Effects of building ventilation on SARS-CoV-2 transmission - a preliminary study

Yuguo Li 李玉国
Department of Mechanical Engineering
/ School of Public Health
The University of Hong Kong

We, the ASHRAE community, has a role to play…..

"ASHRAE holds a strong position that engineers play a key role in reducing disease transmission that occurs in buildings."

ASHRAE Position Document on Airborne Infectious Diseases, approved by Board of Directors June 24, 2009

ASHRAE Position Document on Infectious Aerosols

Approved by ASHRAE Board of Directors April 14, 2020
Expires April 14, 2023

Acknowledgement

I thank my hard-working students/post-docs (since 2003), and collaborators in studying Covid-19 transmission

HKU Mech Eng: Shenglan Xiao, Miao Te, Zhang Nan, Jack Chan, Chen Wenzhao, Zhao Pengcheng

HKU Public Health: Hui-Ling Yen, Ben Cowling, Malik Peiris; CUHK: David Hui

Co-Is of outbreak analyses: Qian Hua (South East U), Hang Jian (Sun Yat-Sen U), Liu Li (Tsinghua), Wei Jianjian and Lei Hao (Zhejiang U)

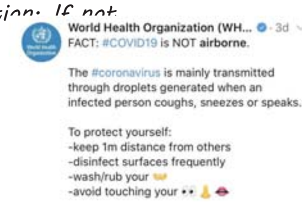
CDCs: Guangdong, Jiangsu and Hunan: Kang Min (Guangdong CDC), Ding Zhen (Jiangsu CDC), Hu Shixiong (Hunan CDC) and many colleagues

To RGC, HMRF, NSFC and HKU for supporting us in studying environment control of infection since 2003.

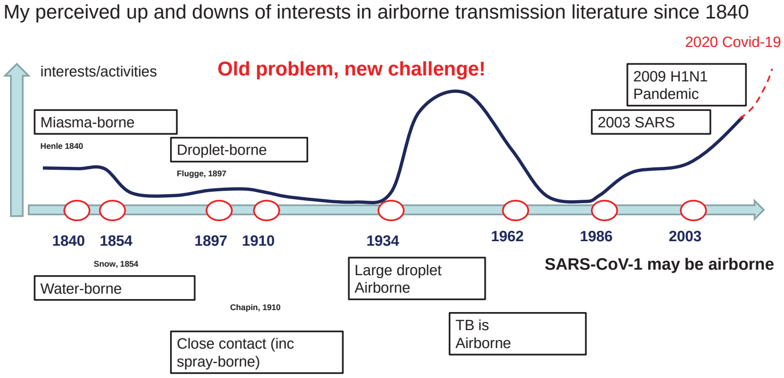
SARS-CoV-2 transmission: *a inconsistency/ambiguity?*

- No authorities admitted airborne transmission yet. (Note: The common wisdom is that airborne diseases are fearful).
- But all national and international authorities recommended maintaining good ventilation. If not airborne, why ventilate?

This inconsistency is at least a century old, the same goes for influenza and SARS-CoV-1.

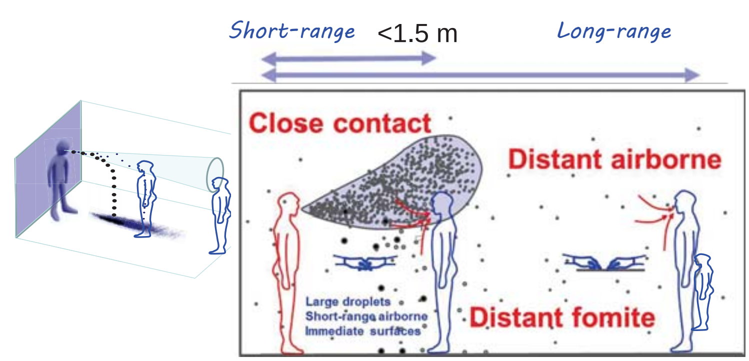


My perceived up and downs of interests in airborne transmission literature since 1840



Modified from Yuguo Li: Technical Plenary, ASHRAE Winter Meeting, Sunday 24 January, 2010, Orlando, USA

Major transmission routes of respiratory infection



Wei J and Li Y (2016). *American Journal of Infection Control, 2016 Sep 2;44(9 Suppl):S102-8.*

Wells-Riley equation – ventilation reduces long-range airborne infection

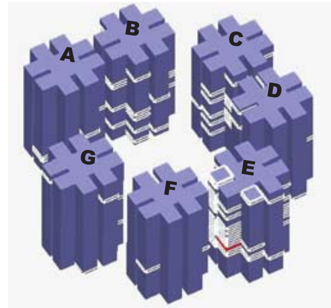
Probability of infection:

$$P = 1 - e^{-\frac{nQp\Delta t}{q}}$$

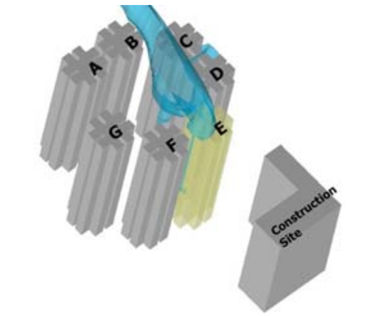
- Number of infectors (n)
- Quanta produced by one infector (quanta/min) (Q)
- Pulmonary ventilation rate of each susceptible (m^3/min) (p)
- Duration of exposure (min) (Δt)
- Room ventilation rate (m^3/min) (q)

Riley, E. C., Murphy, G. and Riley, R. L. (1978). "Airborne spread of measles in a suburban elementary school." *Am J Epidemiol* **107**(5):421-432.

The 2003 Amoy Gardens SARS-CoV-1 outbreak: Spread from Block E to other blocks in the Amoy Gardens Outbreak, causing >300 infected

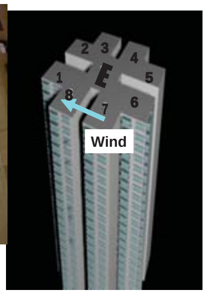


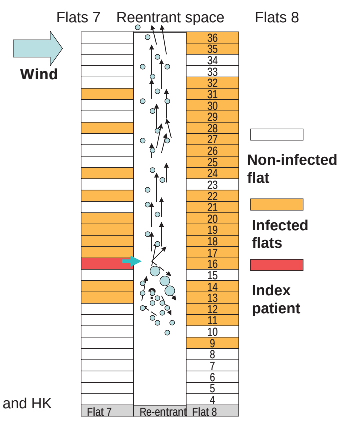
Li Y, Qian H, ITS Yu, TW Wong (2004) Probable roles of bio-aerosol dispersion in the Amoy gardens SARS outbreak - further environmental studies. *International Workshop on Population Dynamics and Infectious Disease in Asia*, 27-29 October 2004, Singapore



Yu ITS, Li Y, Wong TW, Tam W, Chan A, Lee JHW, Leung DYC, Ho T (2004) Evidence of airborne transmission of the severe acute respiratory syndrome virus. *New England Journal of Medicine*, 350, 1731-1739.

Amoy Gardens SARS-CoV-1 outbreak: spread within block E





Similar outbreaks occurred 5 times so far in Guangzhou and HK

Li et al, Indoor Air 2005;15:96-111

Let us look at the Wells-Riley equation again – challenges

Probability of infection:

$$P = 1 - e^{-\frac{nQp\Delta t}{q}}$$

- Number of infectors
- Duration of exposure (min)
- Room ventilation rate (m^3/min)

How many airborne infection outbreaks in which the ventilation rate was measured? If not many, why not?

How many outbreaks that we have access to the detailed human behaviour data? A lot of "missing data sets" (https://github.com/MimiOnuoha/missing-datasets)

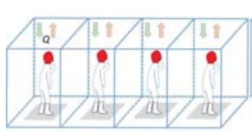
Accurate data of occupant behaviour ($\frac{nQp\Delta t}{q}$) and building parameters ($\frac{nQp\Delta t}{q}$) is prerequisite to determine exposure.

Riley et al (1978) might have been probably the first and also the last study of an airborne infection outbreak where the ventilation rates measured so far.

Lack of such data due to privacy concerns has probably hindered meaningful studies of most outbreaks.

Riley, E. C., Murphy, G. and Riley, R. L. (1978). "Airborne spread of measles in a suburban elementary school." *Am J Epidemiol* **107**(5):421-432.

Consider a room with n people (all infected), each is an infector



$$V\frac{dC}{dt} = q(C_0 - C) + nQ,$$

where nQ are the total quanta generation by n infectors

Assume quanta concentration at mouth of release is C_{mouth}; then $Q = pC_{mouth}$

where p is the pulmonary ventilation rate of each person

At steady state, $C = \frac{nQ}{q} = \frac{pC_{mouth}}{q/n} = C_{mouth}$

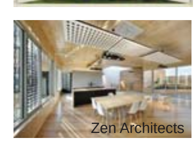
If q per person is the same as p per person (typically at 30 L/min or 0.5 L/s at normal work)

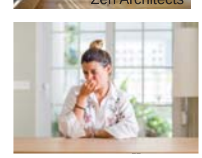
Thus p may be considered as a reference for considering ventilation rate

---

Let us consider four ventilation situations

1. Outdoor air like (q >> the required value, e.g. in those with large open windows) (pleasant air)
2. Good (sufficient) (e.g. $q \approx$ ASHRAE62.1 (e.g. 10 L/s per person) , i.e. about $20p$). A *sufficiently* good ventilation probably leads to no airborne infection for some infection (free from exhaled odour)
3. Poor (insufficient) (q>0.5 L/s per person, but much lower than the minimum required, e.g. 10 L/s per person). (as bad as close to other's breath)
4. Very bad (awful) (q<0.5 L/s per person) (worse than other's breath)

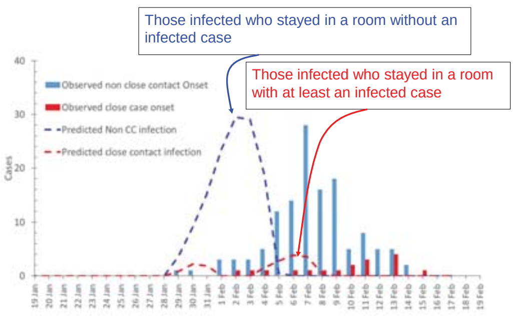




Internet images

Good (sufficient) ventilation 1: *Diamond Princess.*

"sufficient ventilation" probably worked: preliminary study



Xu P et al. Transmission routes of Covid-19 virus in the Diamond Princess Cruise ship. https://www.medrxiv.org/content/10.1101/2020.04.09.20059113v1

Those infected who stayed in a room without an infected case were all infected before quarantine 5 Feb 2020.

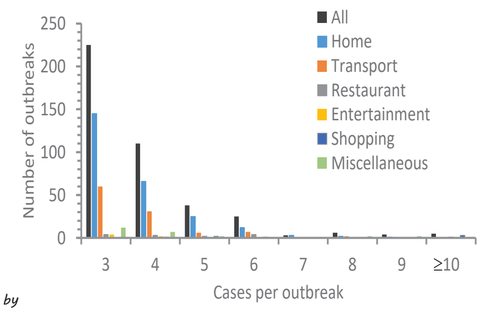
There was no spread between staterooms after 5 Feb 2020.

Room central air-conditioning probably did not play a role.

But no field measurement and lack of more detailed data so far

Outdoor air conditions – probably no long-range airborne infection

Nearly all outbreaks in non-Hubei cities occurred indoors



Searched 7324 cases (66.7% of 10,980 by 318 outbreaks with ≥ 3 cases

Qian, H. et al. Indoor transmission of SARS-CoV-2. https://www.medrxiv.org/content/10.1101/2020.04.04.20053058v1

A incomplete list of involved indoor environments in Covid-19

Mainland China: Apartment, villa, conventional train, high-speed rail cabins, private car, passenger plane, shuttle Bus, noodle house, restaurants, hotel lobby, restaurant dining room, hot pot restaurant, gym, chess room, tea house, mahjong parlour, barbershop, low-end shopping mall, low-end supermarket, hospital, community, thermal power factory, taxi, hotel room/conference rooms, long-distance bus, cruise ships, and prisons

Hong Kong: Hot pot, public estate, Buddhist temple, bars (Lan Kwai Fong, Wan Chai, and Tsim Sha Tsui), wedding bandquet, karaoke,

South Korea: church, hospital, call center and gym

Singapore: migrant dormitories

What do they have in common?
Why not in high end offices, high end shopping centres?

The idea of outdoor air is not new - the idea of Sanatorium (1863-)

Dr Edward L Trudeau (1848-1915)

Dr Trudeau built the first Sanatorium in the US near Saranac Lake, NY in 1882.

Parameters	Big bus B1 from Changsha to city D (12:10 pm to 3:30 pm)	Minibus B2 (15:43 pm – 16:43 pm)
Number of persons (other passengers + driver (conductor))	46	17
Number of infected except index patient	7	2
Attack rate (%)	7/46, 15.2%	2/17, 11.8%
Ventilation rates	1.72 L/s per person	3.22 L/s per person
Exposure time	200 min	60 min

Learning from the two cruise ship outbreaks (Diamond Princess and Dream World), Guangzhou restaurant outbreak, and the Hunan two bus outbreak:

Ventilation less than 3.2 L/s leads to long-range aerosol infection, but greater than 8-10 L/s (speculative) probably do not lead to long-range aerosol infection. No data exists for between 3.2 -8 L/s per person.

However, this does not rule out the short-range transmission.

It is the ventilation rate, not ACH that matters

Parameters	Big bus B1	Minibus B2	Restaurant
Number of susceptible	46	17	88
Number of infected except index patient	7	2	9
Attack rate (%)	7/46, 15.2%	2/17, 11.8%	9/88, 10.2%
Ventilation rates	1.72 L/s per person	3.22 L/s per person	1 L/s per person
ACH	5.02 ACH	10.1 ACH	1 ACH
Exposure time	200 min	60 min	23-82 (overlap)or 48-89 min (total)

$$P = 1 - e^{-\frac{nQp\Delta t}{q}}$$

*As shown by Wells-Riley (with assumptions), it is **not ACH but ventilation rate** affect transmission risk when the source is relatively constant.*

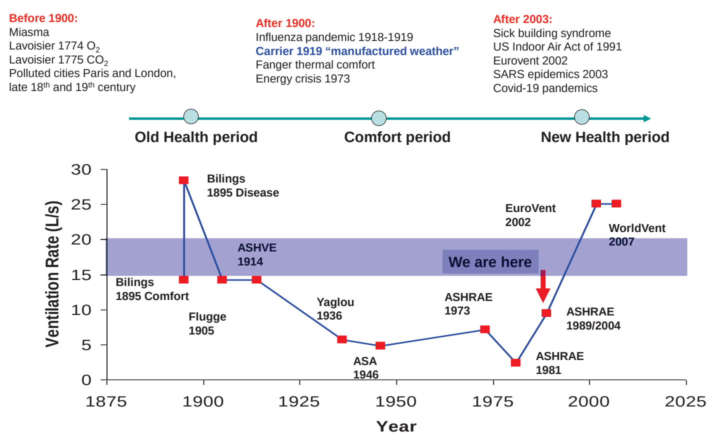
Example: air cabin ventilation

Passenger airplanes may deliver 10 to 12 ACH, and their HEPA filters for recirculation air. Are passenger plane cabins safer than offices where ACH is much lower?

Ventilation rate tells the real story: FAA-specified at atmospheric pressure 3.49 L/s + 50% recirculation = 7 L/s per person. Manufacturers may use higher values (Personal communication, Yan Chen). This is similar to offices.

In term of long-range airborne transmission, an airplane is probably similar to a typical office environment, but risk of close contact transmission will likely be higher in air cabin than in typical offices due to higher people density.

Acknowledgement of Yan Chen



Remembering those infection venues that I listed earlier?

I suspect that in some of those, the ventilation rates were low not just by design, but also due to our standards.

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE *(Continued)*
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values			Air Class
						Occupant Density (see Note 4)	Combined Outdoor Air Rate (see Note 5)		
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Office Buildings									
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1
Miscellaneous Spaces									
Bank vaults/safe deposit	5	2.5	0.06	0.3		5	17	8.5	2
Computer (not printing)	5	2.5	0.06	0.3		4	20	10.0	1
Pharmacy (prep. area)	5	2.5	0.18	0.9		10	23	11.5	2
Photo studios	5	2.5	0.12	0.6		10	17	8.5	1
Shipping/receiving	-	-	0.12	0.6	B	-			1
Transportation waiting	7.5	3.8	0.06	0.3		100	8	4.1	1
Warehouses	-	-	0.06	0.3	B	-			2

Should we reconsider these requirements in ASHRAE 62.1? Implications?

In some spaces, the required minimum ventilation can be as low as 2.7 L/s per person.

Is the occupant component of 2.5 L/s evidence-based?

Public Assembly Spaces									
Auditorium seating area	5	2.5				150	5	2.7	1
Places of religious work-shop	5	2.5				120	6	2.8	1
Courtrooms	5	2.5				70	6	2.9	1
Legislative chambers	5	2.5				50	6	3.1	1
Libraries	5	2.5				10	17	8.5	1
Lobbies	5	2.5				150	5	2.7	1
Museums (children's)	7.5	3.8				40	11	5.3	1
Museums/galleries	7.5	3.8				40	9	4.6	1
Retail									
Sales (except as below)	7.5	3.8				15	16	7.8	2
Mall common areas	7.5	3.8				40	9	4.6	1
Barber shop	7.5	3.8				25	10	5.0	2
Beauty and nail salons	20	10				25	25	12.4	2
Pet shops (animal areas)	7.5	3.8				10	26	12.8	2
Supermarket	7.5	3.8	0.06	0.3		8	15	7.6	1
Coin-operated laundries	7.5	3.8	0.06	0.3		20	11	5.3	2

It appears that with ASHRAE 62.1, a crowded environment is entitled to have a lower ventilation requirement per person?

Should we looked at this again?

CO2 sensor might be used for indicating ventilation for respiratory infection intervention?

Activities	Respiratory flows (m³/h)	Respiratory flow (L/min)	Respiratory flow (L/s)	CO_2 release rate m³/h	CO_2 release rate L/min	CO_2 release rate L/s
Sleep	0.3	5.00	0.08	0.013	0.22	0.0036
Rest/low activity work	0.5	8.33	0.14	0.02	0.33	0.0056
Normal work	2 to 3	33-50	0.55-0.83	0.08-0.13	1.33-3.83	0.022-0.64
Hard work	7 to 8	116-133	1.93-2.22	0.33-0.38	5.50-6.33	0.092-0.106

We consider a respiratory flow of 0.1 L/s. CO_2 generation rate is $c_e q_e$ = 50000 ppm × 0.1 L/s = 0.05×0.1 = 0.005 L/s.

Exhaled air of a person contains 4.0–5.3% (or 40000-53000 ppm) carbon dioxide.
Dhami PS, et al (2015). A Textbook of Biology. Jalandhar, Pradeep Publications.

$$V\frac{dc}{dt} = q(c_o - c) + \dot{V}_{pol} \qquad c = (c_o + c_G)(1 - e^{-nt}) + c_I e^{-nt}$$

$$c_G = \frac{\dot{V}_{pol}}{q}$$

If q= 8 L/s, then $c_G = \frac{\dot{V}_{pol}}{q} = \frac{0.00510^{-3}}{1010^{-3}} = 0.0005$, which means that $c_G = 500$ ppm.

Rebreathed fraction ρ

is the fraction of indoor air that is exhaled breath; Rudnick and Milton (2003)

$$\dot{V}_{pol} = Q(C - C_o);\; c_e q_e = Q(C - C_o);\text{ hence}$$

$$\rho = \frac{C - C_o}{C_e} = \frac{q}{Q}$$

For a typical ventilation rate of 10 L/s, $\rho = \frac{q}{Q} = \frac{0.1}{10} = 0.01$, i.e. an inhaled breath would contain 1% exhaled breath or a breath dilution ratio of 100 times

Breath dilution ratio β

is defined as the reciprocal of the rebreathed fraction (Jiang et al., 2009).

Rudnick, S. N., & Milton, D. K. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor air, 13(3), 237-245.
Jiang, Y., Zhao, B., Li, X., Yang, X., Zhang, Z., & Zhang, Y. (2009). Investigating a safe ventilation rate for the prevention of indoor SARS transmission: An attempt based on a simulation approach. In Building Simulation (Vol. 2, No. 4, pp. 281-289).

The possible minimum required ventilation rates

- 10 L/s per person
- or a breath dilution ratio of 100 times
- or a rebreathed fraction of 0.01.

So it is about how much we dilute our exhaled air in our room. This allows us to compare room dilution to that close to our breath, i.e. comparing long-range airborne and short-range airborne.

Useful to see what do airborne route and large droplet route mean in fluid mechanics

- Airborne transmission refers to the transport by air flow of the virus or virus-containing droplet or droplet nuclei from the source (which can be respiratory, medical or faecal aerosols), which can be inhaled and subsequently lead to disease/infection by the susceptible,
- The transport "medium" is airflow, not air. If there is no airflow, air cannot transport anything by itself (except by diffusion). Airflow is the vector of the droplet nuclei, and droplet nuclei is the vector of the virus. The accurate term is airflow transmission.

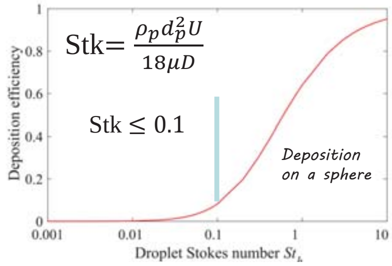
In airborne transmission, fine droplets goes with airflow; and in droplet transmission, large droplet goes with their own momentum

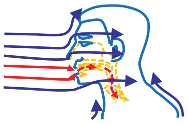
- Droplet transmission refers to the deposition of exhaled large droplets on the (mouth, nose and eye) mucus membrane of the susceptible, and subsequently leads to disease/infection.
- The transport medium is the momentum, not air, and not even (the expired) airflow or jet. These large droplets gained their momentum before release at the mouth. It is the momentum of these droplets that propel themselves to move. The airflow in the expired jet interacts with the droplet movement. The droplet movement is ballistic.

Ballistic - wiki

Unfortunately, existing threshold droplet size in large droplet transmission is wrong! Causing a lot of confusions.

The threshold droplet size is 50-100 microns, not 5 or 10 microns! Only >50-100 microns can deposit on face (1m), and much less on noses, mouth and eyes. Small ones follow airflow.



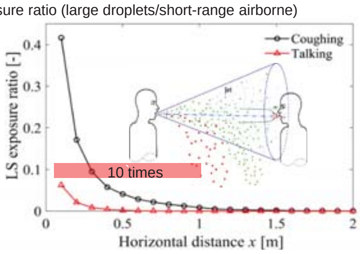


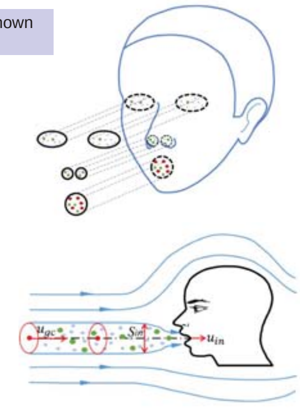
Deposition efficiency of particles in expiratory jet on a face depends on Stokes number

Chen et al. 2020. Short-range airborne route dominates exposure of respiratory infection during close contact. Building and Environment, 176

For close contact transmission, short-range airborne route is shown mechanistically to dominate.

Exposure ratio (large droplets/short-range airborne)

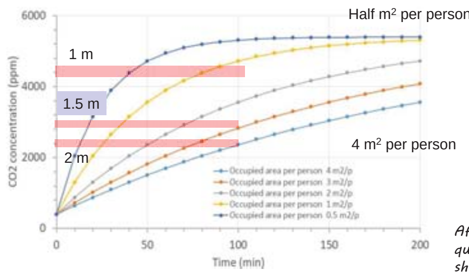


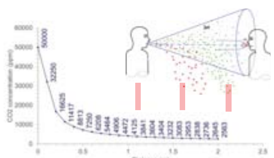


Mechanistically, short-range airborne can be 10 times more important than droplet transmission

Chen et al. 2020. Short-range airborne route dominates exposure of respiratory infection during close contact. Building and Environment, 176

Poor ventilation effectively leads to extended short-range airborne phenomenon, i.e. *a normally non-long-range airborne become airborne or opportunistic airborne transmission*



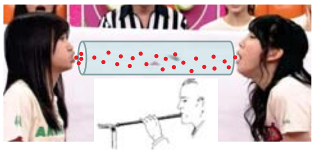


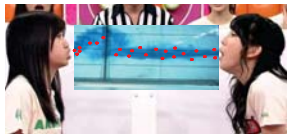
After one hour, the room average air quality is as bad as your exhaled air, i.e. short-range becomes long-range.

1 L/s outdoor air per person

Li Y et al., Extended short-range airborne transmission of respiratory infection. In preparation

In theory, extended short-range airborne can also occur when other air conditions are met, in addition to crowded and/or poorly ventilated





Modified from http://www.cormix.info/picgal/farfield.php

Adapted from Internet images

Connecting two mouths with a tube: lack of entrainment, reminded by an early influenza animal study.

Exhaled through a stable air layer, and can happen in displacement ventilation.

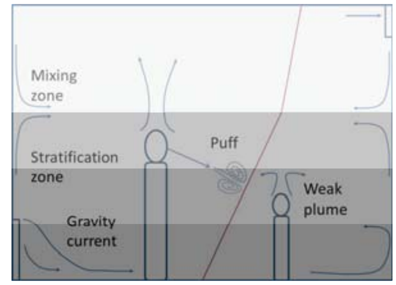
When do we find stable air layer in room ventilation? Displacement ventilation

Displacement Ventilation In Hospital Environments

By Yuguo Li, Ph.D., Fellow ASHRAE; Peter V. Nielsen, Ph.D., Fellow ASHRAE; Mats Sandberg, Ph.D.

ASHRAE Journal, June 2011

"We do not recommend the use of displacement ventilation in hospitals in either single-patient or multiple-patient wards for control of exhaled substances or any harmful infectious aerosols."



Ventilation is important to airborne (or airflow) transmission of Covid-19 in at least two aspects

- *An insufficient ventilation leads to a probably non-airborne transmission of SARS-CoV-2 to long-range airborne transmission. Poor ventilation leads to opportunistic airborne.*
- *Recirculation bubbles (in minimizing inflow of clean air) or stratified air layers (in minimizing dilution) may also enhance the airborne transmission with unfavourable release of infectious aerosols.*

Such opportunistic airborne transmission is not difficult to control with better ventilation provision or engineering design. It is easy to control the long-range airborne portion of the Covid-19 spread – the roles of HVAC engineers.

The so-called airborne inconsistency/ambiguity/paradox might be actually originated from our collective fear of the airborne transmission.

Thus, it may be useful to recognize two different types of airborne infection.

Those not easy to control: *Can occur at normal indoor conditions – might be indeed fearful, e.g. TB; measles and chickenpox (Obligate or preferentially airborne)*

*Those easy to control by better ventilation: Only occur in crowded and poorly ventilated areas – better ventilation and staying away from such locations . (*Opportunistically airborne)

Concluding remarks:

- *There is a continuum of the long- and short-range airborne routes.*
- *Preliminary: Ventilation rate of < 3 L/s per person resulted in SARS-CoV-2 infection in two outbreaks.*
- *Very preliminary: Possible sufficient ventilation of > 8-10 L/s per person would not result in Covid-19 transmission.*
- *There is a need for us to examine the ventilation requirement standards? Why not taking minimizing infection into consideration (flu, Covid-19 and novel infectious diseases)?*

Speculating R&D in post-pandemic indoor environment *(Just search for building/indoor + post-pandemic, post-covid-19, you can find 100s articles – building industry, higher education, individuals, media, business and investment)*

- ***Mankind will reflect deeply** the needs of future indoor environment, or broadly, city design, balance the needs of economics and sustainability of humanity. (What went wrong indoors now? planning for future pandemics)*
- *Refocus on human health, particularly on Covid-19 and other novel infectious diseases.*
- *Transmission routes (exposure dynamics, environment, human behavior) using big data, AI and IoT. (so next time, we can figure the transmission route fast)*
- *Reconsider the harmony between privacy and public good, and let us each release some of our "personal" data for public good use.*

Reflect, refocus, reconsider and release

Thank you