

## REVIEW

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

Julian W. Tang\*

*Department of Laboratory Medicine, National University Hospital, 5 Lower Kent Ridge Road, Singapore 119074, Republic of Singapore*

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,

\*jwang49@hotmail.com

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

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>).

section	location	summer		winter	
		dry-bulb temperature (°C)	RH (%)	dry-bulb temperature (°C)	RH (%)
hospital ward	patient bedroom <sup>a</sup>	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 <sup>b</sup>	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 <sup>c</sup>	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 <sup>d</sup>	25–26	50–60	20–22	40–50
	hydrotherapy treatment room <sup>e</sup>	26–27	50–65	26–28	50–65
	dissection room	24–26	50–60	20–22	40–50
supply section	kitchen	use guidelines for hospital catering services			
	material room	26–27	50–60	20–22	40–50
administrative area	office	26–27	50–60	20–22	40–50

<sup>a</sup>Consider the additional cooling and heating effects of the window in winter and summer (sunlight), respectively.

<sup>b</sup>To maintain at a warmer temperature than the waiting room.

<sup>c</sup>There may be a demand for higher temperatures as required.

<sup>d</sup>May need to compensate for any additional heating effect generated by the X-ray equipment.

<sup>e</sup>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 *Actinomyces* 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.* 1968a,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.

## REFERENCES

- Arundel, A. V., Sterling, E. M., Biggin, J. H. & Sterling, T. D. 1986 Indirect health effects of relative humidity in indoor environments. *Environ. Health Perspect.* **65**, 351–361. (doi:10.2307/3430203)
- Basilico Mde, L., Chiericatti, C., Aringoli, E. E., Althaus, R. L. & Basilico, J. C. 2007 Influence of environmental factors on airborne fungi in houses of Santa Fe City, Argentina. *Sci. Total Environ.* **376**, 143–150. (doi:10.1016/j.scitotenv.2007.01.001)
- Bernstein, J. A., Levin, L., Crandall, M. S., Perez, A. & Lanphear, B. 2005 A pilot study to investigate the effects of combined dehumidification and HEPA filtration on dew point and airborne mold spore counts in day care centers. *Indoor Air* **15**, 402–407. (doi:10.1111/j.1600-0668.2005.00379.x)
- Blachere, F. M., Lindsley, W. G., Slaven, J. E., Green, B. J., Anderson, S. E., Chen, B. T. & Beezhold, D. H. 2007 Bioaerosol sampling for the detection of aerosolized influenza virus. *Influenza Other Respir. Viruses* **1**, 113–120. (doi:10.1111/j.1750-2659.2007.00020.x)
- Blachere, F. M. *et al.* 2009 Measurement of airborne influenza virus in a hospital emergency department. *Clin. Infect. Dis.* **48**, 438–440. (doi:10.1086/596478)
- Bolister, N. J., Johnson, H. E. & Wathes, C. M. 1992 The ability of airborne *Klebsiella pneumoniae* to colonize mouse lungs. *Epidemiol. Infect.* **109**, 121–131.
- Bridges, C. B., Kuehnert, M. J. & Hall, C. B. 2003 Transmission of influenza: implications for control in health care settings. *Clin. Infect. Dis.* **37**, 1094–1101. (doi:10.1086/378292)
- Burch, M. & Levetin, E. 2002 Effects of meteorological conditions on spore plumes. *Int. J. Biometeorol.* **46**, 107–117. (doi:10.1007/s00484-002-0127-1)
- Burge, H. A., Pierson, D. L., Groves, T. O., Strawn, K. F. & Mishra, S. K. 2000 Dynamics of airborne fungal populations in a large office building. *Curr. Microbiol.* **40**, 10–16. (doi:10.1007/s002849910003)
- Cox, C. S. 1970 Aerosol survival of *Escherichia coli* B disseminated from the dry state. *Appl. Microbiol.* **19**, 604–607.
- Cox, C. S. 1971 Aerosol survival of *Pasteurella tularensis* disseminated from the wet and dry states. *Appl. Microbiol.* **21**, 482–486.
- Cox, C. S. 1989 Airborne bacteria and viruses. *Sci. Prog.* **73**, 469–499.
- Cox, C. S. 1998 The microbiology of air. In *Topley & Wilson's microbiology and microbial infections* (eds L. Collier, A. Balows & M. Sussman), pp. 339–350, 9th edn. London, UK: Arnold, Oxford University Press.
- Dennis, P. J. & Lee, J. V. 1988 Differences in aerosol survival between pathogenic and non-pathogenic strains of *Legionella pneumophila* serogroup 1. *J. Appl. Bacteriol.* **65**, 135–141.
- Dinter, P. S. & Muller, W. 1984 Tenacity of bacteria in the airborne state. III. Model studies on the epidemiology of *Pasteurella multocida* influenced by a tropical climate. *Zentralbl. Bakteriol. Mikrobiol. Hyg. B* **179**, 139–150.
- Dinter, P. S. & Muller, W. 1988 The tenacity of bacteria in the airborne state. VI. Tenacity of airborne *S. senftenberg*. *Zentralbl. Bakteriol. Mikrobiol. Hyg. B* **186**, 278–288.
- Dunklin, E. W. & Puck, T. T. 1948 The lethal effect of relative humidity on air-borne bacteria. *J. Exp. Med.* **87**, 87–101. (doi:10.1084/jem.87.2.87)
- Ehrlich, R. & Miller, S. 1973 Survival of airborne *Pasteurella tularensis* at different atmospheric temperatures. *Appl. Microbiol.* **25**, 369–372.
- Ehrlich, R., Miller, S. & Walker, R. L. 1970 Relationship between atmospheric temperature and survival of airborne bacteria. *Appl. Microbiol.* **19**, 245–249.



- Erkara, I. P., Asan, A., Yilmaz, V., Pehlivan, S. & Okten, S. S. 2008 Airborne Alternaria and Cladosporium species and relationship with meteorological conditions in Eskisehir City, Turkey. *Environ. Monit. Assess.* **144**, 31–41.
- Fabian, P., McDevitt, J. J., DeHaan, W. H., Fung, R. O., Cowling, B. J., Chan, K. H., Leung, G. M. & Milton, D. K. 2008 Influenza virus in human exhaled breath: an observational study. *PLoS ONE* **3**, e2691. (doi:10.1371/journal.pone.0002691)
- Fang, Z., Ouyang, Z., Zheng, H., Wang, X. & Hu, L. 2007 Culturable airborne bacteria in outdoor environments in Beijing, China. *Microb. Ecol.* **54**, 487–496. (doi:10.1007/s00248-007-9216-3)
- Garrett, M. H., Rayment, P. R., Hooper, M. A., Abramson, M. J. & Hooper, B. M. 1998 Indoor airborne fungal spores, house dampness and associations with environmental factors and respiratory health in children. *Clin. Exp. Allergy* **28**, 459–467. (doi:10.1046/j.1365-2222.1998.00255.x)
- Gorny, R. L. & Dutkiewicz, J. 2002 Bacterial and fungal aerosols in indoor environment in Central and Eastern European countries. *Ann. Agric. Environ. Med.* **9**, 17–23.
- Gorny, R. L., Dutkiewicz, J. & Kryszka-Traczyk, E. 1999 Size distribution of bacterial and fungal bioaerosols in indoor air. *Ann. Agric. Environ. Med.* **6**, 105–113.
- Hambleton, P., Broster, M. G., Dennis, P. J., Henstridge, R., Fitzgeorge, R. & Conlan, J. W. 1983 Survival of virulent *Legionella pneumophila* in aerosols. *J. Hyg. (Lond.)* **90**, 451–460. (doi:10.1017/S0022172400029090)
- Handley, B. A. & Webster, A. J. 1993 Some factors affecting airborne survival of *Pseudomonas fluorescens* indoors. *J. Appl. Bacteriol.* **75**, 35–42.
- Handley, B. A. & Webster, A. J. 1995 Some factors affecting the airborne survival of bacteria outdoors. *J. Appl. Bacteriol.* **79**, 368–378.
- Hardin, B. D., Kelman, B. J. & Saxon, A. 2003 Adverse human health effects associated with molds in the indoor environment. *J. Occup. Environ. Med.* **45**, 470–478. (doi:10.1097/00043764-200305000-00006)
- Harper, G. J. 1961 Airborne micro-organisms: survival tests with four viruses. *J. Hyg. (Lond.)* **59**, 479–486. (doi:10.1017/S0022172400039176)
- Hatch, M. T., Wright, D. N. & Bailey, G. D. 1970 Response of airborne *Mycoplasma pneumoniae* to abrupt changes in relative humidity. *Appl. Microbiol.* **19**, 232–238.
- Heidelberg, J. F., Shahamat, M., Levin, M., Rahman, I., Stelma, G., Grim, C. & Colwell, R. R. 1997 Effect of aerosolization on culturability and viability of Gram-negative bacteria. *Appl. Environ. Microbiol.* **63**, 3585–3588.
- Hemmes, J. H., Winkler, K. C. & Kool, S. M. 1960 Virus survival as a seasonal factor in influenza and poliomyelitis. *Nature* **188**, 430–431. (doi:10.1038/188430a0)
- Hersoug, L. G. 2005 Viruses as the causative agent related to 'dampness' and the missing link between allergen exposure and onset of allergic disease. *Indoor Air* **15**, 363–366. (doi:10.1111/j.1600-0668.2005.00382.x)
- Hollins, P. D., Kettlewell, P. S., Atkinson, M. D., Stephenson, D. B., Corden, J. M., Millington, W. M. & Mullins, J. 2004 Relationships between airborne fungal spore concentration of *Cladosporium* and the summer climate at two sites in Britain. *Int. J. Biometeorol.* **48**, 137–141. (doi:10.1007/s00484-003-0188-9)
- Huynh, K. N., Oliver, B. G., Stelzer, S., Rawlinson, W. D. & Tovey, E. R. 2008 A new method for sampling and detection of exhaled respiratory virus aerosols. *Clin. Infect. Dis.* **46**, 93–95. (doi:10.1086/523000)
- Ijaz, M. K., Brunner, A. H., Sattar, S. A., Nair, R. C. & Johnson-Lussenburg, C. M. 1985 Survival characteristics of airborne human coronavirus 229E. *J. Gen. Virol.* **66**, 2743–2748. (doi:10.1099/0022-1317-66-12-2743)
- Ijaz, M. K., Karim, Y. G., Sattar, S. A. & Johnson-Lussenburg, C. M. 1987 Development of methods to study the survival of airborne viruses. *J. Virol. Methods* **18**, 87–106. (doi:10.1016/0166-0934(87)90114-5)
- Jericho, K. W., Langford, E. V. & Pantekoek, J. 1977 Recovery of *Pasteurella hemolytica* from aerosols at differing temperature and humidity. *Can. J. Comp. Med.* **41**, 211–214.
- Jo, W. K. & Seo, Y. J. 2005 Indoor and outdoor bioaerosol levels at recreation facilities, elementary schools, and homes. *Chemosphere* **61**, 1570–1579. (doi:10.1016/j.chemosphere.2005.04.103)
- Johnson, D. F., Druce, J. D., Birch, C. & Grayson, M. L. 2009 A quantitative assessment of the efficacy of surgical and N95 masks to filter influenza virus in patients with acute influenza infection. *Clin. Infect. Dis.* **49**, 275–277. (doi:10.1086/600041)
- Karim, Y. G., Ijaz, M. K., Sattar, S. A. & Johnson-Lussenburg, C. M. 1985 Effect of relative humidity on the airborne survival of rhinovirus-14. *Can. J. Microbiol.* **31**, 1058–1061.
- Karra, S. & Katsivela, E. 2007 Microorganisms in bioaerosol emissions from wastewater treatment plants during summer at a Mediterranean site. *Water Res.* **41**, 1355–1365. (doi:10.1016/j.watres.2006.12.014)
- Khan, N. N. & Wilson, B. L. 2003 An environmental assessment of mold concentrations and potential mycotoxin exposures in the greater Southeast Texas area. *J. Environ. Sci. Health A Tox. Hazard. Subst. Environ. Eng.* **38**, 2759–2772.
- Ko, G., First, M. W. & Burge, H. A. 2000 Influence of relative humidity on particle size and UV sensitivity of *Serratia marcescens* and *Mycobacterium bovis* BCG aerosols. *Tuber. Lung Dis.* **80**, 217–228. (doi:10.1054/tuld.2000.0249)
- Lee, J. H. & Jo, W. K. 2006 Characteristics of indoor and outdoor bioaerosols at Korean high-rise apartment buildings. *Environ. Res.* **101**, 11–17. (doi:10.1016/j.envres.2005.08.009)
- Li, C. S. & Kuo, Y. M. 1994 Characteristics of airborne microfungi in subtropical homes. *Sci. Total Environ.* **155**, 267–271. (doi:10.1016/0048-9697(94)90505-3)
- Lighthart, B. 1973 Survival of airborne bacteria in a high urban concentration of carbon monoxide. *Appl. Microbiol.* **25**, 86–91.
- Lowen, A. C., Mubareka, S., Tumpey, T. M., García-Sastre, A. & Palese, P. 2006 The guinea pig as a transmission model for human influenza viruses. *Proc. Natl Acad. Sci. USA* **103**, 9988–9992. (doi:10.1073/pnas.0604157103)
- Lowen, A. C., Mubareka, S., Steel, J. & Palese, P. 2007 Influenza virus transmission is dependent on relative humidity and temperature. *PLoS Pathog.* **3**, 1470–1476. (doi:10.1371/journal.ppat.0030151)
- Lowen, A. C., Steel, J., Mubareka, S. & Palese, P. 2008 High temperature (30° C) blocks aerosol but not contact transmission of influenza virus. *J. Virol.* **82**, 5650–5652. (doi:10.1128/JVI.00325-08)
- Lundholm, I. M. 1982 Comparison of methods for quantitative determinations of airborne bacteria and evaluation of total viable counts. *Appl. Environ. Microbiol.* **44**, 179–183.
- MacIntosh, D. L., Brightman, H. S., Baker, B. J., Myatt, T. A., Stewart, J. H. & McCarthy, J. F. 2006 Airborne fungal spores in a cross-sectional study of office buildings. *J. Occup. Environ. Hyg.* **3**, 379–389. (doi:10.1080/10543400600760438)



- Maher, J. A. & DeStefano, J. 2004 The ferret: an animal model to study influenza virus. *Lab. Anim. (NY)* **33**, 50–53. (doi:10.1038/labani004-50)
- Maines, T. R. *et al.* 2006 Lack of transmission of H5N1 avian-human reassortant influenza viruses in a ferret model. *Proc. Natl Acad. Sci. USA* **103**, 12 121–12 126. (doi:10.1073/pnas.0605134103)
- Maines, T. R. *et al.* 2009 Transmission and pathogenesis of swine-origin 2009 A(H1N1) influenza viruses in ferrets and mice. *Science* **325**, 484–487. (doi:10.1126/science.1177238)
- Marthi, B., Fieland, V. P., Walter, M. & Seidler, R. J. 1990 Survival of bacteria during aerosolization. *Appl. Environ. Microbiol.* **56**, 3463–3467.
- McDermid, A. S. & Lever, M. S. 1996 Survival of *Salmonella enteritidis* Pt4 and *Salm. typhimurium* Swindon in aerosols. *Lett. Appl. Microbiol.* **23**, 107–109. (doi:10.1111/j.1472-765X.1996.tb00042.x)
- Mubareka, S., Lowen, A. C., Steel, J., Coates, A. L., García-Sastre, A. & Palese, P. 2009 Transmission of influenza virus via aerosols and fomites in the guinea pig model. *J. Infect. Dis.* **199**, 858–865. (doi:10.1086/597073)
- Muller, W. & Dinter, P. S. 1986 The tenacity of bacteria in the airborne state. IV: experimental studies on the viability of airborne *E. coli* 0:78 under the influence of different temperature and humidity. *Zentralbl. Bakteriologie. Mikrobiol. Hyg. A* **262**, 304–312.
- Munster, V. J. *et al.* 2009 Pathogenesis and transmission of swine-origin 2009 A(H1N1) influenza virus in ferrets. *Science* **325**, 481–483. (doi:10.1126/science.1177127)
- Myatt, T. A., Johnston, S. L., Rudnick, S. & Milton, D. K. 2003 Airborne rhinovirus detection and effect of ultraviolet irradiation on detection by a semi-nested RT-PCR assay. *BMC Public Health* **3**, 5. (doi:10.1186/1471-2458-3-5)
- Oliveira, M., Ribeiro, H. & Abreu, I. 2005 Annual variation of fungal spores in atmosphere of Porto: 2003. *Ann. Agric. Environ. Med.* **12**, 309–315.
- Pei-Chih, W., Huey-Jen, S. & Chia-Yin, L. 2000 Characteristics of indoor and outdoor airborne fungi at suburban and urban homes in two seasons. *Sci. Total Environ.* **253**, 111–118. (doi:10.1016/S0048-9697(00)00423-X)
- Peternel, R., Culig, J. & Hrga, I. 2004 Atmospheric concentrations of *Cladosporium* spp. and *Alternaria* spp. spores in Zagreb (Croatia) and effects of some meteorological factors. *Ann. Agric. Environ. Med.* **11**, 303–307.
- Ramachandran, G., Adgate, J. L., Banerjee, S., Church, T. R., Jones, D., Fredrickson, A. & Sexton, K. 2005 Indoor air quality in two urban elementary schools—measurements of airborne fungi, carpet allergens, CO<sub>2</sub>, temperature, and relative humidity. *J. Occup. Environ. Hyg.* **2**, 553–566. (doi:10.1080/15459620500324453)
- Riley, R. L. & Kaufman, J. E. 1972 Effect of relative humidity on the inactivation of airborne *Serratia marcescens* by ultraviolet radiation. *Appl. Microbiol.* **23**, 1113–1120.
- Rodriguez-Rajo, F. J., Iglesias, I. & Jato, V. 2005 Variation assessment of airborne *Alternaria* and *Cladosporium* spores at different bioclimatical conditions. *Mycol. Res.* **109**, 497–507. (doi:10.1017/S0953756204001777)
- Sabariego, S., Diaz de la Guardia, C. & Alba, F. 2000 The effect of meteorological factors on the daily variation of airborne fungal spores in Granada (southern Spain). *Int. J. Biometeorol.* **44**, 1–5. (doi:10.1007/s004840050131)
- Sakai, K., Tsubouchi, H. & Mitani, K. 2003 Airborne concentrations of fungal and indoor air pollutants in dwellings in Nagoya, Japan. *Nippon Koshu Eisei Zasshi* **50**, 1017–1029.
- Schaffer, F. L., Soergel, M. E. & Straube, D. C. 1976 Survival of airborne influenza virus: effects of propagating host, relative humidity, and composition of spray fluids. *Arch. Virol.* **51**, 263–273. (doi:10.1007/BF01317930)
- Shaman, J. & Kohn, M. 2009 Absolute humidity modulates influenza survival, transmission, and seasonality. *Proc. Natl Acad. Sci. USA* **106**, 3243–3248. (doi:10.1073/pnas.0806852106)
- Shelton, B. G., Kirkland, K. H., Flanders, W. D. & Morris, G. K. 2002 Profiles of airborne fungi in buildings and outdoor environments in the United States. *Appl. Environ. Microbiol.* **68**, 1743–1753. (doi:10.1128/AEM.68.4.1743-1753.2002)
- Stehmann, R., Rottmayer, J., Zschaubitz, K. & Mehlhorn, G. 1992 The tenacity of *Bordetella bronchiseptica* in the air. *Zentralbl. Veterinarmed. B* **39**, 546–552.
- Stelzer-Braid, S., Oliver, B. G., Blazey, A. J., Argent, E., Newsome, T. P., Rawlinson, W. D. & Tovey, E. R. 2009 Exhalation of respiratory viruses by breathing, coughing, and talking. *J. Med. Virol.* **81**, 1674–1679. (doi:10.1002/jmv.21556)
- Stennett, P. J. & Beggs, P. J. 2004 *Alternaria* spores in the atmosphere of Sydney, Australia, and relationships with meteorological factors. *Int. J. Biometeorol.* **49**, 98–105. (doi:10.1007/s00484-004-0217-3)
- Sze To, G. N., Wan, M. P., Chao, C. Y., Wei, F., Yu, S. C. & Kwan, J. K. 2008 A methodology for estimating airborne virus exposures in indoor environments using the spatial distribution of expiratory aerosols and virus viability characteristics. *Indoor Air* **18**, 425–438. (doi:10.1111/j.1600-0668.2008.00544.x)
- Takahashi, T. 1997 Airborne fungal colony-forming units in outdoor and indoor environments in Yokohama, Japan. *Mycopathologia* **139**, 23–33. (doi:10.1023/A:1006831111595)
- Tang, J. W., Lai, F. Y., Wong, F. & Hon, K. L. In press. Incidence of common respiratory viral infections related to climate factors in hospitalized children in Hong Kong. *Epidemiol. Infect.* **27**.
- Terzieva, S., Donnelly, J., Ulevicius, V., Grinshpun, S. A., Willeke, K., Stelma, G. N. & Brenner, K. P. 1996 Comparison of methods for detection and enumeration of airborne microorganisms collected by liquid impingement. *Appl. Environ. Microbiol.* **62**, 2264–2272.
- Theunissen, H. J., Lemmens-den Toom, N. A., Burggraaf, A., Stolz, E. & Michel, M. F. 1993 Influence of temperature and relative humidity on the survival of *Chlamydia pneumoniae* in aerosols. *Appl. Environ. Microbiol.* **59**, 2589–2593.
- Thomson, C. M., Chanter, N. & Wathes, C. M. 1992 Survival of toxigenic *Pasteurella multocida* in aerosols and aqueous liquids. *Appl. Environ. Microbiol.* **58**, 932–936.
- Trout, C. & Levetin, E. 2001 Correlation of spring spore concentrations and meteorological conditions in Tulsa, Oklahoma. *Int. J. Biometeorol.* **45**, 64–74. (doi:10.1007/s004840100087)
- Tsai, F. C. & Macher, J. M. 2005 Concentrations of airborne culturable bacteria in 100 large US office buildings from the BASE study. *Indoor Air* **15**(Suppl. 9), 71–81. (doi:10.1111/j.1600-0668.2005.00346.x)
- Vonberg, R. P. & Gastmeier, P. 2006 Nosocomial aspergillosis in outbreak settings. *J. Hosp. Infect.* **63**, 246–254. (doi:10.1016/j.jhin.2006.02.014)
- Walker, C. M. & Ko, G. 2007 Effect of ultraviolet germicidal irradiation on viral aerosols. *Environ. Sci. Technol.* **41**, 5460–5465. (doi:10.1021/es070056u)
- Walter, M. V., Marthi, B., Fieland, V. P. & Ganio, L. M. 1990 Effect of aerosolization on subsequent bacterial survival. *Appl. Environ. Microbiol.* **56**, 3468–3472.
- Wathes, C. M., Howard, K. & Webster, A. J. 1986 The survival of *Escherichia coli* in an aerosol at air temperatures of 15 and 30 degrees C and a range of humidities. *J. Hyg. (Lond.)* **97**, 489–496.

- Webb, S. J. 1959 Factors affecting the viability of air-borne bacteria. I. Bacteria aerosolized from distilled water. *Can. J. Microbiol.* **5**, 649–669.
- Won, W. D. & Ross, H. 1966 Effect of diluent and relative humidity on apparent viability of airborne *Pasteurella pestis*. *Appl. Microbiol.* **14**, 742–745.
- Wright, D. N., Bailey, G. D. & Hatch, M. T. 1968*a* Role of relative humidity in the survival of airborne *Mycoplasma pneumoniae*. *J. Bacteriol.* **96**, 970–974.
- Wright, D. N., Bailey, G. D. & Hatch, M. T. 1968*b* Survival of airborne *Mycoplasma* as affected by relative humidity. *J. Bacteriol.* **95**, 251–252.
- Wright, D. N., Bailey, G. D. & Goldberg, L. J. 1969 Effect of temperature on survival of airborne *Mycoplasma pneumoniae*. *J. Bacteriol.* **99**, 491–495.
- Wu, P. C., Li, Y. Y., Chiang, C. M., Huang, C. Y., Lee, C. C., Li, F. C. & Su, H. J. 2005 Changing microbial concentrations are associated with ventilation performance in Taiwan's air-conditioned office buildings. *Indoor Air* **15**, 19–26. (doi:10.1111/j.1600-0668.2004.00313.x)
- Xiao, W. J., Wang, M. L., Wei, W., Wang, J., Zhao, J. J., Yi, B. & Li, J. S. 2004 Detection of SARS-CoV and RNA on aerosol samples from SARS-patients admitted to hospital. *Zhonghua Liu Xing Bing Xue Za Zhi* **25**, 882–885.