The airborne transmission of respiratory pathogens: the importance of ventilation and air distribution in the infection risk

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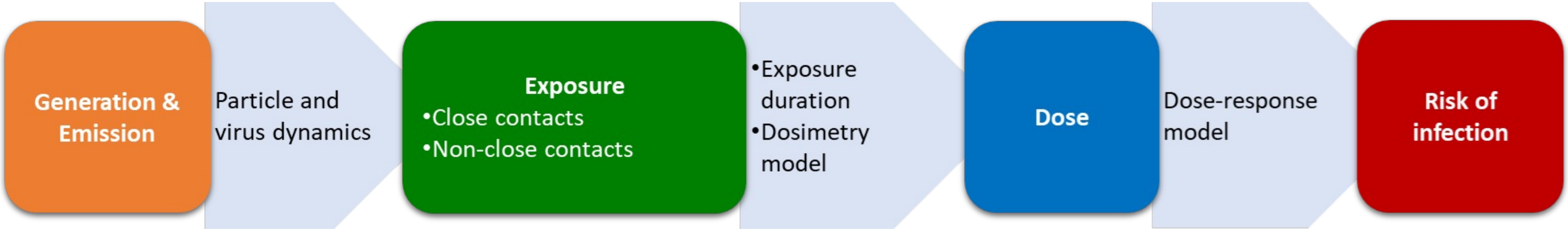
The physics of airborne transmission

Inhaling and exhaling air — breathing — is one of the basic physiological functions of the human being.

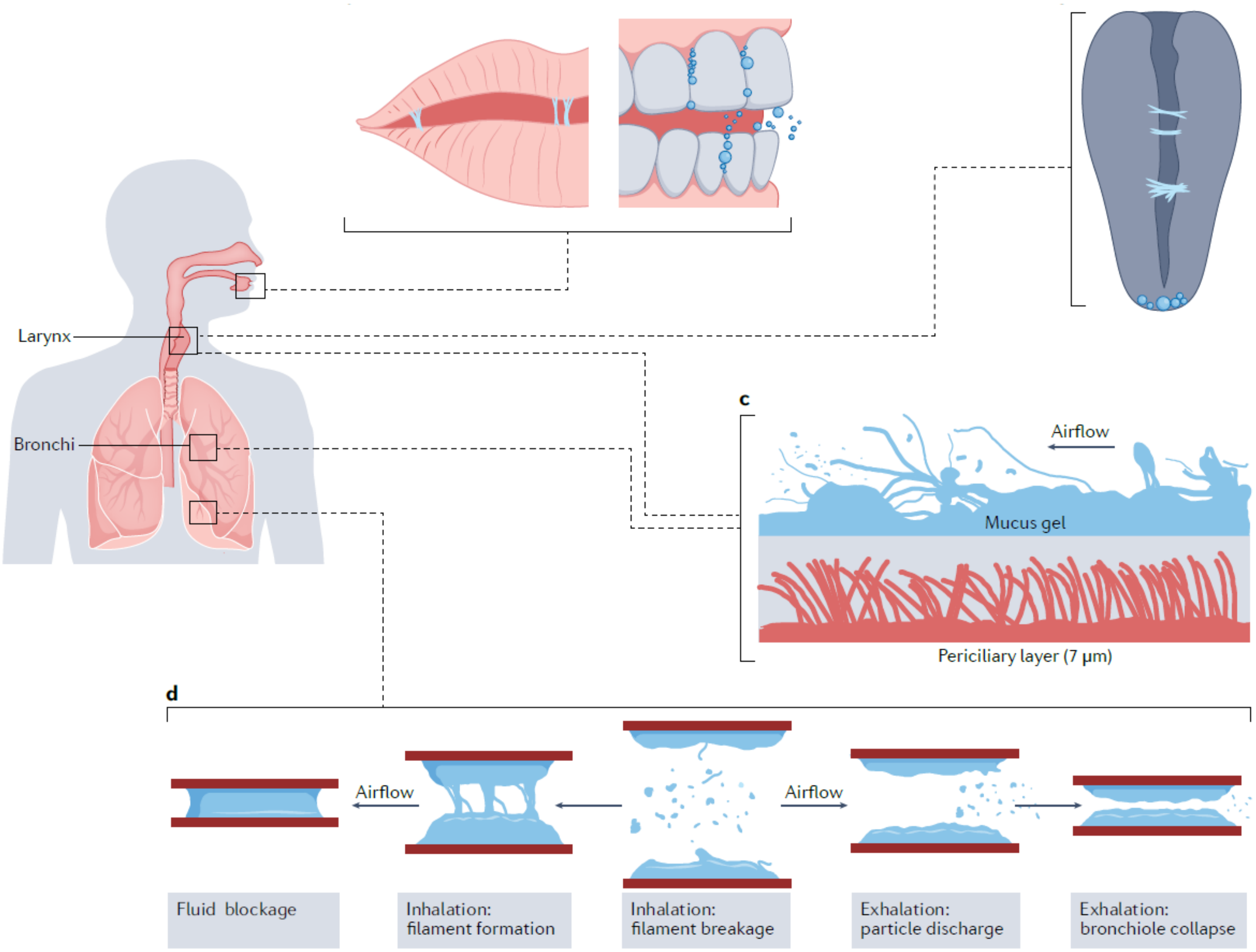
Physics, and more specifically fluid dynamics, is a critical element of the process.

The airborne transmission, from a fluid dynamics point of view is constituted of 4 steps:

1. Generation of respiratory particles
2. Emission of respiratory particles
3. Fate in the air
4. Inhalation & deposition



Respiratory particle generation

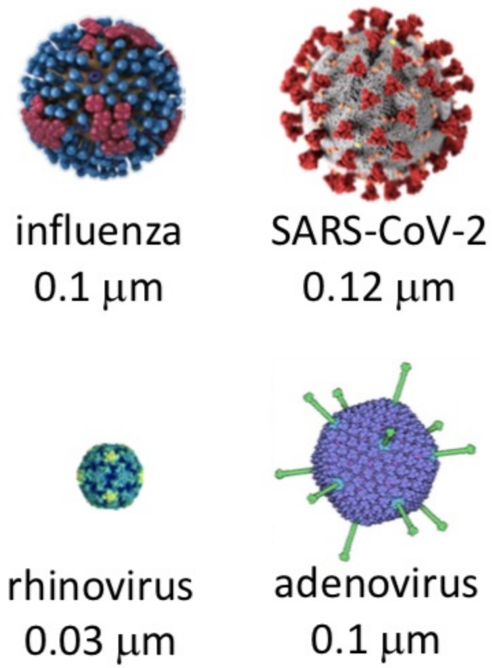


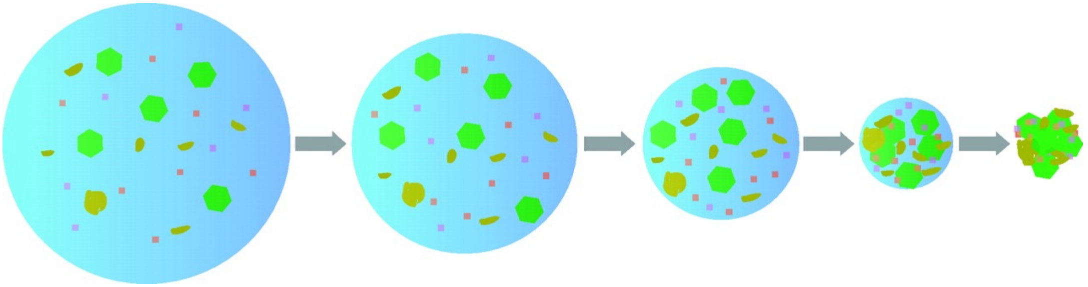
There are two known physical mechanisms to generate the particles emitted from the human respiratory tract:

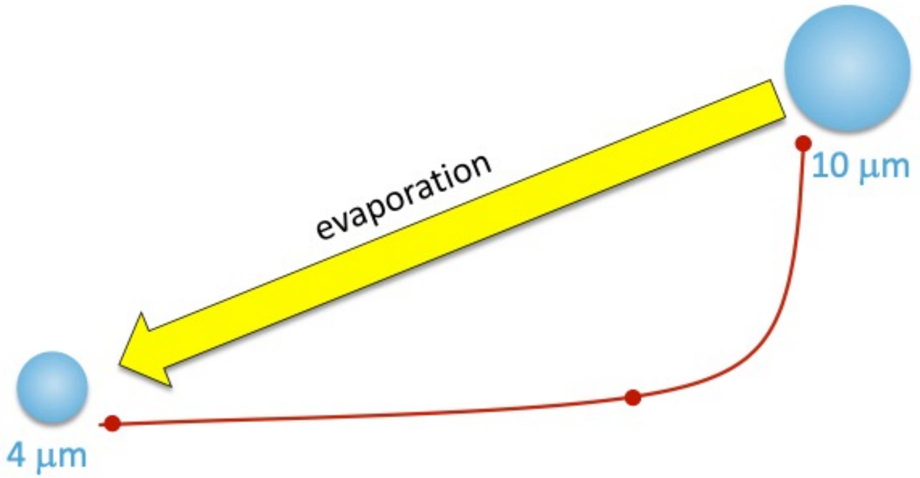
1. **turbulent aerosolization** (larynx and mouth), and the
2. **breakage or burst of a fluid film, filament or bubble** (bronchioles)

Morawska, L., Buonanno, G., Mikszewski, A. et al. The physics of respiratory particle generation, fate in the air, and inhalation. Nature Rev Phys 4, 723–734 (2022). https://doi.org/10.1038/s42254-022-00506-7

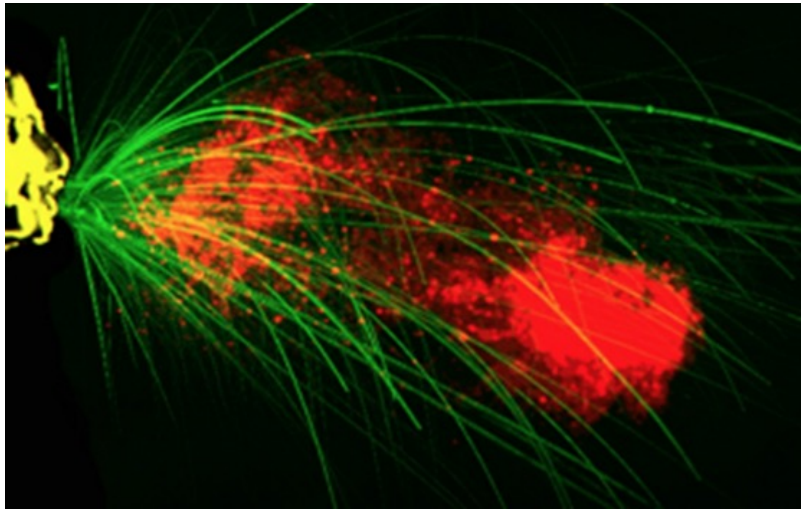
Respiratory particles contain non-volatile material including mucins, non-mucin proteins, salts and cellular debris, saliva, nasal secretions, serum and blood from oral lesions, and even food debris, as well as bacteria, viruses and fungi from an infected subject





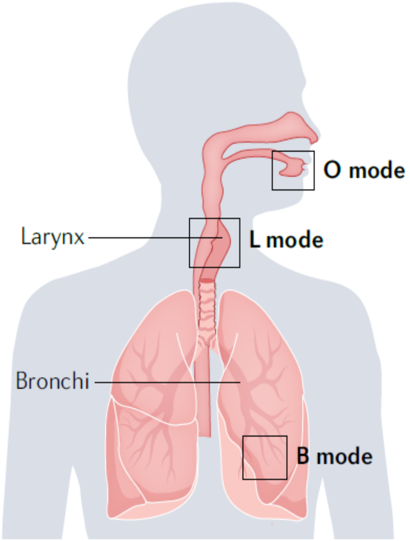


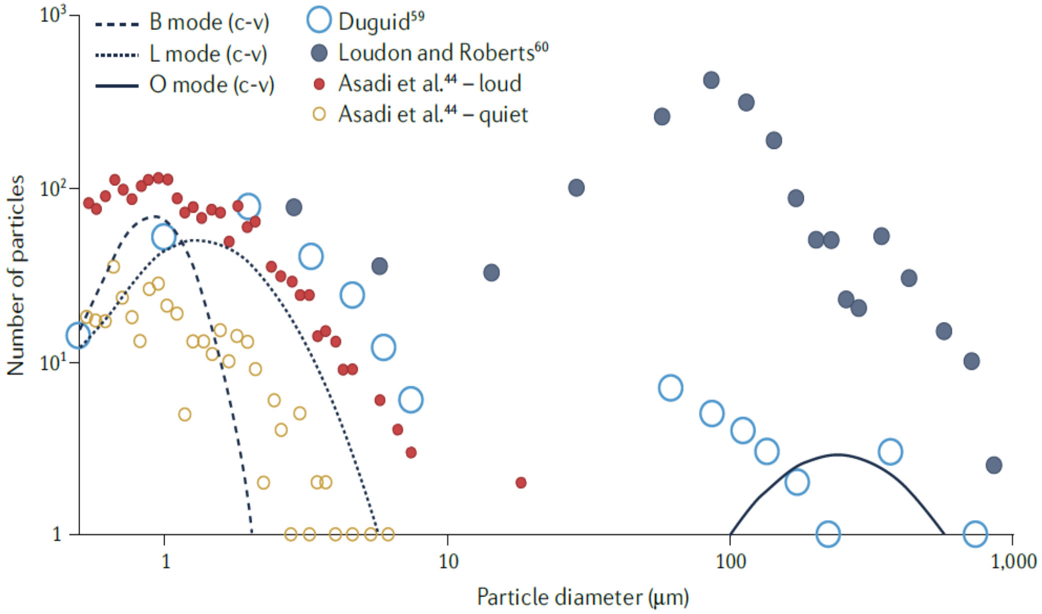
Emission of respiratory particles - The respiratory Big Bang

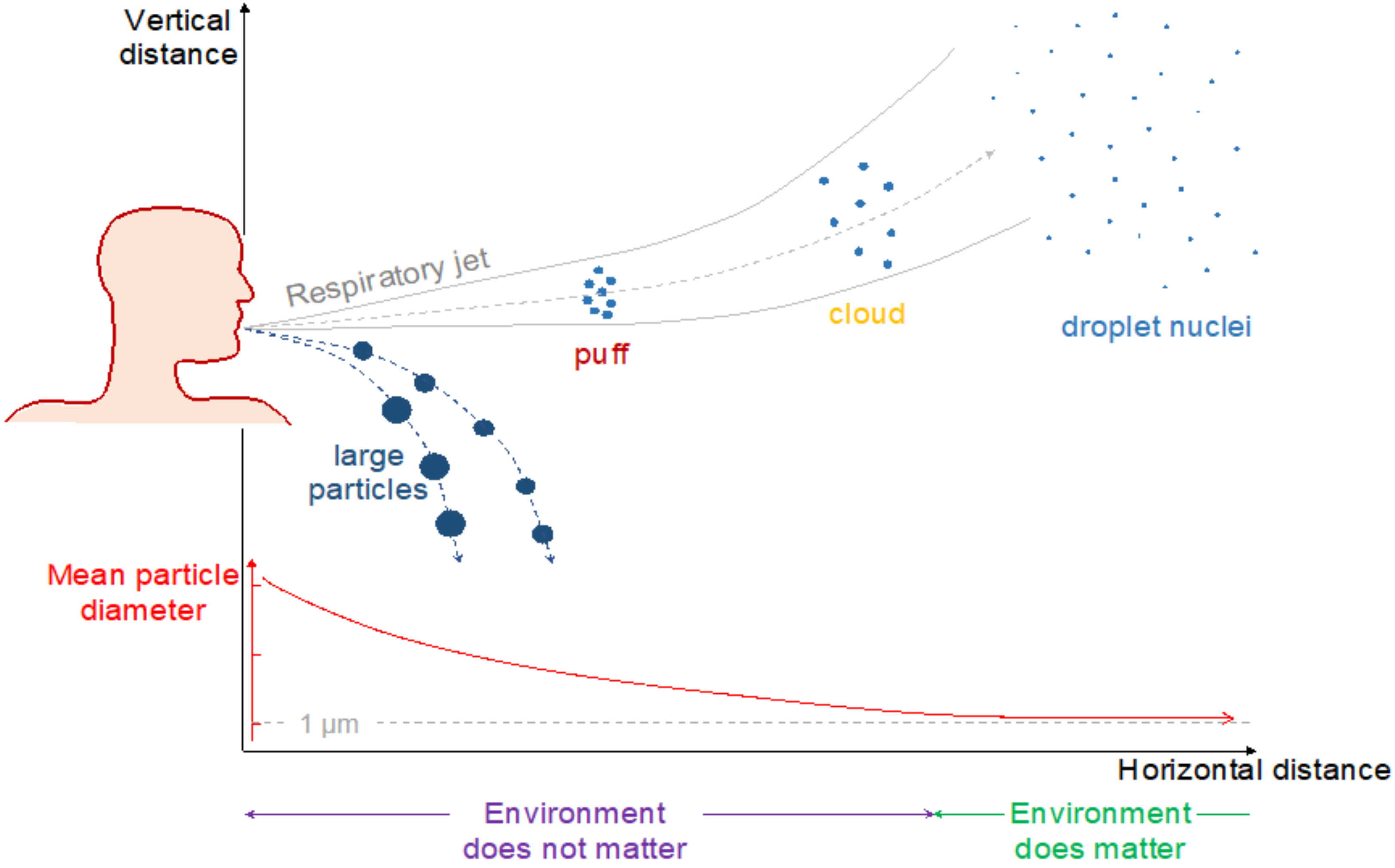


Balachandar et al., 2020. Host-to-host airborne transmission as a multiphase flow problem for science-based social distance guidelines, International Journal of Multiphase Flow 132, 103439

- the B mode from particles generated in small airway bronchioles during breathing,
- the L mode from particles generated in the larynx,
- the O mode from particles generated in the mouth.







The approach based on isolated particles represents the benchmark for public health agency guidelines.

However, it does not consider the role of the warm and moist air of the turbulent gas puff within which the particle is exhaled and which remains coherent for a short time

Morawska, Buonanno, et al. The physics of respiratory particle generation, fate in the air, and inhalation. Nat Rev Phys (2022). https://doi.org/10.1038/s42254-022-00506-7

Ways of transmission of respiratory pathogens

Inhalation transmission occurs when IPs travel through the air and enter the respiratory tract at any point along it. This type of transmission can occur with IPs of any size but, in general, the smaller the IP, the higher the probability of its deposition in the deeper parts of the human respiratory tract. Inhalation transmission can occur when IPs have travelled either a short ("conversational") or a longer distance after emission from an infected person, i.e. inhalation transmission can occur at both a short-range and long-range between the infected and susceptible persons. This term can be used synonymously with the term 'airborne transmission'.

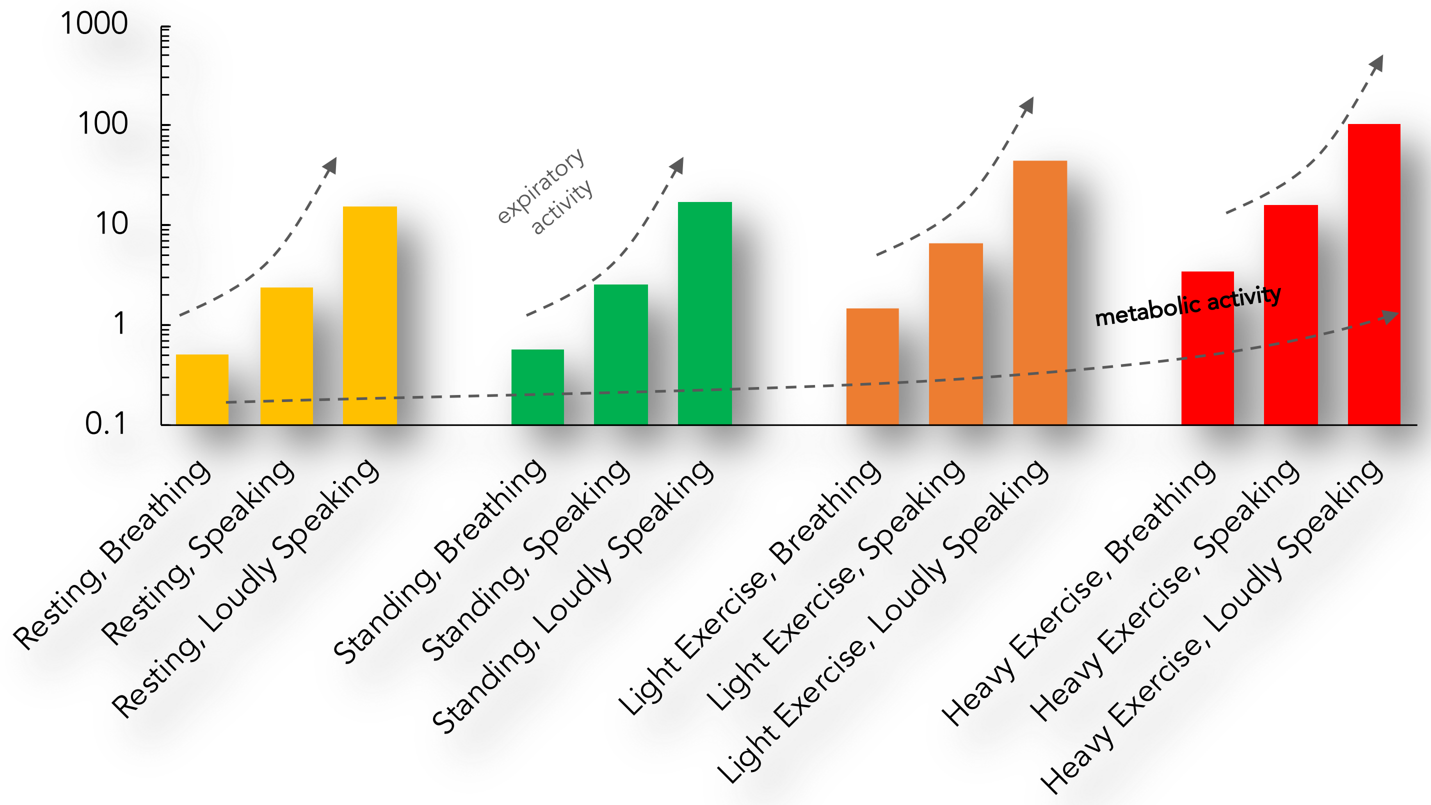
Deposition/Spray transmission could be considered a sub-type of inhalation transmission, but specifically refers to the receipt of infectious particles, IPs (usually of a larger size) by a person, having followed a short range trajectory from the infected person, and which are deposited directly onto the external mucosa of the mouth, nose or eyes.

Touch transmission (excluding direct person-to-person transfer if IPs have not travelled through the air) occurs when IPs are emitted via either inhalation or spray routes as described above, travel through the air, settle on a surface and are then transferred directly to another person when that person touches the contaminated surface and then their own mouth, nose or eyes.

A predictive approach of the infectious respiratory particles emitted

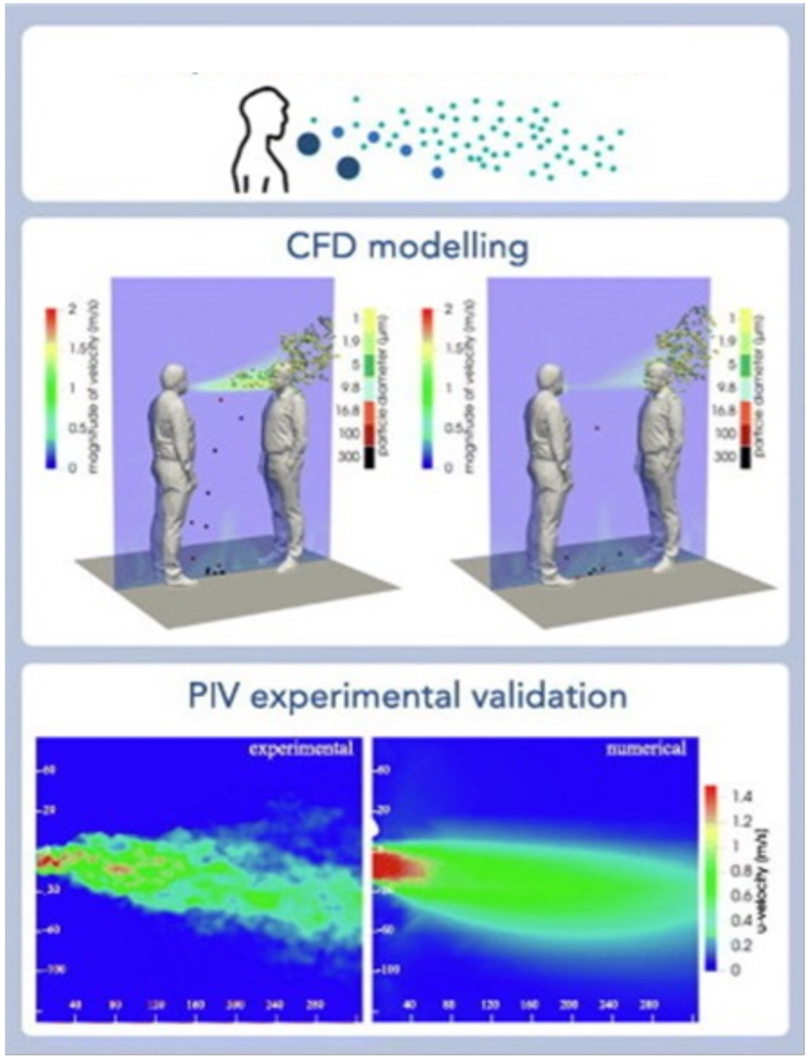
$$ER_q = c_v \cdot c_i \cdot IR \cdot V_d = c_v \cdot \frac{1}{c_{RNA} \cdot c_{PFU}} \cdot IR \cdot V_d$$

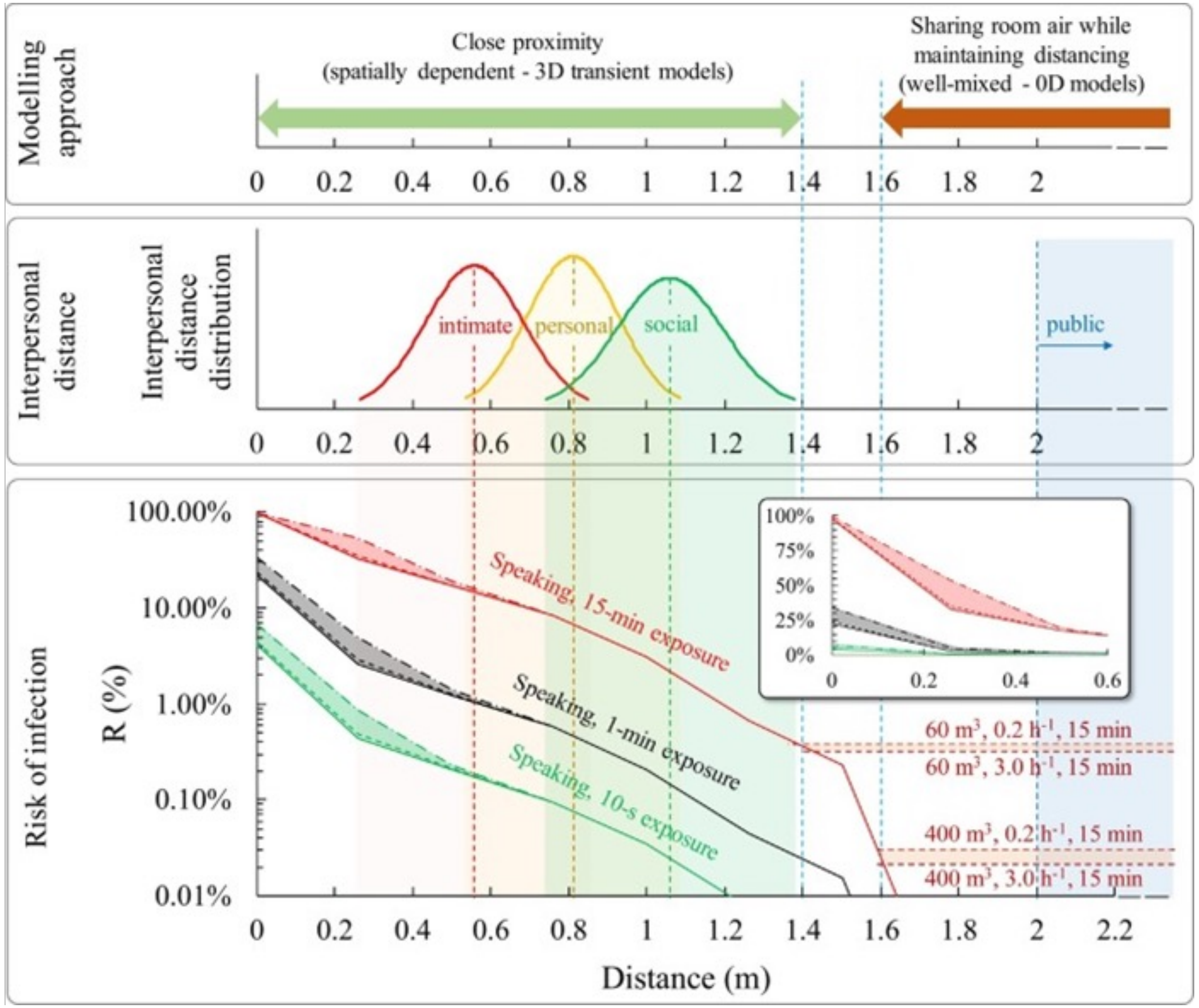
- Droplet volume emission (respiratory activity)
- Expiration flow rate (metabolic activity)
- Viral load & Minimum infectious dose



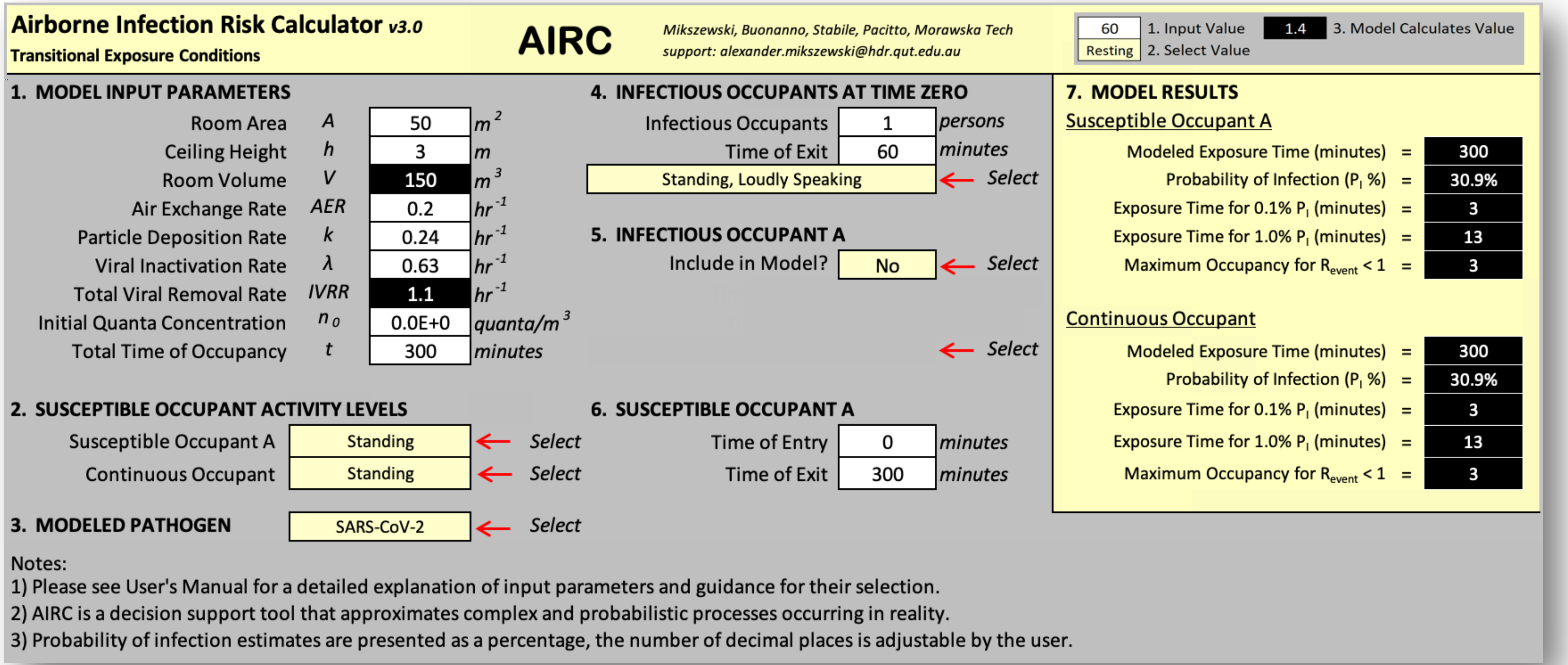
Buonanno G., Morawska L., Stabile L., 2020. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. Environment International 141 - 105794

Airborne transmission at close proximity





Cortellessa, G., Stabile, L., Arpino, F., Faleiros, D.E., van den Bos, W., Morawska, L., Buonanno, G., 2021. Close proximity risk assessment for SARS-CoV-2 infection. Science of the Total Environment, 794, 148749

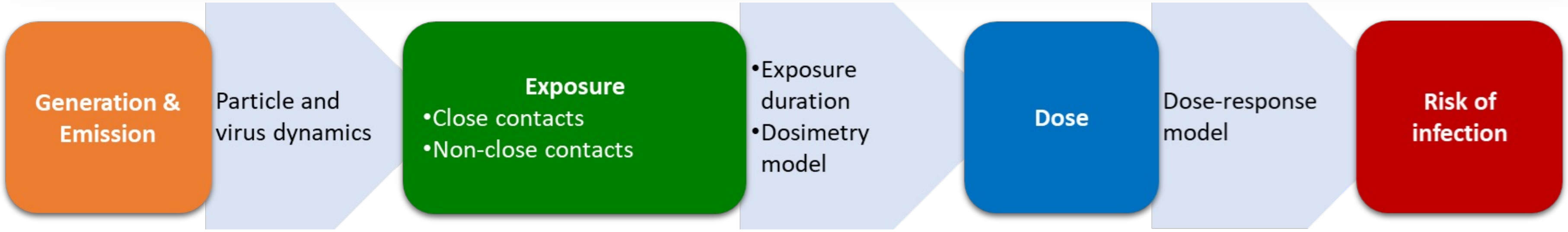


$$n(t) = n_0 e^{-IVRR \cdot t} + \frac{ER_q \cdot I}{IVRR \cdot V}\left(1 - e^{-IVRR \cdot t}\right)$$

$$D_q = IR \int_0^T n(t)dt$$

$$P_I(ER_q) = 1 - e^{-D_q}$$

$$R = \int_{ER_q} \left(P_I(ER_q) \cdot P_{ERq}\right) dER_q$$



$$Max\ Occupants\ for\ R_{event}(t) < 1 = \frac{1}{R(t)}$$

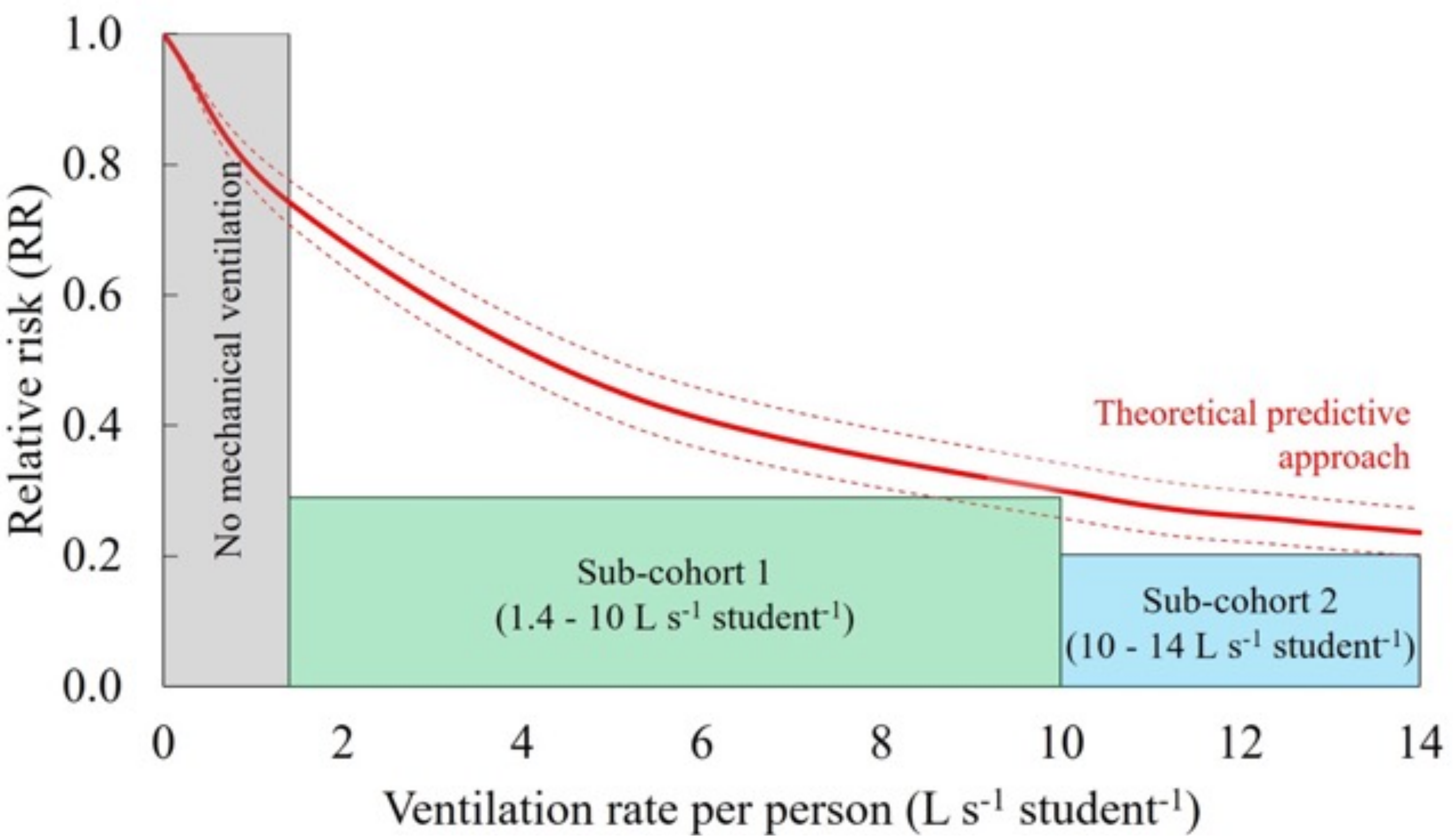
www.unicas.it/siti/laboratori/lami-laboratorio-di-misure-industriali-sezione-meccanica/airborne-infection-risk-calculator.aspx

The government of the central Italy's Marche region funded the installation of MVSs in classrooms.

316 classrooms were equipped with MVSs between 1.4 and 14 L s^{-1} $student^{-1}$.

Halley's comet type event:

1. investment in varying levels of ventilation
2. testing for infections
3. infection waves from Delta/Omicron.



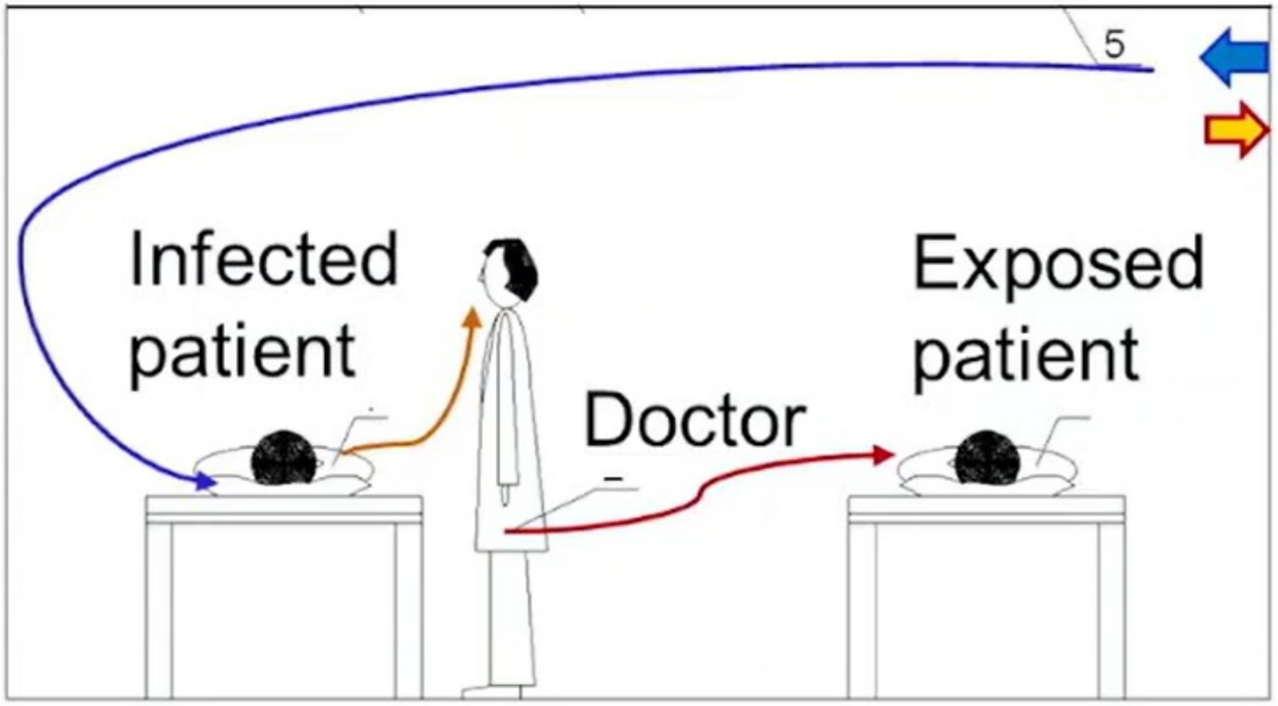
Buonanno G, Ricolfi L, Morawska L and Stabile L (2022) Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: A retrospective cohort study in Italy's Marche region. *Front. Public Health* 10:1087087. doi: 10.3389/fpubh.2022.1087087

Ventilation vs air distribution

The only recommendation cannot be to increase air exchange rates/ventilation to reduce the airborne transmission.

We have to consider also directional flows.

Directional flows can transport viruses.



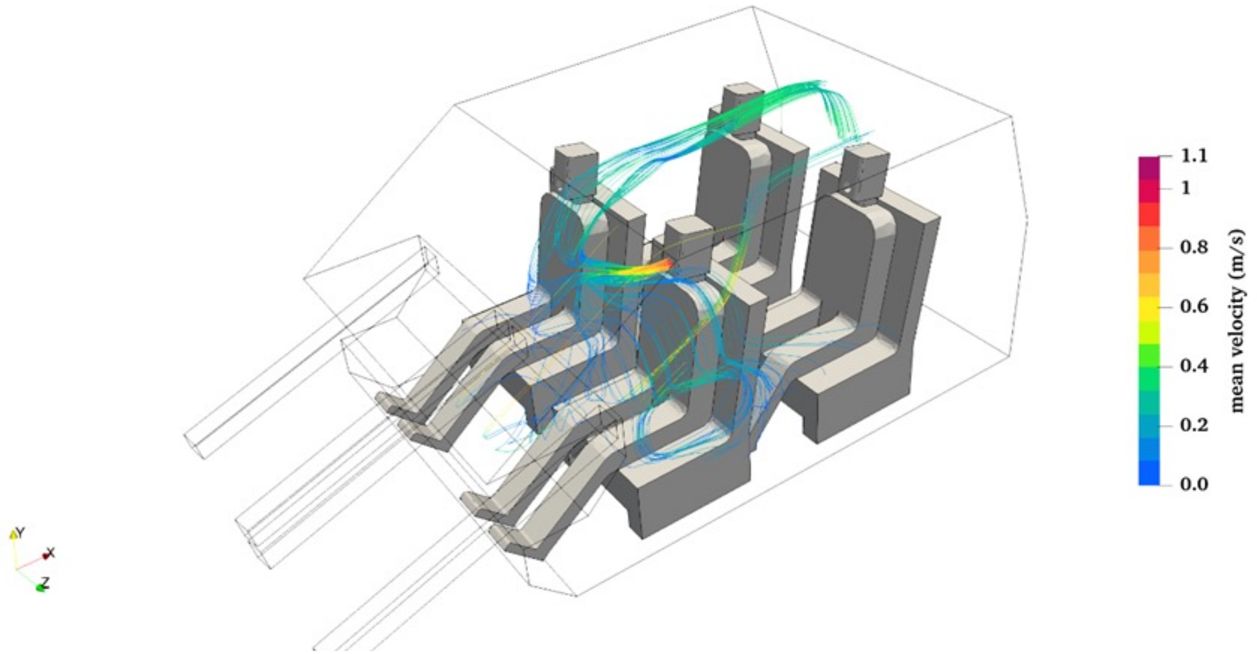
Bolashikov, Melikov et al. 2012, HVAC&R Res.; Pantelic & Tham, 2013, HVAC&R Res.,

Airborne transmission in car cabin

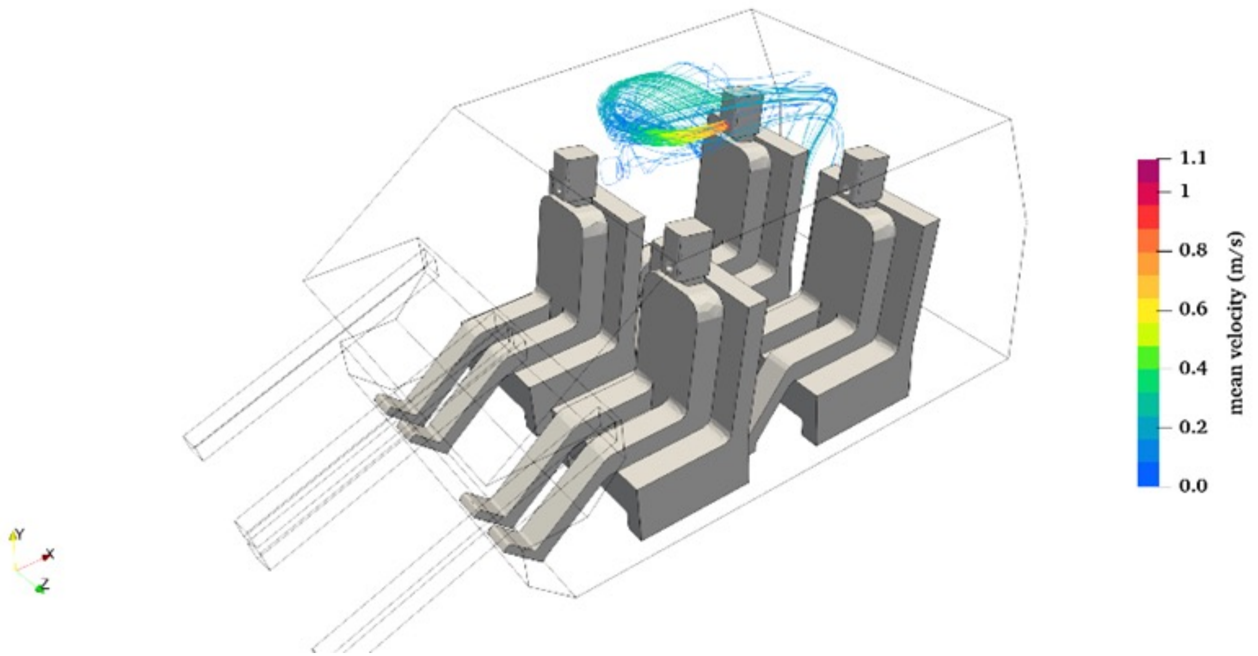
Scenarios investigated (30 min journey)	position of the infected subject	HVAC system flow rate	HVAC ventilation mode	expiratory activity of the infected subject
influence of the position of the infected subject	driver, passenger sitting on the right rear seat (passenger 3)	$Q_{50\%}$	mixed	speaking
influence of the HVAC system flow rate	driver	$Q_{10\%}$, $Q_{25\%}$, $Q_{50\%}$, $Q_{75\%}$, $Q_{100\%}$	mixed	speaking
influence of the HVAC ventilation mode	driver	$Q_{50\%}$	mixed, front, windshield defrosting	speaking

Arpino, F., Grossi, G., Cortellessa, G., Mikszewski, A., Morawska, L., Buonanno, G., Stabile, L. Risk of SARS-CoV-2 in a car cabin assessed through 3D CFD simulations (2022) Indoor Air, 32 (3), art. no. e13012

Influence of the position of the infected subject



Streamlines of the airflows (coloured by velocity) exiting the mouth of the infected driver in case of mixed ventilation mode at 50%



Streamlines of the airflows (coloured by velocity) exiting the mouth of the infected passenger #3 in case of mixed ventilation mode at 50%

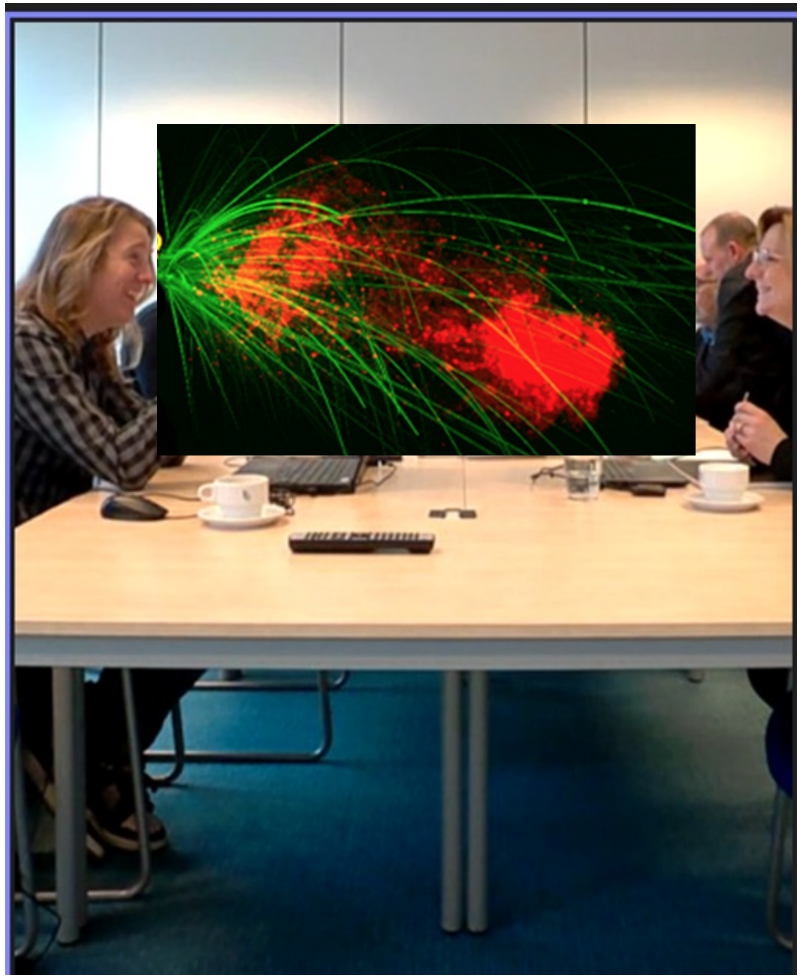
Driver infected

Susceptible subject	Inhaled volume (mL)	Individual infection risk (%) CFD	Individual infection risk (%) Well-mixed
Driver	emitter		
Passenger #1	1.89×10^{-9}	9.2%	
Passenger #2	8.68×10^{-9}	26%	42%
Passenger #3	4.49×10^{-9}	18%	

Passenger #3 infected

Susceptible subject	Inhaled volume (mL)	Individual infection risk (%) CFD	Individual infection risk (%) Well-mixed
Driver	5.17×10^{-11}	0.30%	
Passenger #1	1.42×10^{-9}	7.2%	42%
Passenger #2	1.59×10^{-11}	0.09%	
Passenger #3	emitter		

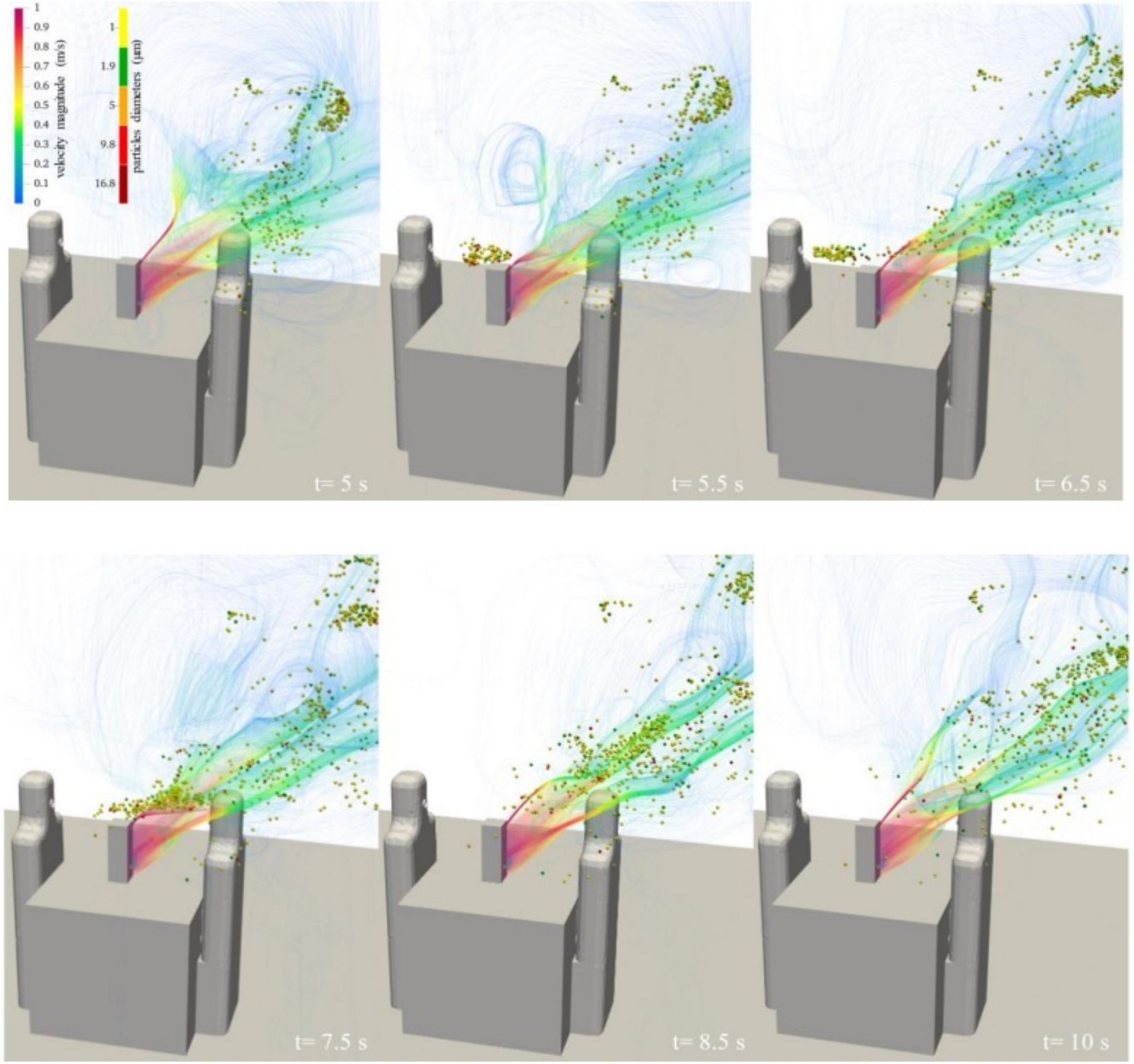
A solution for the short and long range

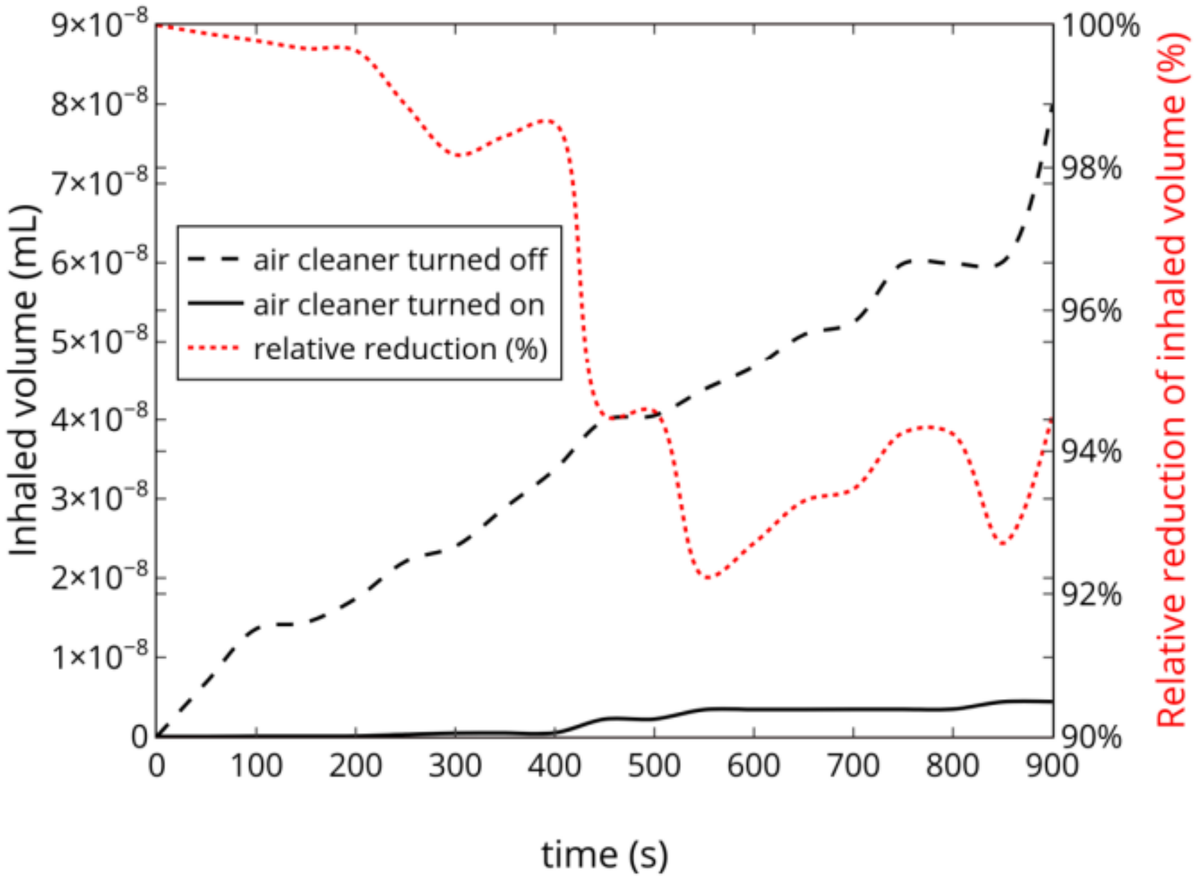


Unprotected from short range airborne transmission

Protected from short range airborne transmission

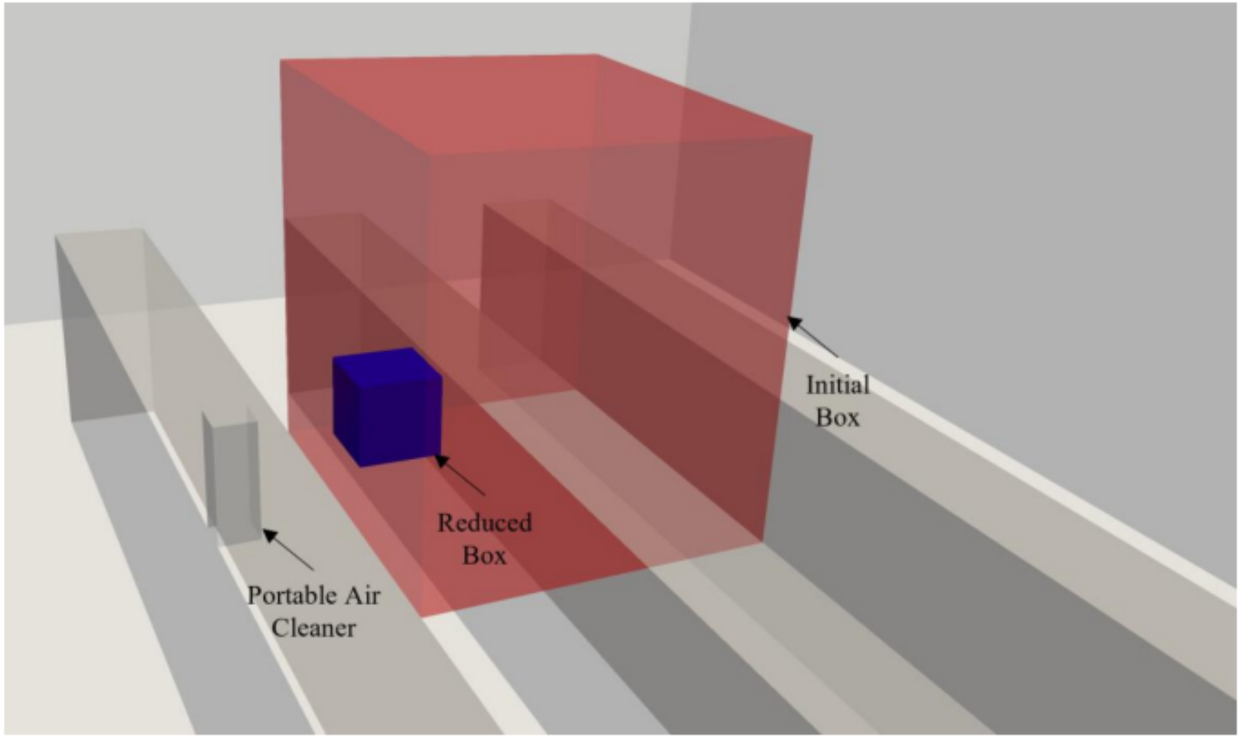
Reducing the close proximity risk – patented device





Cortellessa, G., Canale, C., Stabile, L., Grossi, G., Buonanno, G., Arpino, F. Effectiveness of a portable personal air cleaner in reducing the airborne transmission of respiratory pathogens (2023) Building and Environment, 235, art. no. 110222

Reducing the long range – patented device

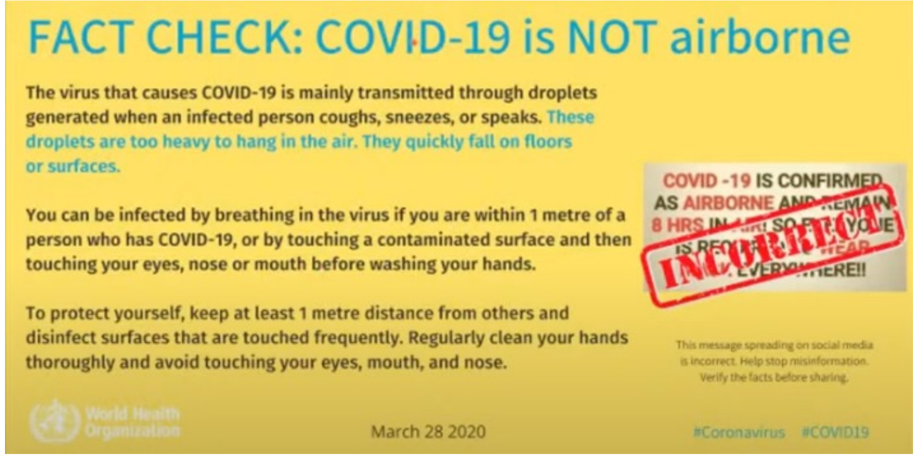


Box	Volume concentration of infectious respiratory particles (mL m^{-3}) without device	Volume concentration of infectious respiratory particles (mL m^{-3}) with device	Relative reduction of volume concentration
Initial box (1.00×1.00×0.88 m)	4.07×10^{-7}	2.08×10^{-7}	49.1%
Reduced box (0.20×0.20×0.20 m)	1.25×10^{-6}	5.95×10^{-9}	99.5%

Take home messages

We can assess short and long range airborne transmission of respiratory pathogens

We can manage short and long range infectious risk through engineering controls as ventilation and air distribution



The New York Times | https://www.nytimes.com/2021/05/07/opinion/coronavirus-airborne-transmission.html

GUEST ESSAY

Why Did It Take So Long to Accept the Facts About Covid?

May 7, 2021

By Zeynep Tufekci

Dr. Tufekci is a contributing Opinion writer who has extensively examined the Covid-19 pandemic.

Paradigm shift to combat indoor respiratory infections

All indoor environments represent the natural habitat for humans and require control of:

1. thermal comfort,
2. odours,
3. air quality,
4. energy consumption but also
5. respiratory infections

POLICY FORUM

Science

INFECTIOUS DISEASE

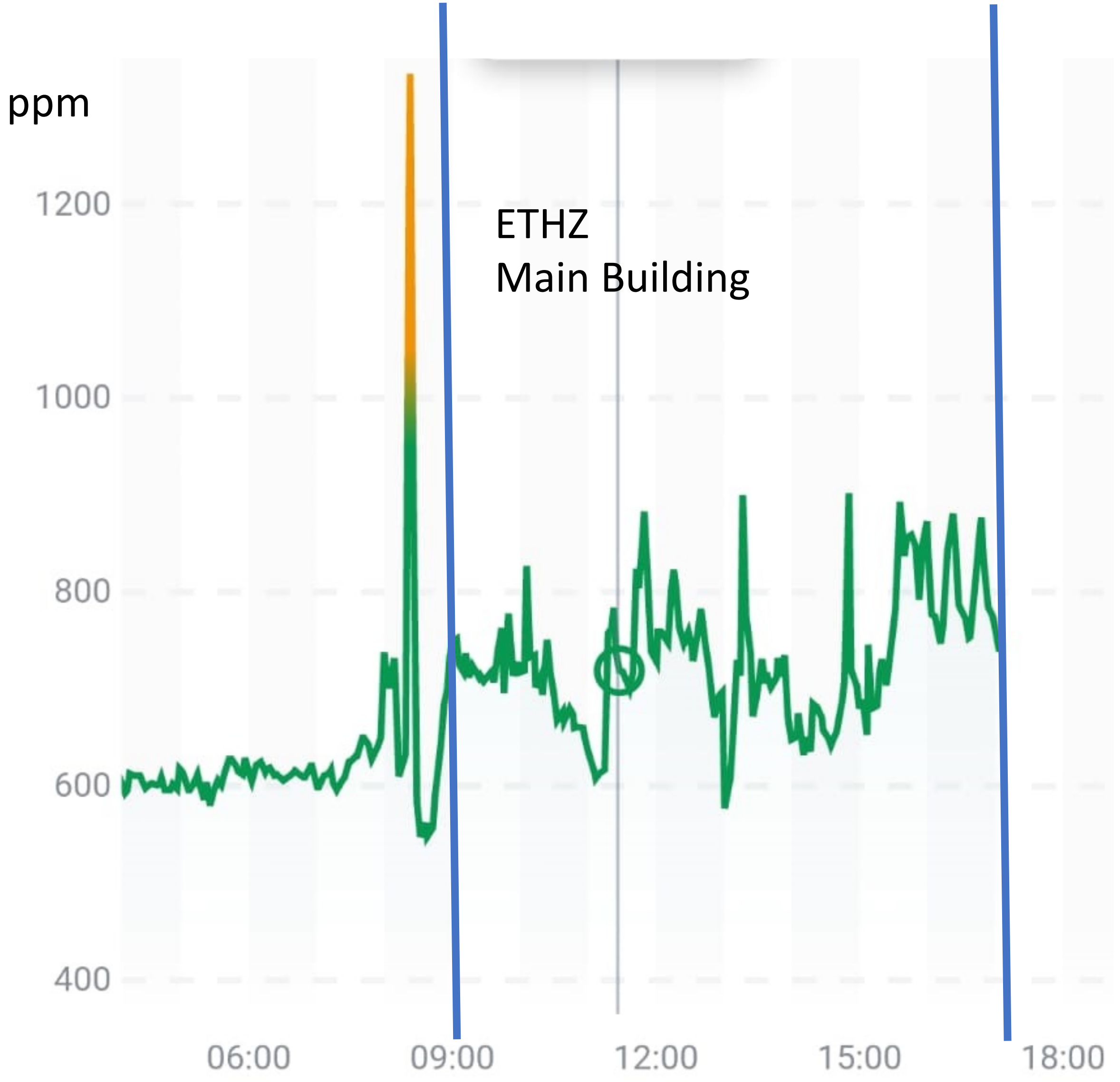
A paradigm shift to combat indoor respiratory infection

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

Science, 372 (6543), • DOI: 10.1126/science.abg2025

Many thanks for your attention



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