitis	0.87
Staphylococcus haemolyticus	Bacteria	Rats	Pneumonia, dermatitis	0.87
Staphylococcus sciuri	Bacteria	Rats	Pneumonia, dermatitis	0.87
Staphylococcus xylosum	Bacteria	Rats	Pneumonia, dermatitis	0.87
Streptobacillus moniliformis	Bacteria	Rats	Inner ear infection	0.64

Table 1. Airborne pathogens and allergens in animal laboratories (cont.)

Airborne pathogen	Group	Source or species infected	Disease	Mean diameter (mm)
<i>Streptococcus pneumoniae</i>	Bacteria	Humans, rats, guinea pigs, rabbits, mice	Pneumonia, meningitis, otitis media, toxins	0.71
<i>Streptococcus pyogenes</i>	Bacteria	Humans, guinea pigs	Scarlet fever, pharyngitis, toxins	0.89
<i>Yersinia pestis</i>	Bacteria	Rodents, fleas, humans	Bubonic plague, pneumonic plague, sylvatic plague	0.71
<i>Yersinia pseudotuberculosis</i>	Bacteria	Rodents, rabbits, guinea pigs	Pseudotuberculosis (guinea pigs)	0.63
<i>Bacillus anthracis</i>	Bacterial spore	Cattle, sheep, mice, horses	Anthrax, woolsorter's disease.	1.12
<i>Micromonospora faeni</i>	Bacterial spore	Agricultural, moldy hay, indoor growth	Farmer's lung, pulmonary fibrosis, allergic reactions	0.87
<i>Micropolyspora faeni</i>	Bacterial spore	Agricultural, indoor growth	Farmer's lung, alveolitis, asthma	1.34
<i>Nocardia asteroides</i>	Bacterial spore	Environment, sewage, rodents, rabbits	Nocardiosis, pneumonia	1.12
<i>Coccidioides immitis</i>	Fungal spore	Environment, soil, guinea pigs, rabbits	Coccidioidomycosis, valley fever, desert rheumatism	3.46
<i>Mucor plumbeus</i>	Fungal spore	Environment, sewage, guinea pigs	Mucormycosis, rhinitis	7.07
<i>Paecilomyces variotii</i>	Fungal spore	Environment, rats	Paecilomycosis, allergic alveolitis, toxins, Volatile organic compounds	2.83
<i>Pneumocystis carinii</i>	Fungal spore	Environment, monkeys, animals	Pneumocystosis	2.00
Animal dander	Allergen	Rats, dogs, cats, horses, etc.	Allergic reactions, asthma, allergy to lab animals	7.00

References: (1,3,4,6,8-13)

Table 2. Airborne contaminants in animal laboratories and animal houses

Contaminant	Average concentration	Location/Condition	Reference
Bacteria	2,851 cfu/m ³	Rat house	14
Bacteria	237,000 cfu/m ³	Swine house	15
Bacteria	477,540 cfu/m ³	Poultry house	16
Bacteria	100,000 cfu/m ³	Swine houses	17
	7,000,000 cfu/m ³	Poultry houses	
Gram-negative bacteria	88,000 cfu/m ³	Swine houses	
	41,000 cfu/m ³	Poultry houses	
Fungi	300 cfu/m ³	Swine houses	
	500 cfu/m ³	Poultry houses	
Rat allergen	62 particles/m ³	Rat rooms, undisturbed	10
	158 particles/m ³	Rat rooms, disturbed	
Dander, allergens	70,629 particles/m ³	Suggested maximum for allergy to laboratory animals	6
Dust particles	24,400,000 particles/m ³	Swine house	14

they are—convenient numerical targets for use in engineering calculations, that do not necessarily reflect any specific health risks, and that are not necessarily based on any established standards or guidelines.

A variety of formal guidelines are available to assist designers and managers of animal research facilities. Perhaps the one in most common use in the U.S. is the *Guide for the Care and Use of Laboratory Animals* (19). Other guidelines, such as various chapters in the *ASHRAE Handbook of Applications* (20), the *AIA Guidelines for Hospitals* (21), and the *ANSI/AIHA Guidelines* (22), also offer specialized information. All of these guidelines offer similar but limited advice about the design and operation of the ventilation or air-cleaning systems. Typically these guidelines recommend 10 to 15 air changes hourly (ACH), where “air change” refers to the replacement of the complete volume of air in a room. The use of 100% outside air generally is specified as an option, and this approach is the predominant one taken currently. A minimum of 50% outside air (or maximum 50% return air) is suggested by some of the guidelines. High Efficiency Particulate Air (HEPA) filtration also is suggested, and charcoal adsorbers sometimes are mentioned as an option. In the previously named guides, no mention is made of the use of ultraviolet germicidal irradiation (UVGI) for air disinfection.

Other than those mentioned previously, no specific design requirements are discussed or suggested in these sources. No specific limits on indoor airborne colony-forming units (cfu) levels are provided but, as explained, the appropriateness of such suggestions would not be known with any real certainty. Such specific technical details are essentially left to the best judgment of the engineers and building designers.

Ventilation and Air Treatment Systems

The variety of methods used to control the spread of airborne pathogens and allergens can be grouped into four categories

(Fig. 1), although they are not entirely independent from each other. The first category comprises source control, the local ventilation of the animal cages. The second is the ventilation system that dilutes the building air and exhausts contaminants to the outdoors. In the third method, the differential pressurization of zones isolates areas from each other and controls the flow of contaminants between zones. The fourth category is composed of air-treatment systems that can intercept and destroy contaminants (e.g., filtration and UVGI).

All buildings have ventilation systems. Even structures without fans or ductwork rely on some sort of natural ventilation, either by design or otherwise. Air is distributed to the various rooms or zones and exhausted or exfiltrated from some or all of these zones. Figure 2 shows a typical supply diffuser (the large ceiling outlet in the foreground) in a procedure room. An exhaust grille also is present on the ceiling near the corner of the room. This set-up is not an uncommon configuration, but it is susceptible to the problem of “short-circuited” airflow. That is, some of the supply air may travel directly to the exhaust grille, and air quality potentially can suffer.

Figure 3 shows a typical exhaust grille located near the floor of an animal housing room. This scenario illustrates the preferred placement of exhaust grilles, because dust and dander tend to settle downwards over time. However, when only a single exhaust grille exists in a room, there is a potential for cages distant from the exhaust grille to experience increased levels of airborne contaminants. Ideally, air would be exhausted all around the perimeter of the room such that an equal amount of air is exhausted from each cage.

Pressurization Control

Rooms and entire building zones can be pressurized to prevent contamination from passing from one area to another. The design principle is to ensure that airflow proceeds from areas of

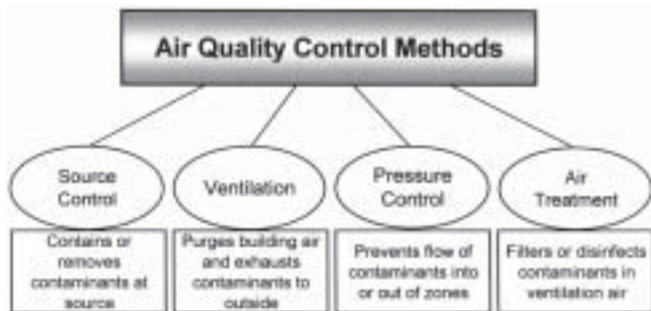


Figure 1. Air-quality control methods.



Figure 2. Ceiling supply diffuser and exhaust register in a procedures room.

low contamination potential to those of high contamination potential. In other words, air must flow from clean to dirty areas and not vice versa. The contaminated exhaust air either is exhausted directly to outdoors or is treated prior to recirculation or removal.

To control the airflow between areas, it is necessary to provide the air directly to the clean areas, usually the offices, and then allow it to exfiltrate through the walls and doorway cracks to less-clean areas. The air must be exhausted from the areas of highest contamination potential simultaneously. The areas with direct supply typically are considered to be positively pressurized, whereas those from which the return air is exhausted are considered negatively pressurized.

Of course, the designation of which areas are under positive versus negative pressure is relative and may depend, literally, on which way the wind is blowing. Consider Fig. 4, which shows a schematic of an office and laboratory facility with pressurization control. The offices with direct air supply are under “double positive” pressure with respect to adjacent areas. The laboratories from which the air is exhausted experience double-negative



Figure 3. Exhaust air grille located near floor in an animal housing room.

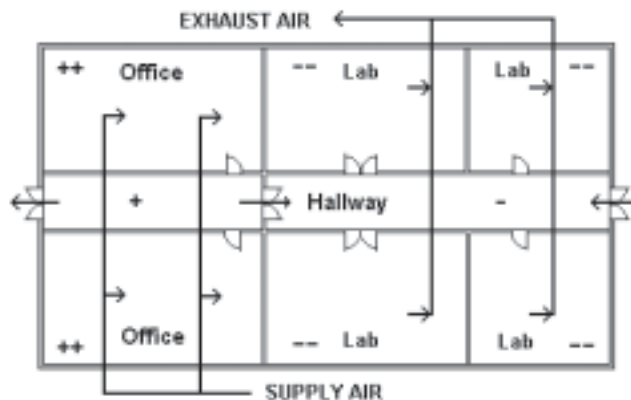


Figure 4. Schematic of basic Pressurization control. The ‘+’ and ‘-’ indicate relative positive and negative pressure, while the ‘++’ and ‘--’ represent higher positive pressure and lower negative pressure, respectively.

pressurization. The areas in between these air-pressure extremes are graduated and may be positive, negative, or neutral with respect to adjacent areas.

It is paramount that the structure is sufficiently airtight to be capable of maintaining these relative pressure differences. The actual measured pressure difference is not critical, as long as it isn’t extreme; it matters only that the direction of airflow is maintained. The underlying reason is that the actual pressure differences between adjacent areas may not be measurable, often being on the order of 5 Pascals (0.02 in. by water gauge) or less and perhaps even fluctuating between positive and negative. Requirements for actual pressure differences are often a recipe for failure during the commissioning of a building. What matters is that the air flows in the proper direction, and this situation can be verified by smoke testing or other means.

Dilution Ventilation

Any ventilation system that draws outside air is displacing an equal quantity of building air, which ultimately exhausts to the outside. Sometimes this scenario is called “purge ventilation,” but because the air constantly is being mixed in the building, “dilution ventilation” is a more appropriate description of the process.

Laboratories and animal facilities often use 100% outside air. By exhausting or exfiltrating the air, it is possible to avoid the use of air-treatment technologies altogether. Air that is exhausted to the outdoors will be disinfected naturally by sunlight, dehydration, and temperature extremes. Although the practice is of dubious value and not subject to any specific regulations (excluding those relating to pollution), many buildings routinely

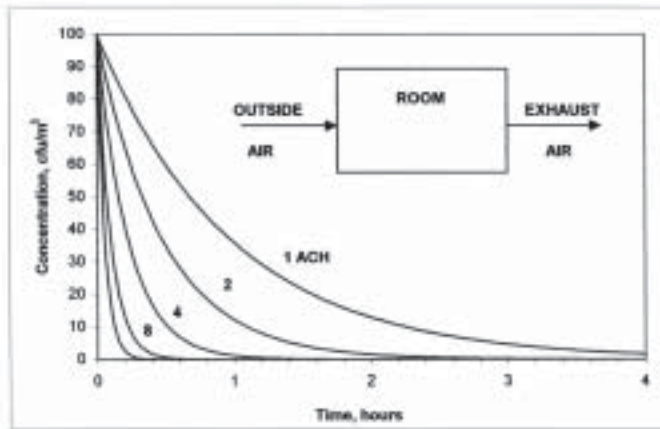


Figure 5. Effect of air change rate on reduction of airborne microbial contamination. The last line (not labeled) represents 12 ACH.

filter or otherwise process the exhaust air prior to its release.

Regardless of what happens on the exhaust side or the percentage of outside air used, predicting the air quality inside the rooms of any facility is a fairly straightforward matter if it is assumed that the air mixes completely. Although it may not always be the case, because poor air-mixing is a common problem, this assumption does allow for a simple approximation of the performance of any building ventilation system.

Consider a model room supplied with 100% outside air in which complete mixing occurs. If the airflow rate is such that the entire room volume is exchanged in 1 h, the room undergoes 1 air change per hour (ACH). In order to evaluate how well room contamination is purged by this particular airflow rate, the room can be considered fully contaminated at the time the ventilation is first turned on. This type of comparison is sometimes called a "drawdown calculation," because it measures how fast the contamination level of a room is reduced (or "drawn down") to some final steady-state condition in which the levels of airborne contaminants remain constant.

Figure 5 illustrates a single room modeled with complete mixing at various air-change rates. In this example, the room initially is contaminated with 100 cfu/m³ and then purged with outside air, which is assumed to be uncontaminated. Results of these calculations show that at 1 ACH, the room can be purged of almost 95% of airborne contaminants in 4 h. This analysis indicates that doubling or quadrupling the ACH has a great influence on how fast the room can be cleansed, but increasing the rate beyond 10 to 12 ACH offers little additional benefit.

Obviously, there is some acceptable level of performance above which no gains are likely to be cost-effective. That is, the cost of moving air for the purpose of purging contaminants may become prohibitive if the air change rate is too high. To put this into perspective, an ACH of 6 to 12 might be a reasonable goal for any animal laboratory or even a hospital operating room, but any increase above these levels may have limited value. This analysis assumes, as stated previously, that the air is completely mixed. If a facility has poor air-mixing, then there might be benefits from even higher ACH levels. One study on rat rooms found that 172 ACH was necessary to control rat allergens, but such high airflow levels could have prohibitive costs (23).

In comparison to other air treatment technologies, boosting the ACH may seem like a simple and effective means of improving air quality. However, this approach ultimately must be considered in terms of the life-cycle cost of the system, especially because fan energy is often the largest single cost. Furthermore, in climates where the outside air reaches extremes of high or low temperatures, the cost of heating, cooling, and dehumidifying the air can be prohibitive.

Recently, the availability of highly efficient air-to-air heat ex-



Figure 6. Naturally ventilated animal cages.

changers, enthalpy wheels, and other technologies have facilitated energy recovery in 100% outside air systems, rendering such an approach feasible even in very cold or hot climates (21, 24, 25). Even so, for any given climate or geographic location, both the performance and the cost of dilution ventilation must be weighed against the cost of the other three methods of controlling air quality, and a choice made on the basis of life-cycle costs.

Source Control

The source of most airborne contaminants of concern is usually the animals and their cages. People themselves can be a source of contaminants, but the prime focus should always be the protection of the workers. It is implicit that a system capable of protecting lab workers from animal diseases also will protect the animals.

Source control must never be neglected. No ventilation system or air-treatment technology can make up for an uncontrolled source. Several approaches are in use today for controlling airborne contamination at the source (26). Figure 6 shows a typical rack of cages for mice. These are naturally ventilated cages and tend to contain much of the dander and dust. Such cages sometimes are designed by using computational fluid dynamics programs to ensure that air flows through the cages and mixes in a manner sufficient to remove both contaminants and heat generated by the animals (27). The room ventilation must remove any airborne contamination produced from such assemblies.

Figure 7 shows the approach that is becoming increasingly more common today—cages with forced or induced ventilation. The flexible hose at the back of the assembly is connected to the exhaust ventilation duct and draws air through the cages. Air enters the cages through slits located near the front. One of the potential problems with induced airflow is that it depends on sufficient negative pressure existing in the ductwork to which it



Figure 7. Animal cages with induced ventilation.

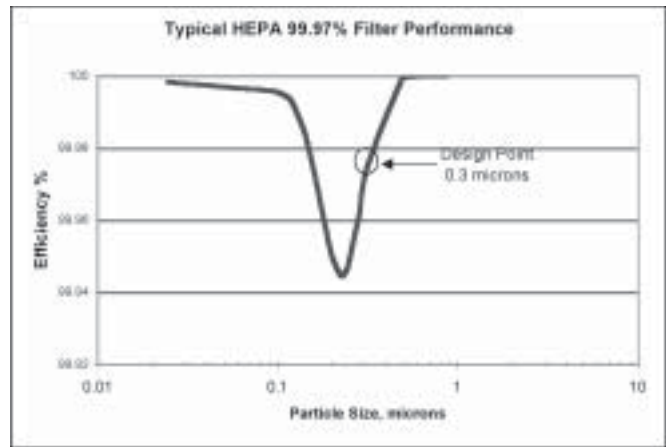


Figure 8. A typical HEPA filter performance curve.

Table 3. Test results for recirculating internal filters

Filter Type	Location	Target	No filters part./m ³	Filters part./m ³	Reduction %	Reference
80-90%	swine house	Particles	24400000	11800000	53	14
		Bacteria	237000	75000	51	
60-90%	poultry house	Particles	7910	4000	51	15
		Bacteria	477540	87589	18	
95%+charcoal	rat house	Bacteria	2907	426	15	16

is connected. Normally, the adequacy of the airflow will be measured and verified during installation.

Some ventilated cage racks provide supply air instead of exhausting air. Still other racks also contain integral filters and fans. One of the problems with systems in which fans are mounted directly on the cage racks is the production of noise and vibrations. Noise, especially in the high-frequency range, can be rather distressing to mice, rabbits, and other animals (19). Another concern is that the filters, often HEPA filters, sometimes are operated well beyond their design face velocity, which is typically 1.27 m/s (250 fpm). Although it may be possible to operate HEPA filters at such increased velocities, the engineer usually should review such specifications. For example, doubling the air velocity through a HEPA filter can cause a tenfold increase in particle penetration (28).

Filtration

The mechanics of filtration are well understood, and performance is highly predictable. The most popular filter type in laboratories today is the HEPA filter, which is rated to remove at least 99.97% of all particles 0.3 μm in diameter or larger when operated at design air velocity. Figure 8 shows a performance curve for a typical HEPA filter operating at the design velocity of 1.27 m/s (250 fpm).

Other filters are available that have nominal ratings of 25% to 95%, which signify total arrestance across the entire range of particle sizes. The performance of any filter is defined by a performance curve, which indicates the actual removal efficiency at any given particle size in the range of 0.1 to 10 μm in diameter. Performance curves provided in manufacturer catalogs usually don't extend into the size-range of viruses. However, modeling methods are available that allow prediction of the complete performance curves for any filter whose physical composition is known (28).

Before analyzing the performance of filters, and comparing their performance with that of dilution ventilation, it is worthwhile to review the literature on filter testing and performance as it relates to animal laboratories and related facilities. Table 3 shows the results of tests using recirculating filter units in ani-

mal facilities. The filters in the Carpenter studies (15, 16) were installed in the ventilating ductwork on the return air side. The exact sizes of the filters in these studies were not specified, but they apparently were between 60% and 90% total arrestance on the basis of the stated operating characteristics. Air samples were taken the day before installation and at weekly intervals thereafter. The total reduction in airborne cfu of bacteria is shown in the last column of Table 3. Considering that dust particles should be removed at near 100% efficiency by such filters, the actual measured total reduction seems rather disappointing. A study on rat houses found no measurable differences in airborne concentrations resulted from the use of HEPA filters (23).

The reason the filters in Table 3 fall short of expectations may be many, but they probably relate mainly to poor air distribution. The flow rate of the filter units was not the problem, because they had approximately the same flow rate as that of the existing ventilation system. If the air had been thoroughly mixed in each of these houses and delivered to the filter unit inlet, the filters likely would have reduced levels much more in accordance with filter performance potential. The filters themselves probably performed adequately, as is usually the case when they are tested independently.

Table 4 summarizes several tests on filters by using viruses, which are the smallest microbes and among the most difficult to remove by filtration. It's clear that in these "once-through" tests, the measured removal rates meet or exceed all filter performance expectations. One unusual result in Table 4 is the last test on MVM, which was removed at a 100% rate even without filtration (35). MVM is not an airborne pathogen and is unlikely to survive aerosolization, so the choice of this microbe for such a test is questionable, albeit somewhat informative.

Consider the same room that was analyzed in Fig. 5 with dilution ventilation, but this time with an assumed internal source of bacteria and viruses (human and animal) and 100 cfu/m³ of fungal spores in the outdoor air. Figure 8 shows the results of an analysis, again assuming complete mixing, in which each of the indicated filters is modeled against the complete array of pathogens in Table 2. An initial concentration of 100,000 cfu/m³ is assumed to exist at time 0, and the filtration system is engaged

Table 4. Summary of virus filtration test results

Filter type	Microbe	Removal %	Researcher
HEPA	actinophage S. virginiae S1	99.997	29
HEPA	T phage E. coli B	99.9915	30
HEPA	T phage E. coli B	99.99	31
HEPA	T phage E. coli B	99.997	32
HEPA	Foot-and-mouth disease virus	99.998	33
40-45%	Marek's disease virus (MDV)	0	34
80-85%	"	100	
HEPA	"	100	
EU6 & EU9	Minute virus of mice (MVM)	100	35
EU6 & HEPA	"	100	
No filter	"	100	

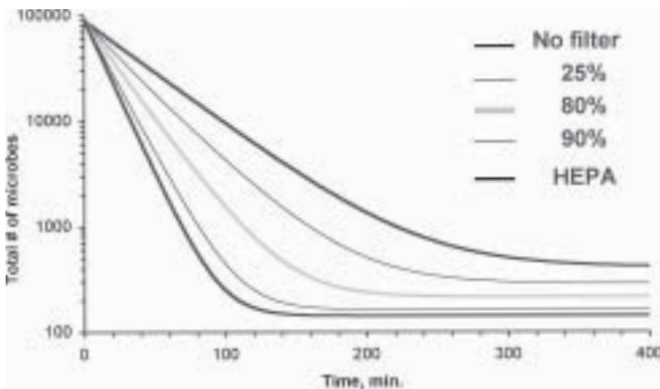


Figure 9. Reduction of airborne microbial contamination by using filtration.

to see how fast levels in the room can be reduced.

Figure 9 shows that dramatic differences exist in the amount of time it takes for the various filter types, and in the absence of a filter, to draw down the modeled contamination level of the room to a few hundred cfu total. All filters are assumed to operate at the same flow rate as that in Fig. 4. It also can be observed that each type of filter reaches different levels. Note that the 80% and 90% filters offer a considerable improvement over using no filters but that the HEPA filter offers little improvement over the 80% and 90% filters. The question of whether HEPA filters are economically viable in comparison with 80% or 90% filters is one worth asking by every designer or building manager.

Regardless of the type of filter used, some degree of penetration of contaminants will occur, because every filter has a range of maximum penetration. Whether the amount of penetration is noteworthy depends on the microbial concentration going into the filter and the infectious dose for each species. Few data of this sort exist, and so what constitutes an acceptable performance goal is a matter of judgment in most cases.

Consider Fig. 10, which shows the results of an analysis of all the pathogens in Table 2 after a single pass through a 99.97% HEPA filter. This analysis assumes that 10^6 cfu of each type of microbe have entered the filter unit. This assumption might be realistic for some viruses but may be unrealistic for bacteria. The number of actual penetrations is indicated, but whether these concentrations are hazardous depends on the infectious dose.

The normal range of indoor concentrations of allergens is about 100 to 1000 cfu/m³, therefore we could seek indoor levels below 100 cfu/m³ as a rough target. For microbes pathogenic to humans, we would prefer levels of 0, although this goal might not be realistically achievable. Perhaps a reasonable upper limit for any type of airborne microbe that is not noted for producing human fatalities would be about 10 to 100 cfu/m³, on the basis of limits that are typical for general areas in hospitals (18). Again, these are merely suggested limits for use in engineering design and should not be taken as across-the-board recommendations,

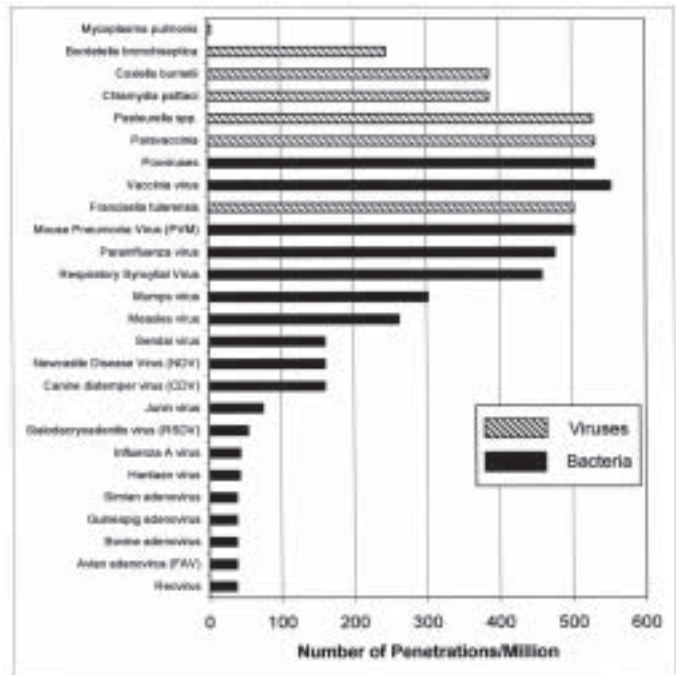


Figure 10. HEPA 99.97% filter—Most-penetrating microorganisms.

because some microbes are more infectious than are others. Whenever particular microbes are of concern, they should be evaluated in-depth.

Ultraviolet Germicidal Irradiation

The other predominant technology for controlling airborne microbes, UVGI, has been in use in various capacities for more than 100 years (36). In a typical UVGI air disinfection system, a UV lamp of perhaps 100 W (total power) is located transverse to the airstream in a duct. Airborne microorganisms passing through this section of duct will be exposed to UV irradiation, both directly from the lamp and from UV light reflected off the duct or any reflective surfaces. Depending on the susceptibility of the specific microbe, the kill rate may be rapid and sufficient to sterilize the air, or it may only be adequate to destroy a fraction of the microbes.

The mechanism of UVGI disinfection is well understood, but the methods of designing effective UVGI systems have been elucidated only recently (36, 37). Furthermore, a shortage of microbiological data on the effects of UVGI has hampered the development of UVGI systems for specific microbes. Guidelines and standards often fail to recommend the use of UVGI or suggest it be used only in conjunction with filtration.

Figure 11 compares the decay curves (also called survival curves) of the three main groups of airborne microbes—fungi, bacteria, and viruses. Viruses are the smallest and, in general, easiest microbes to destroy with UVGI. Spores, in contrast, are the most difficult to inactivate with UVGI, but they are the easi-

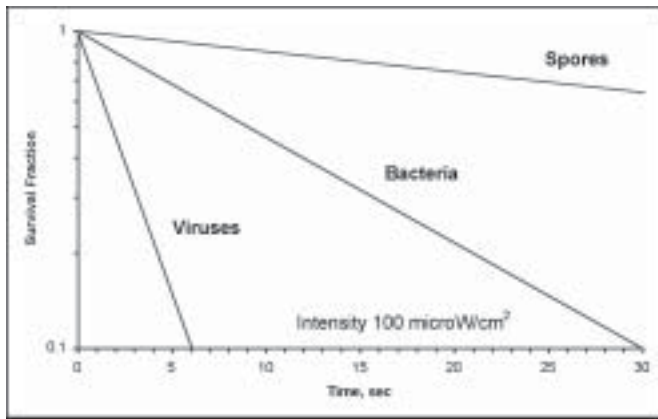


Figure 11. Comparison of microbial groups regarding susceptibility to UVGI exposure.

est to filter out of the air. Bacteria are a mixture of vulnerable and resistant species and present a somewhat greater a challenge. Some bacteria easily succumb to UVGI, whereas others are extraordinarily resistant and require other means of control. However, because large microbes tend to be resistant to UVGI but easy to filter, these two technologies are mutually complementary.

The problem of sizing both components of a combined filter–UVGI air treatment system involves elementary engineering when designers target spores with filtration and viruses with UVGI. In fact it’s a classic case of economic optimization. Various methods can be used to establish the appropriate size of both the filters and the UVGI lamps.

Figure 12 shows an example of a system designed to economically remove the array of dangerous pathogens indicated. The prefilter (i.e., a 25% filter) and the 80% filter successfully remove most of the spores and bacteria. The UVGI system, a system of moderate UV power, manages to eliminate almost all of the remaining pathogens. Such a system could be refined in various ways to reduce the remaining microbes to noninfectious levels. The UV power could be boosted, for example, or the filter could be upgraded to 90%, or the air velocity could be reduced to extend the exposure time.

Carbon Adsorption

Carbon adsorbers serve to remove many odors and volatile organic compounds (VOCs) from the air—which filters and UVGI cannot do. Carbon adsorbers consist of activated charcoal granules packaged in a frame that fits inside an air handling unit much like a filter. Carbon adsorbers have little or no effect on airborne microorganisms, but these products can be used when odors or chemical smells are a problem. For such applications, the manufacturer can be consulted for assistance in sizing a system.

Alternate Technologies

Various other technologies have been applied or are being studied as means of disinfecting air or removing dust. Included among these methods are photocatalytic oxidation (PCO), ionization, electrostatic filtration, and biocidal filters (18). PCO uses UV lamps to irradiate filter-like materials composed of titanium dioxide. This material then oxidizes anything it comes in contact with and generates short-lived hydroxyl radicals, which have the same effect. PCO can remove many VOCs and odors as well as airborne microorganisms, but actual performance data on PCO systems are limited at present.

Ionization has been used in poultry houses as a means of controlling dust, which can carry disease agents. The generation of negative ions tends to cause dust particles to agglomerate and

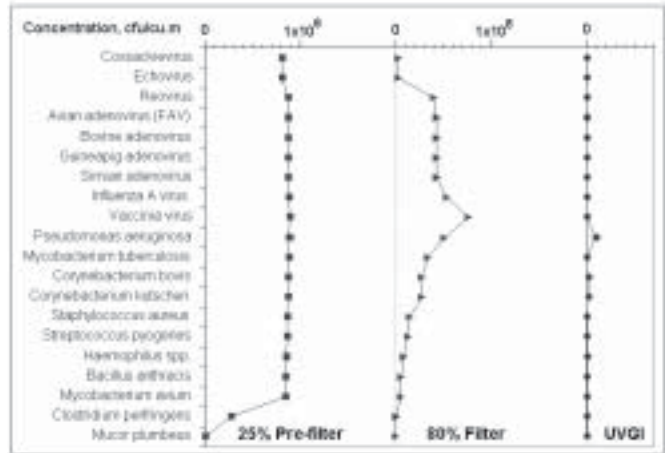


Figure 12. Concentrations of contaminants before and after combined filtration and UVGI. Microbes shown are only those for which UVGI rate constants could be estimated.

settle out of the air. For this same reason, ionization can improve the efficiency of filter units. Published data suggest that the incidence of disease in poultry houses is reduced when negative ionization is used to charge the air (38).

Electrostatic filtration is not a new technology, but various types of electrostatic filtration systems have been developed lately that improve the performance against particles in the size range of microorganisms. Apart from the energy costs, one of the problems with these types of filters is that their performance can suffer due to changes in humidity.

Filters with anti-microbial coatings have been available for some time but have not been popular because of concerns about dislodging of biocidal materials. Occasionally, regular filters that have accumulated fungi or bacteria and are subject to moisture foster microbial growth to the point that the microbes “grow through” the filter material. The main advantage of biocidal filters is that they resist such microbial growth.

Conclusions

The preceding review suggests that much information can be added to the available guidelines to assist laboratory designers and managers needing to select and size air-treatment systems. The literature and analyses we have summarized provide a theoretical basis for comparing the various technologies used for air treatment and allow for some general conclusions to be drawn. Perhaps chief among these is the fact that HEPA filters may not provide the cost-benefits with which they are credited. Ordinary high-efficiency filters, such as 80% and 90% filters, may be sufficient for controlling airborne microorganisms in animal facilities and cost much less than to HEPA filters to own and operate. In light of estimates for a 33,000-cfm ventilation system in Pennsylvania, a HEPA filter costs approximately \$14,200 a year to operate, whereas nominal 90% and 80% filters cost about \$7700 and \$4200 annually respectively (39). These estimates are subject to variations depending on location and operating conditions, but the relative proportions should be similar for any ventilation system.

UVGI technology has potentially beneficial applications in animal laboratories but is underused and essentially is ignored in most guidelines. This technology could be more effectively applied by combining it with medium-efficiency filtration. Such a combination seems ideal and likely would provide the most economic means of controlling air quality inside animal laboratories. A UVGI system can be used to augment an 80% filter for about \$4600 annually (39).

The use of 50% to 100% outside air for dilution ventilation can provide an effective and economic means of controlling air quality when sized for the local climatic conditions. The use of

air-to-air heat exchangers and other types of energy recovery devices in 100% outside air systems offers potentially important cost savings and should be considered in all new designs. Without the use of heat exchangers, 50% outside air would cost more to operate than would a HEPA filter, in most locations (39).

Detailed analysis of the various technologies is possible for any given application, but such results cannot be generalized in light of factors like climate, energy costs, and specific facility requirements. However, life-cycle cost analysis can be performed by engineers to determine the most cost-effective means of disinfecting air and maintaining high levels of indoor air quality in animal laboratories on the basis of the fundamentals we have presented. We hope this information will help designers reduce costs while improving air quality for laboratory workers.

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