Interface focus

J. R. Soc. Interface (2009) 6, S737–S746
doi:10.1098/rsif.2009.0227.focus
Published online 22 September 2009

Review

The effect of environmental parameters on the survival of airborne infectious agents

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The successful transmission of infection via the airborne route relies on several factors, including the survival of the airborne pathogen in the environment as it travels between susceptible hosts. This review summarizes the various environmental factors (particularly temperature and relative humidity) that may affect the airborne survival of viruses, bacteria and fungi, with the aim of highlighting specific aspects of environmental control that may eventually enhance the aerosol or airborne infection control of infectious disease transmission within hospitals.

Keywords: airborne; transmission; infection control; virus; bacteria; fungi

1. INTRODUCTION

Over the past 50–60 years, there have been many publications studying the effect of environmental parameters (e.g. temperature, humidity, sunlight/radiation and pollution) on the survival of airborne infectious organisms (viruses, bacteria and fungi). These have differed greatly in their methodologies so the results of different studies by different teams, even on the same organisms, may be difficult to compare. Yet, why is this of current interest?

The various stages of the successful transmission of airborne infection all depend on the production of an infectious agent from a source or index case and the arrival of sufficient numbers of viable organisms to cause infection (and perhaps disease) in a secondary host. Environmental exposure is a common hazard for all such organisms (whether viruses, bacteria or fungi) during this journey between hosts. Factors such as temperature, humidity (both relative and absolute), sunlight (ultraviolet light) exposure and even atmospheric pollutants can all act to inactivate free-floating, airborne infectious organisms. These factors will affect the various infectious organisms in different ways and degrees, and it is sometimes difficult to make generalizations, especially because different experimental methods have been employed in their investigation.

Such experiments may eventually be useful in the formulation of specific airborne or aerosol infection control guidelines. For example, in the current pandemic influenza A (H1N1/2009) situation, a lot of experimental work has been performed to investigate the survival characteristics of influenza in air and on surfaces. However, is there currently sufficient evidence to say that by maintaining hospital premises at a certain temperature and at a certain relative humidity (RH), this is likely to reduce the airborne survival and therefore transmission of influenza virus when compared with other hospitals that do not adhere to such a tight control of their indoor temperature and RH?

One example of environmental recommendations for hospitals in Japan can be seen in table 1 (kindly supplied and translated by Professor Eiichi Yubune, Associate Professor, Department of System Robotics, Toyo University, Japan).

It can be seen from table 1 that the recommendations for temperature and RH settings in different parts of a hospital differ slightly between summer and winter. In summer, the recommended room temperatures range from as low as 23°C in the ER (emergency room) up to 27°C in various rooms, including in-patient and out-patient areas, as well as X-ray and treatment rooms and offices. The corresponding recommended RH is fairly constant throughout the hospital, ranging between 50 and 60 per cent, with 65 per cent for the hydrotherapy treatment room. In winter, the recommended temperatures are generally slightly lower, ranging from 20°C in some in-patient and out-patient areas, as well as offices, up to 24–26°C in in-patient and out-patient areas. The recommendations for the newborn baby and the hydrotherapy treatment rooms are higher at 27–28°C. Again, the corresponding recommended range of RH is fairly constant, but slightly lower than for summer, ranging from 40 to 50 per cent,

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One contribution of 10 to a Theme Supplement 'Airborne transmission of disease in hospitals'.

Received 11 June 2009
Accepted 21 August 2009

Table 1. An example of environmental control recommendations for hospitals in Japan. Used with permission (translated and slightly edited) from the Human and Society Environment Science Laboratory Co. Ltd, Japan (http://www.h-and-s.biz/index2.htm).

		summer		winter	
section	location	dry-bulb temperature (°C)	RH (%)	dry-bulb temperature (°C)	RH (%)
hospital ward	patient bedroom[a]	24–26–27	50–60	22–23–24	40–50
	nurse station	24–26–27	50–60	20–22	40–50
	day room	26–27	50–60	21–22	40–50
outpatient department	consulting room[b]	26–27	50–60	22–24	40–50
	waiting room	26–27	50–60	22–24	40–50
	dispensary	25–26	50–55	20–22	40–50
	ER	23–24–26	50–60	22–26	45–55–60
central medical care areas	operation room	23–24–26	50–60	22–26	45–55–60
	recovery room	24–26	50–60	23–25	45–50–55
	ICU	24–26	50–60	23–25	45–55–55
	birthing room[c]	24–25–26	50–60	23–25	45–55–55
	newborn baby room	26–27	50–60	25–27	45–55–60
	general survey room	25–26–27	50–60	20–22	40–50
	X-ray studio	26–27	50–60	24–25	40–50
	X-ray operation room[d]	25–26	50–60	20–22	40–50
	hydrotherapy treatment room[e]	26–27	50–65	26–28	50–65
	dissection room	24–26	50–60	20–22	40–50
	kitchen	use guidelines for hospital catering services			
supply section	material room	26–27	50–60	20–22	40–50
administrative area	office	26–27	50–60	20–22	40–50

[a]Consider the additional cooling and heating effects of the window in winter and summer (sunlight), respectively.
[b]To maintain at a warmer temperature than the waiting room.
[c]There may be a demand for higher temperatures as required.
[d]May need to compensate for any additional heating effect generated by the X-ray equipment.
[e]Radiant heaters are preferred.

but up to 55–60% for more critical areas, such as operating theatres and recovery, the intensive care unit and childbirth/delivery suites.

Although these recommendations are mainly for thermal comfort, rather than for infection control purposes, similar recommendations for enhancing the airborne infection control of specific infectious agents may not be too far-fetched in the future—especially if effective, more tightly controllable ventilation systems can be developed, economically, for specific hospital areas.

This review will summarize the main findings of these experiments and extract some generalizations of the data that may be useful in limiting the spread of such airborne infections in hospitals and other healthcare premises. Therefore, only studies related to infectious organisms known to transmit via the airborne route and which infect and cause disease in humans will be included, whenever possible.

2. VIRUSES

Indoor, airborne viruses may be transmitted between susceptible individuals causing disease outbreaks, but they may also have more indirect effects, e.g. the triggering of immune mediated illness, such as asthma (Arundel *et al.* 1986; Hersoug 2005). Many environmental factors may affect virus survival, including temperature, humidity and virus type (lipid and non-lipid enveloped), the presence of surrounding organic material (e.g. saliva and mucus), sunlight (ultraviolet light) or antiviral chemicals. Although multiple studies investigated environmental factors affecting the survival of airborne viruses, it is important to note that many laboratory experiments have used various and different artificial means of producing virus aerosols that may not either be comparable or necessarily represent the real situation of human-to-human transmission of respiratory infectious agents.

Also, often, presumably for safety reasons, animal viruses that share characteristics similar to human viruses from the same virus family have been used in the laboratory experiments as they do not infect humans. So, sometimes, some extrapolation is required when extending the results of such experiments to the similar human viruses. In addition, the air-sampling techniques differ between studies, so generalizations of these results may be difficult.

2.1. Airborne virus survival and temperature

Temperature (T) is one of the most important factors affecting virus survival, as it can affect the state of viral proteins (including enzymes) and the virus genome (RNA or DNA). Viruses containing DNA are generally more stable than RNA viruses, but high temperatures also affect DNA integrity. Generally, as temperature rises, virus survival decreases. Maintaining temperatures above 60°C for more than 60 min is generally sufficient to inactivate most viruses, though this can be very dependent on the presence of any surrounding organic material (e.g. blood, faeces, mucus, saliva, etc.), which will tend to insulate the virus against extreme environmental changes. Most airborne viruses will have been exhaled with a coating of saliva or mucus that will act as an organic barrier against environmental extremes. Higher temperatures for shorter times can be just as effective to inactivate viruses.

Early experiments used artificial sprays to generate virus-laden aerosols of known concentration, either in static systems (Hemmes *et al.* 1960) or in rotating drums or chambers (Harper 1961; Schaffer *et al.* 1976; Ijaz *et al.* 1985, 1987; Karim *et al.* 1985), then collected and counted the number of viable viruses at varying temperatures and/or RHs. Prior to the late 1980s, before the advent of the polymerase chain reaction (PCR), these investigations used culture methods (e.g. plaque-forming assays) to count and assess the viability of surviving viruses. For example, using viral culture methods, Harper (1961) found that low temperatures (7–8°C) were optimal for airborne influenza survival, with virus survival decreasing progressively at moderate (20.5–24°C) then high (greater than 30°C) temperatures. This relationship with temperature held throughout a range of RHs, from 23 to 81 per cent.

Since the advent of PCR methods to assess the presence of influenza and other respiratory virus RNA in the air (Xiao *et al.* 2004; Fabian *et al.* 2008; Blachere *et al.* 2009), there is often the question of whether such viral RNA detection really represents viable viruses.

More recently, using individually caged, separated guinea pigs as both the source and detector of transmitted influenza infection, Lowen *et al.* (2007) demonstrated that influenza transmits through the air most readily in cold, dry conditions, which supports these earlier *in vitro* experimental findings. They also used viral culture (in the form of plaque-forming assays) to quantify the levels of viable influenza virus in the guinea pig nasal washings to ascertain viral transmission. Later, using the same system, they found that higher temperatures of about 30°C tend to block aerosol transmission (Lowen *et al.* 2008). However, the authors do not give details about how far apart these cages were in these experiments, and the guinea pig may not be the best animal model for investigating influenza transmission (Maher & DeStefano 2004; Maines *et al.* 2006), especially as the Hartley strain of guinea pigs that they used do not manifest typical human symptoms of influenza infection (e.g. coughing and sneezing), as the authors have stated themselves, previously (Lowen *et al.* 2006). Interestingly, although they argue that such asymptomatic infection mimics a proportion of humans that do not manifest symptoms when infected with influenza (perhaps up to 50% of infections; Bridges *et al.* 2003), this misses the point that most transmission probably occurs from symptomatic individuals. So perhaps, if anything, the guinea pig model may underestimate the transmissibility of influenza, irrespective of the prevailing environmental conditions, owing to the different nature of influenza infection in these animals when compared with humans.

2.2. Airborne virus survival and relative humidity

The survival of viruses and other infectious agents depends partially on levels of RH, and reducing virus viability may prevent direct transmission of viral infections, as well as the triggering of immune-mediated illnesses such as asthma (Arundel *et al.* 1986; Hersoug 2005).

RH (expressed in percentage) describes the amount of water vapour held in the air at a specific temperature at any time, relative to the *maximum* amount of water vapour that air at that temperature could *possibly* hold. At higher temperatures, air can hold more water vapour, and the relationship is roughly exponential—air at high temperatures can hold *much more* water vapour than air at lower temperatures (Shaman & Kohn 2009).

Generally, viruses with lipid envelopes will tend to survive longer at lower (20–30%) RHs. This applies to most respiratory viruses, which are lipid enveloped, including influenza, coronaviruses (including severe acute respiratory syndrome-associated coronavirus), respiratory syncytial virus, parainfluenza viruses, as well as febrile rash infections caused by measles, rubella, varicella zoster virus (that causes chickenpox; Harper 1961; Schaffer *et al.* 1976; Ijaz *et al.* 1985).

Conversely, non-lipid enveloped viruses tend to survive longer in higher (70–90%) RHs. These include respiratory adenoviruses and rhinoviruses (Karim *et al.* 1985; Arundel *et al.* 1986; Cox 1989, 1998). For example, using viral culture methods, Hemmes *et al.* (1960) showed that aerosolized influenza virus survived longer at lower (15–40%) than higher (50–90%) RHs. In contrast, non-enveloped poliovirus survived longer at higher RHs (greater than 45%). Schaffer *et al.* (1976) found a more complex relationship between airborne influenza virus survival and RH. Again, using viral culture methods, at a temperature of 21°C, they found that influenza survival was lowest at a mid-range (40–60%) of RH. Viral survival was found to be highest at a low (20%) and moderate at a high (60–80%) RH, i.e. showing an asymmetrical V-shaped curve for influenza survival and various RHs at this temperature.

Such differences in survival with RH have been attributed to cross-linking reactions occurring between the surface proteins of these viruses (Cox 1989, 1998).

However, findings from studies are not always consistent, though there seems to be some general indication that minimal survival for both lipid-enveloped and non-lipid-enveloped viruses occurs at an intermediate RH of 40–70% (Arundel *et al.* 1986). Also, it is important to note that temperature and RH will always interact to affect the survival of airborne viruses in aerosols.

The discussions above are an attempt at useful generalizations, though there will always be exceptions depending on individual situations.

Most recently, Shaman & Kohn (2009) revisited the possibility that successful airborne virus transmission and therefore airborne virus survival was more closely correlated to absolute rather than RH. They analysed data from the guinea pig influenza transmission experiments performed by Lowen *et al.* (2007, 2008), converting RH values to absolute humidity values using the Clausius–Clapeyron relation, and found that absolute humidity was more strongly correlated with both the guinea pig influenza transmission and therefore airborne virus survival. They then postulated that variations in absolute humidity may therefore play a role in governing the seasonality of influenza, particularly in temperate regions. However, a recent study examining the correlation between influenza incidence and outdoor climate factors (including temperature, RH and absolute humidity) in Hong Kong did not find a stronger correlation with absolute humidity than other climate variables. This study was conducted in a subtropical rather than a temperate region, and it is known that such relationships between influenza incidence and climate parameters can differ with latitude (Tang *et al.* in press).

2.3. *Conclusions*

It is clear from the above that there is still a need to examine the survival of airborne viruses in a standardized laboratory model with a repeatable, robust methodology. Although useful laboratory results on influenza transmission efficiency (and therefore by implication, virus survival) are still being obtained using small animal models such as mice (Maines *et al.* 2009) and guinea pigs (Mubareka *et al.* 2009), the ferret is probably the best laboratory animal model for studying the infection and transmission of influenza in humans (Munster *et al.* 2009), especially as they manifest similar symptoms. However, at the same time, it is recognized that they are difficult and expensive animals to maintain (Maher & DeStefano 2004; Lowen *et al.* 2006; Maines *et al.* 2006).

In addition, laboratory methods to produce and detect the presence of viruses in aerosols have improved (Blachere *et al.* 2007), particularly with the construction of mechanical 'coughing' machines (Sze To *et al.* 2008), though these cannot replicate the wide variety of respiratory activities that may lead to the aerosolization of aerosol/airborne-transmissible viruses by humans. To this end, more and more experiments are being performed with human volunteers or taking place in real healthcare environments, where humans are the main sources of such potentially infectious aerosols (Xiao *et al.* 2004; Fabian *et al.* 2008; Huynh *et al.* 2008; Blachere *et al.* 2009; Johnson *et al.* 2009; Stelzer-Braid *et al.* 2009). This is the most useful approach to inform and convince infection control teams about the potential risks posed by aerosol/airborne-transmissible infections. However, these studies all differed in the way that they collected the exhaled or airborne viruses, so this will also need to be standardized at some point in the future, in order to develop useful and reliable infection control recommendations based on these air-sampling results.

3. BACTERIA

Multiple studies have also been performed on the survival of airborne bacteria. However, their results are less easy to interpret than with similar studies on viruses. Like viruses, bacteria also have different types of outer coats (Gram-positive surrounded by a peptidoglycan outer coat and Gram-negative surrounded by a lipopolysaccharide outer coat), but in addition, some bacteria (anaerobic species) are highly sensitive and cannot grow in the presence of oxygen. Being larger, bacteria are more sensitive to the methods of their aerosolization, collection and culture, and these factors have to be taken into account when assessing the viability of airborne bacteria in response to different environmental conditions (Cox 1989, 1998).

Previous studies have shown that the process of aerosolization and impingement collection can physically damage the bacterial cell walls (Lundholm 1982; Terzieva *et al.* 1996), and the method of culturing to count the number of airborne, viable organisms may be suboptimal, as not all viable bacteria are able to form colonies after aerosolization (Heidelberg *et al.* 1997). Concerns about the spread of airborne genetically modified organisms led to experiments assessing their viability downwind of their release in aerosol form. The survival of aerosolized Gram-negative bacteria (including *Pseudomonas*, *Enterobacter* and *Klebsiella* species) was found to be greatest in high RH, low T and when they were contained in small droplets, owing to the more rapid droplet evaporation and resulting bacterial desiccation (Marthi *et al.* 1990; Walter *et al.* 1990).

Studies of indoor air from Europe have demonstrated that Gram-positive cocci (*Micrococcus*, *Staphylococcus* species) are the most commonly found bacteria in indoor air environments, though some Gram-negative bacteria (Pseudomonadaceae family, *Aeromonas* species) are also often present (Gorny *et al.* 1999; Gorny & Dutkiewicz 2002). In a study on 100 large US office buildings, it was found that generally Gram-positive cocci were most prevalent in both indoor and outdoor air, followed by Gram-positive rods (e.g. *Bacillus* and *Actinomycetes* species), Gram-negative rods then Gram-negative cocci, with only the Gram-positive cocci showing higher levels indoor versus outdoor and during summer versus winter months. This may be due to the different dress styles worn in these two seasons (Tsai & Macher 2005), with the cooler, shorter summer clothes allowing greater shedding of Gram-positive bacteria from exposed skin surfaces.

3.1. *Airborne bacteria survival and temperature and relative humidity*

Accepting all the variability regarding the methods of aerosolization, collection and culture mentioned above, generally, previous studies have shown that temperatures above about 24°C appear to universally decrease airborne bacterial survival. This has been found with members of Gram-negative, Gram-positive and intracellular bacteria: *Pseudomonas* (Handley & Webster 1993, 1995), *Pasteurella* (Ehrlich & Miller 1973), *Salmonella* (Dinter & Muller 1988), *Serratia* (Ehrlich *et al.* 1970), *Escherichia* (Ehrlich *et al.* 1970; Muller & Dinter 1986; Wathes *et al.* 1986), *Bacillus* (Ehrlich *et al.* 1970), *Bordetella* (Stehmann *et al.* 1992), *Chlamydia* (Theunissen *et al.* 1993) and *Mycoplasma* (Wright *et al.* 1969) species.

The effects of RH are more complex, with experimental conditions again having significant influences on the outcome of experiments. Studies on airborne Gram-negative bacteria such as *Serratia marcescens*, *Escherichia coli*, *Salmonella pullorum*, *Salmonella derby*, *Pseudomonas aeruginosa* and *Proteus vulgaris* have found increased death rates at intermediate (approx. 50–70%) to high (approx. 70–90%) RH environments (Webb 1959; Won & Ross 1966). For some airborne Gram-positive bacteria, *Staphylococcus albus*, *Streptococcus haemolyticus*, *Bacillus subtilis* and *Streptococcus pneumoniae* (type 1), their death rates were also highest at intermediate RH levels (Dunklin & Puck 1948; Webb 1959; Won & Ross 1966).

In contrast, another aerosolized Gram-negative bacillus, *Klebsiella pneumoniae*, demonstrated relative stability at an intermediate RH of 60 per cent (Bolister *et al.* 1992). Some experiments with the Gram-negative rod *Pasteurella* species showed a greater survival in aerosols at high RH levels (Jericho *et al.* 1977; Dinter & Muller 1984), though another study showed that airborne survival was time dependent, with a higher initial survival rate at high RH after 5 min (69 at 79% RH compared with 22 at 28% RH), but a lower survival rate after 45 min (just 2 at 79% RH compared with 8 at 28% RH; Thomson *et al.* 1992).

In addition, the work of Cox and colleagues examined how the initial state of the organisms to be aerosolized may also affect their final airborne survival duration. They defined 'dry-disseminated' as meaning that the organism was aerosolized from a dry dust or freeze-dried powder form and 'wet-disseminated' when the organism was aerosolized from a liquid suspension, e.g. mimicking human mucus or saliva. They found that when the organisms were dry-disseminated they tended to absorb water from the environment (i.e. they partially rehydrated), and when wet-disseminated, the opposite occurred, i.e. they desiccated. Such changes in water content (i.e. rehydration or desiccation) in these aerosolized forms tended to affect the final survival of the airborne organisms in different ways (Cox 1989, 1998). Hence, in this framework, Cox (1971) showed that for wet-disseminated *Pasteurella*, its viability was minimal at 50–55% RH, whereas for dry-dissemination it was minimal at 75 per cent RH.

Another experimental factor that may affect the outcome of such survival experiments is the way the bacteria are cultured. One study showed that plate-grown *Salmonella* species (*Salmonella enteritidis* Pt4 and *Salmonella typhimurium* Swindon) survived longer in aerosol than broth-grown bacteria of the same species (McDermid & Lever 1996). Aerosolized *Legionella pneumophila*, another Gram-negative rod-like bacterium, was shown to be most stable at 65 per cent RH and least stable at 55–60% RH (Hambleton *et al.* 1983; Dennis & Lee 1988). Interestingly, two studies on the survival of aerosolized *Mycoplasma* species showed that survival was optimal at low (less than 25%) and high RH (more than 80%) and worst between these two extremes (Wright *et al.* 1968*a*,*b*). Survival was also poor when there were sudden changes in RH, particularly from a favourable low or high RH to the more lethal intermediate RH range (Hatch *et al.* 1970).

3.2. Conclusions

It is apparent that the situation with the survival of airborne bacteria is much more complicated than with viruses (Cox 1989, 1998). Even bacteria within the same structural classification (e.g. Gram-negative) may vary in how they respond to temperature and RH. Perhaps even more so than with studies on the airborne survival of viruses, the structural variation of potentially airborne bacteria may preclude useful generalizations to be made and individual bacteria may need to be considered separately when investigating their airborne survival.

4. AIRBORNE VIRUSES AND BACTERIA: SURVIVAL AND OTHER ENVIRONMENTAL FACTORS

Ultraviolet light is harmful to both viruses (Myatt *et al.* 2003; Walker & Ko 2007) and bacteria. Two studies with *S. marcescens* showed an increased survival in the presence of UV light at higher RH levels. This was suggested to be due to the protective effect of larger particle sizes, as evaporation would be less at these higher RH levels, thus indicating a protective effect of a thicker water coat against UV radiation (Riley & Kaufman 1972; Ko *et al.* 2000).

For bacteria, the effect of carbon monoxide (CO, simulating a polluted, urban environment) has also been investigated. Using aerosolized *S. marcescens*, it was found that the presence of CO enhanced the death rate at low RH (less than 25%), but protected the bacteria at high RH (approx. 90%). The mechanism underlying these contradictory, RH-dependent effects was suggested to be a CO-uncoupling of an energy-consuming death mechanism at high RH and a contrasting energy-consuming maintenance mechanism at low RH (Lighthart 1973).

Finally, aerosol dissemination of bacteria into different types of atmosphere can also affect the survival characteristics of the organisms. Cox and colleagues showed that the survival of dry-disseminated airborne *E. coli* in a nitrogen atmosphere at low RH was greater than in an oxygen-containing atmosphere, whereas the converse was true at high RH (Cox 1970).

5. FUNGI

Extensive studies have been performed to characterize the levels of both indoor and outdoor airborne fungi and their spores. Perhaps more than viruses or bacteria, airborne fungi and their spores have the potential to be blown into a building that uses natural ventilation and certain species of fungi, e.g. *Aspergillus* species (*Aspergillus flavus* and *Aspergillus fumigatus*), are well-known, potentially life-threatening airborne contaminants when they are blown in through the windows of wards containing immunocompromised patients (Vonberg & Gastmeier 2006). Other fungi hazardous to the immunocompromised include *Blastomyces*, *Coccidioides*, *Cryptococcus* and *Histoplasma* species (Hardin *et al.* 2003). Even in otherwise healthy people working in other indoor environments such as offices and schools, as well as at home, fungi and their spores may trigger hypersensitivity reactions such as rhinitis, sinusitis or asthma.

Indoor fungi associated with such reactions include *Penicillium* and *Aspergillus* species, with *Cladosporium* and *Alternaria* commonly causing such reactions outdoors (Hardin *et al.* 2003). These four fungal species have been found worldwide, in varying mixtures, in both indoor and outdoor environments (Takahashi 1997; Jo & Seo 2005; Lee & Jo 2006; Basilico *et al.* 2007), where airborne levels of fungi vary seasonally, usually being highest in autumn and summer and lowest in winter and spring (Takahashi 1997; Shelton *et al.* 2002; Lee & Jo 2006; Fang *et al.* 2007).

Ventilation systems have a significant affect on indoor levels of airborne fungi, with air-handling units reducing, but natural ventilation and fan-coil units increasing the indoor concentrations of airborne fungi (Burge *et al.* 2000; Wu *et al.* 2005; MacIntosh *et al.* 2006). Dehumidification as well as high-efficiency particulate arrestance (HEPA) filtration have also been used to improve indoor air quality (Bernstein *et al.* 2005; Ramachandran *et al.* 2005).

5.1. Airborne fungi survival and temperature and relative humidity

In contrast to viruses and bacteria, there have been relatively few experimental studies specifically examining the effects of varying T and RH on airborne fungi and their spores. Most of the data relating T and RH to the levels of airborne fungi have been obtained in the indoor or outdoor environments where these organisms are naturally found, rather than in an experimental laboratory. However, the results of such studies certainly show a seasonal variation of airborne fungal and spore concentrations owing to seasonal changes in environmental factors, e.g. temperature, RH, rainfall (precipitation) and wind speed. Generally, fungi and their spores are more resilient than viruses and bacteria, being able to withstand greater stresses owing to dehydration and rehydration, as well as UV radiation (Cox 1989, 1998; Karra & Katsivela 2007). Most studies involved air sampling at various sites within buildings or outdoor locations and a correlation with various contemporaneous environmental parameters over at least 1 year.

Fungal spore counts seem to be highest in summer, both indoors and outdoors (Garrett *et al.* 1998), with higher *Cladosporium* and *Alternaria* counts being seen with higher daily temperatures (Troutt & Levetin 2001). Outdoor fungal spore levels are important in natural ventilation as they affect the resulting indoor levels of these particles. Both of these airborne fungal species can cause or exacerbate hypersensitivity reactions, including asthma. Most studies confirm this positive correlation between spore levels and higher temperatures (Sabariego *et al.* 2000; Khan & Wilson 2003; Hollins *et al.* 2004; Peternel *et al.* 2004; Stennett & Beggs 2004; Rodriguez-Rajo *et al.* 2005; Erkara *et al.* 2008), though at least one Portuguese study found contradictory findings with lower spore concentrations in both August (summer) and January (winter; Oliveira *et al.* 2005).

There seems to be no clear consensus with regard to rainfall (precipitation) and airborne spore concentrations. This could be because of the multiple effects of rainfall, including the removing action of falling raindrops on airborne particles, as well as the resulting increase in RH shortly after rainfall when the temperature is high, causing rapid re-evaporation of the rainwater (Troutt & Levetin 2001; Hollins *et al.* 2004; Peternel *et al.* 2004). Several of these studies also indicated that spore concentrations were higher with higher RH levels (Sabariego *et al.* 2000; Stennett & Beggs 2004; Rodriguez-Rajo *et al.* 2005; Erkara *et al.* 2008), though at least one study demonstrated opposite findings (Sabariego *et al.* 2000).

The variable findings of these studies are probably due to the interaction of all these environmental factors, together with the different times at which these fungi release their spores, in different countries, throughout the year. These problems are summarized by Burch & Levetin (2002), who also discuss the significant influence of thunderstorms on wind speeds, cold fronts and air pressure, which may drive airborne fungal spores in front of them. Hence, naturally ventilated buildings may experience very high airborne spore loads in the hours preceding such weather.

The more pathogenic fungi, *Aspergillus* and *Penicillium* species, can be hazardous to humans in high concentrations owing to their abilities to produce mycotoxins. Studies have shown that they are also present in air both indoors and outdoors, though typically at much lower concentrations than *Cladosporium* and *Alternaria* (Khan & Wilson 2003; Basilico *et al.* 2007). The indoor and outdoor concentrations of *Aspergillus* and *Penicillium* species may vary considerably in both winter and summer, as well as in urban or more suburban environments, with higher T and RH, and suburban areas being generally more favourable for higher airborne spore concentrations (Li & Kuo 1994; Pei-Chih *et al.* 2000; Sakai *et al.* 2003).

5.2. Conclusions

The nature of research on fungi with regard to the environment has been quite different from that conducted with viruses and bacteria. With the latter, the experiments tended to be laboratory based and examined their survival by varying temperature and RH individually or in combination. With fungi, the vast majority of studies have focused on documenting the presence or absence of fungi and their spores in various indoor and outdoor environments, with their survival in such environments apparently being assumed, or at least not being a significant question or confounder in such studies. However, this may not be unrealistic as, unlike viruses and bacteria, the natural life cycle of most fungi involves long-distance dissemination of their spores mainly in outdoor environments where evolution and natural selection over millions of years have designed their spores to be capable of withstanding most environmental insults, such as extremes of temperature, humidity and ultraviolet light.

From an infection control viewpoint, it is already well known that probably the most common urban source of fungi and their spores is from nearby building works, which poses daily risks to immunocompromised patients. Nearby parks and gardens may also act as potential sources of fungal infections in such patients. Given their natural resistance to environmental extremes, infection control of fungi and their spores in healthcare premises should probably focus more on either physical barrier means to reduce their intrusion, such as the installation of permanently sealed (i.e. that cannot be opened by the patient) windows in the rooms of immunocompromised patients, or their physical removal by circulating hospital indoor air through HEPA filters in the vicinity of such patients.

6. SUMMARY

Given the above, eventually, will it be possible to produce recommendations similar to those shown in table 1, for different levels of temperature and RH to enhance aerosol/airborne infection control in different hospital areas? Possibly, but such recommendations will need to take into account the comfort of patients and staff, which is an additional factor that was not considered in any of these pathogen survival experiments. Therefore, for example, although high temperatures (more than 30°C) at relatively high RH (greater than 50%) may reduce the survival of airborne influenza virus, the tolerance of people coexisting in such conditions will also need to be considered.

Also, because different airborne infectious agents (i.e. viruses, bacteria and fungi) will have differing conditions under which they may be optimally suppressed, it will need to be decided which airborne pathogen poses the most risk to patients and staff alike. Such prioritization will be required when specific environmental recommendations are made for healthcare premises.

Finally, it must be remembered that other more individual-level interventions are available to protect staff and patients against airborne pathogens. These include specific vaccinations (e.g. for influenza), as well as the wearing of masks and other personal protective equipment, mainly by healthcare workers. It is likely that a combination of these methods, adapted to specific situations as required, will be used to control the nosocomial transmission of airborne infectious agents. Yet, the basic research to obtain the data on which these policies will depend is still far from complete.

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