Airborne transmission of the virus SARS-COV-2

and other respiratory infections

World Health Organization

Collaborating Centre for Air Pollution and Health

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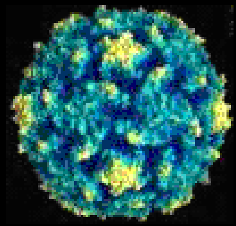
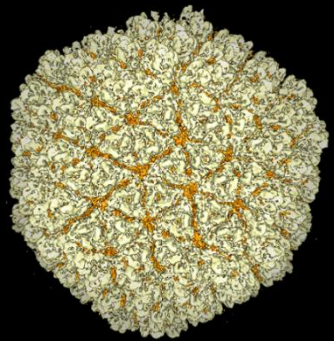

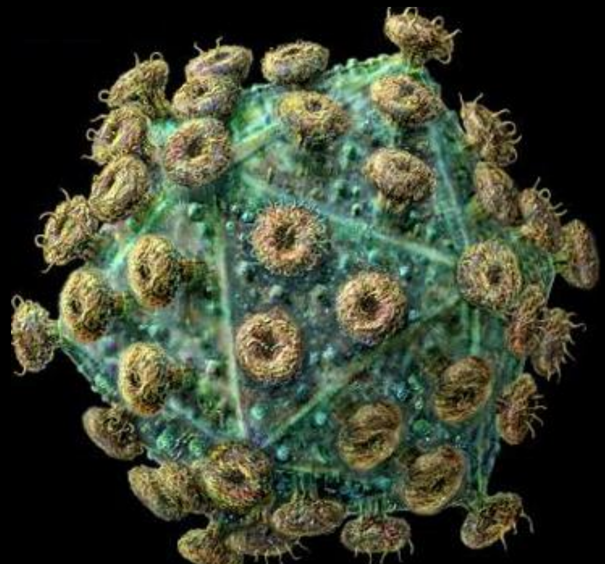
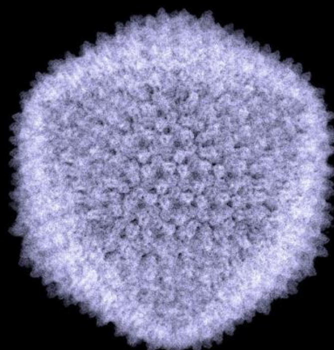

This presention

1. Introduction: airborne transmission
2. Generation of particles during respiratory activities
3. Characteristics of the particles
4. Dynamics of particles in the air
5. Evidence from the outbreaks – modelling
6. Mitigation – beyond COVID-19

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Epidemics and pandemics of the past

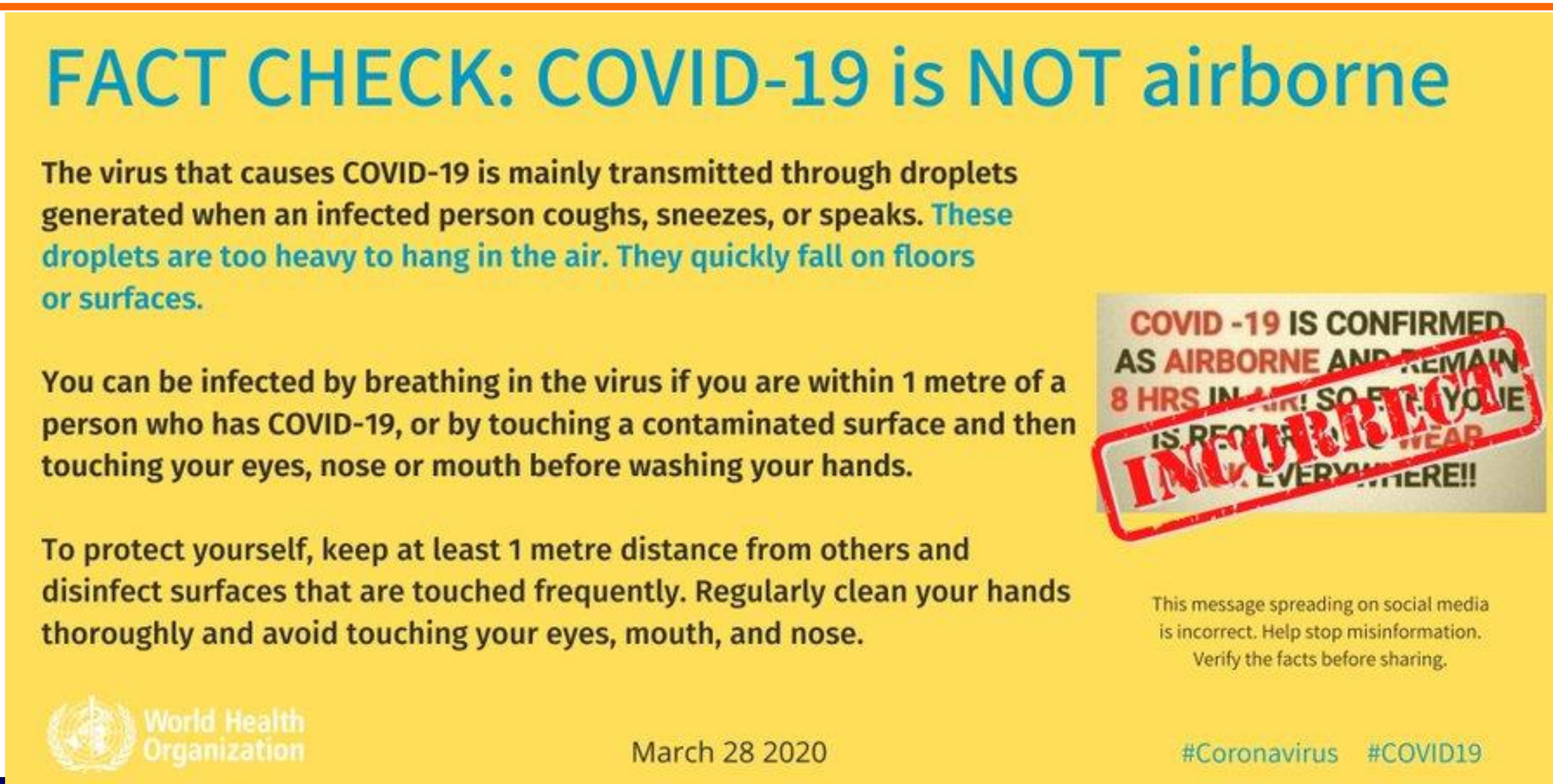
Of respiratory infections

Spanish flu

The Conservations, March 27, 2021

What lessons have we learned?

Confusion: COVID-19



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Airborne transmission of SARS-CoV-2: The world should face the reality

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Airborne transmission
Airborne infection spread

Clinical Infectious Diseases

INVITED COMMENTARY

IDSA Infectious Diseases Society of America

hivma hiv medicine association

OXFORD

It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19)

Australia, and [2]Institute for Applied Environmental Health, University

-19; SARS-CoV-2 virus.

EDITORIALS

Check for updates

Covid-19 has redefined airborne transmission

Improving indoor ventilation and air quality will help us all to stay safe

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Cite this as: BMJ 2021;373:n913
http://dx.doi.org/10.1136/bmj.n913
Published: 14 April 2021

Over a year into the covid-19 par
debating the role and importanc
transmission for SARS-CoV-2, wl
cursory mention in some infectio
guidelines.[1 2]

The confusion has emanated fro
terminology introduced during t
created poorly defined divisions
"airborne," and "droplet nuclei"
leading to misunderstandings o
behaviour of these particles.[3] Es
inhale particles—regardless of the
are breathing in aerosols. Althou
at long range, it is more likely whe
as the aerosols between two peo
concentrated at short range, rath
to someone who is smoking.[4]

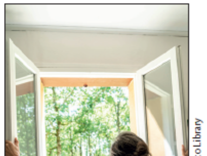
People infected with SARS-CoV-2

Comment

Ten scientific reasons in support of airborne transmission of SARS-CoV-2

Heneghan and colleagues' systematic review, funded by WHO, published in March, 2021, as a preprint, states: "The lack of recoverable viral culture samples of SARS-CoV-2 prevents firm conclusions to be drawn about airborne transmission".[1] This conclusion, and the wide circulation

long-range transmission and overdispersion of the basic reproduction number (R_0), discussed below—consistent with airborne spread of SARS-CoV-2 that cannot be adequately explained by droplets or fomites.[6] The high incidence of such events strongly suggests the dominance



Confusion: COVID-19

"There is no specific evidence to suggest that the wearing of masks by the mass population has any potential benefit.,"

Dr. Mike Ryan, executive director of the WHO health emergencies program

CNN March 31, 2020

Masks are mandatory!

Definitions:
is *IT* aerosol or droplet?

In aerosol science:

Aerosol: an assembly of liquid or solid particles suspended in a gaseous medium long enough to enable observation or measurement

Droplet: a liquid particle

In medical sciences:

Aerosol: smaller particles

Droplet: larger particles

Let's don't worry about these differences!

I will call them particles

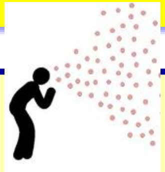
Randall, K.; Ewing, E.T.; Marr, L.; Jimenez, J.; Bourouiba, L. How Did We Get Here: What Are Droplets and Aerosols and How Far Do They Go? A Historical Perspective on the Transmission of Respiratory Infectious Diseases. (April 15, 2021) 2021.

Definitions:
short (close) or long range?

And also: where is the division?

- 1 m?
- 1.5 m
- 1 kangaroo apart?

There is no division, it is a continuum



Closer to the source ⇨ concentrations higher ⇨ shorter exposure time ⇨ infection

Away from the source ⇨ concentrations lower ⇨ longer exposure time ⇨ infection

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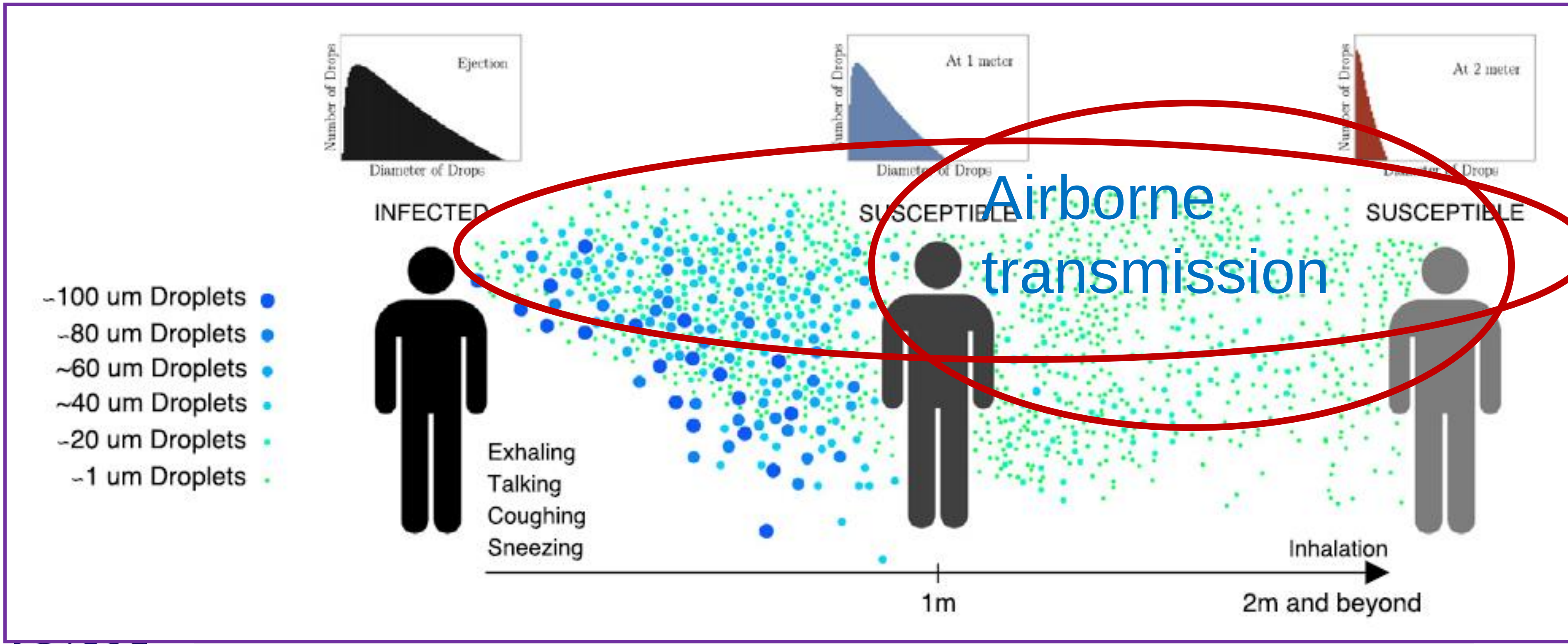
Airborne transmission: inhalation of virus-laden particles

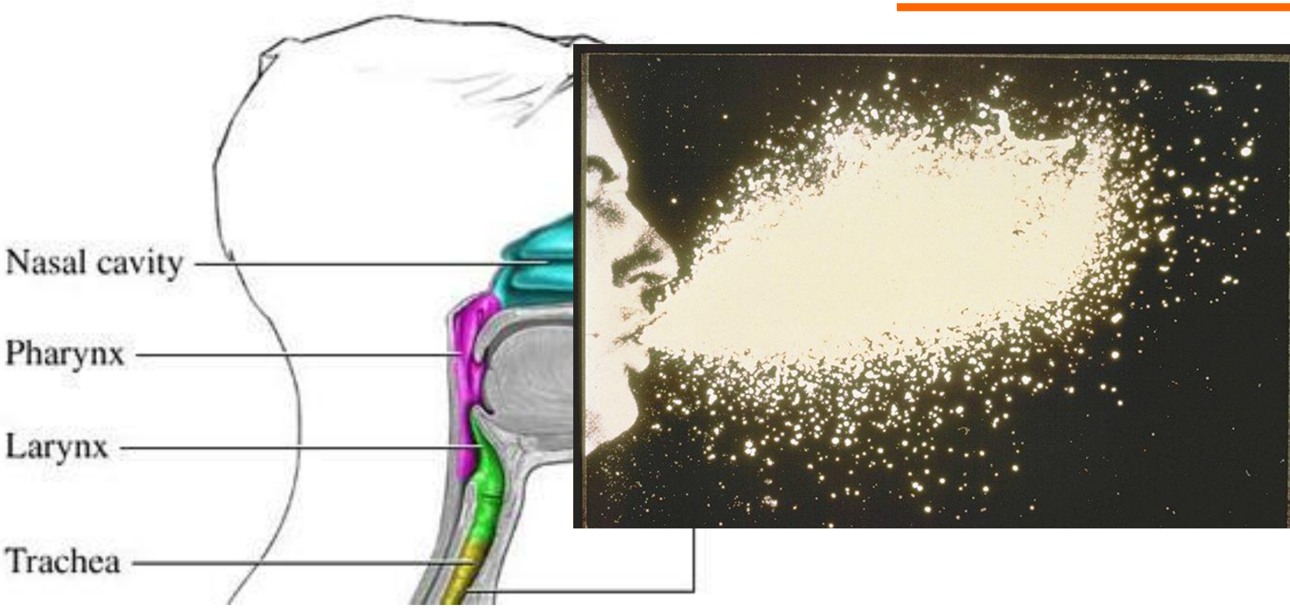


Balachandar, S., Zaleski, S., Soldati, A., Ahmadi, G. and Bourouiba, L. Host-to-host airborne transmission as a multiphase flow problem for science-based social distance guidelines, *International Journal of Multiphase Flow,* 132: 103439, 2020.

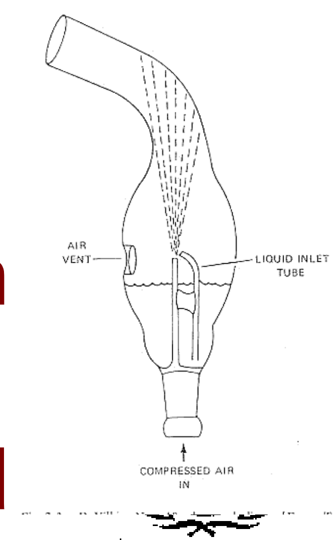
Cortellessa, G., Stabile, L., Arpino, F., Faleiros, D.E., van den Bos, W., Morawska, L. and Buonanno, G. Close contact risk assessment for SARS-CoV-2 infection. https://arxiv.org/abs/2104.10934

PARTICLE AEROSOLIZATION

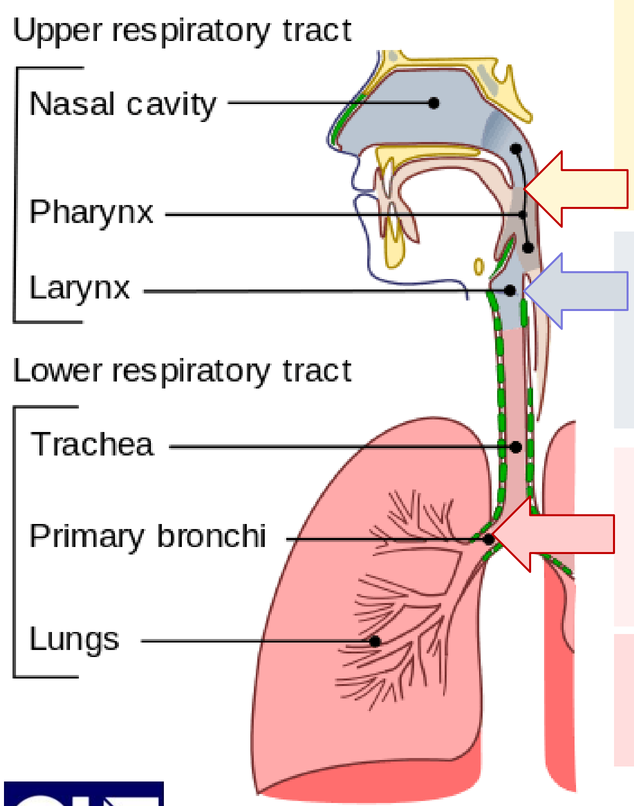
Particle aerosolization in expiratory activities



….results from the passage of an air-stream at a sufficiently high speed over the surface of a liquid



Multiple process of particle aerosolization



Saliva in the **mouth** is aerosolized during interaction of the tongue, teeth palate and lips during speech articulation

Fluid bathing the larynx is aerosolized during voicing due to vocal fold vibrations

Fluid blockages form in respiratory **bronchioles** during exhalation

They burst during subsequent inhalation produce the particles

After formation, the particles undergo processes in the respiratory tract before they are respired

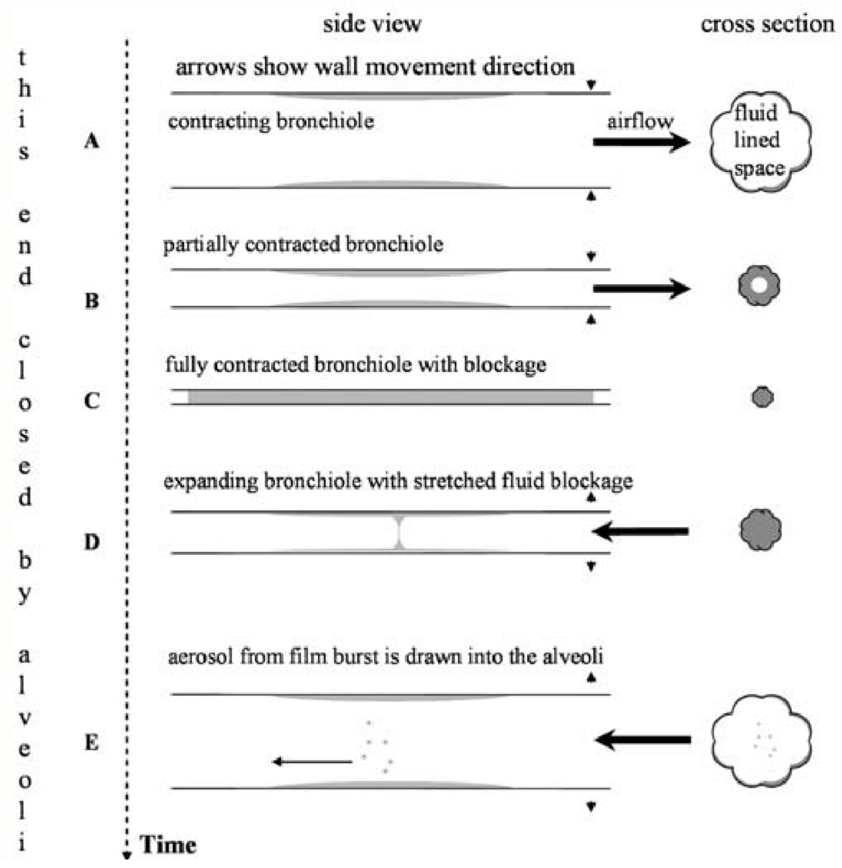
Deposition – changing initial size distribution

Surface deformation (Oratis et al. 2020 A new wrinkle on liquid sheets: *Turning the mechanism of viscous bubble collapse upside down*. *Science*, 369(6504): 685-688, 2020

Bronchiole fluid film burst (BFFB)

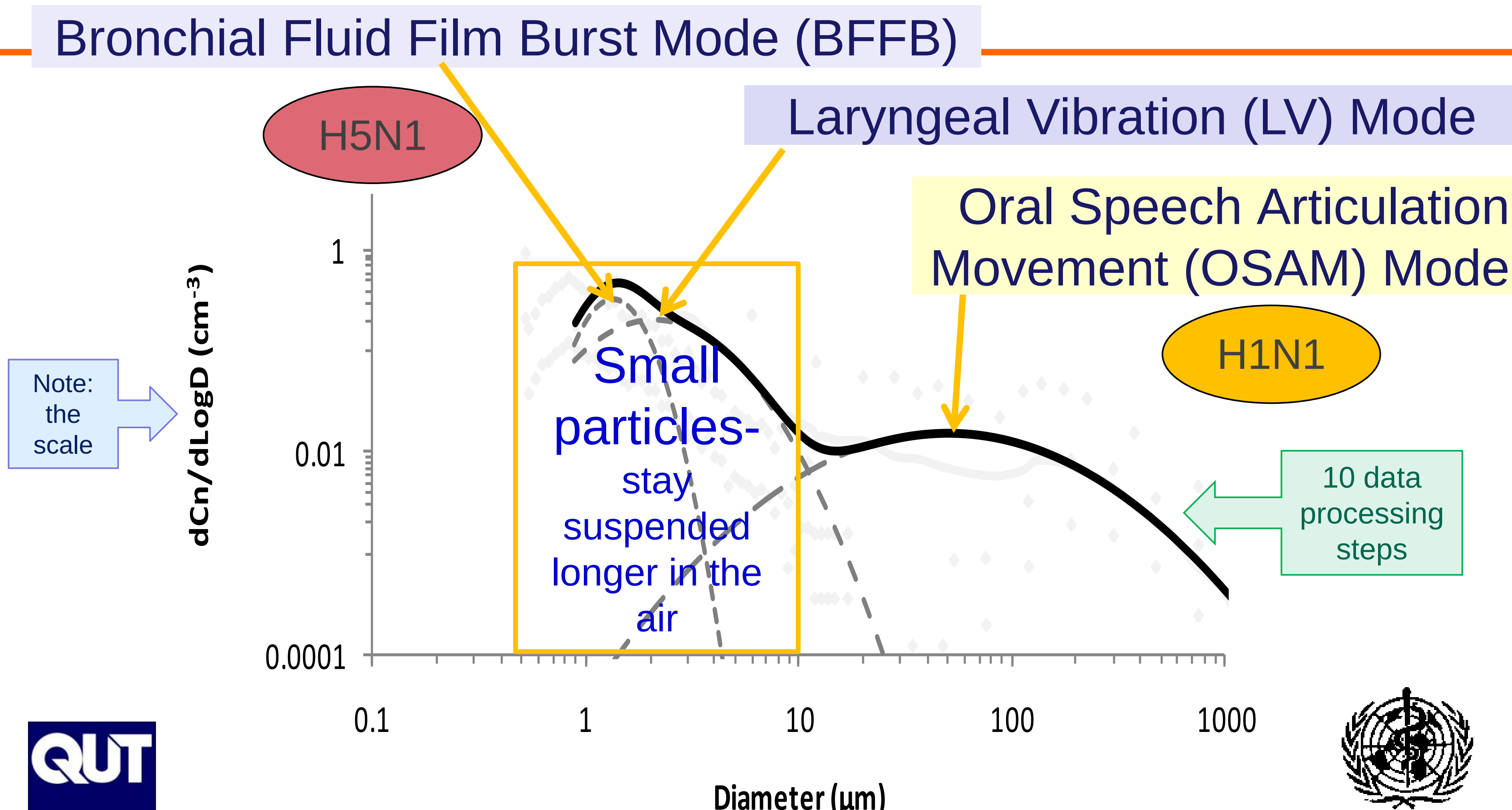
We cannot measure these processes directly, but model and simulate

Johnson, G.R. and Morawska, L. The Mechanism of Breath Aerosol Formation. Journal of Aerosol Medicine and Pulmonary Drug Delivery, 22: 229-237, 2009.



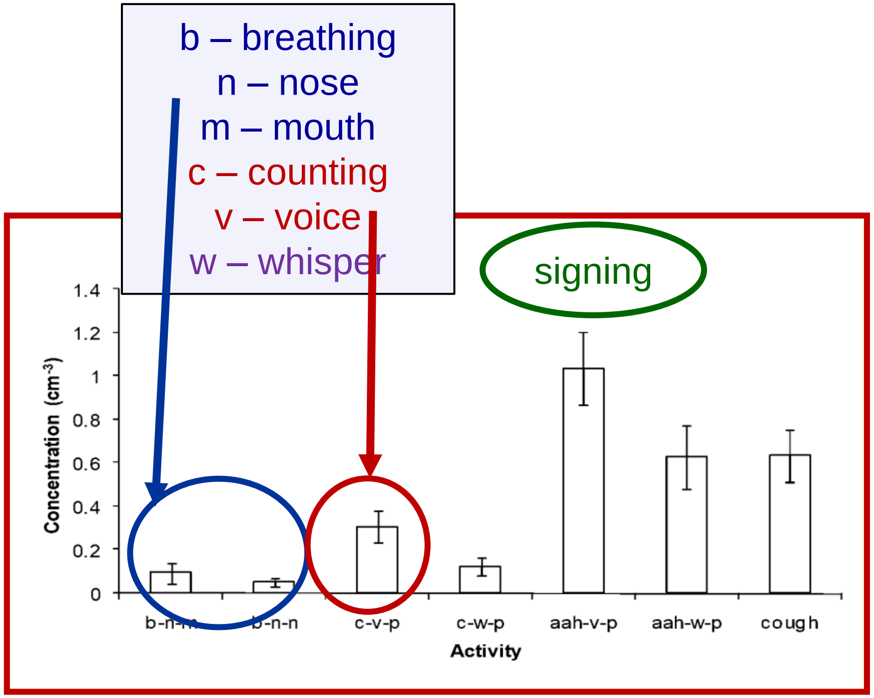
CHARACTERISTICS OF THE PARTICLES

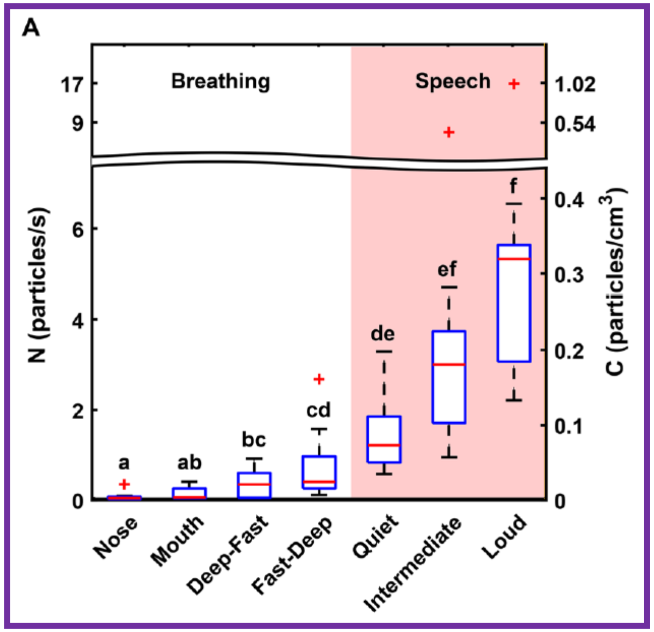
Number size distribution: speech + breathing



Morawska et al., 2009. Size distribution and sites of origin of droplets expelled during expiratory activities. *Journal of Aerosol Science*, 40: 256-269, 2009

Concentration/emission rates of particles – respiratory activities





Morawska et al., 2009. Size distribution and sites of origin of droplets expelled during expiratory activities. *Journal of Aerosol Science*, 40: 256-269.

Asadi et al., 2019. Aerosol emission and superemission during human speech increase with voice loudness. *Scientific Reports,* 20: 9(1):1-0

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Summary: particles generated from respiratory activities

Particle size and emissions:

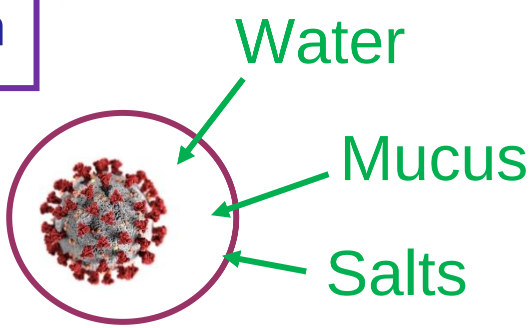
- The majority of particles are < 1 µm (and the vast majority are < 10 µm)
- Such small particles are light ⇨ **can stay suspended** in the air for a long time
- **All respiratory activities** (including breathing) generate particles, but vocalization ⇨ higher emissions than other activities

Virus-laden particles from respiratory activities

Majority within the mid sub-micrometre range and larger

Virus in the particles

Size of a SARS-CoV-2 “naked virus”: ~ 0.12 µm



Size of the virus-laden particles: > 0.12 µm

Particles < 1 µm ⇨ contain higher loads of SARS-CoV-2

Santarpia et al.. The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. *medRxiv,* 2020

Ma et al, ***COVID-19 patients in earlier stages exhaled millions of SARS-CoV-2 per hour***. *CID*, Accepted 26 Aug, In Press.

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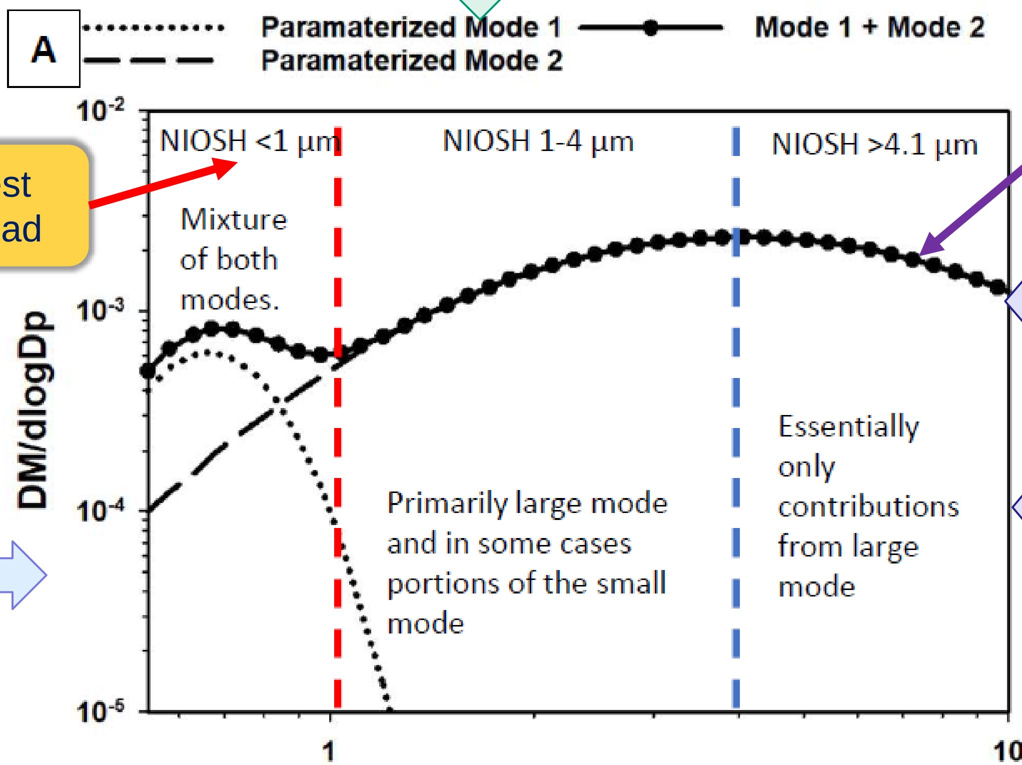
Mass size distributions - mixed acuity COVID-19 rooms

Several data processing steps

All respiratory activities + background

Highest viral load



Note: the scale

Particle size distribution: Aerodynamic Particle Sizer (TSI APS 3321)
0.542- 20 µm, **52 size bins**

Sample collection for virology: NIOSH BC251 sampler
3 stages, cut-off sizes - the red and blue lines

Santarpia et al., 2020. The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. *medRxiv*

Summary: virus-laden particles

Virus in the particles

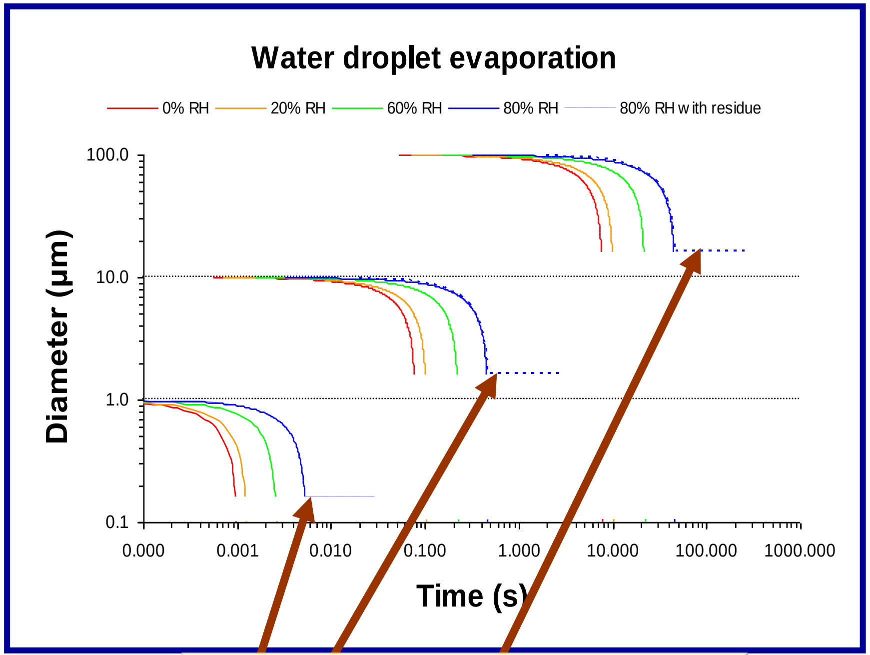
- Overall, smaller particles ⇨ contain higher loads of SARS-CoV-2
- Smaller particles ⇨ from deeper parts of the respiratory tract ⇨ location of the virus
- To the contrary, larger particles ⇨ less virus, as they originate from the mouth
- Therefore, breathing/speaking ⇨ the main source of small, virus-laden particles

PARTICLE DYNAMICS IN THE AIR

Particle evaporation

What we measure is usually already a *droplet nuclei*

Respiratory liquids are water based



Evaporate very fast!

Droplet nuclei (of 0.86% NaCl solutions)

Morawska, L. 2006. Droplet Fate in Indoor Environments, Or Can We Prevent the Spread of Infection. *Indoor Air* 16(5): 335-347.

Composition of respiratory particles:

- Water
- Salts
- Mucus
- Pathogens

Evaporate very fast!

The process is much more complex than for salt solution

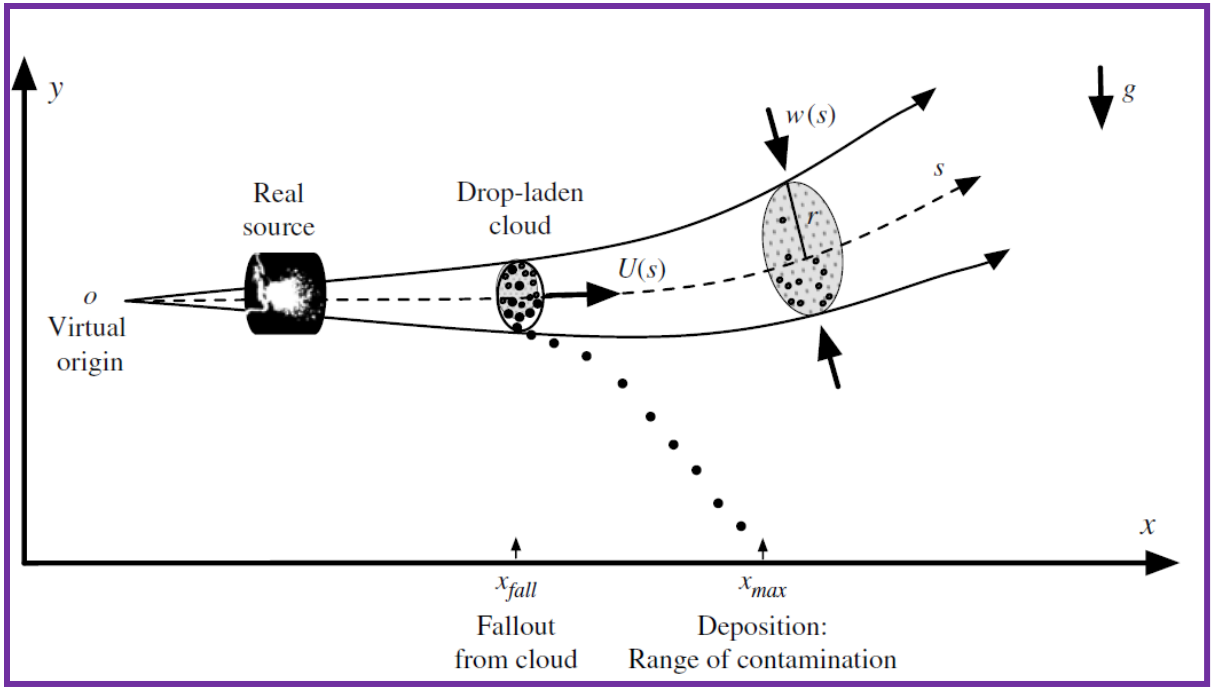
Evaporation to 20 - 40% of the initial size

Particle fate in the air

Particle diameter [μm]	"Falling" time height 1 m [s]
1000	0.3
100	3
10	300
1	30,000

Wells 1934

How do particles from respiratory activities travel in the air?



Bourouiba, L., et al. Violent expiratory events: on coughing and sneezing. *Journal of Fluid Mechanics*, *745:* 537-563, 2014

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Summary: particle dynamics in the air

- Gravitational deposition of large particles
- Flow dynamics of small particles
- Removal by ventilation (and other processes)

Level of understanding:
- Very good quantitative understanding
- Based on empirical studies and modelling

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Typically asked questions

Q: How long will virus-laden particles stay in indoor air?

A: As long as the forces acting on them will keep them in the air.

Minutes?

Hours?

Q: How far will virus-laden particles travel in indoor air?

A: As far as the air flow will take them.

Meters (m)?

Tens of m?

Hundreds of m?

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Physics of respiratory infections

Quantitative evidence:

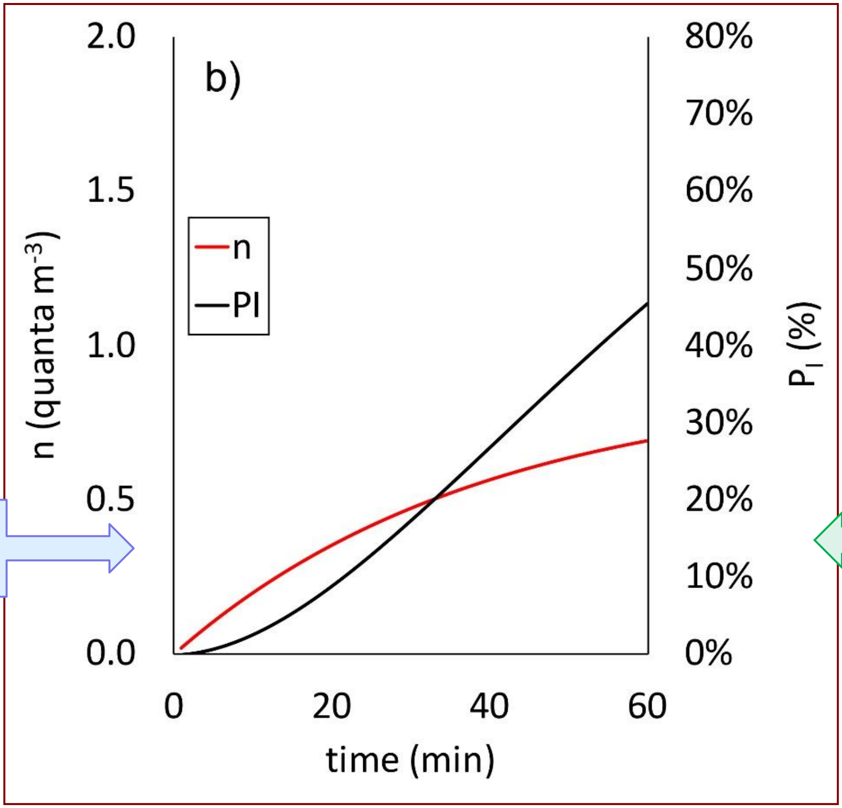
- Characteristics of particles / virus-laden particles from human respiratory activities
- What happens to the particles in the air – transport and removal dynamics
- Deposition of the particles in the respiratory tract upon inhalation

Is such evidence available for each outbreak?

No, because this is a complex process and we never have all the required parameters for real life scenarios

EVIDENCE FROM OUTBREAKS

Skagit Valley choir outbreak



Quanta concentration

Probability of infection

The Mount Vernon Presbyterian Church in Mount Vernon, Wash. (Karen Ducey / For The Times)

53 out of 61 participating infected

ER_q=341 quanta h^{-1}

Modelled results agreed with the outbreak data

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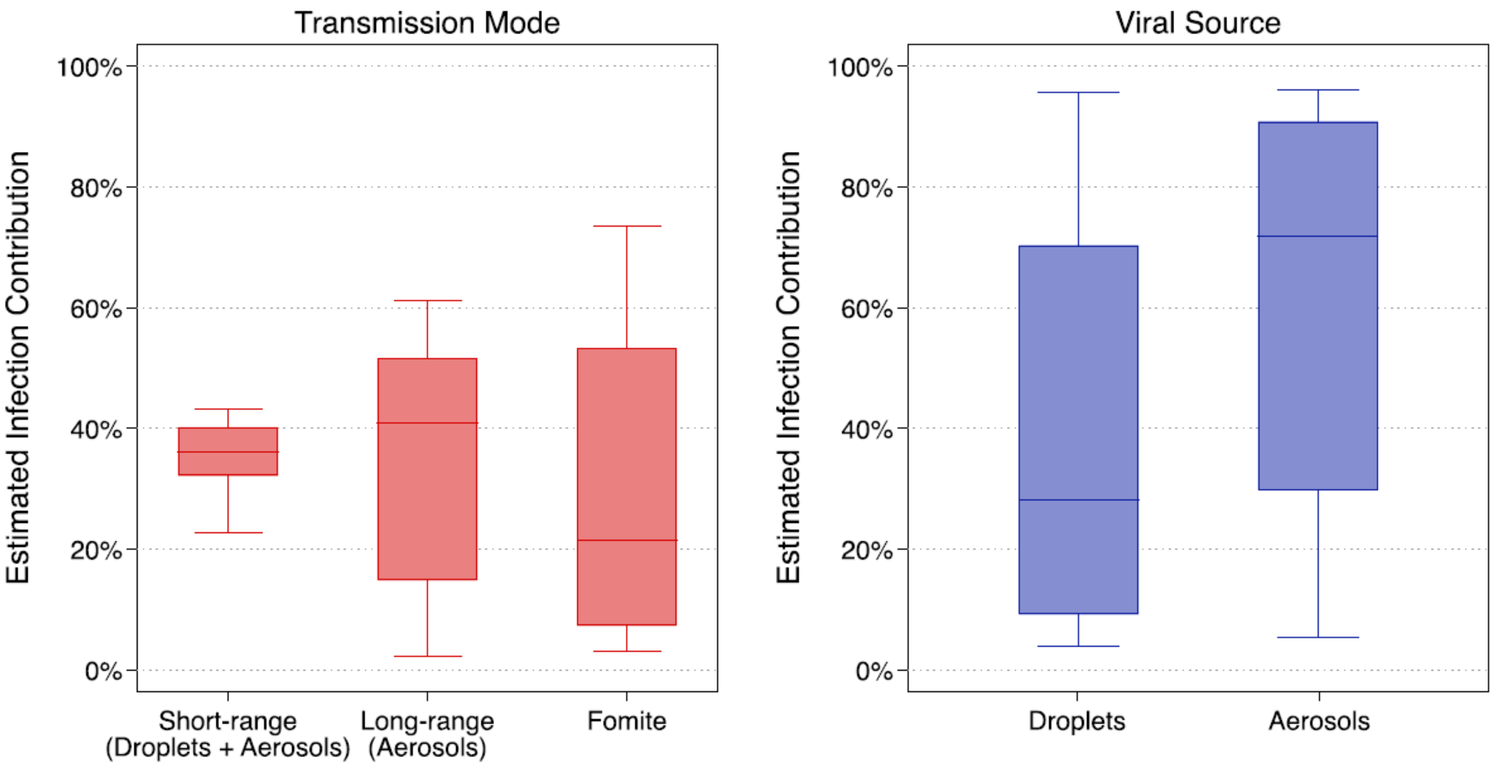
Stable, L., Buonanno, G. and Morawska, L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. *Environment International,* 145: 106112, 2020.

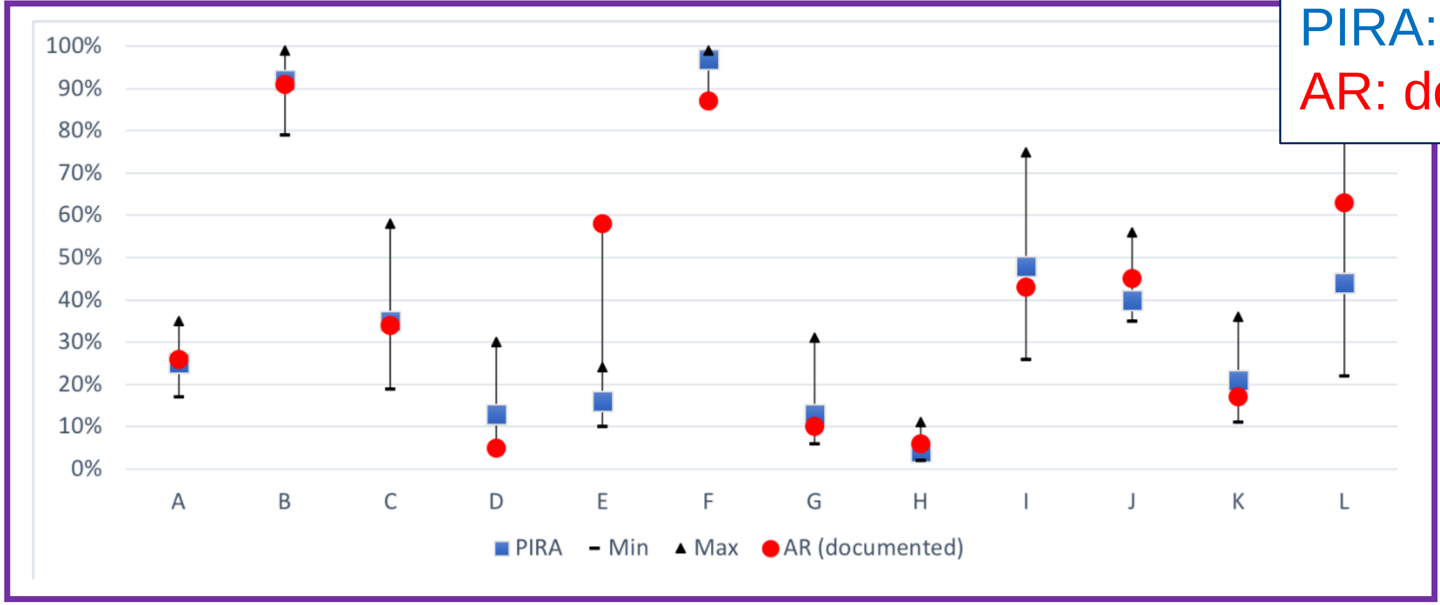
Miller et al. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air,* **Accepted 26 September 2020, In Press**.

Estimates of contributions: transmission modes + viral sources



Azimi et al. Mechanistic transmission modelling of COVID-19 on the Diamond Princess Cruise ship demonstrates the importance of aerosol transmission. *PNAS*, 118(8): e2015482118, 2021

Comparison of infection risk between 12 modelled and documented outbreak data



PIRA: modelled
AR: documented

Kriegel et al. Predicted Infection Risk for Aerosol Transmission of SARS-CoV-2. medRxiv, 2020.
doi: https://doi.org/10.1101/2020.10.08.20209106

Model assumption:
all cases were caused by long-range transmission

Agreement in 9 cases

Airborne transmission must be mitigated!

Why do we question evidence from these processes…

Should gravity be questioned?

…if we accept transport of other objects in the air, and its impact?

A **seed** hundreds of meters from a parent tree?

Dust particles thousands of km from a source causing air pollution episodes?

We don’t trace the **seed** or the dust grain, but rely on various models and other evidence to explain their journey

In a similar way, physics-based evidence should be used to explain airborne transmission or respiratory infections

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Randomized control trials?

The Parachute

Parachutes reduce the risk of injury after gravitational challenge, but their effectiveness has not been proved with randomised controlled trials

Hazardous journeys

Parachute use to prevent death and major trauma related to gravitational challenge: systematic review of randomised controlled trials

Gordon C S Smith, Jill P Pell

Smith and Pell, BMJ, 327, 20–27, 2003

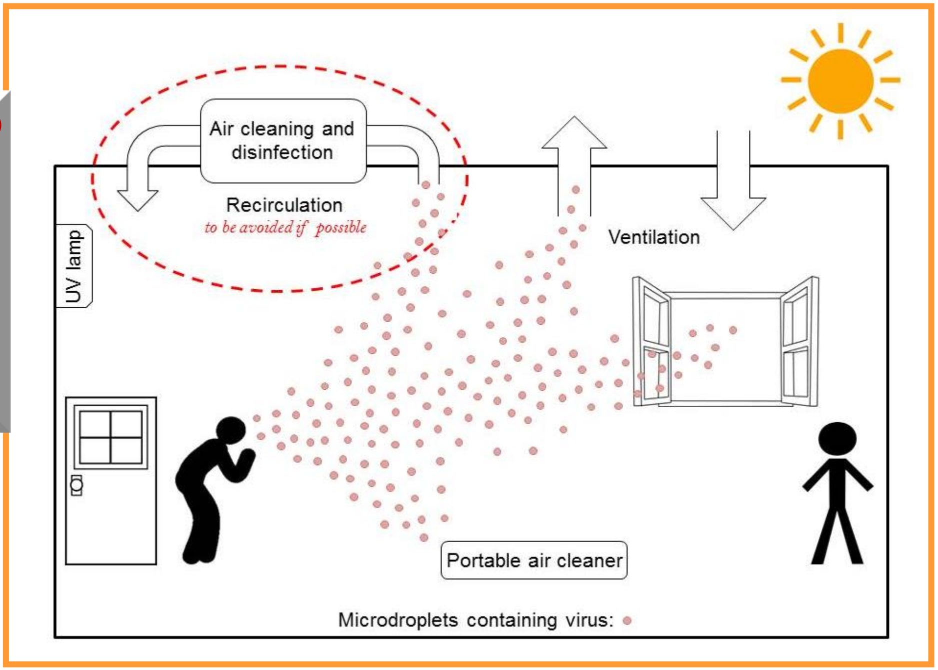
BMJ: firs

Conclusions As with many interventions intended to prevent ill health, the effectiveness of parachutes has not been subjected to rigorous evaluation by using randomised controlled trials. Advocates of evidence based medicine have criticised the adoption of interventions evaluated by using only observational data. We think that everyone might benefit if the most radical protagonists of evidence based medicine organised and participated in a double blind, randomised, placebo controlled, crossover trial of the parachute.

MITIGATION

Building engineering controls

- Sufficient and effective ventilation
- Avoiding air recirculation
- Particle filtration and air disinfection
- Avoiding overcrowding



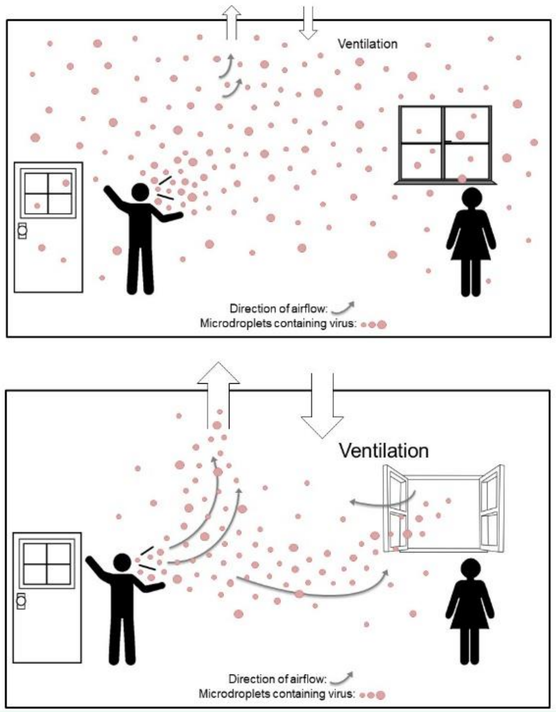
Morawska, et al. How can airborne transmission of COVID-19 indoors be minimised?, *Environment International,* 142: 105832, 2020

Ventilation:
sufficient and effective

Enough of it

Everywhere

Air flow not from person to person



Morawska, L. and Milton, D. "It is Time to Address Airborne Transmission of COVID-19". *Clinical Infectious Diseases*, 6: ciaa939, 2020

SUFFICIENT VENTILATION

What is sufficient ventilation in relation to infection transmission?

Can we use the **existing** ventilation guidelines for controlling infection transmission?

For example, guidelines for CO_2 exhaled by occupants?

To find out we need to use risk assessment models and tools!

Infection transmission: infectious quanta

A quantum is the dose of infectious airborne particles required to cause infection in 63% of susceptible persons

Emitted quanta depend on:

- Location of the pathogen in the respiratory tract
- Physiology of the respiratory tract
- Stage of the disease
- Type of respiratory activity
- THE VIRUS

Risk of infection transmission

Traditional steady-state Wells-Riley model (W-R)

$$Risk = 1 - e^{-\frac{Iqpt}{Q}}$$

Where:

I - the number of infectious source cases

q - the number of infectious quanta produced per source case (quanta/h),

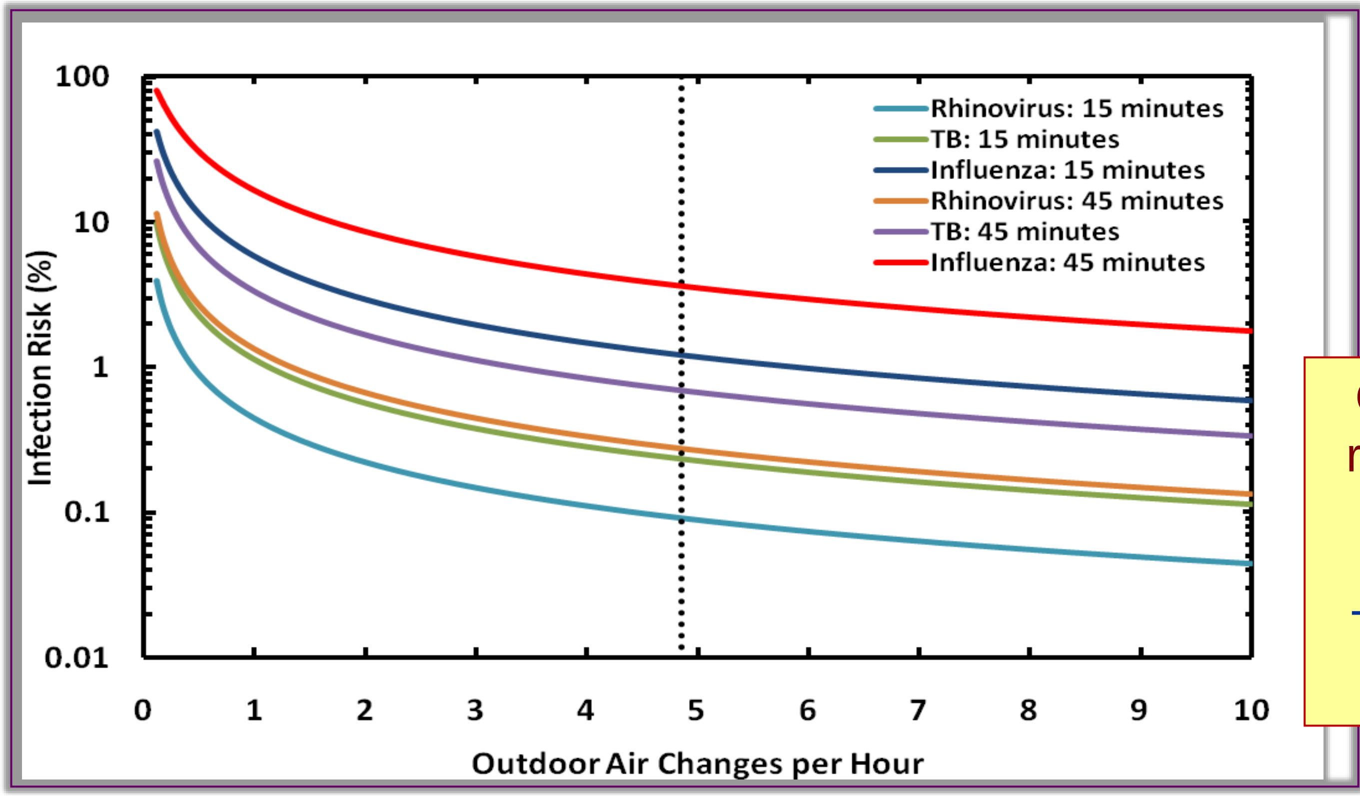
p - the average respiratory ventilation rate of susceptible persons (m^3/h),

t - the duration of exposure (h)

Q - the volume of infection-free (i.e. outdoor) air supplied to the room (m^3/h)

QU

Ventilation and infection risk



Using Wells-Riley model

Quanta generation rates from literature (quanta/hour):
Influenza - 67
Tuberculosis - 12.7
Rhinovirus – 5

The Prince Charles Hospital, Brisbane, Lung Function Laboratory: infection risk for 15 and 45 min occupancy

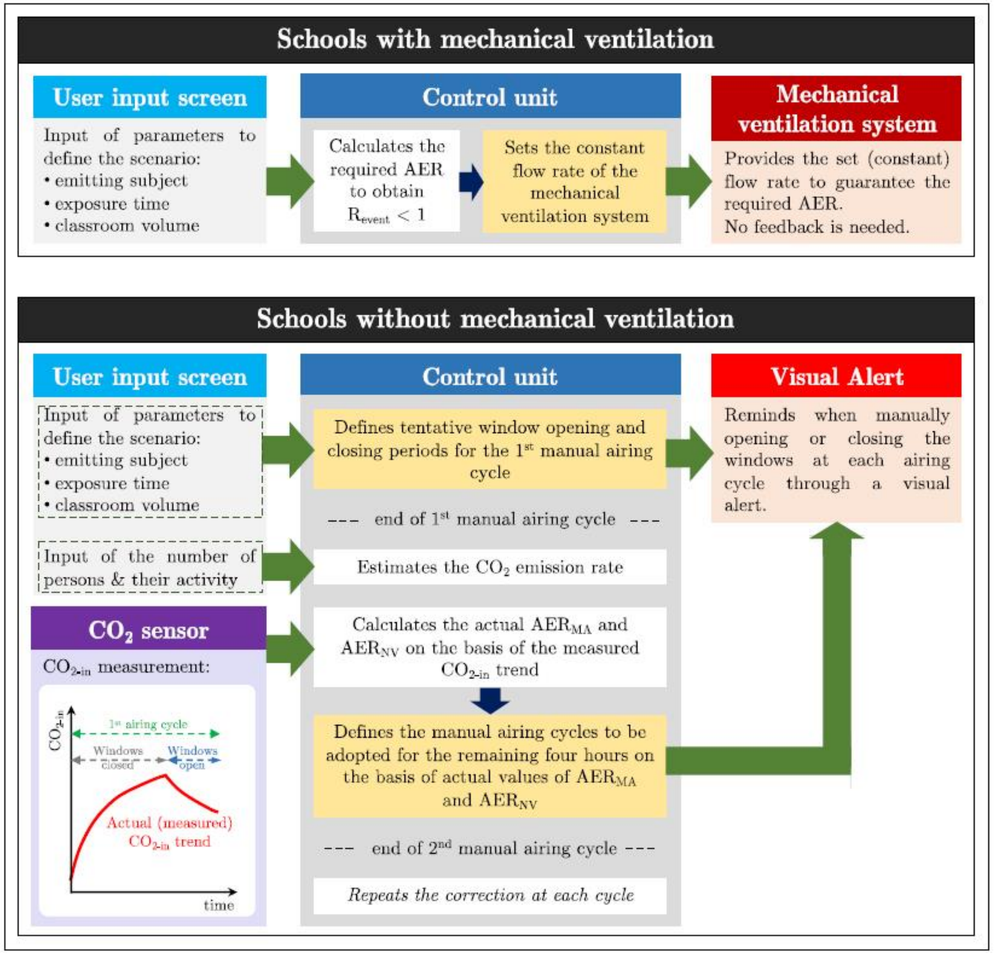
Laboratory for Air Quality and Health
WHO Collaborating Centre

Knibbs et al. *American Journal of Infection Control*, 39: 866-872, 2011

Risk assessment models and tools 1

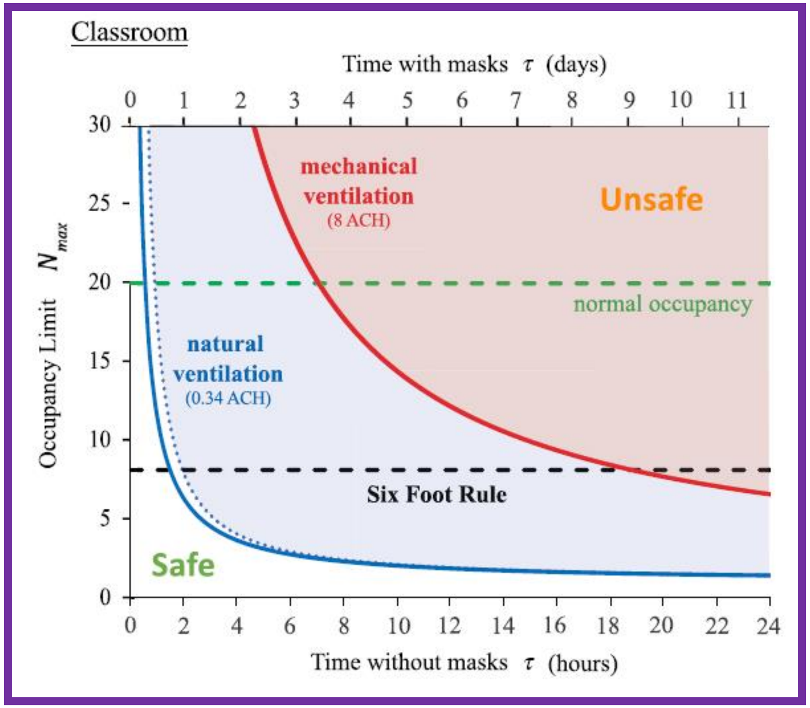
Airborne Infection Risk Calculator (Version 3.0 Beta)

https://research.qut.edu.au/ilaqh/wp-content/uploads/sites/174/2021/04/AIRC-Tool-v3.0-Beta.xlsx



Stabile, L., Pacitto, A., Mikszewski, A., Morawska, L. and Buonanno, G. **Ventilation procedures to minimize the airborne transmission of viruses at schools**. Building and Environment, Accepted 7 June 2021 (*medRxiv*, https://doi.org/10.1101/2021.03.23.21254179)

Risk assessment models and tools 2



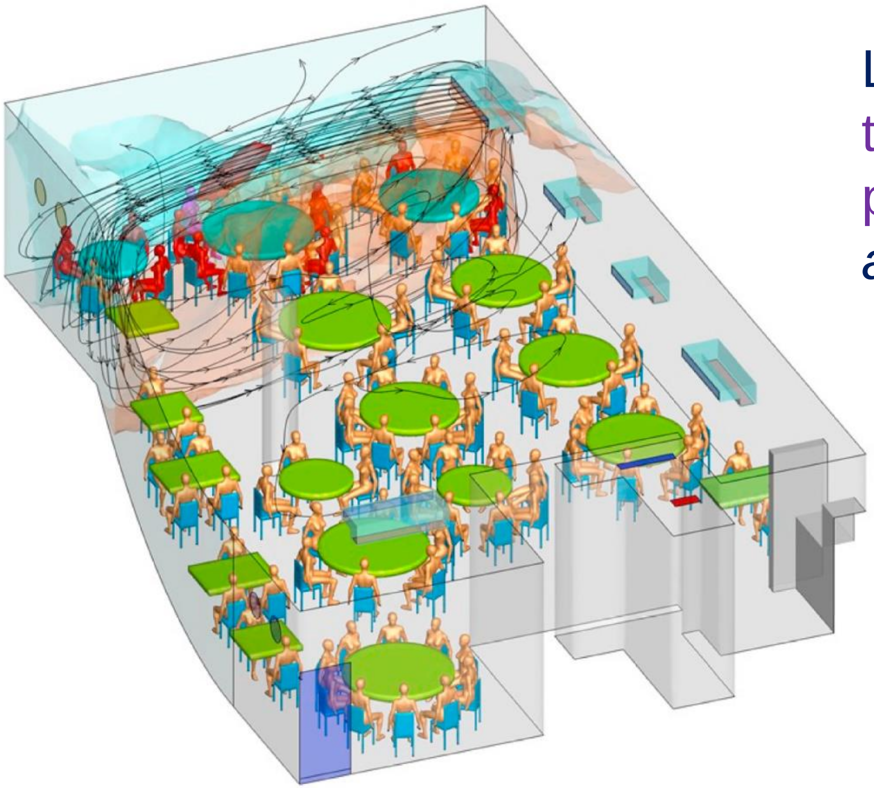
Bazant, M.Z. and Bush, J.W., 2021. **A guideline to limit indoor airborne transmission of COVID-19.** *Proceedings of the National Academy of Sciences*, *118*(17). https://doi.org/10.1073/pnas.2018995118

In summary, assessing the requirements for **sufficient ventilation**
⇓
relatively easy

Assumption: uniform mixing of the air!

EFFECTIVE VENTILATION

Air flow distribution/direction and infection risk



Li, et al. Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. *Building and Environment*, *196*, p.107788, 2021

The flow direction was a problem in this case (in addition to low fresh air supply)

Computation Fluid Dynamic (CFD) Modelling

Will CFD modelling answer all the questions about flow direction?

For specific indoor spaces - mostly

But we need general solutions

In summary, assessing the requirements for **effective ventilation, which is based on air flow**
⇓
still a challenge

How to generalise?

THE FUTURE BEYOND COVID-19

POLICY FORUM

INFECTIOUS DISEASE

A paradigm shift to combat indoor respiratory infection

Building ventilation systems must get much better

By **Lidia Morawska, Joseph Allen, William Bahnfleth, Philomena M. Bluyssen, Atze Boerstra, Giorgio Buonanno, Junji Cao, Stephanie J. Dancer, Andres Floto, Francesco Franchimon, Trisha Greenhalgh, Charles Haworth, Jaap Hogeling, Christina Isaxon, Jose L. Jimenez, Jarek Kurnitski, Yuguo Li, Marcel Loomans, Guy Marks, Linsey C. Marr, Livio Mazzarella, Arsen Krikor Melikov, Shelly Miller, Donald K. Milton, William Nazaroff, Peter V. Nielsen, Catherine Noakes, Jordan Peccia, Kim Prather, Xavier Querol, Chandra Sekhar, Olli Seppänen, Shin-ichi Tanabe, Julian W. Tang, Raymond Tellier, Kwok Wai Tham, Pawel Wargocki, Aneta Wierzbicka, Maosheng Yao**

There is great disparity in the way we think about and address different sources of environmental infection. Governments have for decades promulgated a large amount of legislation and invested heavily in food safety, sanitation, and drinking water for public health purposes. By contrast, airborne pathogens and respiratory infections, whether seasonal influenza or COVID-19, are addressed fairly weakly, if at all, in terms of regulations, standards, and building design and operation, pertaining to the air we breathe. We suggest that the rapid growth in our understanding of the mechanisms behind respiratory infection transmission should drive a para- have been enacted for all aspects of food and water processing, as well as wastewater and sewage. Public health officials, environmental health officers, and local councils are trained in surveillance, sampling, and investigation of clusters of potential food and waterborne outbreaks, often alerted by local microbiology laboratories. There are published infection rates for a large range

"...healthy indoor environments with a substantially reduced pathogen count are essential for public health."

was on thermal comfort, odor control, perceived air quality, initial investment cost, energy use, and other performance issues, whereas infection control was neglected. This could in part be based on the lack of perceived risk or on the assumption that there are more important ways to control infectious disease, despite ample evidence that healthy indoor environments with a substantially reduced pathogen count are essential for public health.

It is now known that respiratory infections are caused by pathogens emitted through the nose or mouth of an infected person and transported to a susceptible host. The pathogens are enclosed in fluid-based particles aerosolized from sites in the respiratory tract during respiratory activities such as breathing, speaking, sneezing, and coughing. The particles encompass a wide size range, with most in the range of submicrometers to a few micrometers (*1*).

Although the highest exposure for an individual is when they are in close proximity, community outbreaks for COVID-19 infection in particular most frequently occur at larger distances through inhalation of airborne virus–laden particles in indoor spaces shared with infected individuals (*2*). Such airborne transmission is potentially the dominant mode of transmission of numerous respiratory infections. There is also strong evidence on disease transmission—for example, in restaurants, ships, and schools—suggesting that the way buildings are designed, operated, and maintained influences transmission.

Yet, before COVID-19, to the best of our

Morawska, L., et al., 2021. A paradigm shift to combat indoor respiratory infection. *Science*, 372(6543): 689-691. https://doi.org/10.1126/science.abg2025.

Paradigm shift: action

We need a "paradigm shift" in how:

- buildings are designed
- equipped, and
- operated

…to minimize all air hazards, **including** airborne infection transmission

Paradigm shift: perception

There must to be a shift in perception that we cannot afford new ventilation systems

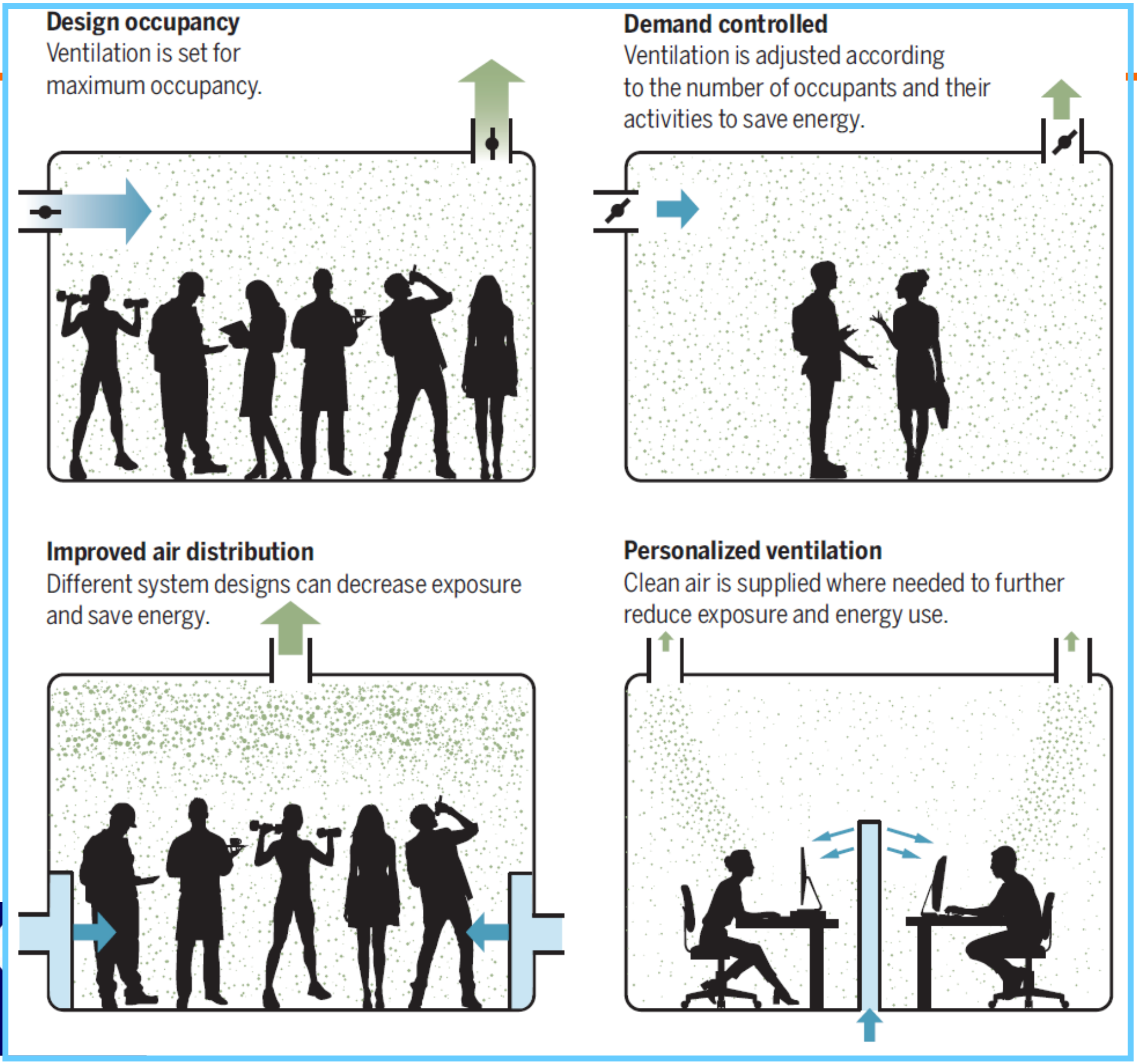
The economic costs of the impacts of indoor air pollution by far exceed all other costs.

Cost of COVID:
$1 trillion (monthly)

Cost of other transmissions in US:
$50 billion (annual)

Costs in Australia:
$52-137 million (annual)

The solutions are here



Morawska, L., et al., 2021. A paradigm shift to combat indoor respiratory infection. *Science*, 372(6543): 689-691. https://doi.org/10.1126/science.abg2025
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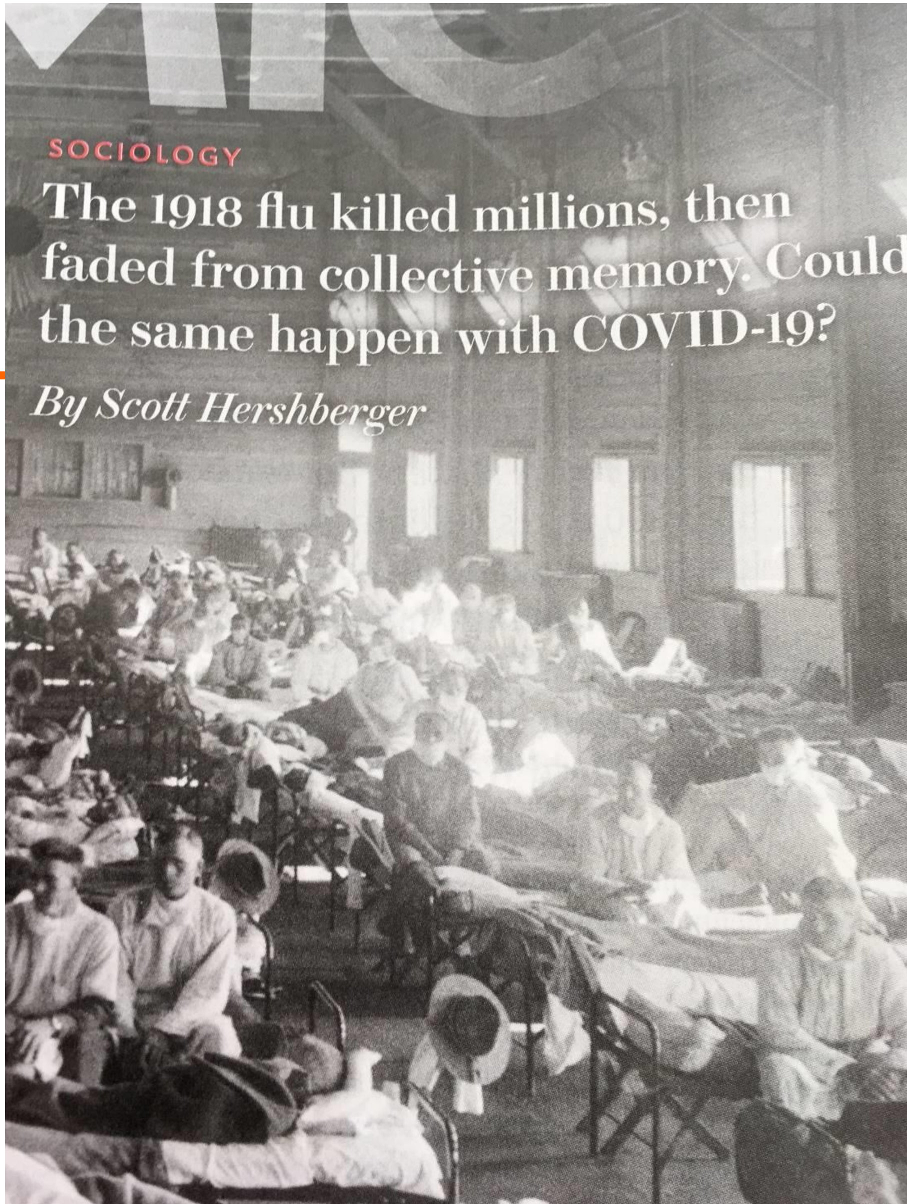

Hershberger, S. The 1918 flu killed millions, then faded from our collective memory. Could the same happen with COVID-19? Scientific American, November 2020

It will happen to COVID-19,
but we hope that the pandemic will influence the paradigm shift in combating indoor respiratory infections…

…on the scale of Chadwick's Sanitary Report in 1842

Sir Edwin Chadwick led the British government to encourage cities to organise clean water supplies and centralised sewage systems

The Parachute

RESEARCH

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Parachute use to prevent death and major trauma when jumping from aircraft: randomized controlled trial

Robert W Yeh,[1] Linda R Valsdottir,[1] Michael W Yeh,[2] Changyu Shen,[1] Daniel B Kramer,[1] Jordan B Strom,[1] Eric A Secemsky,[1] Joanne L Healy,[1] Robert M Domeier,[3] Dhruv S Kazi,[1] Brahmajee K Nallamothu[4] On behalf of the PARACHUTE Investigators

BMJ: first published a

Yeh et all, BMJ 2018;363:k5094

CONCLUSIONS

Parachute use did not reduce death or major traumatic injury when jumping from aircraft in the first randomized evaluation of this intervention. However,

Thank you!

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