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Chapter 1

Basic Indoor Environmental Quality and Microbiology

By Mark Hodgson, LRSC
Chapter 1

Basic Indoor Environmental Quality and Microbiology

Introduction

Evaluating indoor environmental quality (IEQ) is a complex and challenging science under any circumstances. But when the population affected includes severely immunocompromised patients, the level of complexity increases exponentially.

This book examines the effect of microbial contamination on hospitals and the special challenges it presents.

The range of microbial contaminants that could be located in a moisture-impacted building is as broad as nature itself. Due to the abundance of nutrients and the generally welcoming environment created when moisture is added to the hospital environment, one would anticipate a broad range of microbial growth, including bacteria, actinomycetes, fungi, algae, protozoa, arthropods, insects, and higher animals. These organisms interact with each other and with the environment in which they exist, so although we tend to study each item in isolation, the interaction of the components of the natural environment and the mixture of potential health stressors is what makes investigating IEQ issues such an interesting challenge.
Chapter 1

For a number of reasons, which we will discuss in depth in later chapters, it is commonplace to concentrate on the study of fungi as a surrogate for all potential microbial contaminants in a building. The primary reason is that a broad range of water activity supports fungal growth: Fungi are among the most xerophilic (dry loving) of microorganisms, and they can also grow in conditions of water saturation. They are also generally found with other organisms, such as bacteria and dust mites.

What are fungi?

Fungi are a group of organisms that range from mushrooms and toadstools to common bread molds and yeasts. Of particular interest to us are the fungi that can colonize a building and cause health problems.

Biologists commonly classify all living things into five major groupings, called “kingdoms,” which include

1. plants
2. animals
3. bacteria
4. protists
5. fungi

Filamentous fungi, commonly called molds, consist of long chains of linked cells with special reproductive structures. Fungi are defined by their cell wall structure, their means of reproduction, and the way in which they attain nutrients. The sex life of fungi is an education in and of itself, as it includes sexual and asexual reproduction and as many as 28,000 different sexual states exhibited by the same fungus. When investigating fungi in buildings, however, it is especially important to note their cell wall structure and method of gathering nutrition.

The cell wall of fungi is chitinous and contains compounds such as $\beta$ 1-3 Glucans and ergosterol that are allergens. The compounds remain allergenic regardless of the viability of the fungi.

Fungi obtain nutrients by excreting digestive enzymes onto the material on which they are growing.
The enzymes break down the material into its base compounds (usually sugars or amino acids), which then are absorbed by the fungi and used as an energy source to allow the fungi to grow and reproduce. The fungi also secrete other chemicals, such as proteins that include many allergens.

Because the material on which the fungi are growing is being eaten, it loses its structural integrity. If allowed to continue unchecked, fungal growth can destroy an entire structure. This reflects the role that fungi often play in nature—described as “nature’s recyclers,” fungi are responsible for the decomposition of most vegetation in the environment.

Fungal growth is nothing new in buildings. Indeed, the problem is reported throughout history, including references in the Bible (Leviticus 14). It is, however, becoming increasingly common in modern buildings for many reasons, and public awareness is increasing dramatically.

In addition to digestive enzymes, fungi may also excrete chemicals called mycotoxins. Mycotoxins provide a competitive advantage by ensuring that other microorganisms, including bacteria, protozoa, and other fungi, stay away and do not eat the food source on which the fungus is growing.

A side effect of the mycotoxins is their impact on mammalian life, including humans. Exposure to many of them can have some very nasty health effects. Until recently, the majority of studies have concentrated on the effect of eating contaminated foodstuffs, but new studies have also focused on inhalation of mycotoxins.

However, not all mycotoxins are bad. Several of them are used to produce a range of medicinal products—including the most common antibiotics, such as Penicillin—and can be found in many foodstuffs, such as blue cheese, soy sauce, and soda.

**Health effects**

The health effects from fungi are, despite what you may have read, clearly understood and documented. What is not so well understood is the quantity of fungi required to cause the health effect and the various routes of exposure for fungi. See Figure 1.1 at the end of this chapter for examples of the health effects.
Fungi, alive or dead, will continue to cause health problems for susceptible people. This is one reason that the abatement of fungi concentrates so heavily on removal of the fungi rather than just on killing them.

**Background on microbial contamination**

When performing evaluations, first understand the cause of microbial growth in a hospital and where it is most likely to occur. A basic understanding of hospital construction and materials is helpful. In addition, a history of the building, its maintenance, and its operation, will be of great assistance as you search for microbial growth. Knowledge of the heating, ventilation, and air-conditioning (HVAC) system’s operation is also important.

Biological agents (fungi, bacteria, endotoxins, microbial volatile organic compounds [MVOCs], and mycotoxins) will cause problems when the following exist:

- **Amplifier**: Growth site where the organisms find nutrients, water, shelter, and temperatures appropriate for multiplication.

- **Disseminator**: Something that delivers the microorganism or byproduct in aerosol form to occupants (the HVAC system is a significant factor in this area).

- **Reservoir**: Surface/site that contains fungal spores or bacteria without growth. Reservoirs can become amplifiers if the environmental conditions change. Many surfaces may be described as fungal reservoirs in this instance because there is concern over surfaces that contain atypical or elevated reservoirs of fungi.

When inspecting a hospital, anticipate the presence of typical fungal reservoirs that do not present a risk to patient health unless disturbed or allowed to become fungal amplifiers due to a change in environmental conditions. The goal of any evaluation is to assess the occupied space and HVAC system to locate any amplification or atypical reservoir sites and to determine whether their presence is likely to be disturbed by specific activities.
Almost every surface in a building will become a fungal reservoir. It’s critical to ensure that these do not become amplification sites. Therefore, we must work to eliminate or minimize the presence of the elements that amplification requires—but, as we will see, that is quite difficult to do.

**Fungal spores/bacteria**

Fungal spores/bacteria are everywhere in the environment and are disseminated by airborne route, insects, or building occupants. Therefore, we cannot practically exclude fungal spores or bacteria from the built environment. Even when the very best quality of air filtration is applied to a ventilation system, spores will come in a building on personnel and equipment entering a space. Only the most rigorous of clean environments can hope to exclude all extraneous fungal spores, and even then it becomes more a matter of reducing concentrations rather than eliminating all spores.

Although you can use filtration and positive pressurization to prevent or minimize infiltration of fungal spores through the ventilation system, these methods will not prevent spores from being tracked into the environment on shoes and clothing. Use of sticky floor mats and protective coverall clothing for personnel will help; however, there are practical limitations as to how far this approach goes in a working hospital environment.

It is safe to assume that fungal spores and bacteria are present in every environment humans occupy. Indeed, as with many materials, fungi are entrained in the material during manufacture and construction.

**Temperature range**

The majority of fungi will grow between the temperatures of 40° F and 100° F, and some can survive in temperatures as low as -23° F and as high as 140° F.

Many fungi have optimal growth rates at the lower temperatures found in the outdoor environment of temperate climates. They will grow at temperatures far higher and far lower than those found in the controlled climate inside hospitals.

In buildings, human comfort requirements dictate that the temperature falls exactly in the range where microorganisms will grow. Thermal comfort requirements for buildings in the United States
are recommended by the American Society of Heating Refrigerating and Air-conditioning Engineers, Inc. (ASHRAE) Standard 55: 2004, *Thermal Comfort For Human Occupancy*, which considers a number of parameters in determining range of acceptable conditions: dry bulb temperature, relative humidity (expressed as wet bulb temperature), air velocity, activity level, and clothing factor.

It is also important to note that most pathogenic bacteria are thermophilic or thermo tolerant—that is, they prefer elevated ambient temperatures. Incidentally, many hospitals elevate ambient temperatures beyond those of other building types to accommodate patient comfort.

**Nutrient source**

Fungi require appropriate nutrients for growth. They obtain the nutrients through extracellular digestion of the material on which they are growing. There is a wide range of materials that provide suitable nutrient source for fungi, including the following:

- Any organic matter (anything that is now or once was living or is made from once-living things)
- Some inorganic matter
- Surfaces that are or contain the following:
  - Dust
  - Cellulose-based building materials (including ceiling tile, gypsum wallboard, cardboard, paper, paper wall coverings, and sprayed-on fireproofing)
  - Adhesives
  - Natural rubber and latex, including latex-based paints
  - Carpeting and furnishings

Many modern building materials are cellulose-based, such as gypsum wallboard, ceiling tiles, and spray-on fireproofing material. Although they are all highly effective materials when kept dry, they provide ample nutrient sources for fungal growth when wet. Several other modern building materials such as oriented strand board, high-density particleboard, medium-density fiberboard, and wood products all provide a solid nutrient base for fungal amplification.
All of the potential nutrients cannot be removed from the environment. Even with the use of stainless steel and concrete, the dirt, oils, and greases that accumulate on surfaces can support fungal growth. And although many of the nutrient sources inside buildings have been found to be different than those likely to be encountered by fungi in the natural environment, the preponderance of cellulose-based materials in modern construction has reduced the ability of buildings to withstand moisture and has increased significantly the quantity of nutrients available to fungi.

Fiberglass is another material that provides minimal nutrients for fungal growth when first produced. Clean fiberglass may contain a few binding agents that support bacterial growth, but, most manufacturers have shown through independent testing that clean, new material does not support fungal growth. However, when fiberglass is applied as an internal lining in ductwork, it accumulates dirt over time. Eventually, the accumulated dirt trapped in the fibers is sufficient to provide a nutrient base for fungal growth, and the fungal hyphae become entwined in the fiberglass fibers.

In addition, many modern building techniques have replaced traditional durable materials, such as masonry internal walls, with significantly less durable materials, such as gypsum wallboard. In many instances, exterior wall structures, firewalls, elevators, and fire escapes are now constructed with gypsum wallboard as a weight- and cost-saving device. But these are all vulnerable areas in buildings and may be subject to moisture impact.

**Moisture**

Fungi grow in the presence of standing water, condensation, and/or high relative humidity (>68%). Bacteria generally require free (“standing”) water to grow, but many fungi do not; xerotolerant fungi, specifically, can grow at low water activities (low relative humidity). Water activity is the equilibrium relative humidity of a material; several building materials are hygroscopic, absorbing moisture from the air.

Without adequate moisture, fungi cannot grow: Spores will not germinate, nutrients will not be accumulated, biomass will not increase, and fruiting bodies will not be produced. The quantity of moisture at which each of these events occurs will, of course, depend on the event, temperature, and species of fungi.
A later section of this book looks at water activity (the measure of available moisture for fungal growth). All of the other factors fungi need to grow will be present in every hospital. Moisture is the only element you can control.

A microbial evaluation is often better described as a “search for moisture incursion.” In buildings without moisture incursion, there will be no microbial growth. Unless and until you identify the source of all moisture, microbial remediation will not provide a space suitable for reconstruction and reoccupancy.

**Inspecting buildings for fungal amplification**

If remodeling or maintenance activities are likely to disturb dust reservoirs in a hospital, perform a risk assessment to determine the likely impact on patient areas, especially critical care areas. In addition, when infection control indicates a potential problem and you need to perform an evaluation of the building’s condition, take the following actions:

• Determine the building’s history
• Review the building’s construction and materials using a blueprint
• Review the building’s occupancy and use, with particular attention to critical care areas
• Perform a thorough visual inspection of occupied spaces
• Inspect and review the entire HVAC system
• Test relative pressurization relationships, including operating rooms, intensive care units, isolation wards, and oncology and transplant wards (each of which has required pressurization relationships, as does the hospital as a whole)

Include the entire building in the survey as far as is practical, including all HVAC systems. Record the following information in the survey:

• Floor plans
• Site plans
• As-built HVAC drawings and cut sheets
• Copies of previous indoor air quality reports
• Details of previous remediation activities, including clearance tests
Interior space

There are numerous sources of moisture and places within a building where you can find it.

**External sources of moisture**

Moisture enters the building as liquid and gas (water vapor).

Kinds of direct leakage as liquid include

- weather-induced (e.g., flooding, rain, wind, snow) leaks
- groundwater incursion through subgrade walls and floors (including capillary action)
- plumbing leaks

Kinds of direct leakage as gas (water vapor) include

- infiltration through doors, windows, construction joints, cracks (due to wind and incorrect pressurization)
- diffusion through building envelope materials (due to vapor pressure differentials and improperly located or improperly installed vapor barriers)

**Internal sources of moisture**

Such sources include the following:

- Human-generated vapor (i.e., normal respiration)
- Operations-generated vapor or liquid, such as
  - sinks and showers
  - decorative fountains
  - wet construction materials
  - wet processes
  - cooking
Relative humidity

Relative humidity is the amount of moisture contained in a unit of air relative to the maximum amount of moisture that unit of air can contain at a specific temperature.

Air is saturated when it contains the maximum amount of moisture possible at a specific temperature (100% relative humidity). Relative humidity can be increased by increasing vapor pressure (moisture content) and by decreasing temperature.

Measure relative humidity in the occupied space. Use the psychometric chart to determine dew point, which is the temperature at which the air is saturated and can hold no more moisture. At the dew point, moisture will condense out of the air causing dampness in building fabrics and potentially fungal growth.

Condensation

Moisture in the form of vapor will condense on surfaces that have temperatures at the dew point temperature of the air. Dew point temperature is the temperature at which the air/vapor mix reaches 100% relative humidity. The dew point describes the thermodynamic point at which the rate of condensation equals the rate of evaporation.

The colder the surface, the higher the relative humidity adjacent to that surface. The coldest surface in a room will likely be the location where condensation happens first, should the relative humidity rise to 100%. This coldest surface is referred to as the “first condensing surface.” Such surfaces can include

- room corners in cold climates during heating season
- windows
- thermal bridges, such as structural studs
- vapor barrier in an external wall system
- insulation in an exterior wall system
- interior surface of exterior walls during cooling season
- supply air diffusers
Inspect the building structure to determine whether condensing surfaces are likely. Assess the potential for changing circumstances with changing seasons.

**Determination of building history**

In many instances, buildings may have suffered historical water damage that resulted in fungal growth. Careful questioning of maintenance personnel may reveal areas of moisture impaction that, although not immediately apparent, have resulted in fungal growth and suggest areas where an investigator should start to look for it.

Through appropriate questioning of facilities managers, human resources personnel, medical personnel, safety/industrial hygiene personnel, and building occupants, establish a history of the building and include the following:

- The age of the building
- Last refurbishment (identify what was refurbished)
- Current building use
- Previous building and land use
- Number of occupants
- Number of complaints and the location(s) and nature of the complaints
- Water/moisture incursion incidents
- Remediation efforts previously undertaken
- Maintenance schedule
- Housekeeping (who, what, and how often)
- Pesticide use/rodent control
- HVAC maintenance (identify who performs it)

Review the architectural plans to determine construction methods, air distribution systems, and alterations and additions to the space.
Editor’s note: The following section is from Richard C. Summerbell, PhD, “Significance of Molds in Indoor Proliferation,” www3.sympatico.ca/ross.fraser/Richard9.htm. The nonitalicized portions are additional information from Mark Hodgson, LRSC.

A. Allergenicity

1. Type 1 allergies (immediate-type hypersensitivity)
Fungi may cause allergic rhinitis similar to that caused by pollen grains, with watery, itchy eyes, runny nose and sneezing, and other irritation to the mucous membranes. *After asthmatics become allergically sensitized to one or more of them, they may trigger asthma attacks. Most asthmatics have multiple allergies.* These allergies are, however, due to the individual’s genetic profile, with an immediate response that will occur regardless of previous exposure. It is important to note that there is presently no scientific evidence that fungi cause adult onset asthma, though fungi are certainly one of the many triggers for those who are already asthmatics.

2. Type 3 allergies (delayed-type hypersensitivity)
In certain susceptible individuals, after prolonged heavy exposure or a single massive exposure, fungi may cause hypersensitivity pneumonitis (extrinsic allergic alveolitis), characterized by wheeze, shortness of breath, cough, chest tightness, and, in some prolonged cases, pulmonary fibrosis.

*There has been a custom of giving each new subtype of hypersensitivity pneumonitis an evocative medical nickname, such as Farmer’s Lung, Maple Bark Stripper’s Disease, Cheese Workers lung, and so on.*

3. Allergic bronchopulmonary aspergillosis (ABPA) or other allergic bronchopulmonary mycosis
Persons who have been asthmatic for many years may progress to have their bronchial passages colonized by a fungus, usually Aspergillus fumigatus, but sometimes another organism such as Bipolaris hawaiensis, Wangiella dermatitidis, or Pseudallescheria boydii. *Constant allergic response helps to maintain the fungal colonization, and first-line therapy is often with steroids.* Reducing the level of inflammation may result in elimination of the colonizing organism. Some studies have made tentative links between exacerbations of ABPA and moldy homes. Cystic fibrosis patients also may get allergic bronchi-pulmonary mycosis with extensive colonization with an Aspergillus species.
4. Allergic mycotic sinusitis

Allergic mycotic sinusitis is a colonizing infection of mucus adhering to the sinus walls. A range of different fungi have been isolated from sinus cavities, though the presence of fungi alone does not immediately indicate colonization. Otherwise, it is very similar to ABPA, except that patients need not necessarily have had asthma or cystic fibrosis. To date, no discrete connection with indoor mold proliferation has been shown in any individual cases, but that may be from lack of investigation.

B. Chemical irritation

Several epidemiological studies have shown that non-specific respiratory symptoms in both non-allergic and allergic persons are linked to excess building moisture and mold growth. In fact, the difference in response between the two groups of persons appears not to be significant. This means that there is very likely to be a non-allergic mechanism behind the irritation reported. At the same time, there is a body of literature concerning relatively intense toxin-like effects exerted by moldy materials on workers who have disturbed or have been exposed to substantial quantities. In addition, liver cancer has been epidemiologically linked to occupational respiratory exposure to the fungal toxin group known as the aflatoxins (from Aspergillus flavus and close relatives). Animal model experiments have shown that inhaled aflatoxin forms DNA adducts (places where the toxin alters DNA by binding to it) in the lungs and in the liver.

1. Mycotoxin effects

One candidate for the agent of the direct chemical effects apparently exerted by respiratory or other contact with molds is the mycotoxins. The class of small fungal secondary metabolites, which has been given the name “mycotoxins,” is known to include many compounds that are highly toxic to vertebrates (such as humans). Most of the well-characterized toxic effects are from animal feeding situations, either natural mycotoxicosis outbreaks caused by contaminated animal feed or laboratory experiments based on feeding (or connected artificial experimental situations such as parenteral injection of purified toxins into experimental animals). Ingestion of mycotoxin-contaminated foods by humans results in similar symptoms. Toxic effects have also been found in laboratory experiments in which animals are exposed to mycotoxins via the respiratory tract. In cases involving humans and airborne exposure, the most suggestive of a direct mycotoxin effect are those in which heavily mold-exposed workers develop severe symptoms reminiscent of animal mycotoxicoses or contaminated-food mycotoxicoses. The link between inhaled aflatoxin and liver cancer has already been mentioned.
2. Glucan effects

Beta-1,3-glucan is a major structural component of almost all fungal cell walls. It is a polymer of glucose, similar to cellulose but with less tendency to be found in strands. It bears considerable structural similarity to very toxic molecules, known as endotoxins, secreted by some bacteria, particularly some gram-negative organisms. This similarity caused Dr. Ragnar Rylander, an endotoxin expert, to investigate it as a possible candidate for the chemically irritating component found in mold conidia. It was found to activate pulmonary alveolar macrophages PAMs, possibly making the lungs hyperreactive to a wide variety of foreign materials. Also, in double-blind inhalation exposure trials conducted with human volunteers, exposure correlated significantly with some non-specific respiratory symptoms. The most strongly correlating symptom, however, was headache. The contribution of glucans to indoor mold irritation is still under investigation; glucan effects may add to or synergize mycotoxin effects, or may be mistaken for mycotoxin effects in fungi where the actual amount of mycotoxin present in conidia is not sufficient to cause symptoms.

3. Volatile chemical effects

Most molds, especially those with dry conidia, produce volatile odor constituents. In a few cases, these are fruity or flowery and may be adapted to attract arthropod dispersers (e.g., insects carrying the mold conidia to new growth sites). Usually they are musty or earthy and are probably adapted to deter grazing and feeding invertebrates and vertebrates, or at least to give a distinct “not food” odor to mold colonies and their underlying nutritional substrates. A few such volatiles have been found to be directly irritating to vertebrates. Apart from experiencing such direct physiological irritation, humans and other vertebrates may be adapted to avoid such odors, and there may be a legitimate “psychological” objection to their presence in rooms. Mold growth in buildings may be accompanied by the growth of Streptomyces species, which usually have very strong earthy volatile odors. In addition, in very wet materials, copious bacteria may grow and may emit typical rotten or sour smelling odor molecules.

C. Invasive pathogenesis

Of the regularly occurring indoor mold proliferation species, only a few have significant potential as opportunistic pathogens, and even these usually require a relatively strong immunocompromised patient before they can be regarded as dangerous. Warm, moist environments, such as the upper surface of ceiling tiles, dirty heating ducts affected by condensation, or areas downstream of humidifiers, may grow Aspergillus fumigatus, the best known opportunistic mold fungus. This species also tends to occur in
potted plant soils, particularly where these have not been exchanged for fresh soils (e.g., by repotting) for several years. Usually, a patient needs to have a relatively high degree of neutropenia (deficit in neutrophil type white blood cells, an essential component of the immune system) before he or she is seriously threatened with invasive disease by this organism. Most such patients are persons taking leukemia chemotherapy or drugs designed to prevent rejection of transplanted organs. Occasionally, other predisposing factors are found, such as heavy, prolonged corticosteroid use. AIDS patients are at little risk for such diseases unless they develop lymphomas or are taking potentially neutropenia-inducing drugs such as ganciclovir. In recent years, because of the emergence of antibiotic-resistant bacteria in hospitals, some hospitals have begun to send severely neutropenic patients home. These patients are at high risk of infection by indoor infestations of Aspergillus fumigatus, Aspergillus niger, Aspergillus nidulans, Aspergillus flavus, Aspergillus terreus, Pseudallescheria boydii, Fusarium solani, Fusarium oxysporum, Fusarium moniliforme, Fusarium proliferatum, and some other species. People who do not have these specific immunocompromising conditions, however, are not at significant risk of invasive disease from any of these fungi (with the possible exception of P. boydii punctured into the dermis or the eye).

It should be noted that the source of the fungi that cause these infections can be from either inside or outside the building. Though fungal amplification within the building fabric is the most common cause of nosocomial infection, inadequate filtration on ventilation systems allowing infiltration of fungi from the outdoor air and simply disturbing existing reservoirs of fungal spores may be sufficient to cause outbreaks of fungal disease.

Note that many members of the public, especially those advised by practitioners of various alternative medicines, often incorrectly assert that their immune systems are compromised. Such assertions should not be taken at face value until convincing detail about actual predisposing conditions is disclosed.
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