

Microbial Contamination in Airplane Cabins: Health Effects and Remediation

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Abstract Microorganisms that affect human health are found in all indoor environments, including cabins of commercial aircraft. Those that arise from human sources can be transmitted by direct contact, droplets, or the airborne route. Infections from human sources include Influenza, Rhinovirus, SARS and tuberculosis. Transmission by the airborne route can be reduced by sterilizing the air with ultraviolet germicidal irradiation, or by diluting the contaminated air with outdoor air through ventilation. Microbes arising from environmental sources include bacteria, fungi and other organisms such as protozoa. These usually have very simple requirements for growth – water and a simple substrate such as dust. They cause health effects through direct infection rarely (one example is Legionella), but more commonly cause immune reactions resulting in hypersensitivity or allergy mediated diseases. Environmental sources of microbial contamination are best prevented, but can be remediated through cleaning, germicidal chemicals, or ultraviolet germicidal irradiation. Airborne microbial substances including toxins, antigens and viable organisms can be removed by outdoor air ventilation or filtration. In aircraft cabins transmission of pathogens from human sources is difficult to control, but airborne transmission can be reduced through increased outdoor air ventilation or filtration. Environmental microbial contamination can, and does occur in aircraft cabins. These microbial sources are best prevented but, if detected, can be removed through cleaning or

disinfection. Ultraviolet germicidal irradiation is an under-utilized technology that may be useful for sterilizing air as well as potential environmental sources.

Abbreviations

TB	Tuberculosis
UVGI	Ultraviolet germicidal irradiation
ACH	Air changes per hour
HVAC	Heating ventilation and air conditioning
SARS	Severe acute respiratory syndrome
HEPA	High efficiency particulate air

1

Introduction

As air travel increases globally health risks of air travel become of greater concern. This is because of the direct impact on the health and well-being of passengers (and crew), the potential economic consequences (including legal compensation for damages), and the broader public health impact. The recent SARS outbreak demonstrated how rapidly an epidemic can spread globally though modern air travel. This review will examine the types of microbes that are found in this environment, their sources, health effects, and remediation or prevention.

Microbes that affect human health within the indoor environment originate from two sources – humans and the environment. Microbes from human sources typically cause disease through infectious mechanisms. They include common viruses such as rhinovirus, influenza viruses and measles. Human to human transmission of viruses within the indoor environment has been well documented [1–3]. SARS (severe acute respiratory syndrome) is a new Coronavirus that quickly achieved global recognition as it appears to be highly transmissible within the indoor environment [4, 5], and causes severe manifestations with a high case fatality rate [6–8]. Transmission of certain forms of pneumonia such as that caused by the Adenovirus [9] and *Streptococcus Pneumoniae* [10] has been demonstrated within indoor environments. Tuberculosis, a pathogen which can remain viable airborne for more than 24 hours within the indoor environment, has been transmitted in a wide range of indoor environments [11, 12], including aircraft cabins [13–15].

Microbes from environmental sources must be capable of growth within the environment. This growth results in the generation of aerosols of microorganisms, or of microbial particles or toxins. These are then inhaled by humans. Such micro-organisms include many species of bacteria, fungi and other micro-organisms such as protozoans [16]. Most of these are not considered highly pathogenic, as most do not cause direct infections in humans. Rather they cause health effects through allergic or immune mechanisms.

2

Environmental Sources within the Indoor Environment

Most environmental fungi and bacteria require only water, and a simple substrate for growth. Substrates can be dust, furnishings, or building materials. Many organisms grow well in the absence of light (in fact natural sunlight will often kill them). Given these simple requirements for growth, it should be no surprise that environmental micro-organisms are ubiquitous in the indoor environment. Abundant growth, leading to high concentrations, can occur on any surface with sufficient water. This includes building materials that have been damaged by flooding, ground water or spillage [17], anywhere that condensation of water occurs, such as air conditioning systems or where there is standing water, such as water cooling towers, and humidification systems. Microbial contamination has been identified within all parts of modern ventilation systems, including filters [18, 19], air conditioning chillers [20–22], drip pans [20], humidifiers [23], and ducts [24, 25]. In addition, mold and bacterial contamination is common in areas of food preparation or consumption.

Microbial growth on surfaces does not directly affect human health, except rarely if they are ingested or contact skin directly. In almost all instances health effects result from inhalation of airborne microbial organisms, antigens, or toxins. This means the microbial substances must be aerosolized – in one of several ways. The most obvious is disturbance by human activity, including normal work activities, and cleaning. The latter can cause “bursts” of very high concentrations of microbes, creating a particular hazard for those present [26, 27]. In the heating ventilation and air conditioning (HVAC) systems the moving currents of air can act to aerosolize, and then efficiently disperse the microbes or their products throughout the occupied spaces. Once aerosolized the microbes, and their antigens or toxins, will remain airborne for some time and therefore can be inhaled by humans in that environment.

3

Mechanisms of Health Effects of Microbial Contamination in the Indoor Environment

Micro-organisms cause health effects in humans through three general mechanisms: direct infections, toxins, and immune mediated reactions [28]. Direct infectious complications are those that result from true infection of the human host by a microbial pathogen. Acquisition of infection is almost always by inhalation, although the infectious particles can impact on the upper or lower airways, with different resultant clinical manifestations. For example rhinoviruses that cause the common cold and influenza viruses, preferen-

tially impact in the upper airways perhaps because they are bound to small airborne dust particles. By contrast, airborne TB bacteria are in droplet nuclei of 1–5 microns size. Particles of this size will reach the alveolar level of the lung and therefore cause a pneumonia-like condition. Other examples of potentially airborne microbes that cause direct infectious health effects include measles and SARS. Some organisms can cause infectious diseases, or immune mediated syndromes. For example *Legionella pneumophila* can result in pneumonia, termed “Legionnaire’s disease”, [29, 30] but can also be a systemic illness that is immune mediated, termed “Pontiac Fever” [29, 31]. It is unknown if these manifestations reflect differences in the infecting dose, or the host response.

Micro-organisms produce a substantial array of toxins, but to date their health effects are poorly understood. These include endotoxin – produced by certain bacteria, and mycotoxins produced by certain fungi. Experimental exposure to high concentrations of endotoxin has produced fever, difficulty breathing, and short-lived changes in lung function. [32–34]. In cross-sectional population based studies, exposure to relatively low levels of endotoxin has been linked to non-specific building related symptoms, and sickness absence [35–37]. However, in these cross-sectional studies, the findings could also have been due to substantial confounding, since no relationship between endotoxin levels and health effects was found in several other studies. The health effects of mycotoxins, produced by certain fungi, such as *Stachybotrys Atra*, are more controversial [38]. Mycotoxin exposure has been linked to health effects in uncontrolled case reports and case series [39]. In one case-control study this toxin was linked to pulmonary haemorrhage in infants [40]. However in a subsequent publication, this study’s methods were heavily criticized, findings reversed in re-analysis, and conclusions withdrawn – by the same agency that conducted the original case-control study [41]. In summary, although many microbes produce toxins, and intuitively toxins can not be good, there is inconclusive evidence they actually cause health effects in the concentrations found in the indoor environment.

Microbial health effects can also be mediated by immune reactions, through allergic or cell mediated mechanisms [42]. Allergic manifestations are mediated by mast cells that release histamine upon exposure to microbial products such as proteins, or components of the cell wall. Symptoms occur soon after exposure, and range from itchy watery eyes, with nasal stuffiness, congestion and discharge typical of allergic rhinitis to chest tightness, wheezing and difficulty breathing typical of asthma. Persons with a personal or family history of allergy or atopic illnesses, are more likely to manifest allergic responses to airborne microbial contaminants.

The other major mechanism of immune reaction is a cell mediated response to inhaled allergens. This response, mediated by lymphocytes, often manifests only hours after exposure, making the diagnosis less obvious than with immediate allergic responses. Manifestations include pneumoni-

tis, which resembles pneumonia, causing dyspnea, chest tightness, hypoxia in severe cases, and systemic symptoms of fever, chills and sweats. This hypersensitivity pneumonitis has also been described with several other occupational exposures, such as farmer's lung [43, 44]. Milder reactions involving systemic symptoms only, have been termed "Pontiac fever", or "humidifier fever". These terms reflect the geographic locale or source in early descriptions of this problem, rather than the pathogenetic mechanism. Therefore, this problem shall be referred to as hypersensitivity systemic syndrome in this chapter. Interestingly non-smokers are at particularly high risk for this type of immune response [22, 43, 44].

4

Specific Health Effects of Microbial Contamination of the Indoor Environment

Outbreak investigations have been the most frequent method to identify the health effects of microbial contamination of the indoor environment. Typical outbreaks involve a large number of affected individuals who have similar clinical manifestations [21, 45–47]. Subsequent investigation revealed substantial microbial contamination by one, or multiple, microbes. In all outbreaks, improvement occurred when the source was eliminated. Interestingly, in a few outbreaks that were carefully investigated, exposed persons exhibited a range of clinical manifestations ranging from severe disease requiring treatment, to mild symptoms [45, 46]. Those with milder manifestations might normally have been overlooked or considered to have symptoms unrelated to the indoor environment. The microbial cause for these mildly affected persons was established only because others within the same indoor environment were more seriously affected. The variability of clinical manifestations in these outbreaks is unexplained, but most likely reflects variation in individual susceptibility due to age, gender, co-morbid illnesses, cigarette smoking, or other factors [48]. This variability of response has been repeatedly demonstrated, including under carefully controlled conditions [49–52].

Outbreaks have served to demonstrate the pathogenic role of certain organisms, and the potential importance of certain indoor environment sources. Examples include contamination of water cooling towers by *Legionella pneumophila* – causing pneumonia [30, 53] or a hypersensitivity systemic syndrome [31, 53], fungal contamination of air conditioning systems or water damaged building materials leading to hypersensitivity pneumonitis and asthma [23, 45, 46], and contamination by multiple organisms of stagnant water in humidifiers [21] – causing hypersensitivity pneumonitis or systemic syndrome.

The role of microbial contamination of the indoor environment and health effects at a population level is undefined. This is because in non-outbreak

situations microbial levels are lower [54–57], and the link between these low microbial levels and health effects is much harder to establish. At lower concentrations of organisms, only the most susceptible of the exposed individuals will be affected, and their clinical manifestations may be mild and non-specific [48, 54]. As well, lower levels of microbial contamination are more difficult to measure accurately because of the variability of concentrations related to time of day, human activity, ambient temperature and humidity [58, 59]. When microbial concentrations are very high, these variations are relatively unimportant, but become progressively more important at lower concentrations. There is some evidence of the population impact of microbial exposures in the home environment from surveys of the health effects of bacteria and fungi in homes or residences [60–67]. Although not directly applicable, this is the most important source of information on the health effects of microbes. Even here the most consistent relationships with health effects have been with markers of bacterial and fungal growth, such as visible mold, or damp damage, and not with actual measured airborne microbial concentrations [61, 63, 66, 68–70].

In one study in the non-residential environment, low concentrations of *Alternaria* in the filters of some HVAC systems of large office buildings were linked to respiratory symptoms and positive allergy skin tests to *Alternaria* [71]. However this relationship was detected only in 2% of the total study population, and only by means of a complex series of investigations.

5

Role of Ventilation in Microbial Effects on Health

The term ventilation of the indoor environment generally refers to mechanical exchange of indoor air with outdoor air. The primary objective of this exchange is to remove indoor air pollutants. The mechanical systems can also heat or cool, humidify or de-humidify, and filter the air being delivered to the indoor space. As such these mechanical systems can act to disseminate airborne microbial contaminants, but can also reduce the concentration of microbes in indoor air, through dilution.

A number of population-based studies have demonstrated a clear link between ventilation levels and microbial transmission. These include Influenza and rhinovirus outbreaks [1, 3], excess occurrence of adeno-viral pneumonia among military recruits housed in mechanically ventilated barracks [9] compared to naturally ventilated barracks and excess occurrence of Strep pneumonia in prison inmates where there was greater crowding and less ventilation [10]. A recent study documented that within office buildings, airborne rhinovirus concentrations were higher when building outdoor air supply was lower [72].

The best evidence for a link between ventilation levels and microbial transmission has come from studies of tuberculosis. In one study, an office worker with contagious TB infected many of her co-workers, some of whom had no direct contact but worked in offices ventilated with the same re-circulated air as the affected worker. This implied that the ventilation system, by recirculating germ-laden air, acted to disseminate the infection throughout the building. Transmission was mathematically related to ventilation level in this study [73]. A second study detected significantly higher transmission of TB infection to hospital workers on clinical units with lower levels of ventilation [74].

Given the recent intense interest in SARS, it is important to mention that the mode of transmission of SARS is somewhat unclear. There is evidence that SARS is transmitted by means of droplets, or direct contact from person to person [4, 5], but given that it is a respiratory pathogen, there remains a possibility that airborne transmission also occurs. Therefore, at this time it is prudent to consider that SARS may be transmitted by the airborne route, in which case increasing levels of ventilation could help reduce the risk of transmission.

6 Control of Microbial Contamination

There are two general approaches to microbial control in any indoor environment. The most effective long term solution is elimination of all locations of microbial growth (source control) [75]. The alternative, if elimination of all possible sources is impossible, is to eliminate airborne microbes through sterilization, filtration, or dilution.

Source control, the preferred approach, can be further sub-divided into prevention or remediation [76]. Prevention implies preventing the conditions that favour microbial growth. Given the dependence of microbes on water, the most successful and practical approach is to prevent water accumulation, condensation, or infiltration, as well as any subsequent water damage. This means installation of dehumidification systems where humidity levels are high such as environments at or below ground level (obviously not a problem on aircraft!). Prevention of water infiltration means water proofing the building shell, particularly at or below ground level [17]. Prevention of condensation with air-conditioning systems is not possible. Instead the objective is rapid removal of all condensate, because if water accumulates it will quickly become contaminated. Humidification systems should be designed without a reservoir of standing water. The best systems use steam humidification, rather than ultrasonic or other forms of nebulization of cool water [77].

Prevention also includes careful selection of equipment, furnishings, and building materials that will not act as media for microbial growth. In the

indoor environment, carpets are an important and common source of microbial contamination [78], particularly where food or drinks are prepared or consumed. Having no carpets, or selecting low-pile carpets is an important preventive measure. Other furnishings and equipment should be selected with similar criteria – they should have smooth surfaces, reducing accumulation of microbial substrate (dirt), reducing surface area for microbial growth, and facilitating cleaning.

Remediation is the term applied to elimination of microbial sources after contamination has occurred. The most effective method is to completely remove contaminated sources such as damp damaged carpets, furnishings, draperies, insulation or other building materials. Cleaning can be effective, but is often a less permanent solution. In some cases, such as cleaning ventilation ducts, or changing filters, these actions can result in important release of microbial products, resulting in very high, albeit transient microbial exposures [26, 27]. Therefore these activities should be performed when the occupants are not present, and significant care must be taken to prevent an occupational hazard to those performing these tasks [27]. Microbial reduction can also be accomplished with germicidal chemicals, but it is important to recognize that these chemicals may themselves be associated with health effects. Therefore chemical cleaning must be done when the occupants are absent, and appropriate precautions must be taken to ensure the workers doing the cleaning are not exposed. Furthermore, sufficient time must have elapsed before the occupants so return, that all traces of the chemicals have dissipated.

Reduction of airborne concentration of microbes can be achieved by direct sterilization of air through use of natural sunlight or ultraviolet germicidal irradiation (UVGI). Because the sterilizing ultraviolet rays of natural sunlight are largely eliminated by glass, natural sunlight is not a practical option for air sterilization within most indoor environments. UVGI has been used to sterilize air and thereby prevent airborne transmission of certain diseases, most notably measles transmission within schools and tuberculosis transmission within hospitals and other health care facilities [79]. UVGI is also used for sterilizing air in meat packing plants, pharmaceutical manufacturing, and operating rooms [80].

The efficacy of UVGI in sterilizing air is therefore unquestioned, but its application is limited by certain potential hazards. These include eye irritation, and a theoretical risk of skin cancer. Therefore UVGI cannot be used in occupied spaces, or if used, only to irradiate the upper air of the room with the fixtures constructed and mounted to prevent direct irradiation of the human occupants [79]. However, in other areas, such as within the HVAC system, UVGI is potentially highly useful within the ducts to sterilize the air, or to irradiate the air-conditioning systems to eliminate condensate-related microbial contamination [81]. In one recent study UVGI irradiation of air-conditioning systems in 3 large office buildings resulted in a signifi-

cant reduction of allergic, and systemic syndrome-type symptoms in 771 office workers [82]. The most significant improvement was seen in the most susceptible – i.e. workers who had a history of atopy or allergy, as well as non-smokers. In summary, it would appear that UVGI is an under-utilized technology that may be a useful addition to the microbial control armamentarium.

A major limitation of airborne sterilization is that the killed airborne microbes, although no longer able to cause infections, may still be immunogenic and result in allergic or hypersensitivity manifestations. Filters can be effective to eliminate viable and non-viable microbes, as well as microbial particles. However, the efficiency of the filter is an important determinant of the beneficial effects. Although filters found in most HVAC systems will trap microbes that are adherent to airborne dust particles, they will not trap particles of 1–5 microns size [83]. These are termed respirable particles, as they can reach the alveoli when inhaled. Particles of this size may contain microbial antigens, such as proteins or cell wall parts, or viable bacteria, such as tuberculosis. These pathogenetically important particles will only be trapped by more efficient HEPA filters (high efficiency particulate air filters). HEPA filters will trap more than 99% of particles of 0.3 micron size or larger [83]. However these filters are much more costly, and because of their greater resistance they require greater fan strength and energy to operate, further increasing their cost, and limiting their applicability. An additional limitation of filters is that they must be changed frequently, as they become contaminated. Several reports have documented that poorly maintained filters can become a source of airborne microbial contamination [19, 84]. At the time of changing the filters, there can be a substantial airborne burst of microbes released which can pose significant hazards to those in the occupied space [85, 86]. Therefore it is recommended that filters are changed when the indoor environment is not occupied and the occupational hazard for those changing the filters is prevented by suitable protection [85, 86].

Dilution of indoor airborne pollutants of all types – including viable microbial organisms, toxins, or antigens – through exchange with outdoor air (i.e. ventilation) is a commonly used solution. At very low indoor air exchange rates, very high concentrations of indoor contaminants can be seen. As ventilation is increased, these concentrations will decline rapidly at first, but the benefits become progressively less, with progressively higher air exchange rates, as demonstrated in Fig. 1. Above six air exchanges per hour, further increases in ventilation will have little additional benefit. The disadvantages of increased ventilation include the increased fan strength required to achieve the ventilation, and the substantial energy costs to heat or cool as well as to humidify or dehumidify the outdoor air brought in [71]. It is because of these energy costs that outdoor air exchange rates have been reduced over the past 20 years in modern buildings and aircraft.

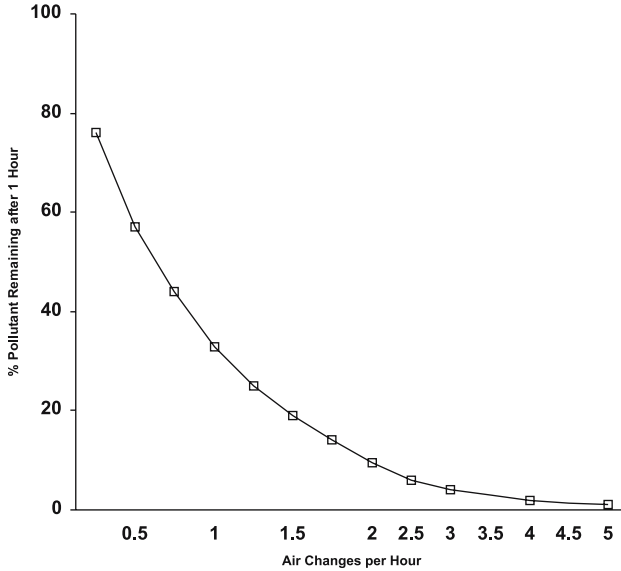


Fig. 1 Effects on pollutant concentration at the end of 1 hour of exchange with unpolluted outdoor air at varying rates of exchange

Microbial transmission from human to human that is mediated by droplets or direct contact will not be affected by environmental conditions. Increasing levels of outdoor air supply will have little beneficial effect. However organisms that are transmitted from human to human by the airborne route, such as tuberculosis, measles, or influenza, will be affected by changes in ventilation [1, 3, 9, 10, 73]. Increasing the outdoor air supply will increase the removal of the airborne microbes, by replacing contaminated air with clean outdoor air. This will result in reduced probability of inhalation by humans. However, as with all other indoor pollutants, dilution of infectious microbes by outdoor air will be most effective if pre-existing ventilation levels are low, but will have diminishing returns above a certain level.

7

Microbes within Aircraft – Sources and Health Effects

Although it seems highly likely that transmission of microbes from passenger to passenger through droplets or direct contact does occur during commercial airlight, there is little documentation of this phenomenon [87]. There is some evidence of airborne transmission of microbes within aircraft, mostly from investigations of potential transmission of tuberculosis [88]. Tuberculosis has received more attention than other pathogens for several reasons. The disease is serious. Tuberculosis bacteria can survive in airborne droplet nuclei

for more than 24 hours – potentially important during prolonged flights. The condition is rare in many populations nowadays, making transmission events easier to detect than for common viruses such as the rhinovirus. Nine investigations of potential TB transmission aboard commercial aircraft have been published [13–15, 89]. In only two of the nine was evidence of transmission found [13, 15]. One was related to a flight attendant who was infectious for a prolonged period of time; despite this, the risk to passengers was very low, and far less than the risk for household contacts of the same contagious cases [13]. These investigations provide useful information because this transmission of TB can be considered a proxy of airborne transmission of many other pathogens whose transmission is much more difficult to measure [88].

Other health effects of microbial exposures such as allergic or hypersensitivity disorders have not been investigated at all among passengers on commercial air flights. These problems could occur in this environment. For example, given the regular consumption of food and drink, microbial contamination of carpets, and furnishings seems plausible. As well, microbial contamination of aircraft ventilation system filters has been documented [84]. However, because human subjects are exposed infrequently, and for relatively brief periods, the health effects resulting from these exposures would be very difficult to detect, without a highly systematic investigation directed to detect them.

8

Microbial Control in Aircraft

Prevention of human to human transmission mediated by droplets or contact can only be prevented by controlling the source – in this case the humans themselves. This means screening the passengers as well as the crew. During the height of the SARS epidemic passengers were screened for fever and cough, although often only after arrival in certain countries. To prevent SARS transmission (and also prevent transmission of many other respiratory pathogens) one would have to screen all passengers and crew for fever and cough. Embarkation would be denied to anyone failing the screening. Apart from the logistic difficulties of screening all passengers rapidly prior to embarkation, this would also have substantial cost implications because of delayed travel. Other approaches to limiting transmission of potentially contagious respiratory disease would be to require wearing of masks by such passengers. However, wearing masks may be seen as branding the passengers, creating stigma and substantial anxiety for the affected passenger and all around them. This would also raise the possibility of later legal repercussions. Nonetheless, in an epidemic of a serious airborne transmitted illness such as SARS, these measures may be justified to

protect other passengers, and to diminish the international spread of disease.

Prevention of immune mediated health effects is best achieved by source control. This means elimination of potential microbial sources such as contaminated or water damaged carpets or upholstery and scrupulous attention to maintenance with frequent changes of filters in the ventilation systems. An additional option is to install UVGI to irradiate the filters to prevent their becoming a source of microbial contamination.

Using filtration to eliminate microbes has many limitations, as noted above. These include failure to trap respirable pathogenic or immunogenic particles from microbes with standard filters, and becoming sources themselves. High efficiency HEPA filters may be impractical because of the increased ventilation fan strength and energy requirements to overcome the filter resistance.

Outdoor air ventilation can be increased to dilute and remove airborne contaminants. A limitation of this approach in commercial aircraft is that the outdoor air is at low pressure, and is very dry and cold. Therefore this air must be compressed and heated to aircraft cabin pressure, which incurs substantial energy costs. These energy costs have driven aircraft manufacturers and operators to minimize outdoor air supplied to aircraft cabins over the last two decades. However certain minimum standards must be maintained in order to minimize the risk to passengers. It has been suggested that the low relative humidity contributes to a higher incidence of upper respiratory tract infections in the week following air travel [90], which could be prevented through modest humidification.

Another untested option would be install ultraviolet germicidal irradiation within the aircraft ventilation systems. This UVGI could irradiate, and effectively sterilize recirculated air, reducing the potential for airborne transmission of certain pathogens. This could reduce the need for outdoor air exchange rate, thereby conserving energy. However this technology would have no effect on airborne microbial antigens and their associated health effects, nor on transmission mediated through droplets or direct contact. This application of UVGI appears theoretically sound, but has not been evaluated.

9 Summary

In summary, exposures to many different microbes can occur within aircraft cabins. Most of these are from human sources, and can result in transmission of infectious diseases, particularly viral illnesses such as common colds, measles, influenza or even SARS. These are spread by direct contact or by droplets, so environmental control measures are limited. For these situations source control is the only effective method, but this implies screening passen-

gers prior to embarkation, with denial to ill passengers on grounds of possible contagiousness. This would only be justified in an outbreak situation of a serious pathogen such as SARS. For pathogens, such as tuberculosis, that are transmissible by the airborne route, the risk can be reduced by greater ventilation, meaning greater outdoor air exchange rate.

The other microbial contaminants that are commonly seen in homes and non-industrial environments and result in immune mediated disorders such as asthma, rhinitis, or hypersensitivity syndromes are less likely within this environment. However, contamination can and does occur. Much of this should be preventable by careful selection of appropriate furnishings and materials, as well as thorough and regular cleaning and maintenance. Adequate ventilation can play some role in reducing exposure to any indoor air pollutants, including airborne microbes or their antigens and products. The potential role of ultraviolet germicidal irradiation requires further evaluation, although for certain purposes this technology should be safe and effective.

Acknowledgements Dr. Menzies receives a research salary award from the Fond de Recherche en Santé du Québec.

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