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Discussion

Airborne Infection Control in Health Care Facilities

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Documented correlations between building occupant health effects and exposure to indoor airborne contaminants are very limited because of low indoor concentrations and confounding exposure elsewhere. However, an important exception has been found in hospitals where immune compromised patient mortality has been directly linked to increased indoor airborne fungal contamination caused by construction activity. Inhalation of viable Aspergillus spores often results in invasive pulmonary aspergillosis, a disease with a high fatality rate. A review of the literature is given and recommendations and needs are outlined for barriers, filtration, air pressure control and bioaerosol sensors.
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Introduction

Indoor air quality is an important aspect of buildings in the developed world as most people spend 90% or more of their time indoors. Therefore exposure to airborne pollutants indoors is often more significant than outdoors. Three methods are commonly cited to control indoor airborne concentrations: *a*) source control, *b*) dilution with outdoor air, and *c*) removal. Source control may result in the ban of certain materials or activities, e.g., smoking, or selection of building and furnishing materials with reduced emission rates. Maintaining the air pressure in a space greater than in its surroundings eliminates most of the uncontrolled infiltration of contaminants. Dilution has traditionally meant the supply of outdoor air. The assumption has been that outdoor air is cleaner than indoor air, a concept that has prevailed since Victorian times. The amount of outdoor air required per occupant is often based on ASHRAE Standard 62 [1]. Contaminant removal has been introduced relatively recently to protect building occupants against airborne particles and gases. Particulate filtration is used in nearly all buildings. The quality of filtration continues to increase as filters become better at removing airborne particles with minimal pressure drop. Gas filtration is rarely used except when a specific gaseous source is known to exist and is usually located near the source or at the outdoor air intake.

Operating a building with adequate outdoor air flow, pressure control and filtration requires heating and cooling energy as the outdoor air psychrometric conditions are rarely those desired for the supply air. Fan power is necessary to overcome pressure drop losses across the filters and through the remainder of the air handling system. The cost to operate the fans is a large fraction of the annual energy expense in many commercial buildings. Although this energy use constitutes an operating cost to the building owner, there are some building types where energy cost is not the primary concern; e.g., clean rooms and hospitals. The primary function of a clean room is to protect products from exposure to airborne contaminants that would decrease the yield. Hospitals and other health care facilities must protect patients from airborne microorganisms that can cause disease.

This paper focuses on an issue that requires proper ventilation system design and operation because of the significant impact of improper performance on health care delivery cost, patient infection and potential litigation. The buildings of interest are not those that are occupied and operating normally but those that are partially occupied and undergoing expansion or renovation. Patient death rates have been found to be significantly higher in wards near construction or renovation projects than in those with no construction activity nearby. Documentation of this trend is reported, causes identified, and engineering solutions are presented.

Trends in the Health Care Industry

The annual construction cost for health care facilities in the US is approximately $17 billion. Renovation and remodeling consti-

Fig. 1 Photograph of new construction in front of a 1970's hospital building with mechanical ventilation that was added to a 1920's building originally designed for natural ventilation with operable windows.

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Table 1 Documented reports of construction-related hospital-acquired outbreaks due to fungus, 1995–2000.

Reference	No. Patients Infected	No. Patient Deaths	Probable Cause
[17]	4	4	Unknown
[18]	5	Not Available	Air returns not sealed in renovation area allowing contaminated air to be distributed to occupied areas
[19]	7	6	Direct openings between patient rooms and areas above and below and negative pressure in 4 of 16 patient rooms
[20]	3	1	No barriers installed between patients and remodelling of adjacent radiology department
[21]	4	Not Available	Exterior packaging of dressing material contaminated during construction in central inventory. Patients contaminated when boxes opened prior to dressing changes.
[22]	36	17	Unknown. 4 cases prior to construction, 28 cases during construction and 4 cases after control measures implemented.
[23]	8	5	Directly related to increased fungal spores aerosolized by soil excavation.
[24]	3	2	Outbreak coincided with nearby renovation activity.
[14]	21	6	One-half of patient rooms had negative pressure with respect to hallway. Air pressure was less than in connecting hospital causing unfiltered air from construction site to enter from hospital building and proceed into patient rooms.
[25]	8	Not Available	Inadequate barriers between patient rooms and renovation in adjacent nursing station. Air pressure not controlled and insufficient local filtration.

tute 70%; new construction the remaining 30% [2]. Figure 1 shows a progression of building ages and styles typical of many large medical complexes. Older buildings are seldom replaced but serve as components of the renovated facility. The loss of patient revenue precludes shutting down existing facilities so they continue to function at near normal capacity during the entire construction or renovation process. The average patient admitted to a hospital has more severe health issues than in the past and the length of stay is shorter. Hospital finances are tighter resulting in staff shortages and potential patient care problems. Hospital acquired infections result in approximately 88,000 unnecessary deaths and $3 billion in additional costs annually [3]. When patients become infected, the question becomes whether the infection was the result of time spent in the hospital or whether it was community acquired. With shorter lengths of stay in the hospital, the increasing number of procedures that leave patients susceptible to infection, and the ability to detect very low levels of infection through noninvasive techniques, it is becoming increasingly difficult to determine the source.

More hospitals are now incorporating separate isolation rooms for infectious patients such as those with drug-resistant tuberculosis (TB) and patient protection rooms for those with compromised immune systems, primarily those undergoing bone marrow transplants. Emergency rooms are held at negative pressure with respect to the rest of the hospital with local exhaust to isolate potential airborne microorganisms generated by walk-in patients from the hospital staff and the remaining patient population.

Hazards from Airborne Microorganisms

Airborne particles of biological origin can be allergenic, such as pollen, dander, and insect parts. This paper focuses on those that can cause disease. Some of these are known as viable particles because they can grow and propagate given sufficient nutrients and growth conditions. Transmission can be from other humans, from animals or from the environment. Human to human transmission via an airborne route has been documented for tuberculosis (TB), smallpox, chickenpox, measles, mumps, rubella, and influenza.

Environment to human transmission of *legionella* bacteria, filamentous fungi and *bacillus anthracis* (anthrax) are well known. A group of filamentous fungi known as *Aspergillus*, is of special concern in hospitals. There are 200 species with *Aspergillus fumagatis* spores being of most concern. They are ubiquitous in the environment as they have been found at 3000 m altitude and can survive in battery acid. Spore size is approximately 3–5 microns in diameter that corresponds to a settling velocity of approximately 5×10^{-4} m/s. This allows them to remain airborne for an extremely long time and to be inhaled. Outdoor concentrations range from 1 to 10 colony-forming units (or viable spores) per cubic meter (CFU/m^3). This fungus is thermotolerant to 45 C so it thrives at human body temperature. When a person's immune system is compromised due to disease or immune suppressing drugs, which is a routine procedure in transplant therapy, the *Aspergillus* can vigorously grow on various body tissues. Damage can occur on the cornea, skin, and burn wounds; on an operative site for a valve, organ, or stent; or in the respiratory system. Antifungal therapy for these infections, amphotericin B, is not always successful which usually leads to patient death. Survival was estimated at only 7% for patients with invasive aspergillosis whereas it was 54% for a control group with chronic leukemia [4]. Invasive aspergillosis was diagnosed as being the second most common fungal infection in cancer patients [5]. The fatality rate was found to be between 45–94%. A systematic review of five years of data from 1995–2000 including 50 studies and 1941 patients [6] showed that bone marrow transplant patients had the highest case fatality rate at 86.7%. This agrees with a previous study [7] that had found a 90% rate.

Documented Construction Related Patient Infections

Very little data directly relates building occupant health to indoor airborne contaminant exposure because the concentrations are very low, and health effects are usually the result of a combination of indoor and outdoor exposures over an extended time period. An exception to this is hospital patient mortality caused by invasive aspergillosis [8]. The patient population in a hospital is much more susceptible to disease than the general public. Those undergoing treatment for leukemia or receiving bone marrow transplants are particularly susceptible. Patients reside in well known locations within the building so their exposure can be well documented. Although considerable effort is taken to protect patients against infection, construction related activity within the building or nearby can generate additional airborne fungal spores. Improper control of the indoor air cleanliness during construction can result in increased patient exposure, illness, and death.

Several published reports document the link between construction activity and patient infections. Airborne microbial sampling was not conducted during patient exposure in many of the cited cases. However, there is sufficient evidence to suggest that construction activity is the primary cause. In recent studies, airborne and surface microbial sampling protocols were used before, during and after construction to correlate construction activity, microbial concentration and patient health effects.

Fungal infections in leukemia patients were traced to *A. niger*, *A. flavus* and *A. fumigatus* that had grown on fireproofing material sprayed on building members [9]. Subsequent disruption of ceiling tiles below this allowed *Aspergillus* fungi into the patient rooms. Three patients in a renal transplant ward developed aspergillosis during a two-month renovation project on an adjacent floor [10]. No patients were infected during the eight-month period that followed the construction. An outbreak of invasive pulmonary aspergillosis (IPA) in patients at Milwaukee County Medical Center was traced to road construction adjacent to the hospital where copious amounts of soil fungi were aerosolized. Eleven immunosuppressed patients at Fitzsimons Army Medical Center developed aspergillosis [11]. This coincided with extensive renovation of the medical intensive care unit and several hospital wards. An epidemiological study of 22 cases of invasive aspergillosis in the Edouard Herriot Hospital in Lyon, France associated these cases with renovation activities in the hospital [12]. Four of five patients who developed invasive aspergillosis following high-dose chemotherapy treatment were located in rooms adjacent to a construction staging area [13]. Swab samples taken in the exhaust ducts from special care rooms showed 109 mold colonies from rooms adjacent to construction versus 44 from rooms distant to the construction. Of this total count, the *A. fumagatis* counts were five times larger in ducts near the construction.

Monitoring *Aspergillus* cases during construction of a building nearby resulted in 21 confirmed cases in Maryland; six of these patients died [14]. Only 10 cases had been reported the entire previous year. With no cases of invasive aspergillosis for the previous two years, eight cases were found in a Finnish hospital following window replacement [15]. A study of 96 cases of aspergillosis at the Fred Hutchinson Cancer Research Center in Seattle showed a relative risk of 1.8 during construction activity compared with patients who received transplants at other times [4]. An outbreak of aspergillosis at a 450-bed community hospital in Pittsburgh has been well documented [16]. Case-patient rooms were closer to the renovation activity that occurred in the same half of the ward than non-case patient rooms. Case-patients were also closer to construction on the west wing.

Table 1 contains documented construction related outbreaks of aspergillosis that were published between 1995–2000. The number of patient deaths in some of these cases was not published because of litigation. The probable cause includes unblocked air return grilles in the construction area, inadequate barriers to separate the construction area from the occupied area, and the lack of proper air pressure control. Air pressure differences between interconnected buildings is a concern in addition to the pressure within individual patient room with respect to the adjacent hallway.

Contamination of medical laboratories can produce false-positive infection data. Isolation of *A. niger* from inpatient clinical specimens changed from a rate of 0.17/10,000 patient days before construction to 6.4/10,000 patient days during construction at a veterans hospital in Texas [26]. A new air duct had been installed adjacent the laboratory just prior to these elevated readings with no barriers erected to control the dust levels. Several patients were unnecessarily placed on anti fungal drugs before the laboratory data were shown to be invalid.

Microbial Growth on Ventilation Filters

Particulate air filters used in building ventilation systems are designed to collect airborne particulate matter with minimal pressure drop. Standard methods for test have recently been developed by ASHRAE [27] and the European Union [28] that report capture efficiency as a function of particle size for new, clean filters.

Another issue is microbial growth on loaded filters. Microbial growth can occur whenever the viable spores find adequate nutrients, moisture and temperature. Some types of filter media such as cellulose, binder materials and frames supply these nutrients. Atmospheric dust contains between 30–40% organic matter by mass. Thus a filter with sufficient dust loading will contain the nutrients necessary to support microbial growth. Growth rates are then determined principally by the temperature and relative humidity levels of the air passing through the filter. Growth will generate volatile organic compounds and the potential exists for grow-through where the hyphae grow to the back side of the filter and spores are then released into the cleaned air supplied to the building. Thus a filter that was installed as an air cleaning device may become a source of odors and microbial airborne contaminants in the air handling system

Simmons and Crow [29] found substantial microbial growth on new and loaded cellulosic filters when the relative humidity was higher than 70%. Colonies of *A. niger*, *A. fumagatus*, *A. flavus*, *A. versicolo*r and others were found on unused filter media. The production of a wide range of volatile organic compounds has been measured from used air filters and insulation material [30]. Moritz et al. [31] observed microbial growth on loaded filters in a building air handling unit when the filters were exposed to long periods of outdoor air at relative humidity levels above 80%. No growth was seen on filters in a similar air handing system with preheaters located before the filters. Maus et al. [32] observed significant growth of *A. niger* on used filters when the relative humidity was above 85% and the filters were not exposed to air flow. A study was performed to investigate the influence of multi-layered polymer media versus fiberglass media on microbial growth rates [33]. The polymer media exhibited less growth and fewer viable species than fiberglass during the initial loading. However, the amount of nutrient loading in the dust cake on both filters was nearly equal after six weeks so that no measurable difference occurred beyond this point.

Control Measures

To be effective, the control of indoor airborne microorganism concentrations during construction requires cooperative effort between the architectural and engineering design team and implementation by health care facility staff and the contractors. Often new construction is immediately adjacent to sensitive areas of a

Fig. 2 Photograph showing new construction of a large heart center connected to an existing hospital building near the MRI/CT Scanning unit

hospital. Figure 2 shows a new addition being connected to an existing building near the MRI unit. Controls in this case include blocking and relocating outdoor air intakes, increasing the level of filtration, sealing exterior penetrations including operable windows, providing an air tight barrier between the construction area and the occupied area, and providing positive pressure in the existing building relative to the construction area. Other issues include the effects of vibration on sensitive medical equipment, contamination of the interior spaces from foot traffic and mechanical outages. This remainder of this section focuses on the engineering aspects of airborne microorganism control.

Barriers. Fire rated barriers are normally recommended to be installed between the construction area and the occupied areas of the building. The premise is that an air-tight barrier will assist in the maintenance of a pressure difference between the occupied and contaminated sides. With an adequate pressure difference, advection of aerosol particles across the barrier can be prevented. No data are available to indicate how much leakage area should be allowed. Numerous utility penetrations including piping, cabling and ductwork pose a challenge. Figure 3 shows the construction side of a barrier installed in a corridor of a hospital undergoing renovation. The barrier is constructed of metal studs and dry wall with a 2-h fire rating. Seams and joints are sealed with tape to assist in pressure control across the barrier. The barrier must extend to the floor or roof above and all duct, piping and electrical utility penetrations must be well sealed to isolate the occupied zone from the construction zone.

Pressure Control. It is desired to maintain a positive air pressure on the occupied side of the barrier with respect to the construction side. This requires continuous pressurization of the occupied area or continuous exhaust of the construction area or both. This is very difficult to achieve in practice as the pressure difference is governed by natural phenomena such as wind and stack effects in addition to mechanical pressurization or depressurization. Obvious leakage sites in the occupied area such as operable windows should be sealed. Pressurization can be accomplished by utilizing the existing mechanical ventilation system to supply filtered air to the occupied space. HEPA filters should be installed at the supply diffusers as added protection. Depressurization is typically provided by operating exhaust fans at openings in the building envelope in the construction zone. The pressure difference necessary for contaminant containment is not known. The Center for Disease Control [34] recommends a pressure difference of 2.5 Pa (0.001 in water) for protection isolation rooms. The American Institute of Architects [35] recommends 25 Pa (0.01 in water) across construction barriers. Others have recommended higher values [36].

Fig. 3 Photograph of the construction side of a barrier in a hospital corridor separating the construction zone from the occupied area (Source: Richard Hermans, Center for Energy and Environment, Minneapolis, MN)

Audio and visual alarms are usually specified to monitor the pressure difference across the barrier. An alarm can be an indication of ventilation system malfunction or the consequence of a utility outage. The output signal can be connected into the building automated control system for monitoring alarms and recording pressure difference levels versus time and activity.

Air Filtering. A comprehensive study of the effect of filters and laminar airflow on *Aspergillus* species was conducted at the Hotel-Dieu Hospital adjacent to Notre-Dame Cathedral in Paris [37]. Four hundred three air samples were obtained during the ten month period prior to construction, 230 were taken during the 6-month construction period and 414 were taken in the 8 months following construction activity. In addition, similar numbers of surface samples were obtained over the same time periods. Three areas were monitored: units with no protective air supply, units with HEPA filtration alone and units with both HEPA filtration and laminar airflow. Significantly more air samples were positive for *Aspergillus* species in the units with no filtration during the construction activity than before or after. Similar results were found in the units with HEPA filtration alone where the mean airborne concentration of *Aspergillus* rose from 4 CFU/m^3 to 24.7 CFU/m^3. Only the units with both HEPA filtration and laminar airflow showed no *Aspergillus* in the 142 samples taken. The authors concluded that HEPA filtration alone is not sufficient to protect patient exposure to construction-related fungal contaminants; a combination of filtration and air flow control is necessary. They also recommended other control methods including sealing off the construction zone, wetting rubble, sealing windows, and limiting construction traffic through occupied wards.

In another study conducted at the Rambam Medical Center in Haifa, Israel, only one case of invasive pulmonary aspergillosis (IPA) was diagnosed during the three years preceding construction activity [38]. However six cases were diagnosed during the first four months of construction. Airborne concentrations of *Aspergillus* species rose to a mean value of 15 CFU/m^3 in the wards near the construction site. Measurements taken in the newly completed hematological ward with HEPA filtration and ventilation control showed a much lower mean value of 0.18 CFU/m^3. No patients housed in the new ward developed IPA although contruction continued in other parts of the facility. The authors conclude that drug treatments alone were not effective in reducing the risk of IPA, but that the HEPA filtered air flow in the new unit eliminated the concern.

Often the dust loading is significantly higher during construction so the building air intake filters need to be replaced more often than normal. HEPA filters at the supply terminal units will remove any particulate contamination that penetrates the supply air ductwork providing they are well sealed. Air passing through the filters should remain at a relative humidity level below 70% to prevent microbial growth in the dust cake. Personal respiratory protection is also required when patients must be relocated for procedures outside their protective environment.

Monitoring. The air pressure difference between the clean and contaminated zones is a secondary variable. It is more informative to know the time dependent bioaerosol concentration in the occupied zone. Background levels obtained before construction activity commences can be compared with measurements taken during construction. Large volumes of air must be sampled to obtain statistically significant results because of the low concentrations of spores present in well controlled occupied areas. Presently, real time bioaerosol sensors are too expensive to be used in this application. Measurements are thus taken periodically using viable bioaerosol impaction and growth techniques. Elevated concentrations can serve to initiate an investigation into the cause before patient protection is severely compromised. Another

issue is that many elevated concentrations occur as short-term bursts. Periodic air sampling may miss these bursts and thus not correlate well with patient exposure. An alternative is to use a continuous particle counter for the measurement of total aerosol concentrations versus time with periodic sampling for bioaerosols. The particle counter output can be connected to a local alarm or interfaced with the building automation system for remote monitoring and data logging.

Engineering Challenges

Although the discussion here focuses on health care facilities undergoing construction, similar airborne contamination issues exist with all building types. Most building occupants are not as susceptible to adverse health effects as hospital patients so the relationship between exposure to construction generated contaminants and resulting health effects is not as clearly defined. Perhaps mechanical systems should be designed to be more readily adaptable to the operation needed when renovation occurs. The total cost may be lower to incorporate this capability when the system is first built than to change it when the renovation project begins. Similar exposure and control issues exist in buildings with no construction activity as contaminants may originate outside the building or be released within. Smoke control technology is well developed for large releases of airborne contaminants from fires. Similar control measures can be applied to the containment of other airborne contaminants provided appropriate sensors and air movement devices are utilized.

Filtration of both supply and return sides of an air handling system will assist in isolating contaminants generated within a portion of a building. Filtered returns would also reduce the level of microbial contamination found in most air return plenums and ducts. This will require additional first cost, maintenance and fan power so the need for this level of protection should be determined from a risk assessment. Filtration systems with better particulate capture efficiency, lower pressure drop and less microbial growth are desired. It will be useful to know more about the effect of air psychrometric conditions on the microbial growth rate on loaded filters so that filters and air handling systems can be better designed and operated to prevent growth.

Real time bioaerosol sensors that are low-cost, rugged and reliable and can identify microbes of interest are needed. These sensors can be incorporated into a building control system for pressurization control. It would be useful to monitor the outdoor air at the fresh air intake in addition to selected locations indoors. A typical particle counter could also be useful to detect bursts although they provide no information concerning the nature of the burst. If a burst is detected, then a secondary sampling system for bioaerosol could be activated without overloading it with normal airborne dust.

A risk assessment should be made on a given building to determine if it should receive additional protection from airborne bioaerosols. If, as in the case of hospitals, the occupant population is susceptible to serious health consequences, then it may be prudent to specify and install the necessary prevention and monitoring equipment.

Summary

Construction-related hospital patient deaths are now well documented and the causes and control measures to mitigate the problem are becoming well understood. Education and training are being provided to hospital infection control practitioners and contractors in an effort to alleviate the problem. The cost effectiveness of most recommended control measures is not known. Additional research is necessary to determine what controls are most useful and to better document necessary levels of air pressure difference, air flow rate, filtration efficiency, contaminant concentration, and other parameters.

The lessons being learned by protecting patients from airborne microbial exposures in hospitals can be applied to other airborne contaminants and to nearly all building types. The air handling systems and the means of control are very similar. The difference is in the associated health effects that may be negligible for most naturally occurring contaminants. The costs, both financial and energy, associated with installing and maintaining a control system may be similar so that a thorough risk assessment should be made before a decision is made on a specific facility.

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References

[1] ASHRAE Standard 62-2001, ''Ventilation for Acceptable Indoor Air Quality,'' American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.
[2] Bartley, J. M., 2000, ''APIC State-of-the-Art Report: The Role of Infection Control During Construction in Health Care Facilities,'' Am. J. Infect. Control, **28**(2), pp. 156–169.
[3] Sandrick, K., 2001, ''Clearing the Air,'' Health Facilities Management, May, pp. 16–20.
[4] Wald, A., Leisenring, W., Van Burik, J., and Bowden, R. A., 1997, ''Epidemiology of Aspergillus Infections in a Large Cohort of Patients Undergoing Bone Marrow Transplantation,'' J. Infect. Dis., **175**, pp. 1459–1466.
[5] Kaiser, L., Huguenn, Y., Lew, P. D., Chapus, B., and Pettet, D., 1998, ''Invasive Aspergillosis,'' Medicine, **77**, pp. 188–194.
[6] Lin, S.-J., Schranz, J., and Teutsch, S. M., 2001, ''Aspergillosis Case-Fatality Rate: Systematic Review of the Literature,'' Clin. Infect. Dis., **32**, pp. 358–366.
[7] Denning, D. W., 1996, ''Therapeutic Outcome in Invasive Aspergillosis,'' Clin. Infect. Dis., **23**, pp. 608–615.
[8] Kuehn, T. H., Gacek, B., Yang, C.-H., Grimsrud, D. T., Janni, K. A., Streifel, A. J., and Pierce, M., 1996, ''Identification of Contaminants, Exposures, Effects and Control Options for Construction/Renovation Activities,'' ASHRAE Trans., **102**(2), pp. 89–101.
[9] Aisner, J., Schimpff, S. C., Bennett, J. E., Young, V. M., and Wiernek, P. H., 1976, ''Aspergillus Infections in Cancer Patients: Association with Fireproofing Materials in a New Hospital,'' J. Am. Med. Assoc., **235**(4), pp. 411–412.
[10] Arnow, P. M., Anderson, R. L., Mainous, P. D., and Smith, E. J., 1978, ''Pulmonary Aspergillosis During Hospital Renovation,'' Am. Rev. Respir. Dis., **118**, pp. 49–53.
[11] Opal, S. M., Asp, A. A., Cannadu, P. B. Jr., Morse, P. L., Burton, L. J., and Hammer, II, P. G., 1986, ''Efficacy of Infection Control Measures During a Nosocomial Outbreak of Disseminated Aspergillosis Associated with Hospital Construction,'' J. Infect. Dis., **153**(3), pp. 634–637.
[12] Perraud, M., Piens, M. A., Nicoloyannis, N., Girard, P., Sepetjan, M., and Garin, J. P., 1987, ''Invasive Nosocomial Aspergillosis: Risk factors and Hospital Building Works,'' Epidemiol. Infect., **99**, pp. 407–412.
[13] Iwen, P. C., Davis, C., Reed, E. C., Winfield, B. A., and Hinrichs, S. H., 1994, ''Airborne Fungal Spore Monitoring in a Protective Environment During Hospital Construction, and Correlation with an Outbreak of Invasive Aspergillosis,'' Infection Control and Hospital Epidemiology, **15**(5), pp. 303–306.
[14] Thio, C. L., Smith, D., Merz, W. G., Streifel, A. J., Bova, G., Gay, L., Miller, C. B., and Perl, T. M., 2000, ''Refinements of Environmental Assessment During an Outbreak Investigation of Invasive Aspergillosis in a Leukemia and Bone marrow Transplant Unit,'' Infection Control and Hospital Epidemiology, **21**(1), pp. 18–23.
[15] Ruutu, P., Valtonen, V., Tiitanen, L., Elonen, E., Volin, L., Veijalainen, P., and Ruutu, T., 1987, ''An Outbreak of Invasive Aspergillosis in a Hematologic Unit,'' Scand. J. Infect. Dis., **19**, pp. 347–351.
[16] Burwen, D. R., Lasker, B. A., Rao, N., Durry, E., Padhye, A. A., and Jarvis, W. R., 2001, ''Invasive Aspergillosis Outbreak on a Hematology-Oncology Ward,'' Infection Control and Hospital Epidemiology, **22**(1), pp. 45–48.
[17] Alvarez, M., Ponga, B. L., Rayton, C., Gala, J. G., Porto, M. C., Gonzales, M., Martinez-Suarez, J. V., and Rodriguez-Tudela, J. L., 1995, ''Nosocomial Outbreak Caused by *Scedosporium prolificans* (inflatum): Four Fatal Cases in Leukemia Patients,'' J. Clin. Microbiol., **33**(12), pp. 3290–3295.
[18] American Health Consultants, 1995, ''Aspergillosis: A Deadly Dust May be in the Wind During Renovations,'' Hospital Infection Control, **22**(10), pp. 125–126.
[19] American Health Consultants, 1995, ''Construction Breaches Tied to Bone Marrow Infections,'' Hospital Infection Control, **22**(10), pp. 130–131.
[20] Berg, R., 1995, ''Nosocomial Aspergillosis During Hospital Remodel,'' *Infections and Nursing Practice: Prevention and Control*, Soule et al. (eds.), Mosby, St. Louis, pp. 271–274.
[21] Bryce, E. A., Walker, M., Scharf, S., Lim, A. T., Walsh, A., Sharp, N., and Smith, J. A., 1996, ''An Outbreak of Cutaneous Aspergillosis in a Tertiary-care Hospital,'' Infection Control and Hospital Epidemiology, **17**(3), pp. 170–172.
[22] Loo, V. G., Bertrand, C., and Dixon, C., 1996, ''Control of Construction-Associated Nosocomial Aspergillosis in an Antiquated Hematology Unit,'' Infection Control and Hospital Epidemiology, **17**(6), pp. 360–364.

[23] Lueg, E. A., Ballagh, R. H., and Forte, V., 1996, ''Analysis of the Recent Cluster of Invasive Fungal Sinusitis at the Toronto Hospital for Children,'' J. Otolaryngol., **25**(6), pp. 366–270.
[24] Sessa, A., Meroni, M., Battini, G., Pitingolo, F., Giordano, F., Marks, M., and Casella, P., 1996, ''Nosocomial Outbreak of Aspergillus Fumagatis Infection Among Patients in a Renal Unit,'' Nephrol. Dial Transplant, **11**, pp. 1322–1324.
[25] Patterson, J. E., Peters, J., Calhoon, J. H., 2000, ''Investigation and Control of Aspergillosis and Other Filamentous Fungal Infections in Solid Organ Transplant Recipients,'' Transplant Infectious Disease, **2**, pp. 22–28.
[26] Laurel, V. L., Meier, P. A., Astorga, A., Dolan, D., Brockett, R., and Rinaldi, M. G., 1999, ''Pseudoepidemic of *Aspergillus Niger* Infections Traced to Specimen Contamination in the Microbiology Laboratory,'' J. Clin. Microbiol., **37**(5), pp. 1612–1616.
[27] ANSI/ASHRAE Standard 52.2-1999, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.
[28] European Standard EN779, 2002, ''Particulate Air Filters for General Ventilation-Determination of the Filtration Performance,'' European Committee for Standardization, Management Centre: rue de Stassart, 36, B-1050, Belgium.
[29] Simmons, R. B., and Crow, S. A., 1995, ''Fungal Colonization of Air Filters for use in Heating, Ventilating and Air Conditioning (HVAC) Systems,'' J. Ind. Microbiol., **14**, pp. 41–45.
[30] Ahearn, D. G., Crow, S. A., Simmons, R. B., Price, D. L., Mishra, S. K., and Pierson, D. L., 1997, ''Fungal Colonization of Air Filters and Insulation in a Multi-Story Office Building: Production of Volatile Organics,'' Curr. Microbiol., **35**, pp. 305–308.
[31] Moritz, M., Peters, H., Nipko, B., and Ruden, H., 2001, ''Capability of Air Filters to Retain Airborne Bacteria and Molds in Heating, Ventilating and Air Conditioning (HVAC) Systems,'' Int. J. Hyg. Environ. Health, **203**, pp. 401–409.
[32] Maus, R., Goppelsroder, A., and Umhauer, H., 2001, ''Survival of Bacteria and Mold Spores in Air Filter Media,'' Atmos. Environ., **35**, pp. 105–113.
[33] Kemp, P. C., Neumeister-Kemp, H. G., and Murray, G. L., 2001, ''Survival and Growth of Mocro-organisms on Air Filtration Media During Initial loading,'' Atmos. Environ., **35**, pp. 4739–4749.
[34] Dykewicz, C. A., 2001, ''Hospital Infection Control in Hematopoietic Stem Cell Transplant Recipients,'' Emerg. Infect. Dis., **7**(2), pp. 263–267.
[35] Guidelines for Design and Construction of Hospital and Health Care Facilities, 2001, The American Institute of Architects, Washington, DC.
[36] Rice, N., Streifel, A., and Vesley, D., 2001, ''An Evaluation of Hospital Special-Ventilation-Room Pressures,'' Infection Control and Hospital Epidemiology, **22**(1), pp. 19–23.
[37] Cornet, M., Levy, V., Fleury, L., Lortholary, J., Barquins, S., Coureul, M.-H., Deliere, E., Zittoun, R., Brucker, G., and Bouvet, A., 1999, ''Efficacy of Prevention by High-Efficiency Particulate Air Filtration or Laminar Airflow Against *Aspergillus* Airborne Contamination During Hospital Renovation,'' Infection Control and Hospital Epidemiology, **20**, No. 7, pp. 508–513.
[38] Oren, I., Haddad, N., Finkelstein, R., and Rowe, J. M., 2001, ''Invasive Pulmonary Aspergillosis in Neutropenic Patients During Hospital Construction: Before and After Chemoprophylaxis and HEPA Filters,'' Am. J. Hematol., **66**, pp. 257–262.