Germs, Ventilation, Occupancy Density and Exposure Duration: A Thirteen Setting Pathogen Inhalation Comparison

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ABSTRACT

A ventilation based mathematical comparison of pathogen inhalation of groups of persons exposed to the exhaled breath of one infected person for worst case design exposure times is made for thirteen transportation and building settings all of which, with the exception of offices, typically have high occupancy densities (ODs). The comparison identifies intercontinental air travel with flights up to 15 hours as the setting of highest risk followed by theater, sports arena, classroom grades 9+, continental flight, commuter train, classroom grades 3-8, bar, restaurant, gambling casino, lecture hall, office and subway in that order. The range of inhalation values calculated indicates ventilation standards are far from uniformly protective against airborne infectious disease transmission for worst case exposure periods.

INTRODUCTION

A body of knowledge is emerging which indicates airborne transmission of certain infectious diseases can occur and air travel is a setting of concern in this regard.

- There has been transmission of smallpox, measles, tuberculosis, SARS (severe acute respiratory syndrome), seasonal influenza and H1N1 during commercial flights.[1] [2] [3] [4] [5] [6] [7] There is also evidence suggesting that transmission of these diseases could have an airborne component susceptible to control by ventilation measures.[8] [9]
- A study found flight attendants and school teachers report a higher prevalence of work-related upper respiratory symptoms, chest illness, and cold or flu than the general working population.[10] In this study, flight attendants were significantly more likely than teachers and

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other working women in general to report chest illness during the prior three years (32.9%, 19.3%, 7.2%, respectively) and both flight attendants and teachers were more likely to report five or more episodes of cold or flu in the past year than were other working women (10.2% of flight attendants, 8.2% of teachers, 2.3% of referents).

- Influenza cases are likely underreported since about one third of influenza A infected persons, symptoms or signs widely used for influenza case definitions (e.g., fever or cough) are unreliable for identifying infectious individuals.[11]
- The evidence of airborne transmission of infectious diseases between passengers sitting in the same row and several rows apart, along with the measurement and modeling findings that there is airborne viable particulate movement from a point source both laterally and longitudinally in passenger aircraft cabins, indicates that the recirculation system filtration, even though HEPA, does not prevent the spread of airborne infectious agents in passenger cabins as this is occurring prior to the time that pathogens in the air are directed to these filters, and that other mechanisms such as in-cabin personal air filtration systems are needed.[12] [13]
- The aircraft cabin slot diffusers disperse particle and gaseous air contaminants from a single source in a row past others in both directions in the same row and in other rows in measurable quantities six or more rows forward and backward.[14] [15] [16] [17] [18] Whether the gasper (personal air outlet) is on or not, air is being circulated between passengers by slot diffuser airflows originating near the side wall and above the aisles (Figure 1).
- Persons sitting in aisle seats may be most at risk apparently due to people movement in aisles.[19] [20] [21]
- Lower levels of relative humidity (RH) such as occurs in aircraft cabins shortly into cruising flight, increase the potential for influenza and possibly other respiratory infections when a source is present.[22]

Figure 1 *Economy section in a wide-body passenger aircraft cabin showing several overhead personal service units with their individually controlled gaspers (personal air outlets) and reading lights. The main cabin ventilation supply is provided by sidewall slot diffusers located just below the overhead stowage bins and ceiling slot diffusers located just above the stowage bins near the aisle. IAT photo May 14, 2010.*

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- A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, reduced space sharing (e.g., shared office), and reduced occupant density have the theoretical potential to reduce inhalation exposures to infectious aerosols by more than a factor of two. On this basis, using 1996 data, 16 to 37 million cases of common cold or influenza would be avoided each year in the U.S. with savings of $6 to $14 billion in 1996 dollars.[23]

To date ASHRAE IAQ standards have focused on point in time at equilibrium chemical exposures. This paper sets out ventilation and design time parameters needed to address the infectious disease concern for thirteen commonplace building and transportation settings.

In an earlier investigation, infectious aerosol inhalation rates were calculated to be two to six times higher in aircraft than in office buildings, depending upon filter efficiencies and occupant activity level. This difference is because the per person rates of both fresh air supply and recirculation air filtration are substantially lower in passenger aircraft, and the occupancy densities (OD: the average conditioned spatial volume per person) which affect the time for occupant-sourced air contaminant to reach equilibrium level, are substantially higher.[24 25 26 27]

In this investigation communicable pathogen inhalation rates and amounts for design (worst case) exposure time periods, are calculated for thirteen common place transportation and building settings all of which, with the exception of offices, have relatively high occupancy densities. Offices, while low OD, are included because they are the most reported on indoor environment from an air quality perspective, and as such are frequently used as a baseline reference by scientists and others including the World Health Organization and airline industry spokesman who currently advise that indoor air quality (IAQ) in aircraft is as good as or better than in offices.[28 29] The thirteen settings are: narrow and wide body passenger aircraft, commuter train cars, subway cars, bars, restaurants, gambling casinos, theaters, sports arenas, classrooms grades 3-8 and grades 9+, lecture halls and offices.

INFECTIOUS DISEASE PATHOGEN TRANSMISSION CALCULATIONS

Sneezing and coughing are not the only potential sources of occupant-sourced infectious aerosols. Tests for influenza, for example, found virus in the exhaled breath of infected persons during normal at rest (tidal) breathing.[30]

Airborne occupant-generated infectious aerosol concentrations in a uniformly mixed system, like any occupant bioeffluent concentration (e.g. human breath, perspiration, perfume, clothing and skin oil volatile organic compound emissions), are governed by occupancy density (OD), air supply rate per person, the effectiveness in getting that supply air to the breathing zone, and the quality of the supply air.

Bioeffluent concentration in a uniformly mixed system is a function of bioeffluent generation rate, time, spatial volume per person, per person ventilation rate and ventilation effectiveness.

$$C = \int(N/v)dt - \int(N/v)dt \int(V \cdot V_e/v)dt + \int(N/v)dt \int(V \cdot V_e/v)dt \int(V \cdot V_e/v)dt - ....$$

$$= N \cdot t/v[1 - V \cdot V_e \cdot t \cdot /2v + (V \cdot V_e \cdot t/v)^2/(2.3) - (V \cdot V_e \cdot t/v)^3/(2.3.4) + ...]$$

$$= N/(V \cdot V_e)[\{V \cdot V_e \cdot t/v - (V \cdot V_e \cdot t/v)^2/2! + (V \cdot V_e \cdot t/v)^3/3! - (V \cdot V_e \cdot t/v)^4/4! + ...\}]$$

$$C = [N/(V \cdot V_e)][1 - \exp(-V \cdot V_e \cdot t/v)] \quad (1)$$

where

C = bioeffluent concentration in the space at time t

N = rate of bioeffluent generation/person in the space

t = time

v = spatial volume/person (the inverse of occupancy density)

V = infectious aerosol-free ventilation rate (fresh + filtered recirculation air + envelope infiltration rate) per person

V_e = effectiveness in supplying the ventilation air to each occupant's breathing zone

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Input parameters

The ventilation, filtration and occupancy density parameters used for the thirteen environments are listed in Table 1 along with their references and assumptions.[31] [32]

Pathogen-free ventilation rates were calculated by summing fresh rate per person, Infiltration rate per person, and pathogen filtration rate per person,

Pressurized spaces are assumed to have no infiltration and other spaces to have 0.3 ach of infiltration on average.

Pathogen filtration rates are based upon HVAC recirculation rates, assumed filters used, MERV ratings for particle removal in the 0.3 to 5 micron respirable suspended particle (RSP) size range as provided in ASHRAE Standard 52.2, assuming that HEPA, MERV 13 and MERV 8 filters remove 100%, 30% and 15% of airborne pathogens, respectively.

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Table 1. Building and Vehicle Ventilation, Infiltration, Highest Filter Efficiency and Ceiling Height Assumptions

Location	Fresh air ventilation, cfm/p (L/s/p)	Recirc air, cfm/p (L/s/p)	Filter efficiency in removal of pathogens, % [b]	Infectious aerosol free HVAC recirc air, cfm/p (L/s/p)[b]	Infiltration, ach[b]	Infectious aerosol free Infiltration air, cfm/p (L/s/p)[b]	HVAC conditioning air, cfm/ ft^2 (L/s/m^2)[b]	Persons/ 1000 ft^2 (p/100 m^2) floor area	Average ceiling height, ft (m)[b]
Toronto subway car (full with most standing)	7.5[b] (3.5)	0.0[b]	0.0	0.0	0.3	0.1 (0.5)	2.5 (0.11)	333 (31)[c]	8 (2.4)
Aircraft cabin, narrow-body	7.5[a] (3.5)	7.5[a] (3.5)	100.0	7.5 (3.5)	0.0	0.0	2.6 (0.11)	170 (15.8)[b]	6 (1.8)
Aircraft cabin, wide body	7.5[a] (3.5)	7.5[a] (3.5)	100.0	7.5 (3.5)	0.0	0.0	2.4 (0.11)	150 (13.9)[b]	8 (2.4)
Japanese commuter train car	11.6[d] (5.5)	0.0[b]	0.0	0.0	0.0	0.0	1.7 (0.075)	150 (13.9)[d]	8 (2.4)
Gambling casino	9.0[e] (4.2)	9.0[b] (4.2)	30.0	2.7 (1.3)	0.3	0.5 (0.2)	2.2 (0.096)	120 (11.1)[e]	12 (3.7)
Sports arena spectator area	8.0[e] (3.8)	8.0[b] (3.8)	0.0	0.0	0.3	1.3 (0.6)	1.9 (0.083)	120 (11.1)[e]	30 (9.1)
Bar	9.0[e] (4.2)	9.0[b] (4.2)	15.0	1.4 (0.7)	0.3	0.6 (0.3)	1.8 (0.079)	100 (9.3)[e]	12 (3.7)
Lecture hall	8.0[e] (3.8)	8.0[b] (3.8)	0.0	0.0	0.3	0.7 (0.3)	2.4 (0.11)	150 (13.9)[e]	20 (6.1)
Restaurant	10.0[e] (4.7)	10.0[b] (4.7)	0.0	0.0	0.3	0.9 (0.4)	1.4 (0.061)	70 (6.5)[e]	12 (3.7)
Auditorium, theater	5.0[e] (2.4)	5.0[b] (2.4)	15.0	0.75 (0.35)	0.3	1.0 (0.5)	1.5 (0.066)	150 (13.9)[e]	30 (9.1)
Classroom grades 9+	13.0[e] (6.1)	13.0[b] (6.1)	0.0	0.0	0.3	1.4 (0.7)	0.9 (0.039)	35 (3.3)[e]	10 (3.0)
Classroom grades 3-8	15.0[e] (7.1)	15.0[b] (7.1)	0.0	0.0	0.3	2.0 (0.9)	0.8 (0.035)	25 (2.3)[e]	10 (3.0)
Office	17.0[e] (8.0)	80.0[b] (38)	30.0	24.0 (11)	0.0	0.0	0.5	5 (0.5)[e]	10 (3.0)

a) footnote 24, b) assumed, c) footnote 31, d) footnote 32, e) footnote 25.

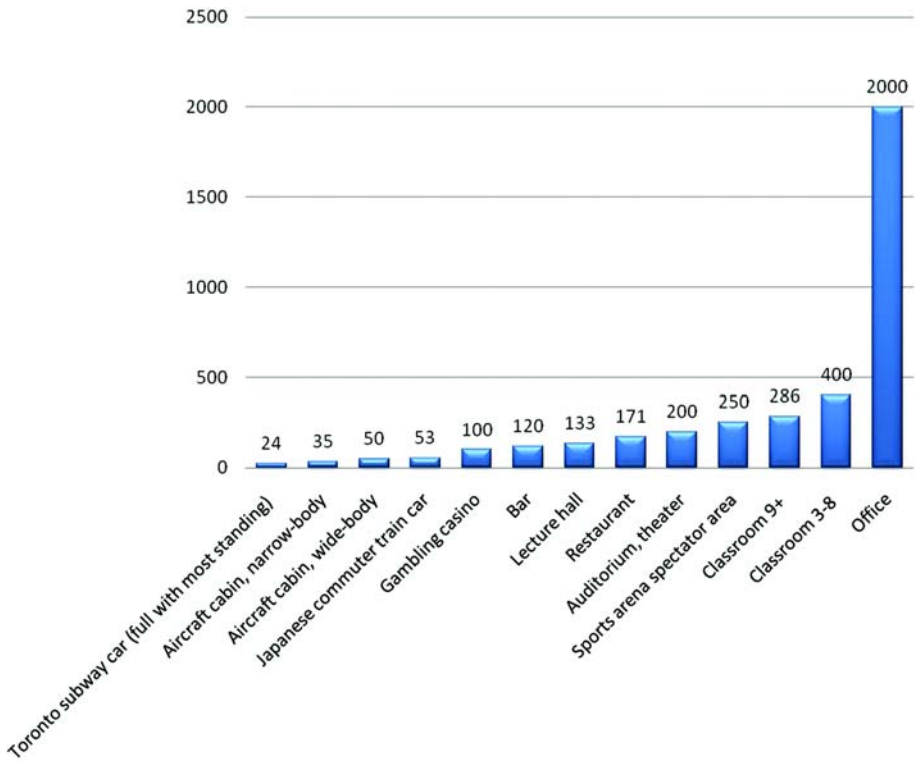

Figure 2 *The spatial volumes per person (ft^3).*

Design exposure time, the maximum time period during which a group of persons might be exposed to an ill person, were used rather than exposure time norms because these are required in sizing HVAC for worst case conditions.

Spatial volume per person is based on occupant densities per unit floor area and assumed ceiling heights.

The spatial volumes per person used are compared in Figure 2 and the pathogen-free ventilation supply rates used (outdoor air plus recirculation air plus infiltration ventilation rates per person) are compared in Figure 3.

Table 2 summarizes the pathogen-free ventilation rates and spatial volumes per person for each derived from Table 1. It includes the design occupancy exposure times, and also for comparison purposes. The environment with the highest ach, a subway car, has the second lowest outside air supply rate per person. Similarly, the environment with the highest outside air supply rate per person, an office, has the lowest ach.

Group inhalation from the exhaled breath of an influenza-infected person

Fabian *et al* found between <3.2 to 20 influenza virus RNA copies per minute (up to 1,200 virus per hour) in the exhaled normal at rest breath (tidal breathing) of infected persons, indicating that sneezing and coughing are not the only potential source of infectious aerosols. Seventy percent of the 67 to 8,500 particles/liter in the breath had diameters between 0.3 and 0.5 microns, with rarely any larger than 5 microns.[30] The average Fabian influenza generation rate, $N = 11$ influenza virus generated per minute continuously in the exhaled breath of one influenza infected person, not including coughing generation, is used in the calculations that follow.

Assuming group rather than individual inhalation to address in part the non-uniformity of infectious aerosol sourcing (i.e. only one occupant of a number of occupants exposed is an infectious aerosol source), and assuming V*e* = 1 for all occupants, solving Equation (1) and incorporating 'at rest' inhalation and exhalation rates of 0.28 cfm/p, (0.15 L/s/p) the thirteen environment group inhalation amounts over the first 30 minutes of exposure are illustrated in Figure 4: Virus inhalation in the thirteen environments during the first 30 minutes of exposure based upon a uniformly mixed system, no pathogen loss of viability with time, and exposure time, fresh air ventilation, filtration and occupancy density differences. *T e* = time to equilibrium (maximum) concentration to 3 figure accuracy in minutes. 4. The times to reach the equilibrium (maximum) concentration, t_e, for each setting, when the rate of inhalation is constant and the infectious aerosol is uniformly mixed by air currents in a relatively short time frame, are shown in the legend. The smaller the ratio of *V*/*v*, the longer it takes occupant generated air pollutants to reach their maximum (equilibrium value) and the lower the dose for that period. For example, occupant generated airborne viruses and gases in offices reach their equilibrium values three hours of occupancy, while in an aircraft this occurs after only 12 to 18 minutes of occupancy, making the ratio of their exposures

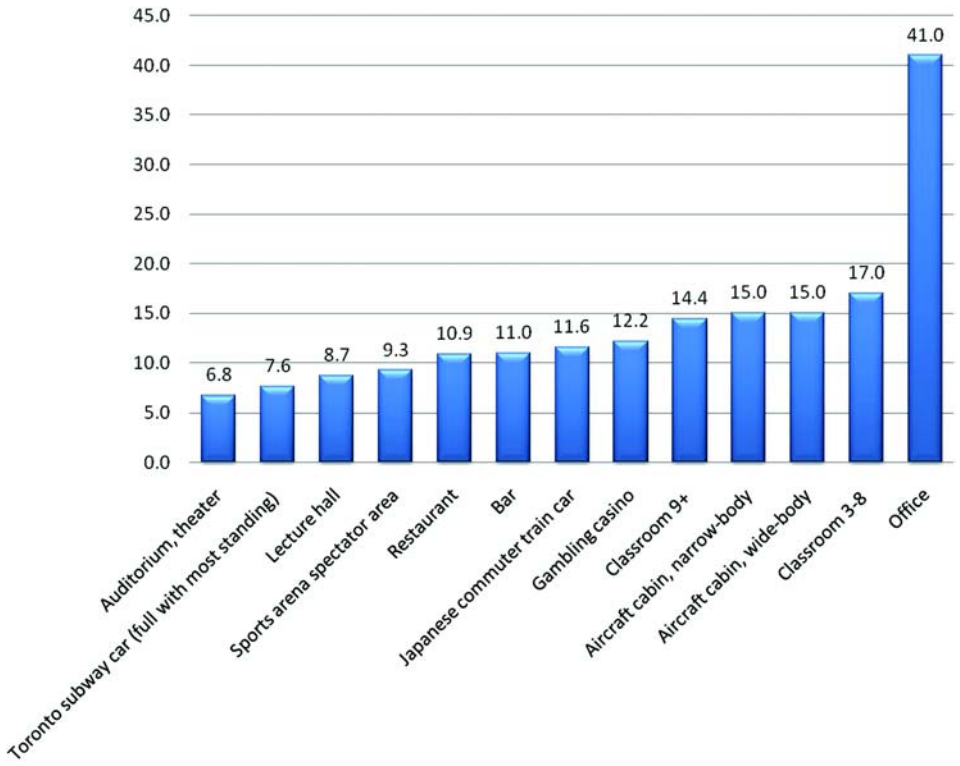

Figure 3 *Pathogen-free ventilation rates per person used for the thirteen environments, (cfm/p).*

Table 2. Spatial Volume per Person, Group Design Exposure Periods, Infectious Aerosol- Free Ventilation Air per Person and Spatial Outside Air Changes per Hour Used

Location	Spatial vol./p, v, ft^3 (m^3)	Group design exposure time, hrs	Total infection- free outside + filtered recirc + infiltration air, V, cfm/p (l/s/p)	Outside air changes/hr, ach	Fresh air ventilation, cfm/p (L/s/p)
Subway car	24 (0.68)	0.5	7.6 (3.5)	19.1	7.5 (3.5)
Aircraft cabin, narrow-body	35 (0.99)	6.0	15.0 (7.1)	12.8	7.5 (3.5)
Aircraft cabin, wide-body	50 (1.4)	15.0	15.0 (7.1)	9.0	7.5 (3.5)
Japanese commuter train car	53 (1.5)	4.0	11.6 (5.5)	13.0	11.6 (5.5)
Gambling casino	100 (2.8)	3.0	12.2 (5.8)	5.7	9.0 (4.2)
Bar	120 (3.4)	3.0	11.0 (5.2)	4.8	9.0 (4.2)
Lecture hall	133 (3.8)	2.0	8.7 (4.1)	3.9	8.0 (3.8)
Restaurant	171 (4.8)	3.0	10.9 (5.1)	3.8	10.0 (4.7)
Auditorium, theater	200 (5.66)	4.0	6.8 (3.2)	1.8	5.0 (2.4)

Table 2. Spatial Volume per Person, Group Design Exposure Periods, Infectious Aerosol- Free Ventilation Air per Person and Spatial Outside Air Changes per Hour Used *(continued)*

Location	Spatial vol./p, v, ft^3 (m^3)	Group design exposure time, hrs	Total infection- free outside + filtered recirc + infiltration air, V, cfm/p (l/s/p)	Outside air changes/hr, ach	Fresh air ventilation, cfm/p (L/s/p)
Sports arena spectator area	250 (7.08)	5.0	9.3 (4.4)	2.2	8.0 (3.8)
Classroom grades 9+	286 (8.1)	6.0	14.4 (6.8)	3.0	13.0 (6.1)
Classroom grades 3-8	400 (11.3)	6.0	17.0 (8.0)	2.6	15.0 (7.1)
Office	2000 (56.6)	8.0	41.0 (19.3)	0.5	17.0 (8.0)

greater than simply the ratio of the ventilation rates. At the 10 minute mark for example, the exposure to occupant bioeffluent will be 21 times higher in a narrow body aircraft than an office, while after five hours it will be 3.2 times higher.

Group influenza virus inhalation amounts calculated for the design exposure periods for the thirteen environments are shown in Figure 5. These calculations indicate that intercontinental air travel with flights up to 15 hours is the setting with by far the highest infectious aerosol inhalation risk, assuming similar mixing efficiencies, ventilation effectiveness and other influencing factors, followed by a theater, sports arena, classroom grades 9+, continental flight, commuter train, classroom grades 3-8, bar, restaurant, gambling casino, lecture hall, office and subway in that order.

DISCUSSION

Exposure time clearly is an important factor in the infectious aerosol inhalation calculations provided in Figure 5. Persons in the environment with the shortest design exposure time, a subway car, also have the lowest infectious aerosol numbers inhalation, while those in the environment with the longest design exposure time, a long haul wide body aircraft, also the highest infectious aerosol inhalation. The results in Figure 5 should *not* be used to compare inhalation rates since design codes generally do not prescribe filtration rates and occupancy density parameters and assumptions were made favoring aircraft because their relatively long design exposures already singled them out. The relationship is not linear with time, since pathogen free ventilation rate and occupancy density are also factors. For example, while spectators in a sports arena have 25% longer exposure to infectious aerosols than those in a theater, the amount inhaled is 4% lower. Given that equilibrium concentration is 1/3 higher in the theater and the occupancy density 25% higher, one might have expected an even lower inhalation in the sports arena in the 5 hour design exposure period. The reason this is not the case is that during that extra hour of exposure in the sports arena the inhalation number increases by 30% from 70 to 91 infectious particles. The occupancy density for sports arenas does not include the playing field, only the spectator stands per the ASHRAE standard. Including the playing field substantially reduces the spectator inhalation rate and the total virus inhaled for the stadium/arena design period. The range of inhalation amounts calculated for the thirteen settings varies widely indicating that ASHRAE and other IAQ and ventilation standards are far from uniformly protective against airborne infectious disease transmission in the thirteen transportation and building environments examined. A useful next step would be to conduct a survey of actual ventilation rates and occupancy densities in each of these settings so that actual versus standard permitted risks can be evaluated.

The time for bioeffluents to reach their maximum (equilibrium) concentration, varies widely between the thirteen settings (Figure 4). This time often is not considered when interpreting field measurements, and leading to errors in data interpretation. For example, the use of point in time carbon dioxide concentrations in an office setting might lead to a significant over estimate of ventilation rate per person. ASHRAE standards should begin to address time weighted exposures and design exposure times, not only for infectious aerosols but also for contaminant gases and particles since dose as well as point in time exposures can be important for all three classes of air contaminants.

A ventilation effectiveness of 1 is unlikely for all occupancy and thermal conditioning conditions in any of the thirteen settings. While the ASHRAE IAQ standard for passenger aircraft assumes Ve = 1 under any condition, the ASHRAE standard for buildings has provided values for Ve of ranging between 0.5 and 1 for zones without plug flow (i.e. with standard ceiling diffusers and returns), depending upon HVAC system diffuser and return locations, on any short circuiting between them (Ve = 0.5), and whether the air is cooling (Ve = 1) or heating with supply air 8C above the space temperature (Ve = 0.8).[24 25] Based on this guidance, it seems likely that Ve

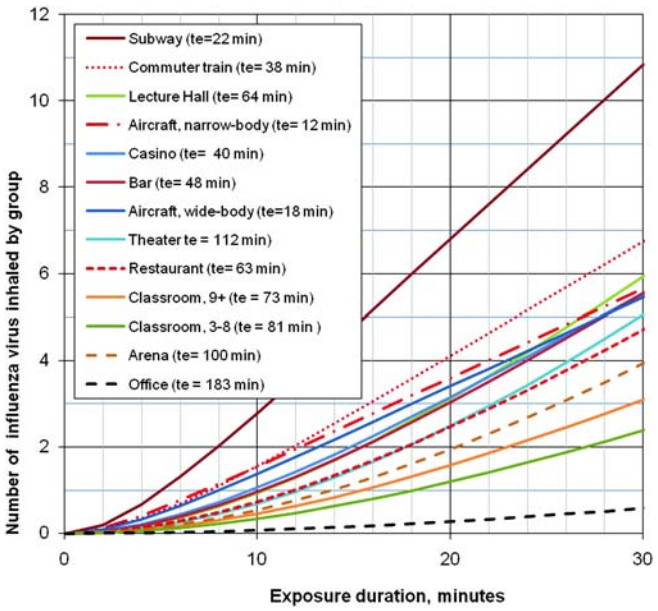

Figure 4 *Virus inhalation in the thirteen environments during the first 30 minutes of exposure based upon a uniformly mixed system, no pathogen loss of viability with time, and exposure time, fresh air ventilation, filtration and occupancy density differences.* T e *= time to equilibrium (maximum) concentration to 3 figure accuracy in minutes.*

will be less than 1 in many of the thirteen settings during the fall and winter heating season in temperate climates, when influenza transmission peaks.[22 33]

On the other hand, the average concentration of the infectious aerosol in the occupancy zone of interest will be less than that of a uniform distribution for several reasons, so one will offset the other to some extent. One reason for lower than uniform mixing concentration is that the infectious aerosol sourcing will not be uniform and its average concentration therefore will be limited by the local ventilation rates.[34] However, except for plug flow, this reduction should be small since RSP, particularly ultra fine particles (0.1 micron), act more like gases moving by Brownian motion as well as by entrainment in the air currents, eddies and the moving occupant wakes.[14 15 16 17 18 35 36] A second reason for a lower than uniform mixing concentration is the settling of particulate with time. A third reason is the loss of viability with time. This is discussed separately below. A fourth reason is impingement

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35. Sze To, G.N., et al. 2009. "Experimental Study of Dispersion and Deposition of Expiratory Aerosols in Aircraft Cabins and Impact on Infectious Disease Transmission." Aerosol Science and Technology, 43:5, 466 – 485.
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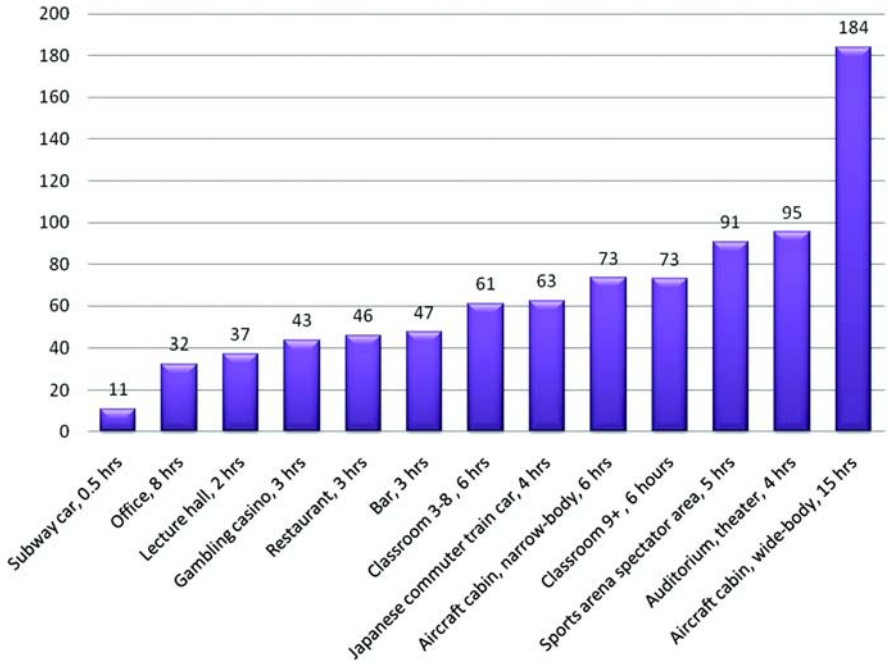

Figure 5 *Numbers of influenza viruses inhaled for the design exposure period during at rest, awake, tidal breathing in the thirteen environments by groups exposed to the exhaled breath (coughing not included) of one infected person based upon a uniformly mixed system.*

losses. This loss might be higher for water aerosols than for solid aerosols because of their adhesion to surfaces. Impingement losses, while not mentioned by the author of an aerosol dispersion experiment, is an alternative reason for the faster decay with distance of a bacteria-carrying moisture aerosol than occurred for a tracer gas and a solid particle aerosol.[18] A fifth reason applies specifically to aircraft. This is the flight cycle deposition of cabin humidity on the cold fuselage behind the insulation (passing there via cabin liner leaks, drawn by stack pressures during flight and pushed during descent by cabin re-pressurization). This humidity condensation freezes during flight and melts in warm weather while the aircraft is on the ground. Some of this moisture is drained away and some re-enters the cabin during ascent as the cabin depressurizes.[37]

Humidity affects not only the continued viability and dispersal of viruses; it affects the susceptibility of the receptor. Too high or too low are both negatives from an occupant protection perspective. The optimal levels of RH that prolong infectivity vary appreciably on the basis of the virus. Under experimental conditions, rhinoviruses, other picornaviruses, and adenoviruses tend to survive best at high relative humidities (approximately 70%–80%), whereas the viability of RSV, parainfluenzavirus, and influenzavirus A is better at the lower relative humidities (<30%). Low levels of humidity, however, enhance evaporation and may cause the metamorphosis of large particles into droplet nuclei that become airborne with distant dispersal. Conversely, small particles may be humidified during inhalation and balloon into larger particles that settle in the upper respiratory tract.[38] One study investigation postulates that at 20C, transmission efficiency is highest at low RH, when influenza viruses in an aerosol are relatively stable, and desiccation of exhaled respiratory droplets produces droplet nuclei. Transmission is diminished at intermediate RH when viruses are relatively unstable, but improves in parallel with influenza virus particle stability at higher humidities. At high RH, evaporation from exhaled particles is limited, respiratory droplets settle out of the air, and transmission is blocked. At 5C, transmission is more efficient than at 20C, but is reduced to a rate of 50% at higher humidities.[22]

Ventilation rates may vary widely from those provided in standards. For example, some building HVAC systems may take advantage of free cooling with outside air flow rates of more than five times the ASHRAE standard minimum in the fall and early winter.

The efficiency of filters in removing infectious aerosols is another unknown. Fabian *et al* pointed out that 70% of the 67 to 8,500 particles/L in the breath of an influenza infected person had diameters between 0.3 and 0.5 microns, with rarely any larger than 5 microns.[30] This suggests that filtering of 0.3 micron particles may not be essential in removing significant numbers of viruses and that the MERV 13 filters for example could be more effective in removing pathogens than the 30% value used. In this regard, while HEPA filters are the 'gold' standard in 0.3 micron and larger particle removal efficiency, the number of 0.3 micron and larger particles removed in buildings with MERV 13 filters (which remove 30% of 0.3 micron and larger particles) is three times greater than in aircraft with HEPA filters (which remove 100% of 0.3 micron and larger particles) because of the 10 times higher recirculation rate per person in buildings. Further, the finding that no systems or measures are in place in aircraft to prevent the spread of infectious agents over several rows and that infectious disease transmission within an aircraft cabin occurs prior to the time pathogens in the air are directed to the HEPA filters or exhausted outdoors indicates that other mechanisms such as in-cabin personal air filtration systems are needed. The use of local air filters could be a key mitigating measure. In aircraft increased filtration can be obtained without increasing HVAC recirculation by adding Venturi entrainment to create air flow through a filter drawn by the motive gasper air supplies. This can increase the supply of pathogen-free ventilation air by several times and create filters at the breathing zones of all passengers thereby trapping a portion of any infectious aerosols before they disperse throughout the cabin.[13]

Most transportation systems such as subway cars and commuter trains, as well as passenger aircraft, have high occupancy densities (ODs; the number of people per unit volume of conditioned space), in comparison with common building settings. In this regard, the spatial volume per person used in buildings is higher than normally would be expected, but it is the ASHRAE building IAQ standard default value.[25] Selecting a typical spatial volume per occupant in the spectator area of an arena is a challenge since it will vary depending upon where the occupant is sitting in a sloping stadium stands, how close to the performance area, and whether there is a balcony or the main roof above. If spatial volume per person was double or triple the 250 ft^3/occupant used, the arena design period virus inhalation would decrease from 91 to 82, and from 91 to 73, respectively. Both of these inhalation predictions are still relatively high and comparable to narrow-body flight and grades 9+ classroom values.

Occupant breathing rate is another variable. Dozing in aircraft and on commuter trains, for example, is common. If everyone dozed 50% of the time and dozing reduces virion generation rate by 1/6 and inhalation rate by 1/6 during dozing, then infectious viral aerosol inhalation would be reduced by ~1/3 (i.e. group virion inhalation would be 126 not 184 on a 15 hour flight and 43 not 63 on a four hour commuter train ride). In fact a leveling off of airborne viable bacterial abundance

37. Walkinshaw, D.S., et al. 2001. "An environment control system for aircraft having interior condensation problem reduction, cabin air quality improvement, fire suppression and fire venting functions." US Patent Office #US 6491254, European Patent Office #EP1140625 (Germany, France, Spain, Sweden, United Kingdom), Canada Patent Office #CA 2256887, German Patent Office #DE69927178.

38. Hall, C.B. 2007. "The spread of influenza and other respiratory viruses: complexities and conjectures." Infectious Diseases Society of America. CID 2007:45 (1 August): 353-359.

after midflight has been noted by La Duc, et al.[39] On the other hand, with the exception of cruise ships, the intermixing of persons from different population centers and continents in passenger aircraft is unique versus most other public transportation and building settings. Furthermore, passenger aircraft, with their assigned seating and flights ranging up to 15 hours or more, prolong specific pathogen exposure times over most other venues.

CONCLUSION

- ASHRAE IAQ and ventilation standards are far from uniformly protective against airborne infectious disease transmission in the thirteen transportation and building environments examined.
- Of thirteen common transportation and building environments examined using ventilation and occupancy parameters from ASHRAE IAQ standards where available, and design exposure periods, long haul flights up to 15 hours pose the highest risk of respiratory infection by the air route from a ventilation design and occupancy density perspective. This is followed by theater, sports arena, classroom grades 9+, continental flight, commuter train, classroom grades 3-8, bar, restaurant, gambling casino, lecture hall, office and subway in that order.
- The time for bioeffluents to reach equilibrium concentration varies widely for these thirteen settings, ranging from 12 minutes in a narrow body aircraft to 3 hours in an office. This time is needed when interpreting the implications of point in time rather than dose measurements and in setting ventilation standards to mitigate bioeffluent chemical and biological exposures.

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[39] La Duc, M.T., T. Stuecker, K. Venkateswaran. 2007. "Molecular bacterial diversity and bioburden of commercial airliner cabin air." *Can. J. Microbiology* 53:1259 – 1271.