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Managing building-related *Aspergillus* exposure

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Aspergillus exposure is difficult to avoid. Indoor dust contains spores and thermotolerant molds may colonize damp or water-damaged building materials or components. Dust control should be part of diligent maintenance since disturbing dusts, especially during building renovation, can expose occupants to spores. Colonization of HVAC systems can shed spores into a building and expose occupants. Mold colonization warrants prompt and effective remediation, including removal of the colonization with associated debris and dusts without unduly exposing remediation workers, and while controlling fugitive dusts. Cleaning may suffice for non-porous surfaces, but colonized porous materials typically must be removed. Determining successful remediation can be challenging; the objective is not to sanitize, but a building in a 'normal and typical' state, a state that is often poorly defined. This is even more troublesome for colonized HVAC components and for health care facilities. Practical remediation assessment emphasizes inspection and then environmental monitoring. Air sampling may prove useful after inspection and monitoring, assuming prior consensus on the purpose of sampling and interpretation of results. Thoughtful design, careful construction and renovation, and diligent operation and maintenance of a building are all needed to minimize the exposure of building occupants to mold.

Keywords *Aspergillus* exposure, mold colonization, mechanically-ventilated buildings

Introduction

Mechanically-ventilated buildings provide great benefits in increased comfort to building occupants. Outdoor air (OA) is usually brought into mechanically-ventilated buildings to dilute bioeffluents. The location of the OA intake may introduce bioaerosols, including viable thermotolerant spores into the building [1]. Mechanical ventilation systems typically have ducts that carry air through the building, which also provide sites for dust, including spores to accumulate. Even if this accumulation remains dry, and any accumulated spores dormant, the dust can become an exposure source to occupants if the dust is disturbed and becomes entrained in the airstream since the ducts are often downstream of the main filters.

A key distinction occurs between accumulations of dry dormant spores, and active mold growth (colonization or amplification) on damp or wet materials. Mold colonization typically produces abundant spores which for thermotolerant species are an obvious infection concern in health care facilities. Most mold growth indoors will also produce and abundantly shed other particles ($PM_{2.5}$ range) that are laden with metabolites (e.g., allergens, glucans). These may contribute to the 'damp building effect' although the mechanism(s) underlying this effect remains controversial [2].

In addition to importing, collecting and distributing dormant spores, HVAC systems can facilitate mold colonization of building materials in several ways. Mechanical ventilation can cause pressurization imbalances, which can induce mold growth in the envelope (outer walls) of buildings. HVAC systems also directly affect moisture balances in indoor air and materials as discussed below. Mechanical ventilation can also collect and re-distribute fungal material that is shed from moldy surfaces elsewhere in the building that are

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colonized due to roof or plumbing leaks, rising damp, or other moisture problems.

Heating, ventilating and air-conditioning (HVAC) systems in warm climates change the moisture balance of the air when cooling. In hot, humid climates, refrigerant cooling systems induce condensation. In hot, dry climates evaporative coolers intentionally add moisture to air streams. Both also can affect the moisture content of building materials, as well as air. Evaporative coolers are predominantly used in residential settings though, and are not discussed further here. The cooling coils in a refrigerant cooled HVAC are recognized as a condensation source, and so the system is designed to accomodate the condensate water. The rest of the HVAC system, however must also accommodate the potential for condensation to occur on any surface that is cooled below the dew point of air that is exposed to that surface. This can include the surfaces of ducts or refrigerant piping running through unconditioned space. This can also include objects or surfaces that are overcooled by air discharged from the HVAC system (Fig. 1). Mold growth also results from leaks and other water damage to building materials.

Fig. 1 Poster with mold colonization in lower left corner induced by cooling the glass below the dew point. Note the parabolic contour of the top edge (arrows) of the colonized area, corresponding to the conical discharge of cold air from an HVAC duct above the poster.

Regardless of the source of moisture permitting mold growth to occur, visible mold growth (active or dormant colonization) should not be tolerated in occupied indoor environments [3]. This is especially true for health care facilities. Remediation is the process of removal and cleaning of mold colonization in buildings. It must include removal of visible colonization and provide protection [4,5]. Additionally, any health care facility needs to be concerned with the presence of viable spores of thermotolerant molds that might lead to infections in immunocompromised patients.

Humidity control is crucial to limiting the ability of mold to colonize indoor materials. There are no established standard levels of humidity that must be maintained. General recommendations are to maintain indoor humidity in the range of 40–60% relative humidity (RH). However, these guidelines are for occupied spaces and are designed to assure comfort of the occupants. Mold colonization is more directly driven by substrate moisture which is affected by airflow (restricted in wall cavities) and temperature (cool in ducts) as well as RH. The design and operation of the building and building components must be sensitive to which materials are used in places within a building that may accumulate moisture, regardless of the RH of the air.

The occurrence of spores in ordinary settled dust on surfaces has been referred to as ‘Table Top Molds’ or TTM [3]. TTM lacks the accumulation of metabolites in/on a substrate associated with colonization, either active or past. Unfortunately several widely used methods of sample analysis detect colony forming units (CFUs), DNA copies (‘cell equivalents’) or airborne spores and do not discern between settled dormant spores (TTM) and colonization. The distinction between TTM and colonization is crucial since this affects the appropriate remediation response. These responses can vary from a simple improvement in housekeeping, to removal of small areas of wall materials, to extensive demolition of parts of a building under strict engineering controls.

Principals of building-related mold exposure control

The soundest manner of controlling mold exposure is prevention. This requires attention to the design, construction and operation of buildings. If mold growth does develop in a building, controlling exposure will require remediation of the mold, that is, removal of the materials with precautions to preclude spread of spores.

Prevention can often be attained with well-chosen OA intake, adequate filtration, planned and balanced airflows, and routine maintenance. Mold will colonize building materials or components that become wet, are allowed to remain damp or are exposed to sufficient humidity. Since materials vary greatly in their sensitivity to mold growth, sensitive materials should be avoided where moisture is reasonably expected to occur. In normal use, almost all building materials will accumulate dirt and dust, which contains organic substrates for mold, and often can absorb moisture. In occupied spaces, this accumulation is constantly removed by cleaning. In interstitial spaces of a building, such as wall cavities, ventilation ductwork, shafts, pipe chases, etc. such accumulations may remain unnoticed. Mold growth can develop in such accumulations even on materials that are otherwise resistant to mold growth. Such growth can increase exposure to molds as spores are shed. This can increase risks particularly when mold growth occurs on materials in ventilation ducts, elevator shafts or other spaces subject to airflows. Any mold-colonized material will need to be remediated. Appropriate techniques for remediation vary with the situation, but controlling exposure invariably requires that the colonized material be remediated [6].

Building-related features of an *Aspergillus*-resistant hospital

The total avoidance of *Aspergillus* spores, particularly of *Aspergillus fumigatus* and *Aspergillus flavus*, is not practical in indoor environments that are mechanically ventilated and supplied with adequate outdoor air (OA). These fungi are widespread in outdoor air at least seasonally, and in some areas constantly. Thus, there is often some degree of risk of bringing spores into a building with OA. A far greater risk occurs though when suitable substrates (warm and wet) for colonization are present in a building. In heating climates, the building environment, and any water-damaged materials from leaks are protected from cold, and in cooling climates portions of the heating, ventilation and air-conditioning (HVAC) system remain constantly wet during the cooling season. Either situation can permit colonization and sporulation. Colonization should be prevented, but when present must be located and cleaned effectively. Also, the moisture source must be identified and corrected, either by changes in design, materials or operation.

Prevention

Design

Design issues should be carefully considered for buildings intended to house vulnerable patients [1]. Although pressurization between corridor and rooms is very effective for isolation of contagious pathogens, pressure differences across building envelopes may cause significant moisture accumulation and mold growth on building materials. As shown in Wiseman [7], a 2.5 Pa pressure differential will induce up to 200 l/s of air infiltration in a building with the 'tightness' of a typical laboratory. In a humid climate, this amount of air infiltration can drive sufficient moisture accumulation in the walls to permit mold growth. Use and placement of insulation, air barriers and vapor retarders in the envelope wall must be designed to work in conjunction with the ventilation system to avert mold growth problems in walls, especially in cold climates and in hot, humid climates [8]. Such growth typically includes *Aspergillus* spp. and spores from such growth can infiltrate interior spaces through unplanned (and hence unfiltered) airways [9].

The potential for construction materials to support mold growth should be considered for use where moisture may occur. Some newly developed building materials are made without cellulose and numerous anti-microbial treatments of building materials are now available. These can be used in place of moisture sensitive materials in areas where moisture may be expected.

The location of the OA intake, selection of interior materials and design criteria of a HVAC system all can contribute to moisture accumulation and mold growth in the HVAC (Fig. 2). OA intakes should be above grade, and materials used in HVAC interiors should be moisture resistant and/or able to withstand cleaning. In cooling climates, HVAC equipment should be designed to adequately and independently temper both humidity and temperature at partial as well as peak load.

Construction

Construction and renovation activities can impact accumulation and distribution of *Aspergillus* spores within a facility [10,11]. Renovation often is the greater concern, since it typically involves opening interstitial spaces (e.g., wall voids) that may have dust from many years. Renovation is also more likely than new construction to occur in areas adjacent to portions of the building that remain occupied. Most important in renovation is strict control of dust to prevent escape from work areas into occupied, especially patient areas.

Fig. 2 Tunnel through which outdoor air is routed into the ventilation system of a building. Note water that has collected in the tunnel and wooden pallets and other debris that are wet and in the airstream passing through the tunnel.

Effective dust control usually includes combined administrative and engineering controls. This means that coordination with infection control officers is essential to control exposure to mold spores in occupied buildings from adjacent renovation or construction activities.

Operation

HVAC equipment should be designed and installed to easily permit access, inspection and maintenance. Filters throughout the HVAC system should have a MERV rating of 8 or higher. Up to MERV 17 filters may be appropriate in critical areas. Interior surfaces of HVAC systems should resist dust accumulation, and should be easy to clean, especially in areas of the HVAC that are chronically exposed to moisture. HVAC systems should be commissioned after installation to assure that their performance meets requirements.

Ultraviolet germicidal irradiation (UVGI) has long been used to help control the spread of contagious pathogens in health care facilities. The concept and established efficacy is discussed fully by First *et al*. [12]. The application of UVGI to the control of pathogens that are spread from the built environment rather than from other patients is less well understood, and the effects are better known on bacteria than molds. UVGI has been shown to be an effective means of controlling mold growth inside air-handling units (AHUs) of HVAC systems, as discussed below [13].

In cooling climates mold often grows on the walls of AHUs since these walls are chronically damp (Fig. 3). This condition develops as air is forced at high velocity over the cooling coils where the air is chilled below the dewpoint, causing condensation. The coils also induce turbulence, so that the airflow with condensation droplets impacts onto the walls of the AHU. Since these moist surfaces collect airborne dust, which includes spores and organic material, this niche can produce abundant mold growth on surfaces that are exposed to the airstream of a HVAC. Note that in typical HVACs configurations, this is downstream of the main filters. Typically within several meters downstream from the coils, the flow in a duct becomes laminar and the duct walls collect less dust and moisture, and produce less or no mold growth.

The efficacy of continuous UVGI illumination to reduce mold growth on the walls of AHUs was described by Levetin *et al*. [13]. In this field study, insulation in several AHUs was colonized by an unidentified *Cladosporium* species, *Aspergillus versicolor* and *Penicillium corylophilum*. These species comprised over 90% of the colonies recovered from the

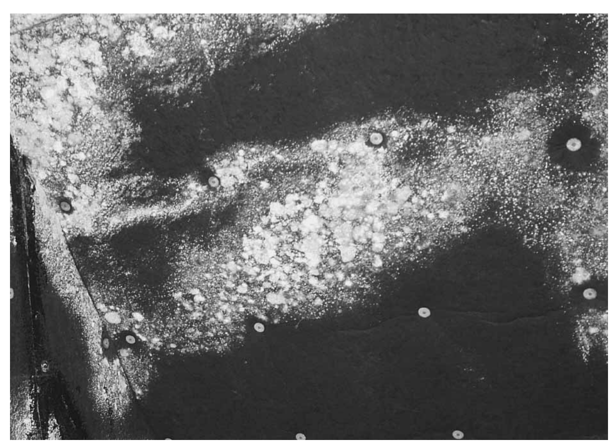

Fig. 3 Fungal colonization of the lining of an air-handling unit in a building. Culturable *Aspergillus fumigatus* was recovered from this area. The supply airstream passes directly over this surface, which is often located after (downstream) the filters.

insulation and from the airstream in test and control AHUs. These molds significantly ($P < 0.05$) decreased approximately one log unit in irradiated AHUs over a cooling season. The same molds significantly increased approximately one log unit in un-irradiated AHUs in the same building. This pattern occurred in the insulation and in the airstream. This indicates that a source of mold growth that commonly occurs in HVAC systems downstream of the filters can be reduced by approximately 2 log units with UVGI. However, even with this difference, it should be noted that the airstream levels of mold were not entirely eliminated. The seasonal increase noted in the un-irradiated AHUs is likely typical of AHUs throughout humid regions, which emphasizes the potential gain in controlling mold growth in HVAC systems by focusing on the source niche.

Response

Operation

The response to any source of mold growth in a health care facility should include certain points. First is to conclusively find and correct the source of moisture. Diligent efforts are also required to determine the full extent of all visible mold growth [1]. Prompt remediation is then required for all visible mold growth, either in readily accessible or in 'hidden' spaces. This applies to mold growth that results from envelope moisture intrusion, poor design or operation of the HVAC, plumbing accidents or floods.

Finding and correcting the source of water damage from discrete, sudden and obvious events, such as burst pipes is usually easy. Condensation problems, especially in building envelopes can be difficult, though. Invasive and destructive procedures such as opening wall assemblies or cutting into ductwork (with appropriate safeguards) for inspections are sometimes required. It is important to identify and correct the true source of the moisture though to avoid recurrences. This often aids as well in establishing the extent of visible mold growth.

When dealing with water damage, the nature of the water may have additional consequences. Water from a broken water line (white water) is cleaner than rainwater running from the roof or a broken sink drain (gray water), which is much cleaner than any water from sewers or that has been in contact with the ground (black water). Sanitizing efforts are entirely appropriate during restoration of damage from gray or black water. Note that the sanitizing is directed primarily against bacteria and viruses; removal of water followed by cleaning and drying affected building materials will control mold growth.

Determining the full extent of water damage and/or mold growth may require opening hidden areas, such as wall cavities. This may be necessary to access areas where water has penetrated, in order to quickly dry all wet materials. In other cases, when the moisture damage may have been insidious and occult, such openings may be required to determine the extent of visible mold growth and remediation needed. If the presence of mold growth is confirmed, then all areas with visible mold growth must be remediated with adequate dust control measures.

Water damage should always be addressed promptly, as delay always increases the damage. The response of molds to any exception to this dogma is almost as reliable as gravity. It is important to assure that all affected areas are detected and addressed with adequate, thorough and prompt drying, as mold colonies can begin sporulation in less than 48 h [14]. Remediation of mold-colonized material requires the physical removal of mold growth, and any associated debris. Mold growth on non-porous materials may be cleaned, but porous materials will need to be physically removed. This must be done in a manner that contains all dust associated with the removal. Diligent dust control measures are used to prevent the spread of any dust generated during cleaning.

In general the acceptability of mold remediation should be assessed in phases. The source of water or moisture should have been corrected during the remediation. Following remediation, a stringent visual and olfactory inspection should first assure that the area remediated is free of all indications of mold growth and colonized material. No associated debris and dust should remain. This means that all surfaces should be stringently inspected for 'white glove' cleanliness. Objective measures of airborne and surface dust can then be used to confirm that remediated areas are dust free. Airborne dust levels should be lower than outdoors and generally in the low double-digit $\mu g/m^3$ range. Levels of residual surface dust loading in the 75–100 mg/m^2 range have been suggested as typical of clean, non-porous surfaces [6,15].

Agreement is lacking on the need for air sampling as part of remediation assessment. Certainly, areas should be deemed clean and mold free by inspection and with low dust levels before sampling is attempted. Since there are no recognized standards against which to compare air samples, agreement on acceptability should also be reached before air sampling is conducted [16,17]. Spore trap type slit impactor samplers are often used for evaluating air in spaces that have been remediated. These permit rapid analysis, but give no indication of viability. As such, they are more useful in health care facilities to identify unacceptable conditions that need further cleaning. In other buildings, spore trap samples are often the only type of sample collected. In health care facilities airborne culturable thermotolerant molds should also be sampled. Cultures obviously require several days at a minimum, to a week or more, to analyze properly and again, there is no recognized acceptable concentration. Suggestions have been made to limit levels of thermotolerant species to only a few CFU/m^3 and *Aspergillus* species an order of magnitude lower. These may be practical levels to indicate a 'clean' environment, but should be recognized as arbitrary rather than derived from empirically-based risk assessments. This lack of empirical, health-based risk assessment is a primary criticism of any routine bioaerosol monitoring. The counter argument is that routine monitoring provides an environmental baseline that is useful at the end of a remediation project as an estimate of what is 'normal and typical' for that building.

Conclusion

There are multiple general issues around buildings that must be addressed to minimize the risks of exposure to *Aspergillus* for all occupants, and especially for high-risk patients. Building envelope designs should consider the possibility of moisture intrusion/accumulation since this can lead to mold growth and shedding spores to the interior spaces. Mold resistance of building materials and sources and routes of OA should be considered. Construction and renovation activities should be carefully planned and closely monitored to preclude the release of any fugitive dusts into occupied areas. Air handling equipment should be well-filtered and able to dehumidify in cooling climates, even at partial load. The HVAC system should also be designed and installed for ease of maintenance, which should be rigorous. UVGI can be useful in certain applications as part of an overall strategy to prevent mold growth, but the limitations of UVGI should be recognized. The value of routine air monitoring remains unresolved. Building operation should include plans to promptly address all moisture problems with appropriate care. Mold growth should be addressed in any building, which is facilitated by understanding moisture behavior in air and in materials. Additionally in hospitals, the diligent control of dusts and culturable thermotolerant molds are critical for minimizing risk to patients.

Disclosure

The author's employer provides consulting services pertinent to mold occurrence and growth in buildings.

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