COVID-19 and Beyond

A Brief Introduction To Passenger Aircraft Cabin Air Quality

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The passenger aircraft industry says passenger cabin air quality is exceptionally good compared with that of other public settings. Some airlines claim the air in aircraft cabins is cleaner than that in offices and is on par with the air in hospitals. Another airline says the air is particularly good because it is very dry, creating a sterile cabin environment. Some say virus particles will only travel one or two rows. Nearly all say the air change rate is high and recirculated air is passed through HEPA filters that remove nearly 100% of airborne viruses.[1–6] This article will review these claims.

Dry Air in Passenger Cabins

The air in passenger cabins is dry, with a relative humidity (RH) of 10% as the flight progresses. Meanwhile, a portion of the cabin air with its ventilation components (very dry outdoor air plus filtered, recirculated air) and humidity components, passes from the cabin to behind the cabin insulation, drawn there through liner leaks and openings by stack pressures. Some of this air is not lost as useful ventilation air. However, all the air drawn there (perhaps 25% of the cabin ventilation air) loses its humidity prior to recirculation, depositing its moisture as condensation on the very cold fuselage behind the insulation. There it freezes during flight, adding nonproductive dead weight. When the frozen water melts when the plane is back on the ground, this moisture causes metal corrosion, hastening metal fatigue and creating microbial growth.[7]

However, in addition to air at 10% RH being uncomfortable, it has been shown to impair nasal mucociliary clearance, innate antiviral defense and tissue repair function in mice and is, therefore, postulated to do so in humans.[8] Additionally, RH this low rapidly turns droplets into aerosols,[9] which disperse more widely, five rows longitudinally either way (*Figure 1*).[10] Aerosols are more likely to inoculate the respiratory system, where the minimum dose requirement to inoculate is lower and the symptoms more severe than if the inoculation occurs in the nasal system where the larger droplets are

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more likely to rest.[11] In the past more limited longitudinal transport has been postulated.[12] However, more recent research on a wide body airplane indicates that a 10% concentration of droplet nuclei remains after traveling 4.39 m (14.4 ft) or five rows.[10]

In terms of the quantifiable increased severe infection risk from COVID-19 and other coronaviruses due to cabin humidity this low, all we know for sure is that influenza in the United States occurs primarily in the fall and winter.[13] This is when relative humidity indoors with a heating system operating is perhaps 20%–35% as opposed to being 50%–65% in summer air-conditioning weather.

In the case of COVID-19 with its person-to-person airborne infection risk, offsetting factors may be in play in buildings. For example, outside air can enter buildings naturally via open windows and envelope leakage, and through door opening in ground-based public transit vehicles. This cannot happen in aircraft. Further, in buildings social distancing is more the norm and occupants in ground-based public transit vehicles often can move around more freely, whereas in aircraft occupants may have to remain in one place for hours with a potentially ill person nearby.

Air Change Rates and Filtration

While aircraft HEPA filtration removes almost 100% of the 0.3 micron and larger particles circulating through them (and supposedly, therefore, all viruses), the amount of air recirculated through these filters and supplied to the passengers is one-eighth the amount circulated through MERV 13 office air filters, which remove at least 30% of 0.3 micron particles and larger. Thus, with their eight times larger airflows through less efficient filters, building filters can remove twice the number of viruses from the air supplied to each office occupant than aircraft HEPA filters remove from the air they supply to aircraft cabin occupants.[14,15]

Aircraft cabin outdoor air changes per hour (ach) are indeed high—perhaps 15 ach for a narrow body aircraft and 13 ach for a wide body aircraft. However, a high outdoor air change in the case of densely occupied spaces like an aircraft cabin or a subway car is not an indicator of a high supply of virus-free air to the occupants. Three parameters govern airborne virus exposure concentration in any space—occupancy density (spatial volume divided by the number of persons in the space), outdoor air supply per person and the rate of virus-filtered air supply per person.

FIGURE 1 Aircraft cabins are high occupancy density, with air currents moving aerosols along four or more rows longitudinally either way, making social distancing impractical and infectious aerosol exposures more likely, while the low cabin humidity weakens our immune system's defense against infections. Humidity is kept low by ventilating with very dry outdoor air that needs to be humidified and also by the continual loss of cabin humidity from the recirculation air due to the movement of a portion of the cabin air to behind the insulation where the moisture in it condenses and freezes on the cold skin and fuselage.

The latter two parameters set the maximum airborne virus concentration, C, while the first parameter (OD) governs how quickly the airborne virus concentration reaches the maximum concentration in a uniformly mixed system. The higher the occupancy density, the faster the airborne virus concentration or any other occupant-generated bioeffluents, such as human breath carbon dioxide and perspiration, perfume, clothing and skin oil volatile organic compound emissions, rise to their maximum value. The governing equation is[14]

$$C = p\left[\frac{N}{VV_e}\right]\left[1-\exp\left(\frac{-VV_e t}{\mathrm{OD}}\right)\right] \qquad (1)$$

where

- C = Bioeffluent infectious aerosol concentration in the space at time t, virus/L
- p = Fraction of infected persons
- N = Rate of bioeffluent infectious aerosol generation/person in the space, virus/s per person
- t = Duration of infectious aerosol generation, s
- OD = Spatial volume/person, L/person
- V = Infectious aerosol-free ventilation rate per person (HVAC outdoor air + virus-filtered recirculation air + envelope infiltration air), L/s per person

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TABLE 1 Some example setting occupancy densities, virus-free air supply rates and outdoor air change rates.[14]

SETTING	OCCUPANCY DENSITY, M^3/PERSON	VIRUS-FREE OUTDOOR AIR AND FILTERED SUPPLY PER PERSON, L/S	OUTDOOR AIR CHANGES PER HOUR
Subway Car	0.7	8.9	72.7
Narrow Body Aircraft	1	6.1	15.3
Wide Body Aircraft	1.6	11.8	12.8
Classroom Grades 9+	8.1	10.9	3
Auditorium, Theater	10.2	10.6	1.2
Classroom Grades 3–8	11.3	12.1	2.5
Lucas Oil Stadium, Spectator Area	26.6	11.3	1.7
Office	28.3	23.1	1.5

V_e = Effectiveness of supplying the ventilation air to each occupant's breathing zone. V_e = 1 in a uniformly mixed system.

Infectious aerosol dose, D, is the time-integrated function of individual inhalation rate, I, and aerosol concentration, C, and is given by

$$D = \int IC\,dt = p\left\{\frac{NI}{VV_e}\right\}\left\{t + \frac{OD}{VV_e}\left[\exp\left(\frac{-VV_e t}{\text{OD}}\right) - 1\right]\right\} \quad (2)$$

where

D = Virus inhaled or dose, virus
I = Inhalation rate, L/s

Based on code data, typical filters, ventilation effectiveness and infiltration rate (zero in aircraft but not in buildings), an infectious virus-free air supply per person, including any ill person, V, and a spatial volume per person (occupancy density, OD) are provided for eight settings in *Table 1*. This table includes ach values for comparison purposes.[14]

An influenza virus generation rate, N, of 11 per minute from an ill person and a normal "at rest" inhalation rate, I, of 0.15 L/s per person for a group of 19 exposed individuals surrounding an infected person (p = 0.05), have been used for these eight settings to calculate airborne virus concentration and inhalation dose scenarios. The predicted airborne virus concentrations in eight settings with the same percentage of ill persons versus time for the first hour for these scenarios are shown in *Figure 2*. Predicted inhalation dose is shown in *Figure 3* for some possible exposure times.[14]

FIGURE 2 Infectious aerosol concentration versus time predictions in the air in the eight settings for a group of 20 persons with one ill person within the group and assuming uniform mixing for the group. It shows how infectious aerosol concentration reaches its equilibrium concentration more quickly the higher the occupancy density, which in turn makes for a potentially higher viral inhalation dose.[14]

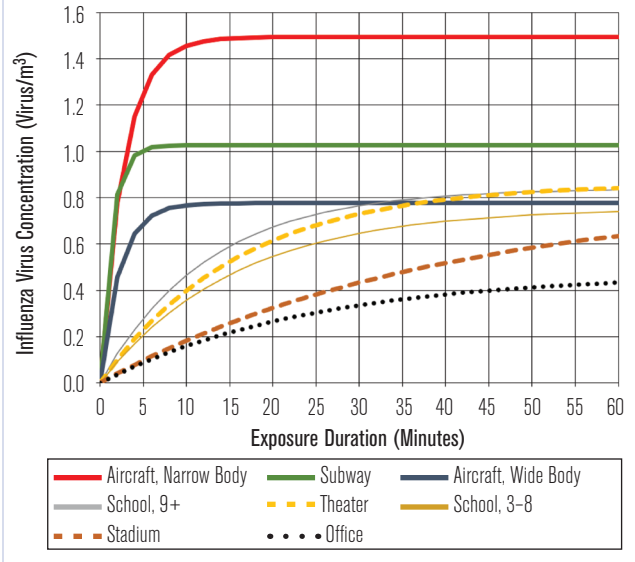


Figure 2 shows the predicted viral concentrations versus time for the eight settings. Comparing these setting concentrations with the setting occupancy density and outdoor air change rate values provided in *Table 1*, shows that the time to virus equilibrium concentration in the air correlates directly with setting occupancy density, and inversely with setting outdoor air change rate. Thus for settings with the same equilibrium concentration and exposure time, the higher the OD, the higher the risk of a viral infection.

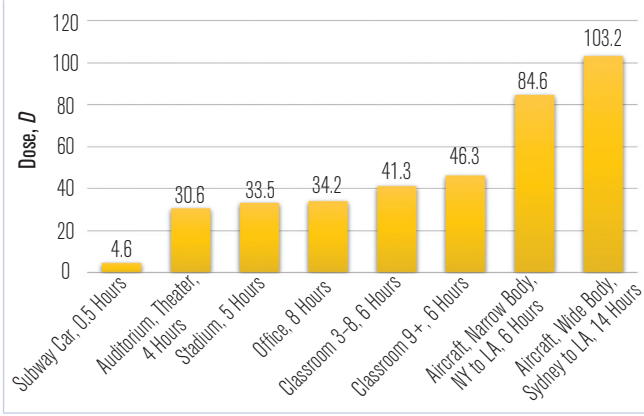
The slight trend variation for theaters is a result of their relatively low outdoor air supply/person but high virus-free filtered recirculation air. Offices, on the other hand, have both higher supplies of outdoor air and virus-free filtered recirculation air, while the sports stadium analyzed had no filtered recirculation air. Further, occupants of offices may never breathe air at its maximum virus concentration, since work hours can be staggered and people continually come and go for meetings, lunch, etc.[15]

It is clear that a high ach is not an indicator of a large supply of virus-free air to occupants in the case of commercial passenger aircraft or subway cars. In fact, just the reverse. The potential airborne virus concentration with an ill person present is higher in the spaces with high air change rates such as passenger aircraft, especially in the first hour or so, than it is, for example, in school classrooms with their much lower 2.5 ach rate or in offices

with their 1.5 ach rate. This high concentration is a result of aircraft cabin high occupancy densities (OD, the spatial volume divided by number of occupants). Other variables being equal, low ceilings make for high occupancy densities. In the case of aircraft and subway cars, their high occupancy densities create both a social distancing problem and a higher potential viral exposure than is predicted for lower occupancy density settings with similar virus-free air supply rates per person.

Turning to another issue with flying, most aircraft passengers also face the problem of being in a lower air pressure environment than that to which they are accustomed. This will lower their blood oxygen content and induce breathing instability, with periods of deep and rapid breathing alternating with central apnea.[16] Such instability was not accounted for in the dose calculations of *Figure 3*.

FIGURE 3 Predicted relative number of viruses inhaled by a group of exposed persons (group total) during normal at rest inhalation from the breath of one infected person for the design exposure periods in the eight settings.[14]



Wearing Masks On Aircraft

Turning to measures with the current fear of COVID-19 exposures in cruise ships and aircraft, major airlines at the time of writing are now requiring masks be worn in flight. This is a necessary step during this pandemic. However, wearing masks is not a viable long-term solution, nor is it a 100% effective solution. Masks will help raise the relative humidity of the air being breathed by trapping the wearer's humidity from his or her exhaled breath and that is helpful as explained. However, that moisture could create microbial growth exposure in a reused mask if it is not kept clean and dry between uses.

Further, masks will help protect others nearby, but not perfectly, so given the close quarters and airflow velocities, aerosols that escape can still move around the cabin perhaps five rows either way. So, while masks will filter out a portion of virus aerosols prior to their inhalation (N95 masks filter 95% of 0.3 micron particles), air can enter or leave via perimeter leakage and bypass the mask filtration. Masks with ventilators should not be allowed because they allow viruses to be exhaled directly into the cabin.

Future Work

Cabin humidity needs to be raised without degrading structural safety and adding dead weight, and this is possible.[7] Further, recirculation air filtration flows need to be increased more than outdoor air intake, as the latter, with its low moisture content when raised to cabin temperature, is counterproductive to raising cabin humidity. The associated higher air velocities with increased virus-free air supply can be used to supply virus-free air more optimally to individuals. Ventilation standards need to set a minimum cabin air filtration flow rate per person for 0.3 and larger micron particles to capture airborne viruses (rather than specifying HEPA filtration only) as well as a minimum outdoor air supply rate per person to dilute both viruses and other human-generated bioeffluents.

Conclusions

Aircraft travel currently poses a relatively high risk of a person acquiring a virus infection, compared with many other public spaces. High air change rates and HEPA filters may sound good, but the parameters that are important are occupancy density, the rate of supply of virus-free outdoor and filtered air to occupants, the duration of any virus exposure and the relative humidity. Further, replacing a MERV 13 filter that removes 30% or more 0.3 micron and larger particles with a HEPA filter that removes 99.97% of such particles is not helpful if the added pressure drop across the HEPA filter reduces the airflow supplied to the occupants by 71% or more. As well, the lower airflows associated with HEPA filters may result in thermal comfort issues and lower ventilation effectiveness.

So, what can you do personally if you need to fly? Get the best mask you can obtain, choose one that does not have a ventilator valve and wear it on the plane. This will help protect both you and your seat mates. If there is an overhead gasper outlet, turn it on and point it between you and a the passenger next to you. This high-speed flow of air will entrain his breath and yours and

take it toward the floor exhaust. However, never point the gasper airflow at your face, as this could bring your neighbor's breath into your breathing zone.[13] Finally, respiratory rates are three times higher during stressful boarding and disembarking than when seated, and 15% lower while sleeping versus seated awake.[17,18] So relax whenever possible!

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