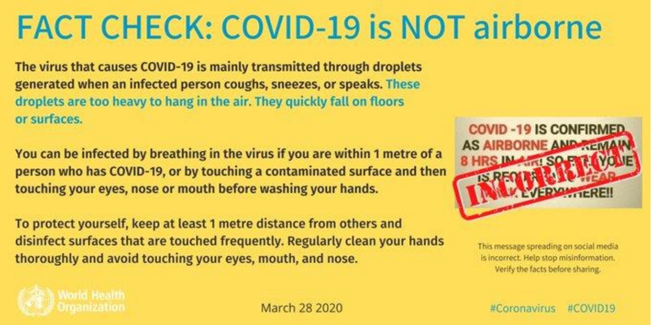
Quantitative Risk Assessment for Airborne Transmission of Disease

COVID-19 Guidance: early 2020



FACT CHECK: COVID-19 is NOT airborne

The virus that causes COVID-19 is mainly transmitted through droplets generated when an infected person coughs, sneezes, or speaks. These droplets are too heavy to hang in the air. They quickly fall on floors or surfaces.

You can be infected by breathing in the virus if you are within 1 metre of a person who has COVID-19, or by touching a contaminated surface and then touching your eyes, nose or mouth before washing your hands.

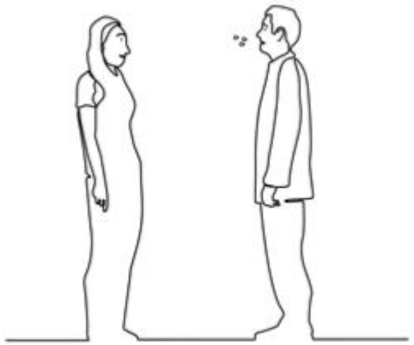
To protect yourself, keep at least 1 metre distance from others and disinfect surfaces that are touched frequently. Regularly clean your hands thoroughly and avoid touching your eyes, mouth, and nose.

This message spreading on social media is incorrect. Help stop misinformation. Verify the facts before sharing.

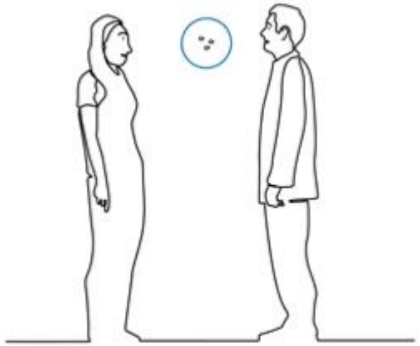
World Health Organization

March 28 2020

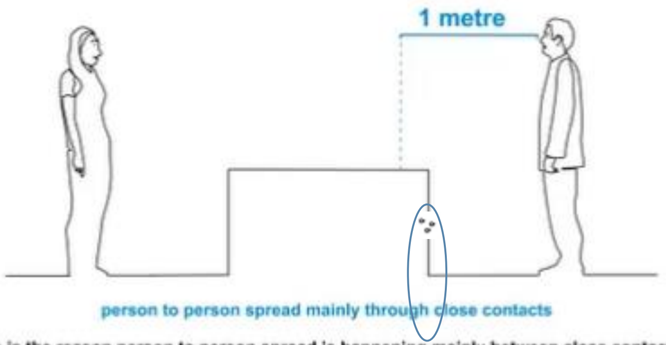
#Coronavirus #COVID19



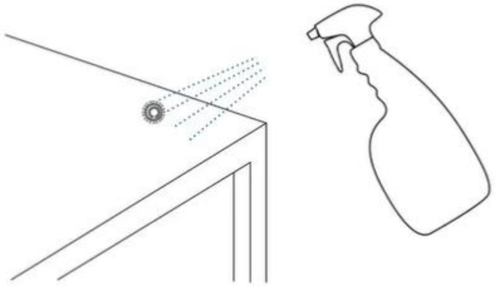
It is spread from person to person mainly through the droplets produced when an infected person speaks, coughs or sneezes.



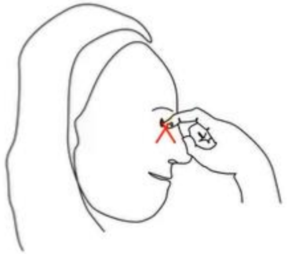
These droplets can land in the mouths or noses of people who are nearby.



This is the reason person to person spread is happening mainly between close contacts.

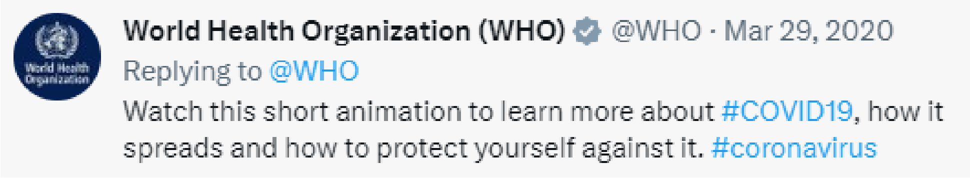


So it is wise to clean surfaces regularly particularly in the vicinity of people infected with COVID-19.



You should therefore avoid touching your eyes, nose or mouth, since contaminated hands can transfer the virus from the surface to yourself.

The most effective way to prevent the spread of the new coronavirus is to clean your hands frequently with an alcohol-based hand rub or soap and water.



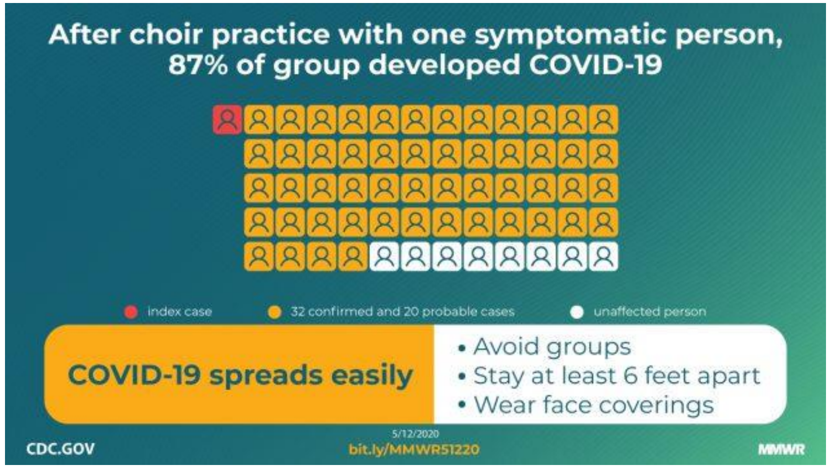
World Health Organization (WHO) @WHO · Mar 29, 2020

Replying to @WHO

Watch this short animation to learn more about #COVID19, how it spreads and how to protect yourself against it. #coronavirus

https://twitter.com/WHO/status/1243972193169616898?lang=en

Problems with the Guidance: Evidence of Superspreading Events



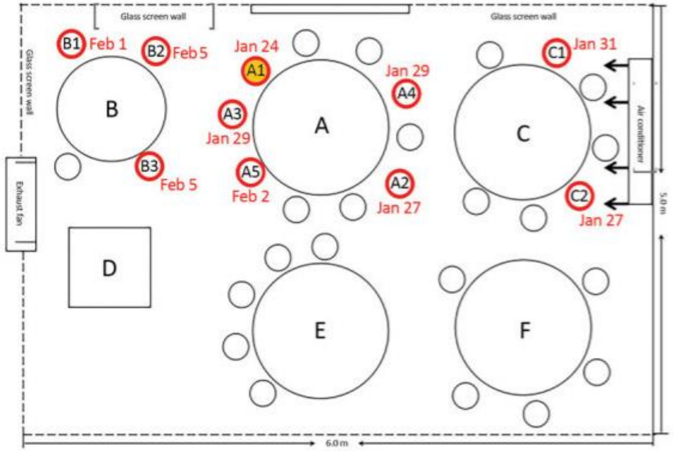
After choir practice with one symptomatic person, 87% of group developed COVID-19

● index case ● 32 confirmed and 20 probable cases ○ unaffected person

COVID-19 spreads easily

- Avoid groups
- Stay at least 6 feet apart
- Wear face coverings

CDC.GOV 5/12/2020 bit.ly/MMWR51220 MMWR



Lu J, Gu J, Li K, et al. COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. Emerg Infect Dis. 2020;26(7):1628-1631. doi:10.3201/eid2607.200764

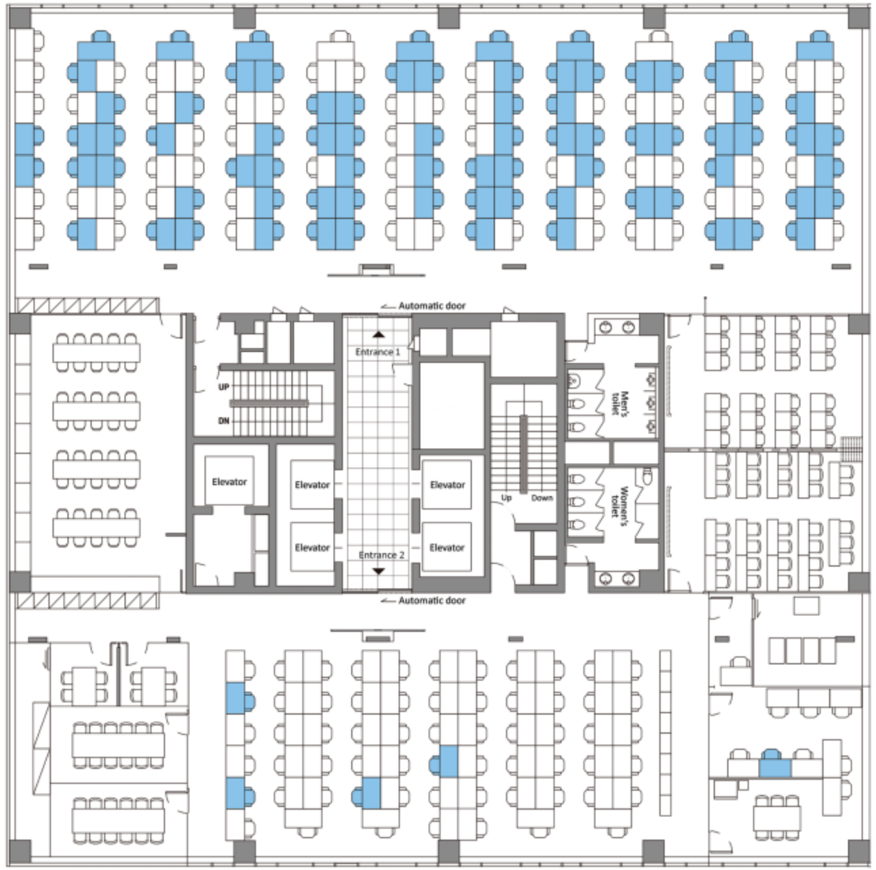
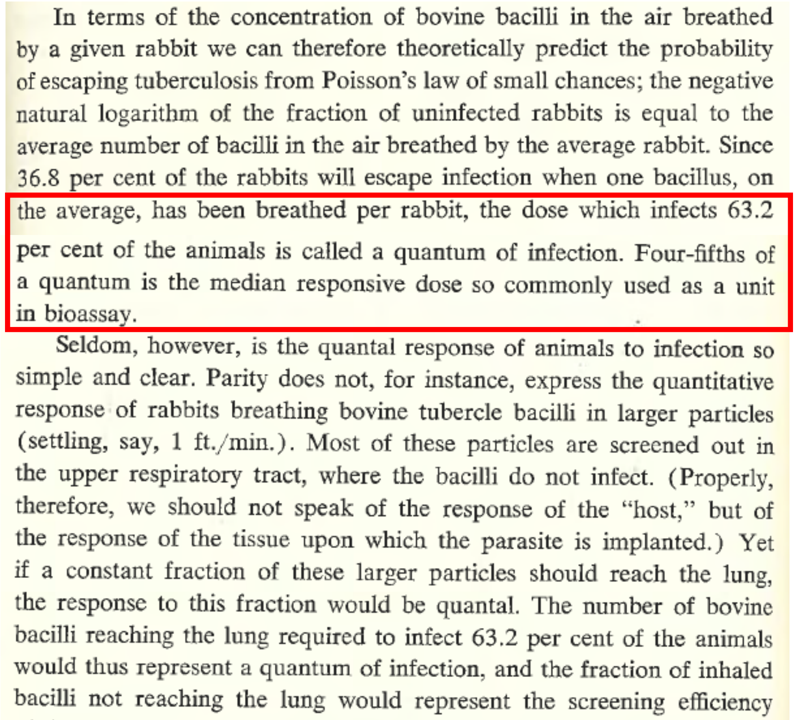


Figure 2. Floor plan of the 11th floor of building X, site of a coronavirus disease outbreak, Seoul, South Korea, 2020. Blue indicates the seating places of persons with confirmed cases.

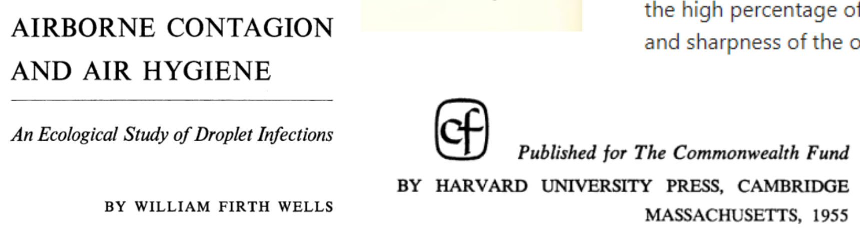
1668 Emerging Infectious Diseases • www.cdc.gov/eid • Vol. 26, No. 8, August 2020

A "Quantum of Infection" (Wells, 1955; Riley et al., 1978)



In terms of the concentration of bovine bacilli in the air breathed by a given rabbit we can therefore theoretically predict the probability of escaping tuberculosis from Poisson's law of small chances; the negative natural logarithm of the fraction of uninfected rabbits is equal to the average number of bacilli in the air breathed by the average rabbit. Since 36.8 per cent of the rabbits will escape infection when one bacillus, on the average, has been breathed per rabbit, the dose which infects 63.2 per cent of the animals is called a quantum of infection. Four-fifths of a quantum is the median responsive dose so commonly used as a unit in bioassay.

Seldom, however, is the quantal response of animals to infection so simple and clear. Parity does not, for instance, express the quantitative response of rabbits breathing bovine tubercle bacilli in larger particles (settling, say, 1 ft./min.). Most of these particles are screened out in the upper respiratory tract, where the bacilli do not infect. (Properly, therefore, we should not speak of the response of the "host," but of the response of the tissue upon which the parasite is implanted.) Yet if a constant fraction of these larger particles should reach the lung, the response to this fraction would be quantal. The number of bovine bacilli reaching the lung required to infect 63.2 per cent of the animals would thus represent a quantum of infection, and the fraction of inhaled bacilli not reaching the lung would represent the screening efficiency of the upper respiratory tract against particles of the larger aerodynamic dimension.

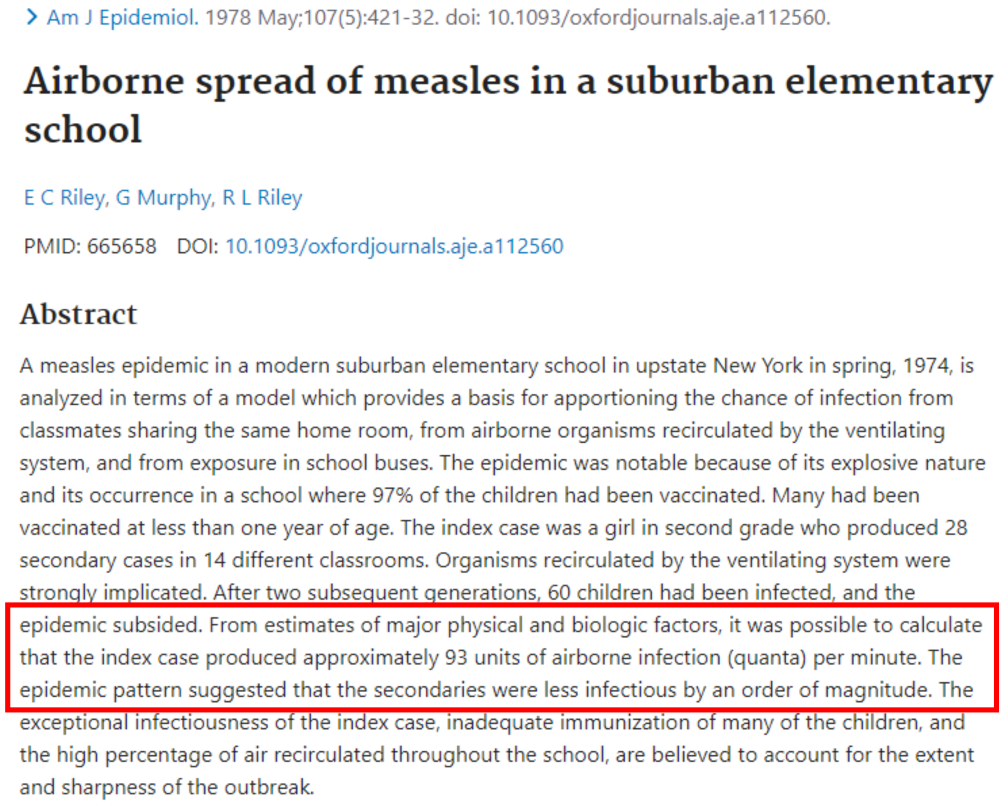


AIRBORNE CONTAGION
AND AIR HYGIENE

An Ecological Study of Droplet Infections

BY WILLIAM FIRTH WELLS

Published for The Commonwealth Fund
BY HARVARD UNIVERSITY PRESS, CAMBRIDGE
MASSACHUSETTS, 1955



› Am J Epidemiol. 1978 May;107(5):421-32. doi: 10.1093/oxfordjournals.aje.a112560.

Airborne spread of measles in a suburban elementary school

E C Riley, G Murphy, R L Riley

PMID: 665658 DOI: 10.1093/oxfordjournals.aje.a112560

Abstract

A measles epidemic in a modern suburban elementary school in upstate New York in spring, 1974, is analyzed in terms of a model which provides a basis for apportioning the chance of infection from classmates sharing the same home room, from airborne organisms recirculated by the ventilating system, and from exposure in school buses. The epidemic was notable because of its explosive nature and its occurrence in a school where 97% of the children had been vaccinated. Many had been vaccinated at less than one year of age. The index case was a girl in second grade who produced 28 secondary cases in 14 different classrooms. Organisms recirculated by the ventilating system were strongly implicated. After two subsequent generations, 60 children had been infected, and the epidemic subsided. From estimates of major physical and biologic factors, it was possible to calculate that the index case produced approximately 93 units of airborne infection (quanta) per minute. The epidemic pattern suggested that the secondaries were less infectious by an order of magnitude. The exceptional infectiousness of the index case, inadequate immunization of many of the children, and the high percentage of air recirculated throughout the school, are believed to account for the extent and sharpness of the outbreak.

Buonanno et al. (2020): The Predictive Estimation Approach

$$ER_q = c_v \cdot c_i \cdot V_{br} \cdot N_{br} \cdot \int_0^{10\mu m} N_d(D) \cdot dV_d(D)$$

ER_q – quanta emission rate

c_v - the viral load in the sputum (RNA copies mL^{-1})
c_i - a conversion factor defined as the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies,
V_{br} - the volume of exhaled air per breath (cm^3; also known as tidal volume),
N_{br} - the breathing rate (breath h^{-1}),
N_d - the droplet number concentration (part. cm^{-3}),
$V_d(D)$ - the volume of a single droplet (mL) as a function of the droplet diameter (D). (determined based of experimental data by (Morawska et al., 2009))

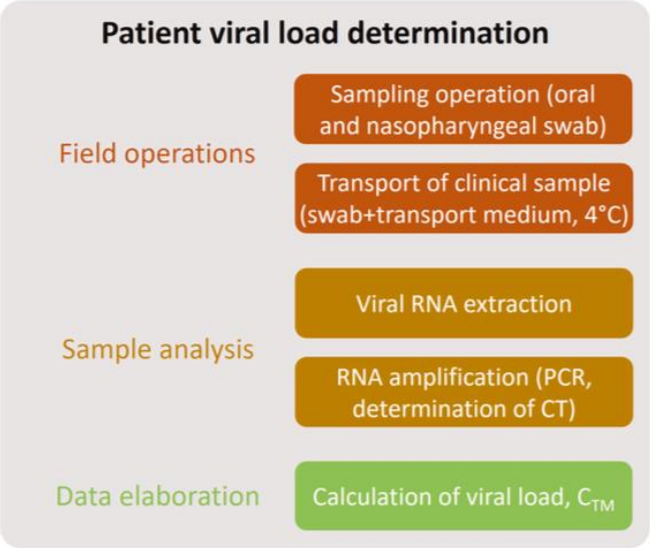
Buonanno G, Stabile L, Morawska L. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environ Int*. 2020;141:105794. doi:10.1016/j.envint.2020.105794

Validation of the modeling approach

We have performed an experimental analysis measuring SARS-CoV-2 RNA copies in airborne particles sampled in a control hospital room occupied by an infected subject whose viral load was also measured.

Experiments were performed for two different respiratory activities: breathing and speaking.

In order to estimate the metrological compatibility, the uncertainty budget for both the experimental method and the theoretical approach was calculated.

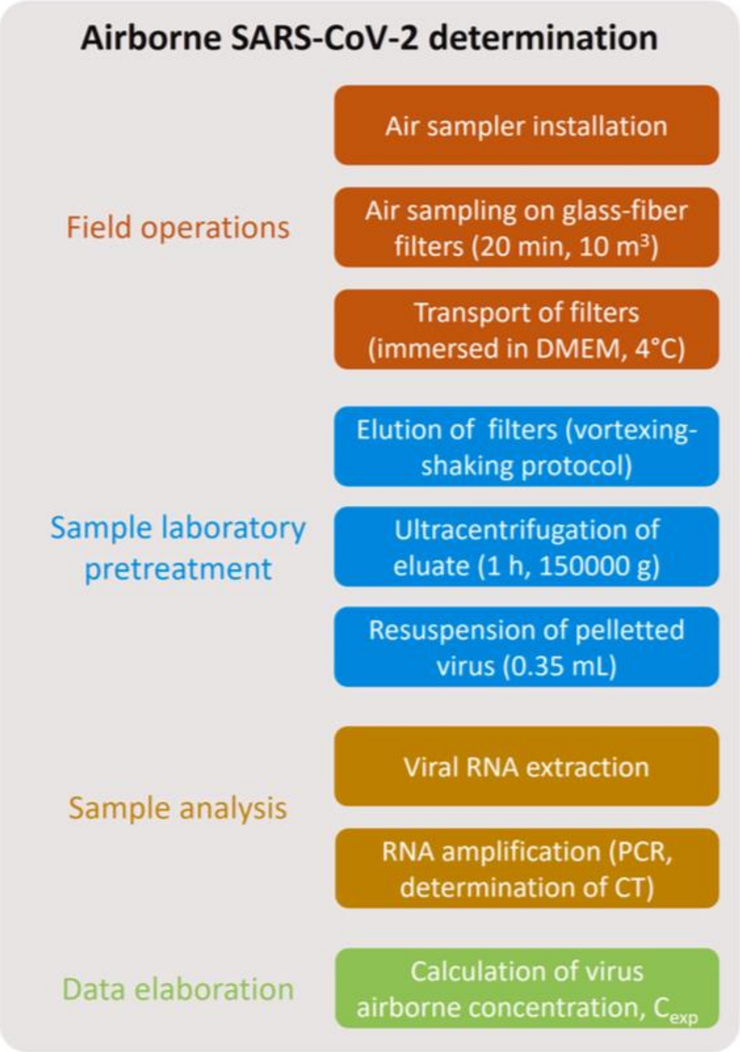


Patient viral load determination

Field operations
- Sampling operation (oral and nasopharyngeal swab)
- Transport of clinical sample (swab+transport medium, 4°C)

Sample analysis
- Viral RNA extraction
- RNA amplification (PCR, determination of CT)

Data elaboration
- Calculation of viral load, C_{TM}



Airborne SARS-CoV-2 determination

Field operations
- Air sampler installation
- Air sampling on glass-fiber filters (20 min, 10 m^3)
- Transport of filters (immersed in DMEM, 4°C)

Sample laboratory pretreatment
- Elution of filters (vortexing-shaking protocol)
- Ultracentrifugation of eluate (1 h, 150000 g)
- Resuspension of pelletted virus (0.35 mL)

Sample analysis
- Viral RNA extraction
- RNA amplification (PCR, determination of CT)

Data elaboration
- Calculation of virus airborne concentration, C_{exp}

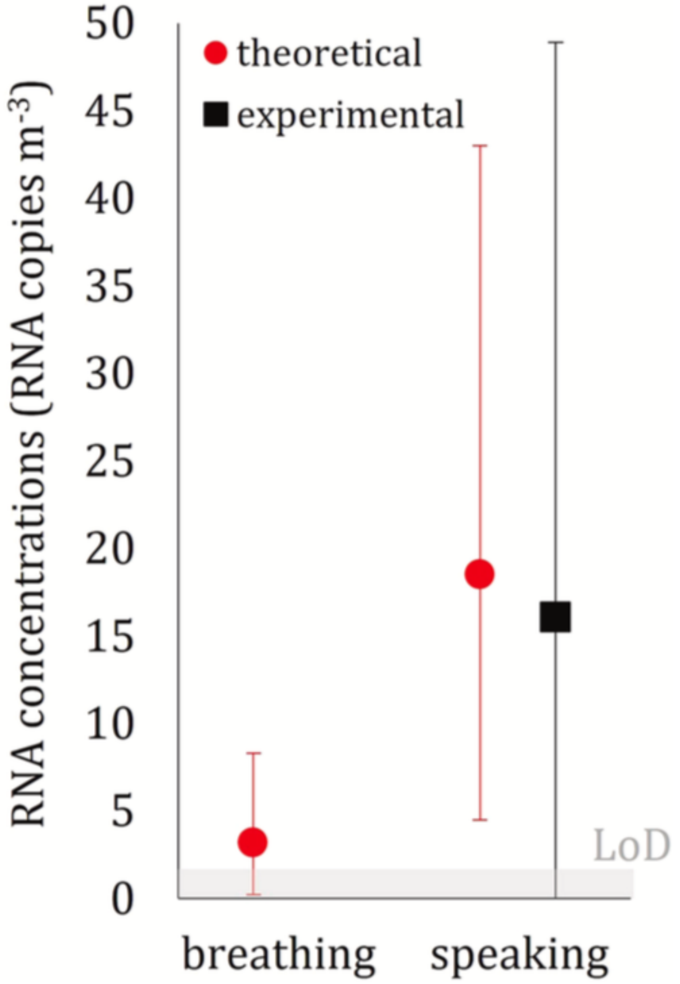
Buonanno G et al. Link between SARS-CoV-2 emissions and airborne concentrations: Closing the gap in understanding. J Hazard Mater. (2022) 428:128279. doi: 10.1016/j.jhazmat.2022.128279


SARS-
COV-2

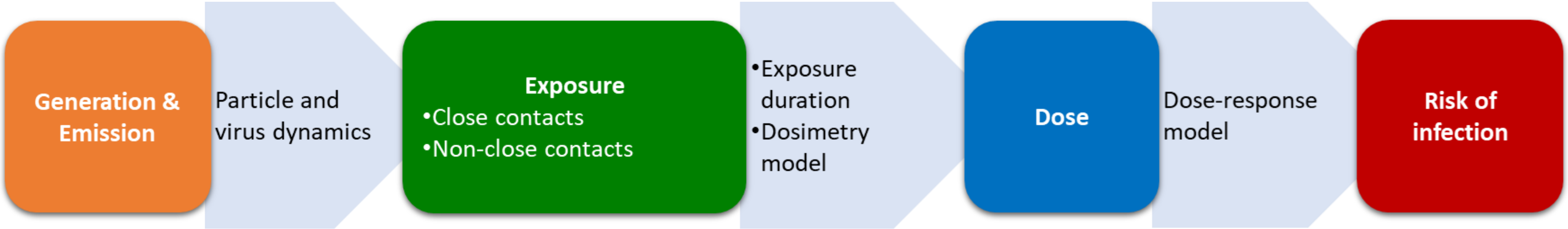
Validation of the modeling approach

A direct link between emission and airborne concentration was demonstrated when the subject was speaking.

The uncertainty budget of the theoretical approach identified the volume particle emission (if the viral load is measured) as the main contributor to the uncertainty.



Buonanno G et al. Link between SARS-CoV-2 emissions and airborne concentrations: Closing the gap in understanding. J Hazard Mater. (2022) 428:128279. doi: 10.1016/j.jhazmat.2022.128279



Generation & Emission

Particle and virus dynamics

Exposure

- Close contacts
- Non-close contacts

- Exposure duration
- Dosimetry model

Dose

Dose-response model

Risk of infection

Exposure to viral concentration *n*(*t*)

$$n(t) = \frac{E}{(AER + k + \lambda) \cdot V} \cdot \left(1 - e^{-(AER+k+\lambda)\cdot t}\right)$$

Dose received by exposed persons

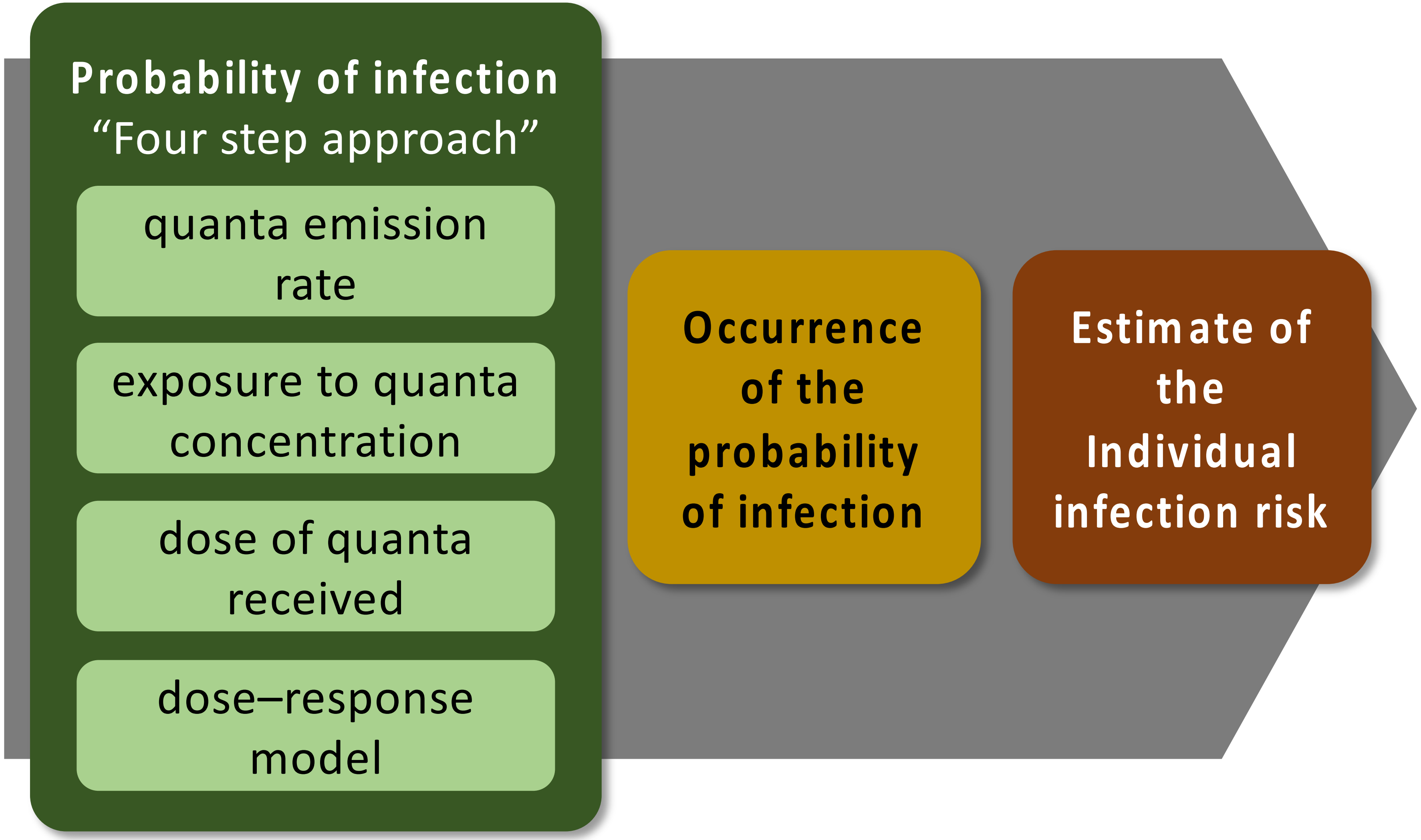
$$D_q = IR \int_0^T n(t)dt$$

Risk of infection

$$R = 1 - e^{-D_q}$$

G. Buonanno, L. Morawska, L. Stabile, Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications, Environment International 145, 2020, 106112, ISSN 0160-4120,

Four steps approach



Probability of infection
“Four step approach”

- quanta emission rate
- exposure to quanta concentration
- dose of quanta received
- dose–response model

Occurrence of the probability of infection

Estimate of the Individual infection risk

Buonanno et al., 2020. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications, Environment Int. 145 – 106112

Retrospective Cohort Study

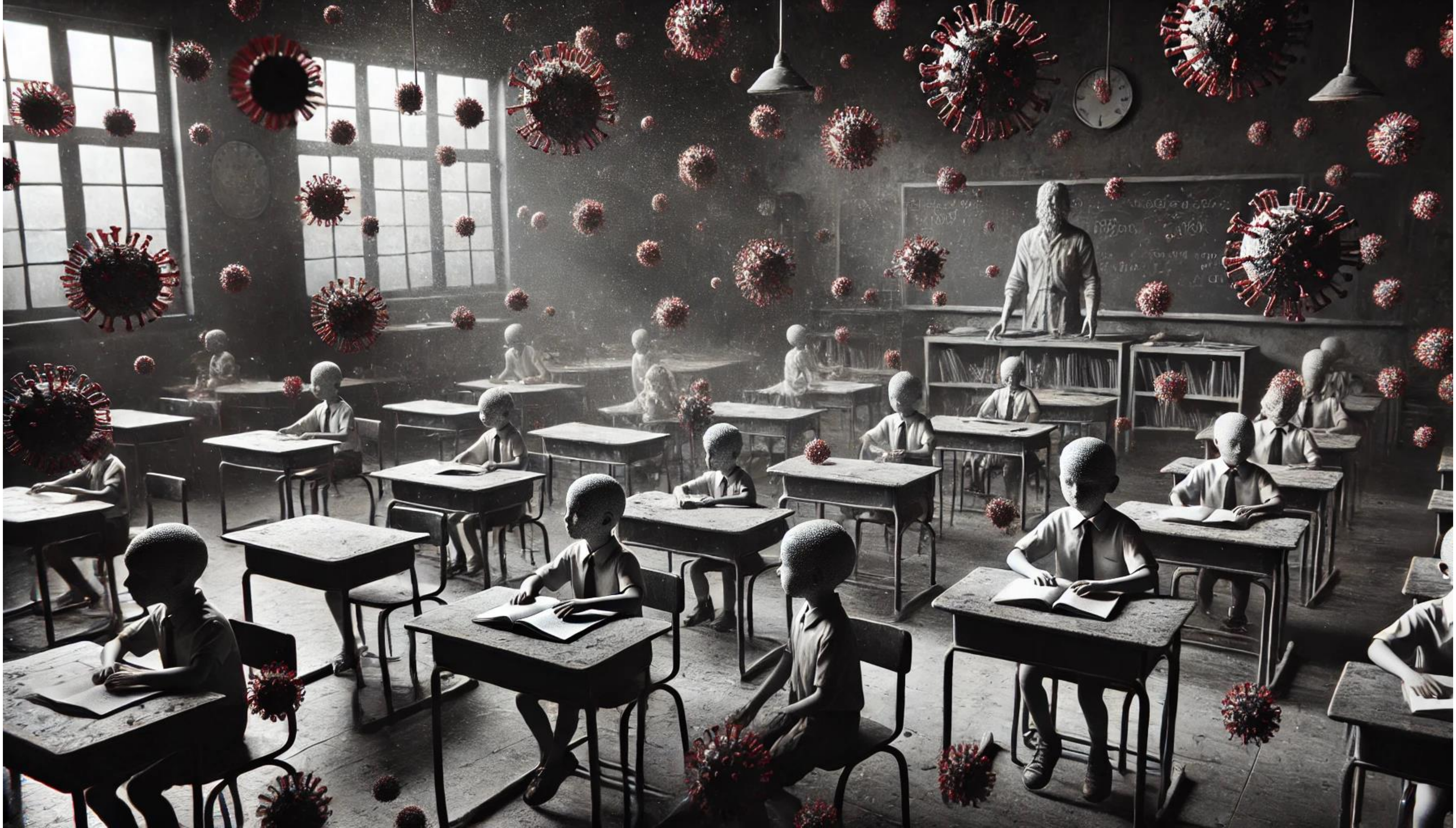
The government of the central Italy's Marche region on March 2021 launched a 9 M€ call to fund the installation of MVSs in classrooms to prevent the airborne transmission of SARS-CoV-2 and limit the adoption of distance learning solutions.

There were a total of 10 441 classrooms with an average occupancy of 20 students per classroom. 10 125 classrooms relied on natural ventilation (i.e. ventilation due to the leakages of the building and to the manual opening of the windows) while 316 were equipped with MVSs.

The maximum (nominal) air flow rates of the MVSs installed in the different classrooms ranged between 100 to 1000 $m^3 h^{-1}$ (with 25th, 50th, and 75th percentiles equal to 360 $m^3 h^{-1}$, 600 $m^3 h^{-1}$, and 800 $m^3 h^{-1}$, respectively) resulting in a ventilation rate per person between 1.4 and 14 L s^{-1} $student^{-1}$.

In order to stratify the analysis, we have also introduced two sub-cohorts: i) the sub-cohort 1 represents the classrooms with MVSs characterized by a ventilation rate per person between 1.4 and 10 L s^{-1} $student^{-1}$ that meets the standard requirements of indoor air quality, ii) the sub-cohort 2 includes classrooms with a ventilation rate per person >10 L s^{-1} $student^{-1}$ and up to 14 L s^{-1} $student^{-1}$ and it could represent a health-based ventilation to protect from airborne transmission.

Buonanno et al., Increasing ventilation reduces the SARS-CoV-2 airborne transmission in schools: a retrospective cohort study in Italy's Marche region, The Lancet – Infectious diseases, submitted

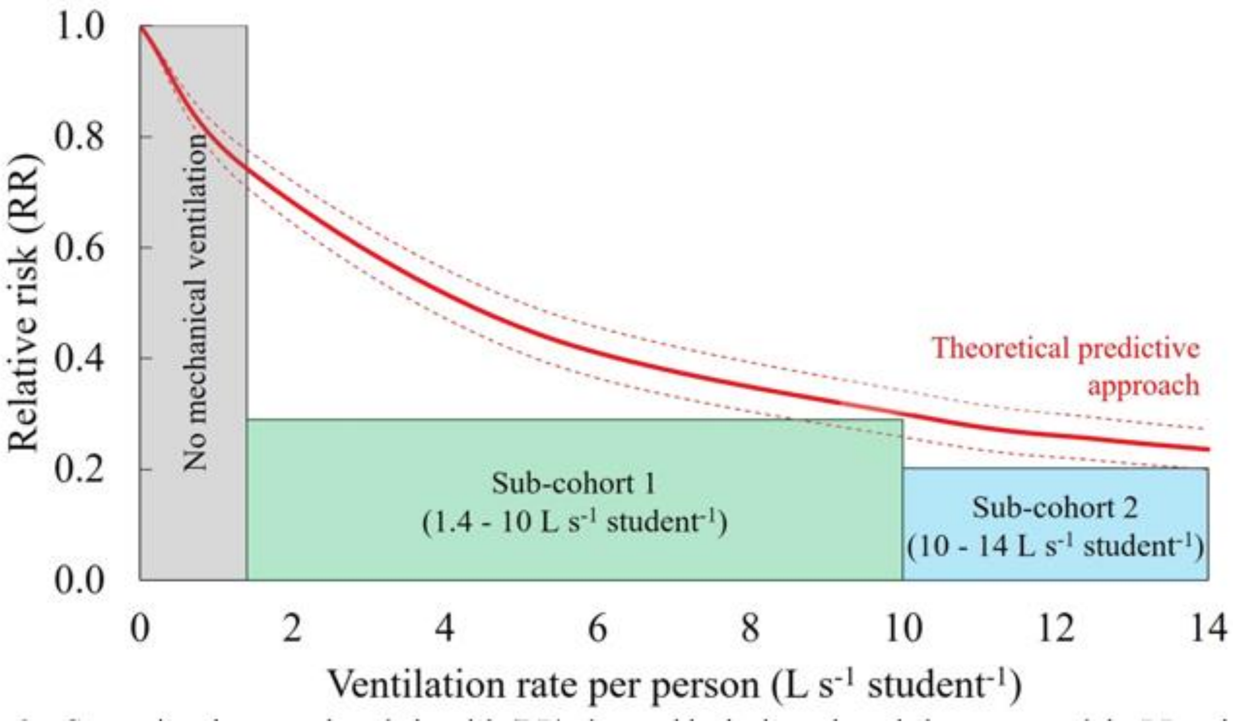


Retrospective Cohort Study

The study represents a Halley's comet because we have had simultaneous (i) waves of infections (Delta and Omicron); (ii) different levels of ventilation in school classrooms; and (iii) monitoring of infections.

The ventilation works…

Validation of the approach through a retrospective cohort study. Possibility of extending the use of the approach, once the scenario has been defined, to any indoor environment of interest.



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

AIRBORNE INFECTION RISK ASSESSMENT TOOLS

Occupancy Considerations in Buildings

Functional Requirements of the Space (Activities & Durations)

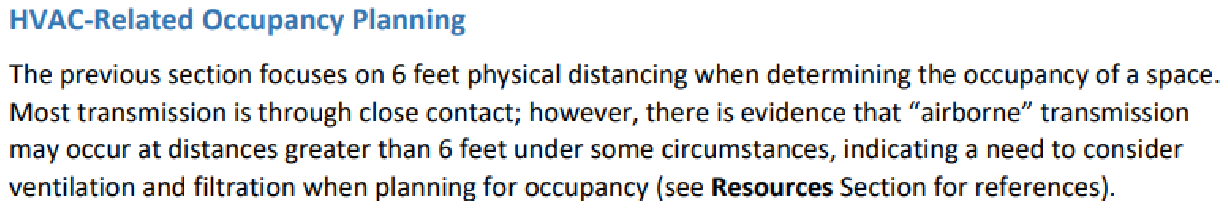
Fire Code

(Emergency Egress)

Building Code Ventilation (Acceptable Air Quality)

Social Distancing

Airborne Transmission?



HVAC-Related Occupancy Planning

The previous section focuses on 6 feet physical distancing when determining the occupancy of a space. Most transmission is through close contact; however, there is evidence that “airborne” transmission may occur at distances greater than 6 feet under some circumstances, indicating a need to consider ventilation and filtration when planning for occupancy (see **Resources** Section for references).

Airborne Infection Risk Calculator Framework

#1) **AIRC Stationary Exposure Conditions (SEC)** – a constant emission source and exposure model that considers the full range of possible quanta emission rates for a selected respiratory activity and their respective probabilities of occurrence. The risk equations are completely solved for three (3) different user-defined exposure times without a time limit.

#2) **AIRC Transitional Exposure Conditions (TEC)** – Transitional exposure scenarios of both infectious and susceptible persons coming and going can be modeled for a total exposure period of up to 8 hours.

Helps users answer the questions:

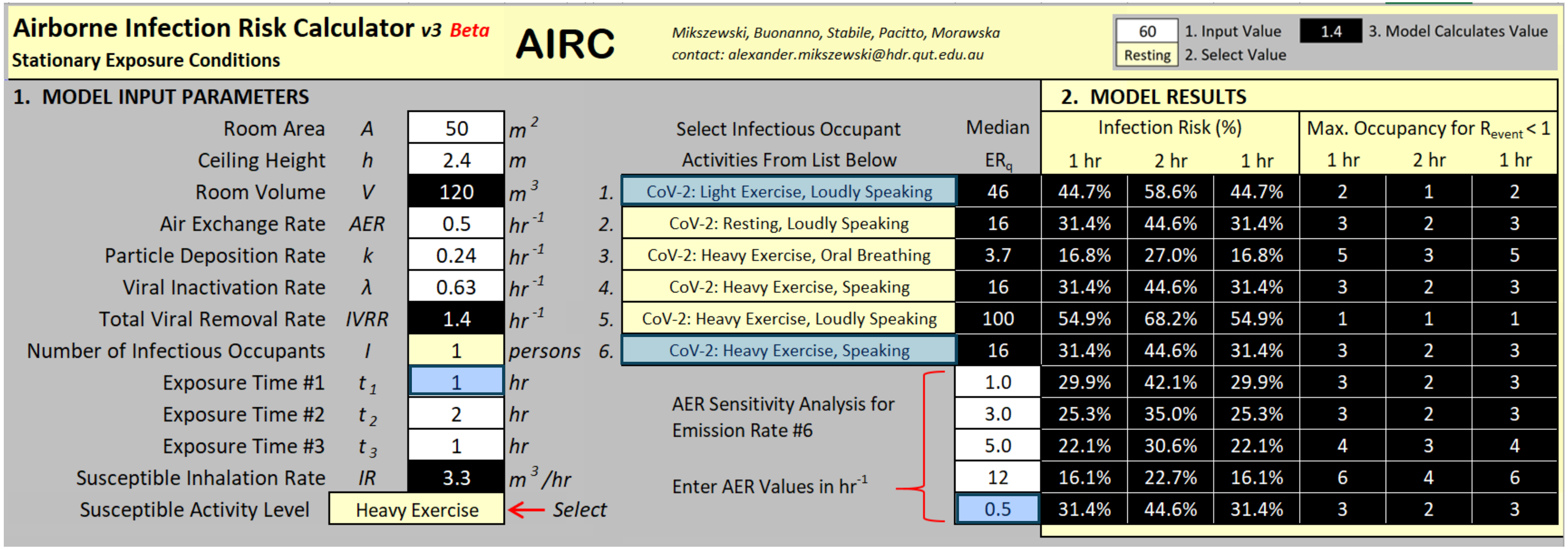
#1) What is the potential infection risk associated with varying lengths of stay in the space?

#2) What number of occupants helps maintain an event reproduction number (R_{event}) less than one to prevent the exposure from further contributing to disease spread in the population?

Example Scenario (SEC)

- Fitness Class
  - Room size: 50 m^2 x 2.4 m = 120 m^3
  - Fan recirculation only (~0.5 air changes per hour)
  - No mask use
  - Instructor is infected
  - High intensity, 1-hour class (e.g. spinning, Zumba)
  - Typical class size ~ 15 students
  - Instructor is only one speaking – no coughing/sneezing

AIRC Tool (SEC)



Airborne Infection Risk Calculator *v3* *Beta*

Stationary Exposure Conditions

AIRC

Mikszewski, Buonanno, Stabile, Pacitto, Morawska
contact: alexander.mikszewski@hdr.qut.edu.au

60	1. Input Value
Resting	2. Select Value
1.4	3. Model Calculates Value

1. MODEL INPUT PARAMETERS

Room Area	*A*	50	*m^2*
Ceiling Height	*h*	2.4	*m*
Room Volume	*V*	120	*m^3*
Air Exchange Rate	*AER*	0.5	*hr^{-1}*
Particle Deposition Rate	*k*	0.24	*hr^{-1}*
Viral Inactivation Rate	*λ*	0.63	*hr^{-1}*
Total Viral Removal Rate	*IVRR*	1.4	*hr^{-1}*
Number of Infectious Occupants	*I*	1	*persons*
Exposure Time #1	t_1	1	*hr*
Exposure Time #2	t_2	2	*hr*
Exposure Time #3	t_3	1	*hr*
Susceptible Inhalation Rate	*IR*	3.3	*m^3/hr*
Susceptible Activity Level		Heavy Exercise	← *Select*

2. MODEL RESULTS

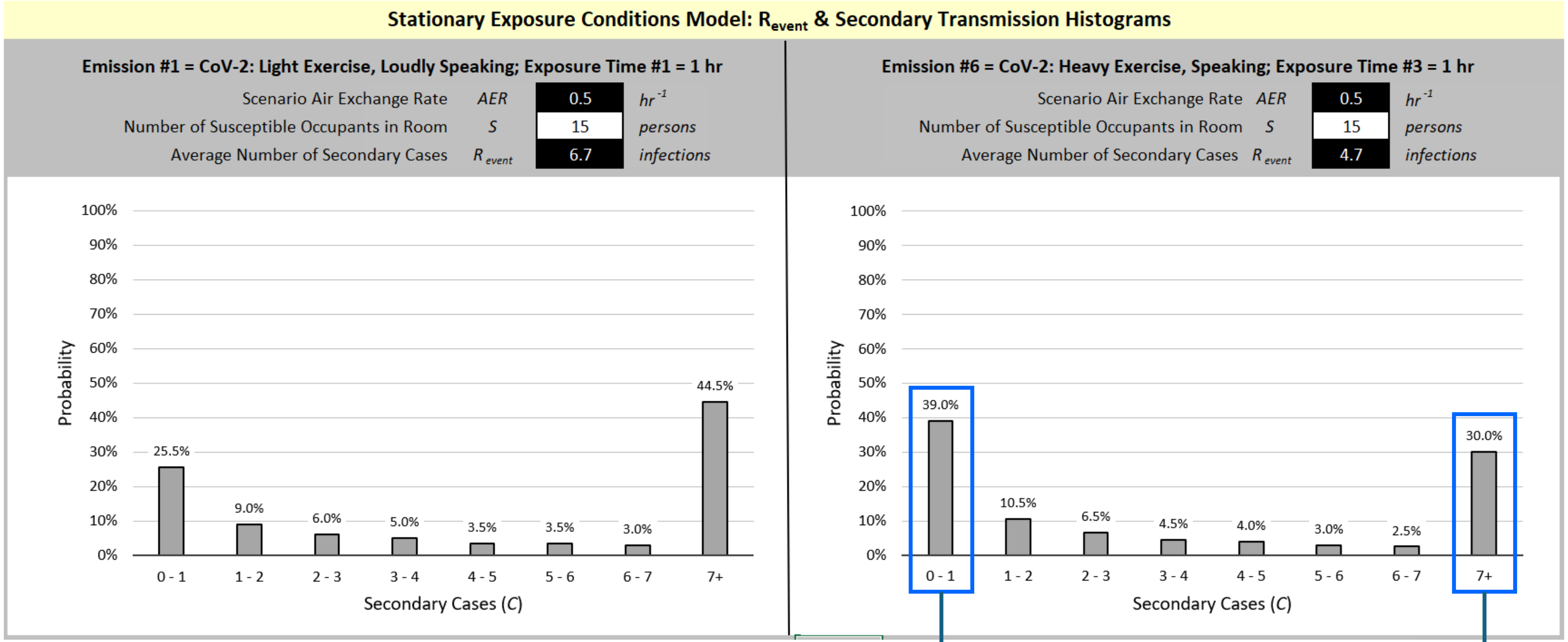
	Select Infectious Occupant Activities From List Below	Median ER_q	Infection Risk (%) 1 hr	2 hr	1 hr	Max. Occupancy for $R_{event} < 1$ 1 hr	2 hr	1 hr
1.	CoV-2: Light Exercise, Loudly Speaking	46	44.7%	58.6%	44.7%	2	1	2
2.	CoV-2: Resting, Loudly Speaking	16	31.4%	44.6%	31.4%	3	2	3
3.	CoV-2: Heavy Exercise, Oral Breathing	3.7	16.8%	27.0%	16.8%	5	3	5
4.	CoV-2: Heavy Exercise, Speaking	16	31.4%	44.6%	31.4%	3	2	3
5.	CoV-2: Heavy Exercise, Loudly Speaking	100	54.9%	68.2%	54.9%	1	1	1
6.	CoV-2: Heavy Exercise, Speaking	16	31.4%	44.6%	31.4%	3	2	3

AER Sensitivity Analysis for Emission Rate #6

Enter AER Values in hr^{-1}

AER	Infection Risk (%) 1 hr	2 hr	1 hr	Max. Occupancy for $R_{event} < 1$ 1 hr	2 hr	1 hr
1.0	29.9%	42.1%	29.9%	3	2	3
3.0	25.3%	35.0%	25.3%	3	2	3
5.0	22.1%	30.6%	22.1%	4	3	4
12	16.1%	22.7%	16.1%	6	4	6
0.5	31.4%	44.6%	31.4%	3	2	3

AIRC Tool (SEC)



Stationary Exposure Conditions Model: R_{event} & Secondary Transmission Histograms

Emission #1 = CoV-2: Light Exercise, Loudly Speaking; Exposure Time #1 = 1 hr

Scenario Air Exchange Rate	*AER*	0.5	*hr^{-1}*
Number of Susceptible Occupants in Room	*S*	15	*persons*
Average Number of Secondary Cases	*R_{event}*	6.7	*infections*

Emission #6 = CoV-2: Heavy Exercise, Speaking; Exposure Time #3 = 1 hr

Scenario Air Exchange Rate	*AER*	0.5	*hr^{-1}*
Number of Susceptible Occupants in Room	*S*	15	*persons*
Average Number of Secondary Cases	*R_{event}*	4.7	*infections*

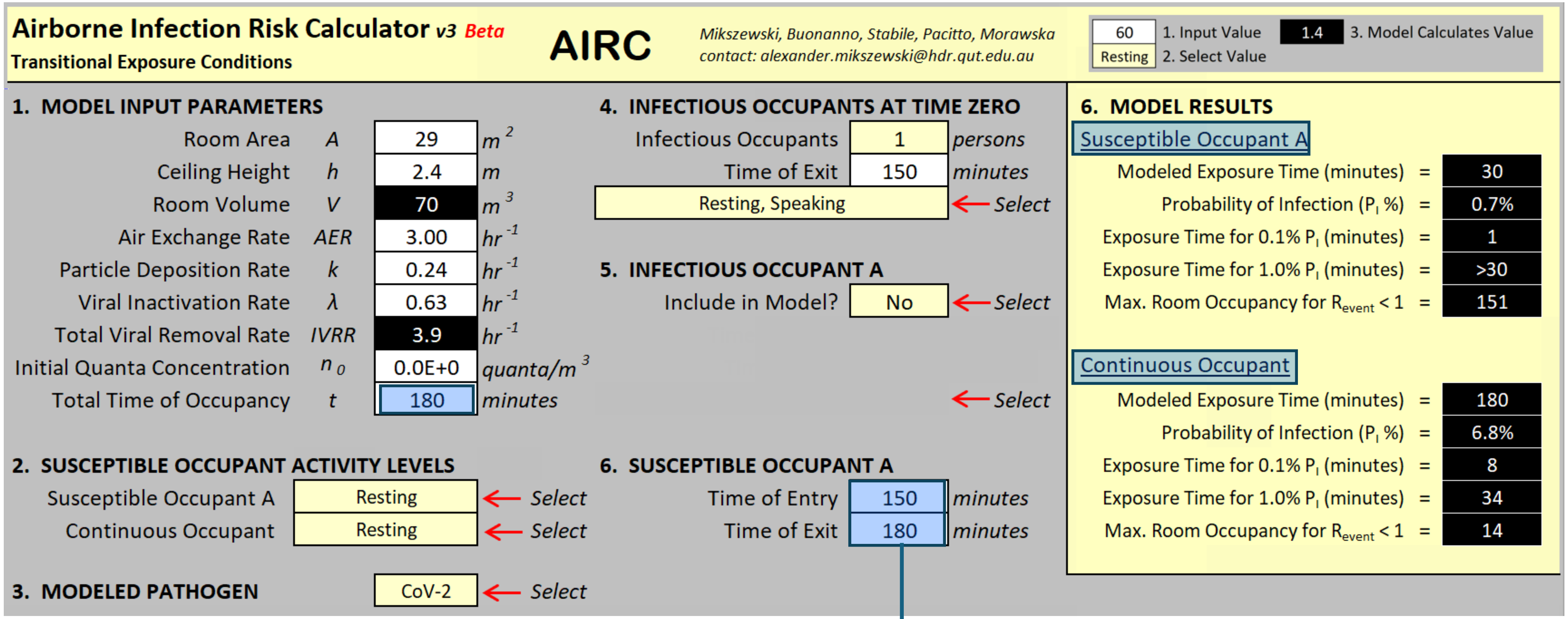
Secondary Transmission Probability = 61%

Superspreading Event Probability = 30%

Example Scenario (TEC)

- Bus Ride
  - Room size: 29 m^2 x 2.4 m = 70 m^3
  - 3.0 air changes per hour (including equivalent filtration)
  - No mask use
  - 1 passenger is infected
  - Infected passenger traveling in a group and talking some
  - Trip length is 2.5 hours

AIRC Tool (TEC)



Airborne Infection Risk Calculator *v3* *Beta*
Transitional Exposure Conditions

AIRC

Mikszewski, Buonanno, Stabile, Pacitto, Morawska
contact: alexander.mikszewski@hdr.qut.edu.au

60 1. Input Value
Resting 2. Select Value
1.4 3. Model Calculates Value

1. MODEL INPUT PARAMETERS

Room Area	*A*	29	m^2
Ceiling Height	*h*	2.4	*m*
Room Volume	*V*	70	m^3
Air Exchange Rate	*AER*	3.00	hr^{-1}
Particle Deposition Rate	*k*	0.24	hr^{-1}
Viral Inactivation Rate	λ	0.63	hr^{-1}
Total Viral Removal Rate	*IVRR*	3.9	hr^{-1}
Initial Quanta Concentration	n_0	0.0E+0	$quanta/m^3$
Total Time of Occupancy	*t*	180	*minutes*

2. SUSCEPTIBLE OCCUPANT ACTIVITY LEVELS

Susceptible Occupant A Resting ← *Select*
Continuous Occupant Resting ← *Select*

3. MODELED PATHOGEN

CoV-2 ← *Select*

4. INFECTIOUS OCCUPANTS AT TIME ZERO

Infectious Occupants 1 *persons*
Time of Exit 150 *minutes*
Resting, Speaking ← *Select*

5. INFECTIOUS OCCUPANT A

Include in Model? No ← *Select*

← *Select*

6. SUSCEPTIBLE OCCUPANT A

Time of Entry 150 *minutes*
Time of Exit 180 *minutes*

6. MODEL RESULTS

Susceptible Occupant A

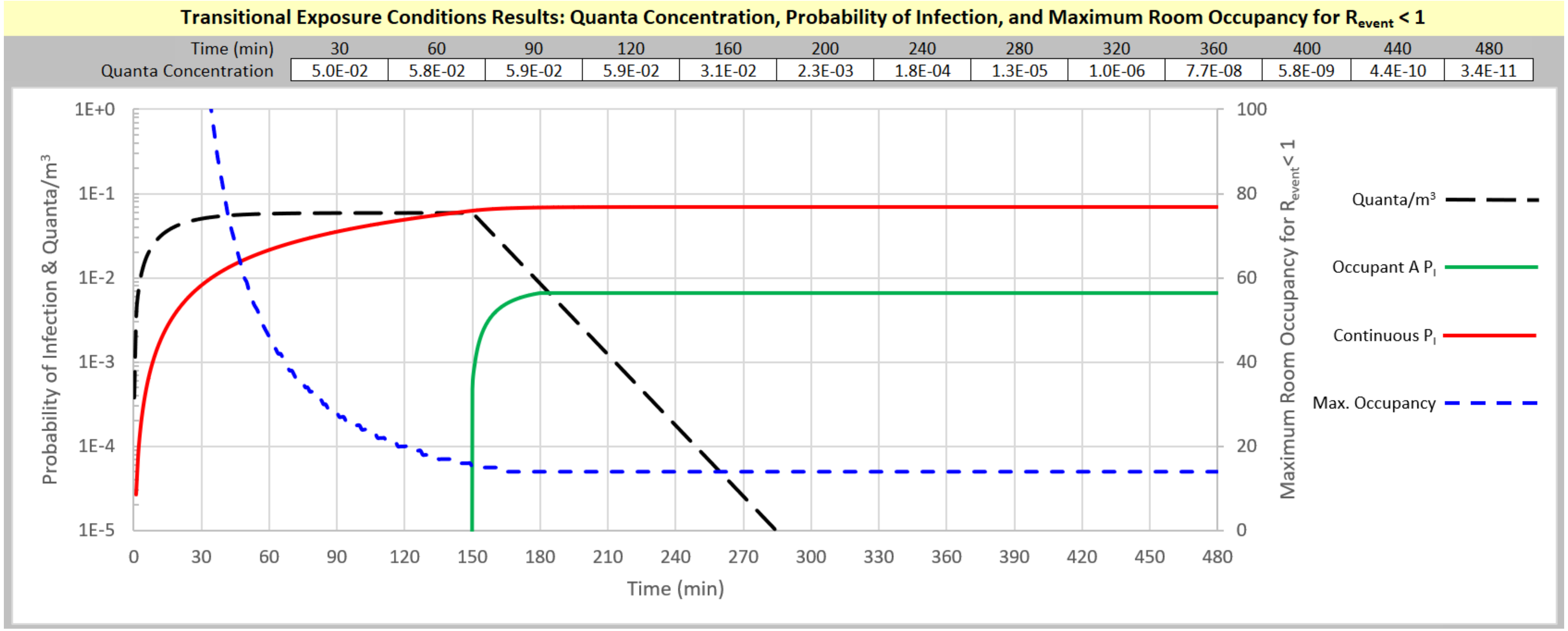
Modeled Exposure Time (minutes)	=	30
Probability of Infection (P_I %)	=	0.7%
Exposure Time for 0.1% P_I (minutes)	=	1
Exposure Time for 1.0% P_I (minutes)	=	>30
Max. Room Occupancy for $R_{event} < 1$	=	151

Continuous Occupant

Modeled Exposure Time (minutes)	=	180
Probability of Infection (P_I %)	=	6.8%
Exposure Time for 0.1% P_I (minutes)	=	8
Exposure Time for 1.0% P_I (minutes)	=	34
Max. Room Occupancy for $R_{event} < 1$	=	14

A rider getting on the bus after the infectious individual has left

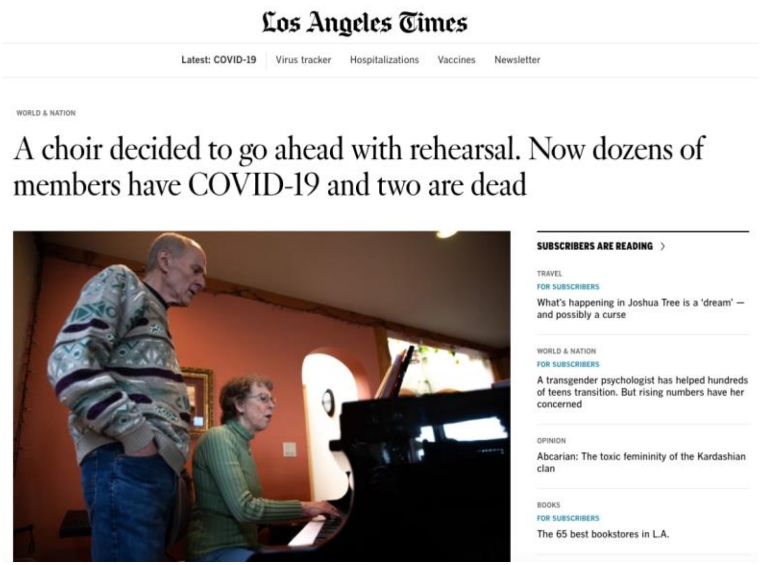
AIRC Tool (TEC)



Transitional Exposure Conditions Results: Quanta Concentration, Probability of Infection, and Maximum Room Occupancy for $R_{event} < 1$

Time (min)	30	60	90	120	160	200	240	280	320	360	400	440	480
Quanta Concentration	5.0E-02	5.8E-02	5.9E-02	5.9E-02	3.1E-02	2.3E-03	1.8E-04	1.3E-05	1.0E-06	7.7E-08	5.8E-09	4.4E-10	3.4E-11

Validation through retrospective cases



Los Angeles Times

Latest: COVID-19 | Virus tracker | Hospitalizations | Vaccines | Newsletter

WORLD & NATION

A choir decided to go ahead with rehearsal. Now dozens of members have COVID-19 and two are dead

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What's happening in Joshua Tree is a 'dream' — and possibly a curse

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OPINION
Abcarian: The toxic femininity of the Kardashian clan

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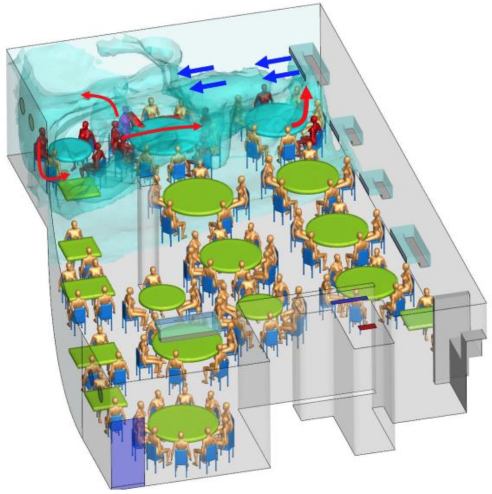
The 65 best bookstores in L.A.

The proposed approach was used for retrospective assessment of documented outbreaks in a restaurant in Guangzhou (China) and at a choir rehearsal in Mount Vernon (US)



This case was recorded on 10 March, in Mount Vernon (Skagit County, Washington State, USA). An attack rate of 53.3% (based on 33 confirmed cases) could represent a conservative estimate, since another 20 probable cases were mentioned by (Hamner et al., 2020).

An index case patient traveled from the Chinese epidemic epicenter, Wuhan, on 23 January 2020 and ate lunch in a restaurant in Guangzhou, China. On the following days, nine other people were diagnosed with SARS-CoV-2 infection

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

Validation through retrospective cases

The required quanta values to obtain the documented probability of infection fall perfectly within the possible values of the emission profiles under consideration (i.e. speaking and singing/speaking loudly in light activity).

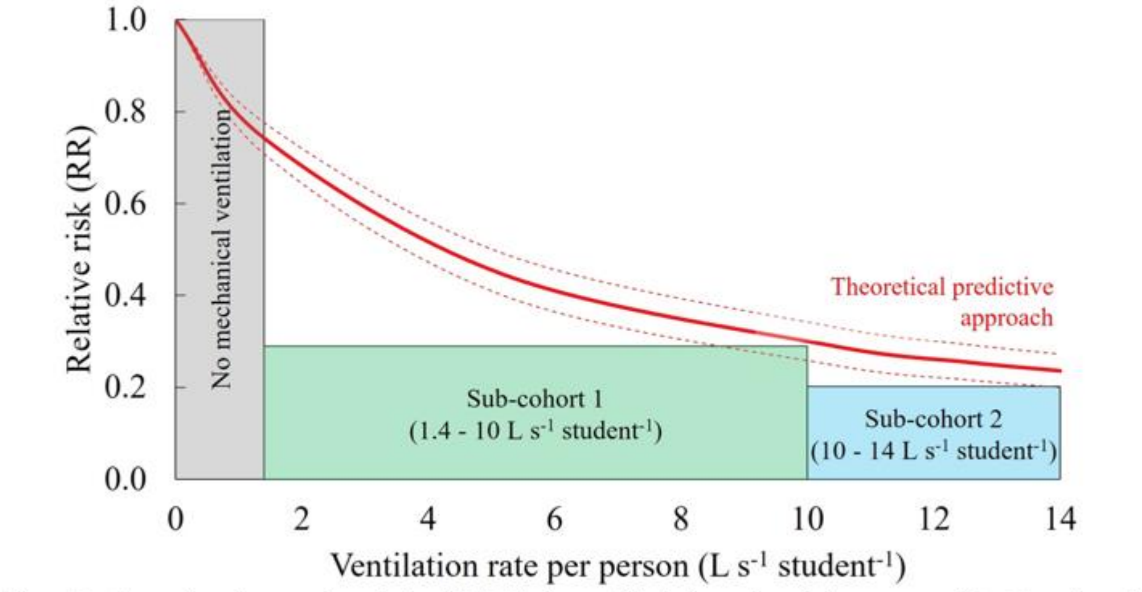
Such emission values present the highest probability of occurrence.

Such outbreaks are not caused by the rare presence of a superspreader, but can be likely explained by the co-existence of conditions, including emission and exposure parameters, leading to a highly probable event, which can be defined as a "superspreading event"

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

Validation through epidemiological study

Parameter	Period of investigation	Classrooms without MVS	Classrooms with MVS
Incidence cases	Sept. 13th - Dec. 23rd, 2021	1272	18
	Jan. 7th - 31st, 2022	1818	13
	Entire period	3090	31
Incidence proportion (per 1 000 students)	Sept. 13th - Dec. 23rd, 2021	6.3	2.8
	Jan. 7th - 31st, 2022	9.0	2.1
	Entire period	15.3	4.9
Incidence proportion ratio	Sept. 13th - Dec. 23rd, 2021	0.45	
	Jan. 7th - 31st, 2022	0.23	
	Entire period	**0.32**	



The agreement between the results obtained from the retrospective cohort study and values calculated through the predictive represents a validation of the approach through a retrospective cohort study.

Such validations confirm the possibility of extending the use of the approach, once the scenario has been defined, to any indoor environment of interest in addition to school classrooms and providing predictive estimates of the effectiveness of the ventilation for different exposure scenarios and variants of concern.

Buonanno et al., Increasing ventilation reduces the SARS-CoV-2 airborne transmission in schools: a retrospective cohort study in Italy's Marche region, The Lancet – Infectious diseases, submitted

Other tools developed during COVID-19 Pandemic

COVID-19 Aerosol Transmission Estimato *File --> Make a Copy OR Download*

Developed by: Prof. Jose L. Jimenez & Dr. Zhe Peng, Dept. of Chem. & CIRES, Univ. Colorado Boul **Shortcut:**

Short d

For mo

Model

5 min.

Record

Informa

El Pais

Subscri

Geograp

Jimenez

reads

Mishra

REHVA CALCULATOR

to estimate the effect of ventilation

COVID-19 airborne transmission

COVID-19 Indoor Safety Guidelin

Kasim Khan, John W. M. B

Bazant & Bush, A guidelin

Monitoring carbon dioxid

http://web.mit.edu/baza

https://github.com/kawe

COVID-19 Risk Calculator

Gain an understanding of how to reduce the risk of COVID-19

REHVA COVID-19 Multi-room Recirculation ULATOR

ARIA

Airborne Risk Indoor Assessment

SAFEAIRSPACES COVID-19 Aerosol Relative Risk Estimator v2

Virus Tool

Update: There is a new version (v2.2) with CO2 calculator and recirculation of purified virus-free air.

The Indoor Scenario Simulator for COVID-19 was developed with financial support from the State Secretariat for Economic Affairs SECO (seco.admin.ch) and in cooperation with Christian Monn, SECO. The update was financed by internal SCOEH funds.

Example Scenario

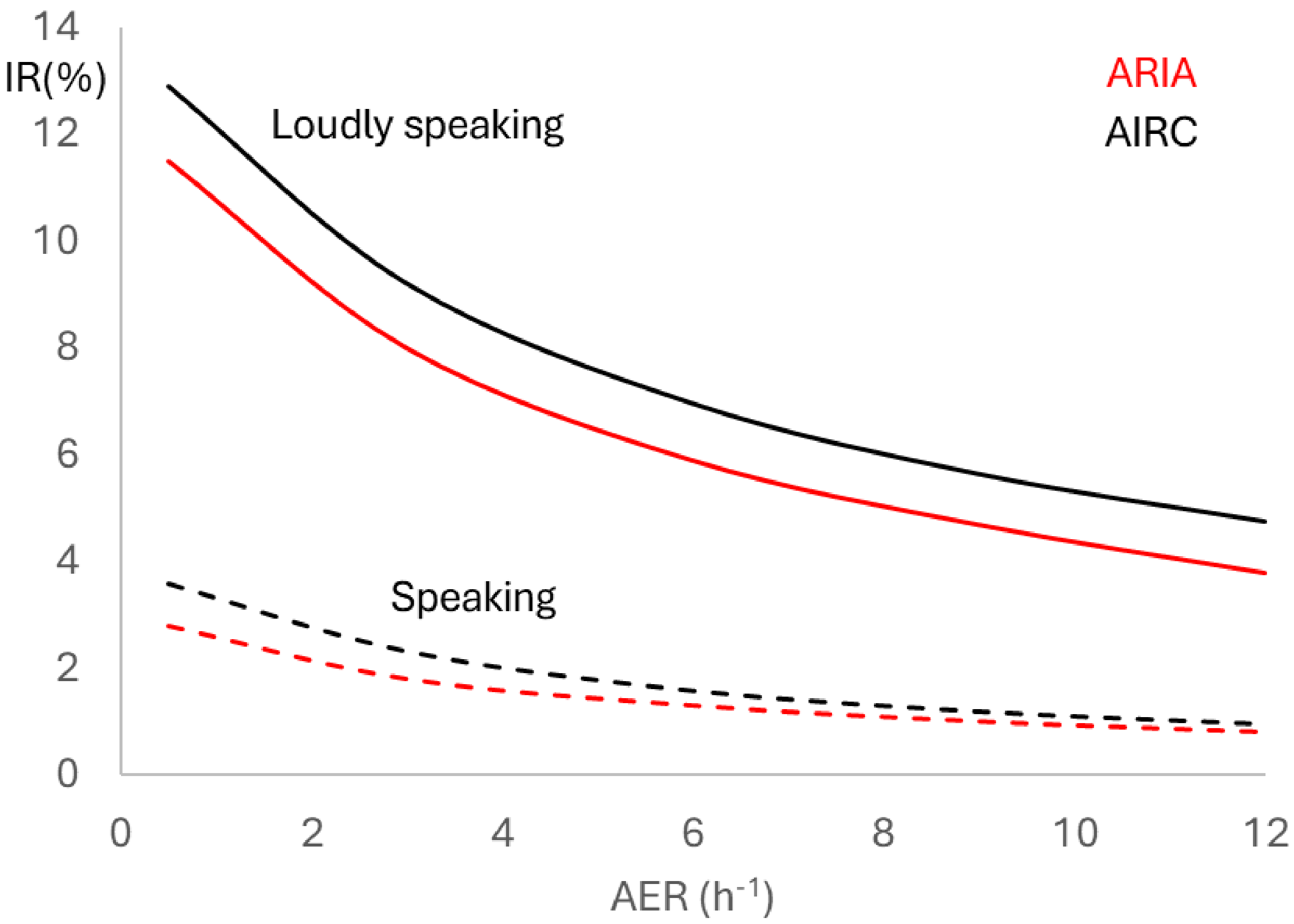
- Classroom
  - Room size: = 150 m^3
  - 0.5, 3, 6, 9, 12 air changes per hour (including equivalent filtration)
  - No mask use
  - Teacher is infected, speaking and loudly speaking
  - 25 students
  - Exposure time is 1 hour
  - SARS-CoV-2 (ancestral strain)

Quanta or viral load approach?

Airborne Infection Risk Calculator *v3.0*
Transitional Exposure Conditions
AIRC

ARIA
Airborne Risk Indoor Assessment

https://iris.who.int/handle/10665/376346
https://partnersplatform.who.int/aria



$$E_n = \frac{\left|C_{exp} - C_{theor}\right|}{\sqrt{U^2_{C-exp} + U^2_{C-theor}}} < 1$$

Two parallel worlds meeting for the first time!

Future Research Directions

More generally – outside of "pandemic mode," who will use these tools and for what specific purposes?

ASHRAE Standard 241 identifies areas of need:

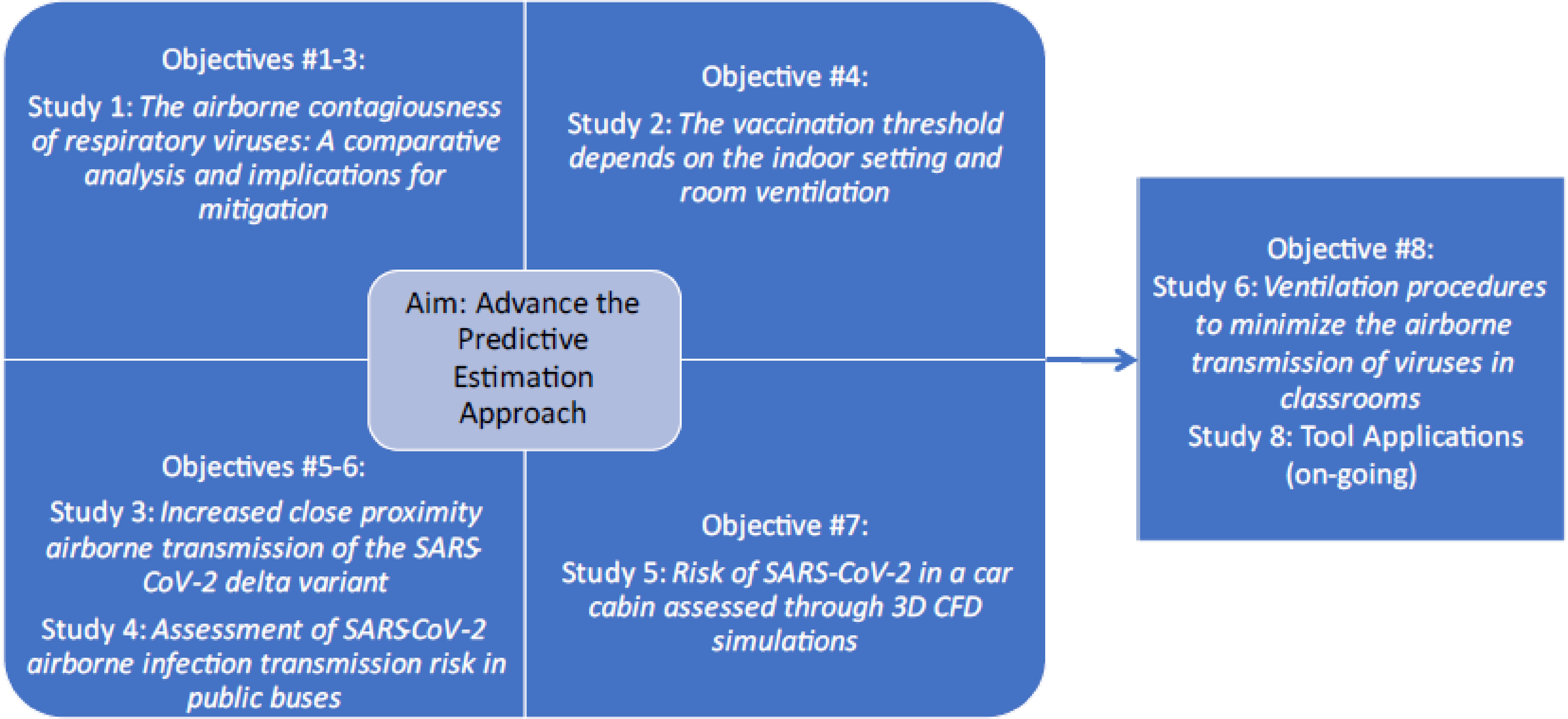
- A risk calculator to develop prescriptive equivalent clean airflow requirements that will support development of custom targets

ASHRAE Standard 241-2023

Control of Infectious Aerosols

Gaps in Knowledge

- How to estimate quanta emission rates in the absence of documented transmission events;
- How to combine close proximity infection risk with longer-range transmission in risk assessment models;
- Comparisons of the completely-mixed model with more complex numerical modeling approaches (CFD); and
- Statistical modeling of multiple infected subjects and estimated probabilities of discrete numbers of secondary transmissions.



Objectives #1-3:

Study 1: *The airborne contagiousness of respiratory viruses: A comparative analysis and implications for mitigation*

Objective #4:

Study 2: *The vaccination threshold depends on the indoor setting and room ventilation*

Aim: Advance the Predictive Estimation Approach

Objectives #5-6:

Study 3: *Increased close proximity airborne transmission of the SARS-CoV-2 delta variant*

Study 4: *Assessment of SARS-CoV-2 airborne infection transmission risk in public buses*

Objective #7:

Study 5: *Risk of SARS-CoV-2 in a car cabin assessed through 3D CFD simulations*

Objective #8:

Study 6: *Ventilation procedures to minimize the airborne transmission of viruses in classrooms*

Study 8: Tool Applications (on-going)

Study 7 is a review paper, *The physics of respiratory particle generation, fate in the air, and inhalation*, that contributes to the broader objective of putting historical work in the current context of the surge of interest and scientific productivity on this topic

The Airborne Contagiousness of Respiratory Viruses

Mikszewski A, Stabile L, Buonanno G, Morawska L. The airborne contagiousness of respiratory viruses: A comparative analysis and implications for mitigation. *Geoscience Frontiers*. 2022;13(6):101285. doi:10.1016/j.gsf.2021.101285

1. **Assess the strength of the predictive estimation approach through literature ER_q review**
2. Compare the contagiousness of respiratory pathogens through the airborne route
3. Assess ventilation and occupancy requirements to minimize airborne transmission

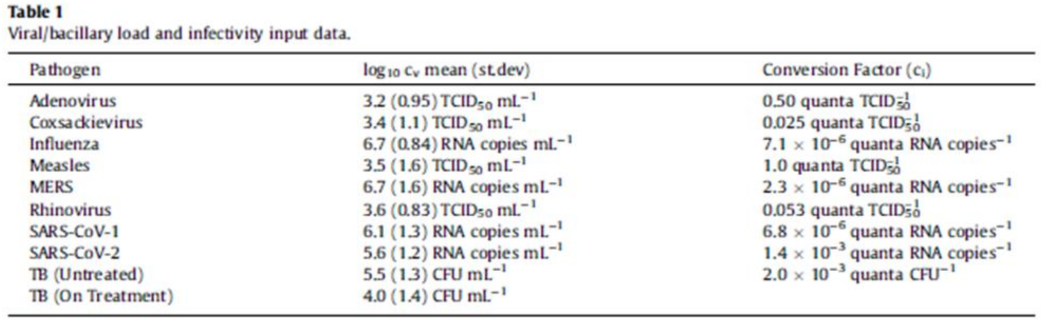
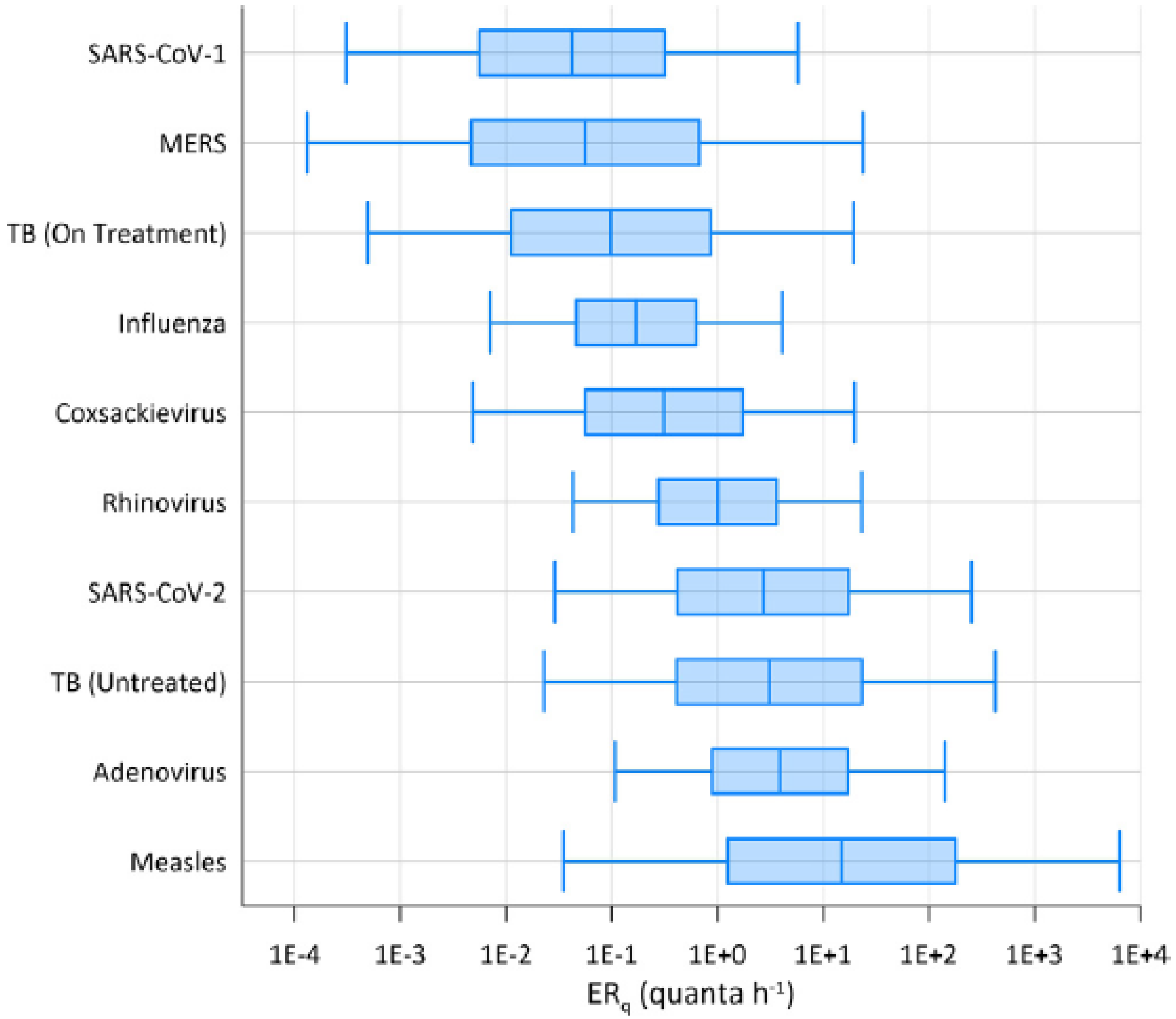


Table 1

Viral/bacillary load and infectivity input data.

Pathogen	$\log_{10} c_v$ mean (st.dev)	Conversion Factor (c_i)
Adenovirus	3.2 (0.95) $TCID_{50}\ mL^{-1}$	0.50 quanta $TCID_{50}^{-1}$
Coxsackievirus	3.4 (1.1) $TCID_{50}\ mL^{-1}$	0.025 quanta $TCID_{50}^{-1}$
Influenza	6.7 (0.84) RNA copies mL^{-1}	7.1×10^{-6} quanta RNA copies^{-1}
Measles	3.5 (1.6) $TCID_{50}\ mL^{-1}$	1.0 quanta $TCID_{50}^{-1}$
MERS	6.7 (1.6) RNA copies mL^{-1}	2.3×10^{-6} quanta RNA copies^{-1}
Rhinovirus	3.6 (0.83) $TCID_{50}\ mL^{-1}$	0.053 quanta $TCID_{50}^{-1}$
SARS-CoV-1	6.1 (1.3) RNA copies mL^{-1}	6.8×10^{-6} quanta RNA copies^{-1}
SARS-CoV-2	5.6 (1.2) RNA copies mL^{-1}	1.4×10^{-3} quanta RNA copies^{-1}
TB (Untreated)	5.5 (1.3) CFU mL^{-1}	2.0×10^{-3} quanta CFU^{-1}
TB (On Treatment)	4.0 (1.4) CFU mL^{-1}	



Significance & Implications of the Findings

1. Quanta emission rate (ER_q) estimates are in good agreement with the range back calculated from experimental studies and superspreading events:

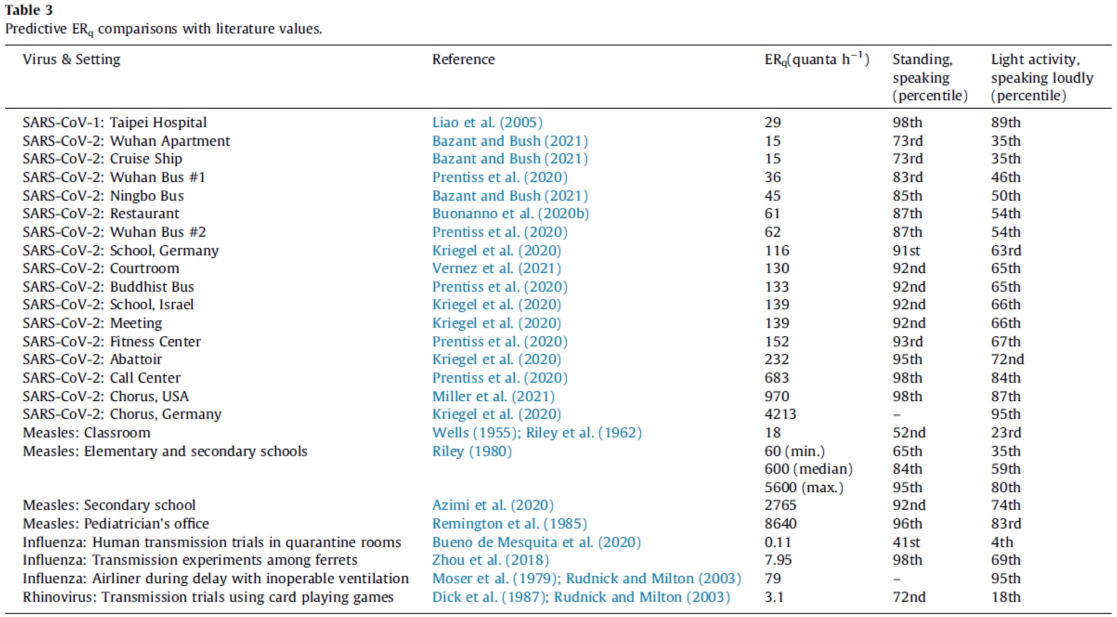


Table 3
Predictive ER_q comparisons with literature values.

Virus & Setting	Reference	ER_q(quanta h^{-1})	Standing, speaking (percentile)	Light activity, speaking loudly (percentile)
SARS-CoV-1: Taipei Hospital	Liao et al. (2005)	29	98th	89th
SARS-CoV-2: Wuhan Apartment	Bazant and Bush (2021)	15	73rd	35th
SARS-CoV-2: Cruise Ship	Bazant and Bush (2021)	15	73rd	35th
SARS-CoV-2: Wuhan Bus #1	Prentiss et al. (2020)	36	83rd	46th
SARS-CoV-2: Ningbo Bus	Bazant and Bush (2021)	45	85th	50th
SARS-CoV-2: Restaurant	Buonanno et al. (2020b)	61	87th	54th
SARS-CoV-2: Wuhan Bus #2	Prentiss et al. (2020)	62	87th	54th
SARS-CoV-2: School, Germany	Kriegel et al. (2020)	116	91st	63rd
SARS-CoV-2: Courtroom	Vernez et al. (2021)	130	92nd	65th
SARS-CoV-2: Buddhist Bus	Prentiss et al. (2020)	133	92nd	65th
SARS-CoV-2: School, Israel	Kriegel et al. (2020)	139	92nd	66th
SARS-CoV-2: Meeting	Kriegel et al. (2020)	139	92nd	66th
SARS-CoV-2: Fitness Center	Prentiss et al. (2020)	152	93rd	67th
SARS-CoV-2: Abattoir	Kriegel et al. (2020)	232	95th	72nd
SARS-CoV-2: Call Center	Prentiss et al. (2020)	683	98th	84th
SARS-CoV-2: Chorus, USA	Miller et al. (2021)	970	98th	87th
SARS-CoV-2: Chorus, Germany	Kriegel et al. (2020)	4213	–	95th
Measles: Classroom	Wells (1955); Riley et al. (1962)	18	52nd	23rd
Measles: Elementary and secondary schools	Riley (1980)	60 (min.)	65th	35th
		600 (median)	84th	59th
		5600 (max.)	95th	80th
Measles: Secondary school	Azimi et al. (2020)	2765	92nd	74th
Measles: Pediatrician's office	Remington et al. (1985)	8640	96th	83rd
Influenza: Human transmission trials in quarantine rooms	Bueno de Mesquita et al. (2020)	0.11	41st	4th
Influenza: Transmission experiments among ferrets	Zhou et al. (2018)	7.95	98th	69th
Influenza: Airliner during delay with inoperable ventilation	Moser et al. (1979); Rudnick and Milton (2003)	79	–	95th
Rhinovirus: Transmission trials using card playing games	Dick et al. (1987); Rudnick and Milton (2003)	3.1	72nd	18th

2. The respiratory pathogens evaluated can generally be grouped as follows:

- **Less** contagious pathogens: Rhinovirus, SARS-CoV-1, MERS, coxsackievirus, TB (on treatment) and seasonal influenza.
- **More** contagious pathogens: untreated active TB, SARS-CoV-2, adenovirus, and measles virus.
- The **more** contagious pathogens are characterized by upper quartile ER_q values above 10 quanta per hour for standing & speaking.

3. Using the same emission rate for multiple infected persons in a shared indoor environment underestimates the cumulative emission by not accounting for the statistical effect of sampling a highly-variable (overdispersed) distribution multiple times.

The Vaccination Threshold for SARS-CoV-2 Depends on the Indoor Setting and Room Ventilation

Mikszewski A, Stabile L, Buonanno G, Morawska L. The vaccination threshold for SARS-CoV-2 depends on the indoor setting and room ventilation. *BMC Infect Dis*. 2021;21(1):1193. Published 2021 Nov 26. doi:10.1186/s12879-021-06884-0

4. Estimate the vaccination threshold for SARS-CoV-2 considering airborne transmission

High Risk Setting #1: Prison Cell Block

High Risk Setting #2: Restaurant

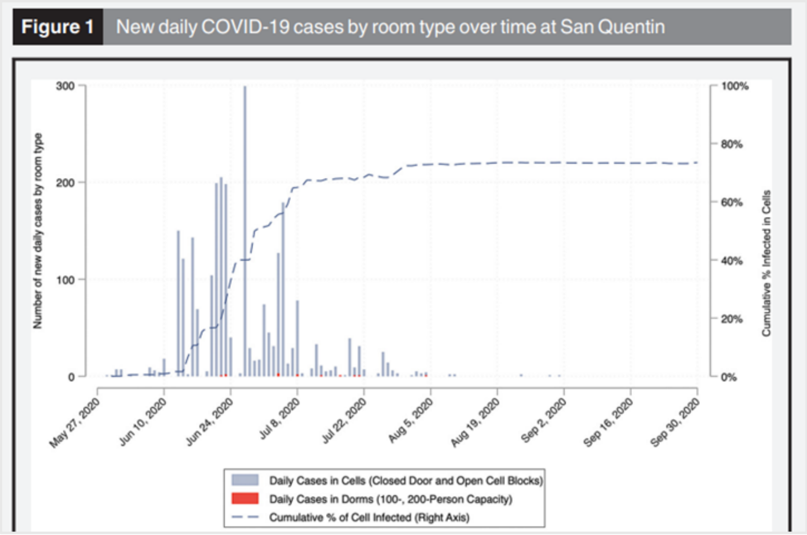
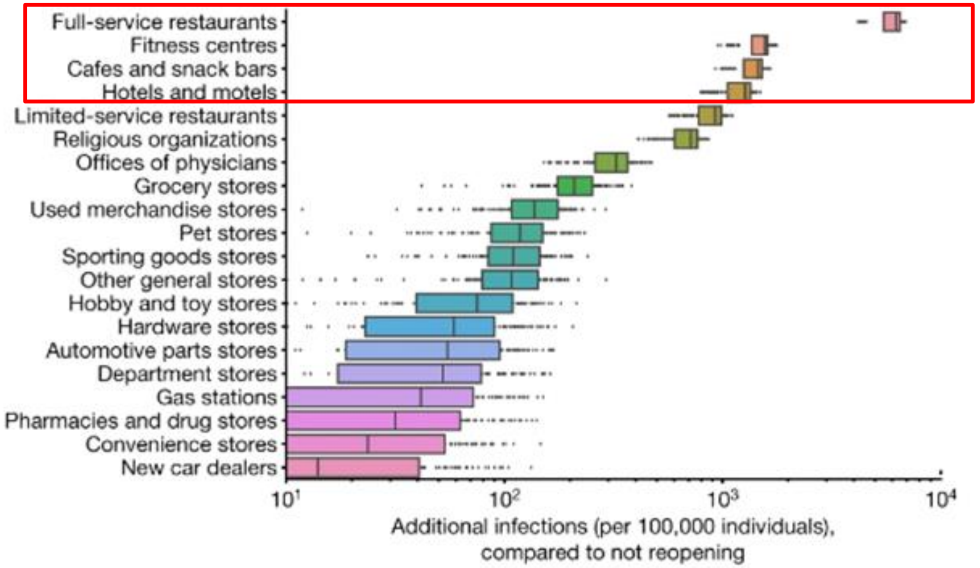


Figure 1 New daily COVID-19 cases by room type over time at San Quentin



Kwan, A., Sklar, R., Cameron, D.B., Schell, R.C., Bertozzi, S.M., McCoy, S.I., Williams, B. and Sears, D.A. (2022), "Respiratory pandemic preparedness learnings from the June 2020 COVID-19 outbreak at San Quentin California State Prison", *International Journal of Prisoner Health*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/IJPH-12-2021-0116

Chang, S., Pierson, E., Koh, P.W. et al. Mobility network models of COVID-19 explain inequities and inform reopening. Nature 589, 82–87 (2021). https://doi.org/10.1038/s41586-020-2923-3

The Vaccination Threshold for SARS-CoV-2 Depends on the Indoor Setting and Room Ventilation

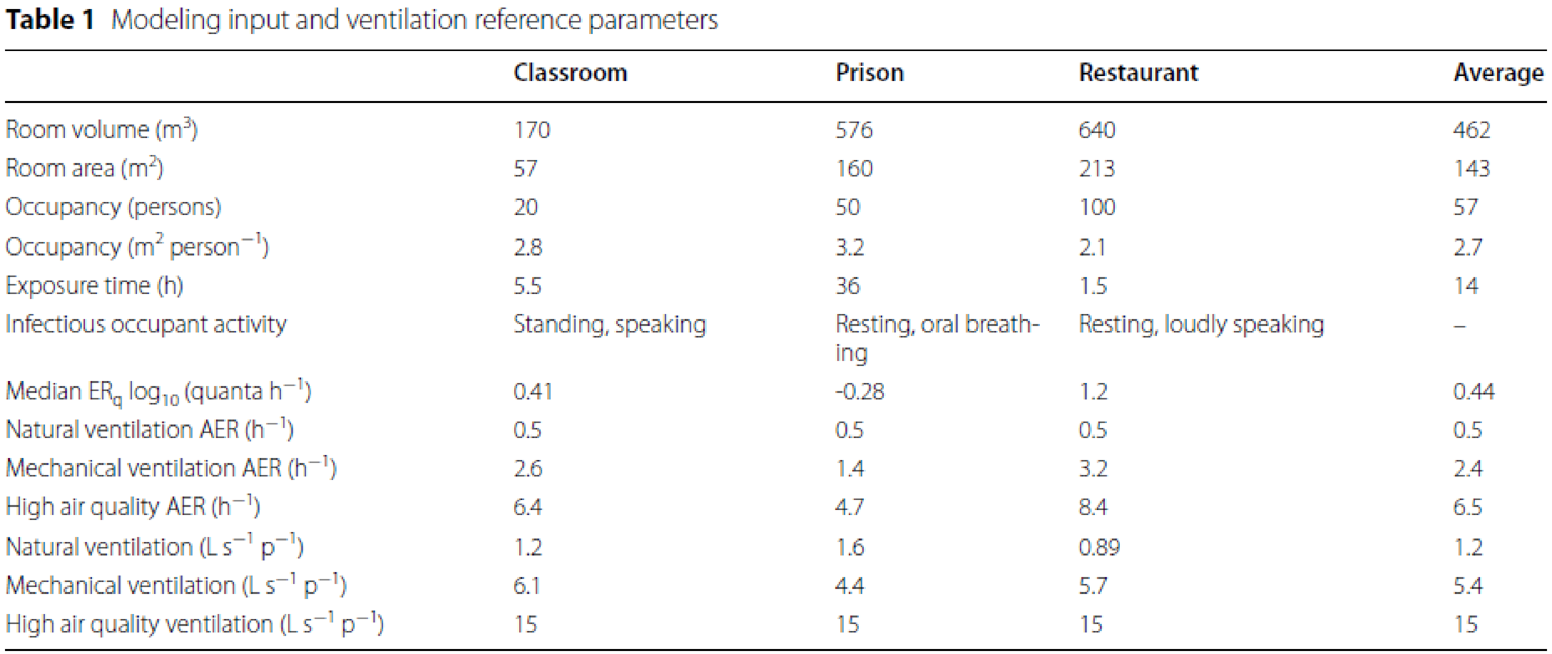


Table 1 Modeling input and ventilation reference parameters

	Classroom	**Prison**	**Restaurant**	**Average**
Room volume (m^3)	170	576	640	462
Room area (m^2)	57	160	213	143
Occupancy (persons)	20	50	100	57
Occupancy (m^2 $person^{-1}$)	2.8	3.2	2.1	2.7
Exposure time (h)	5.5	36	1.5	14
Infectious occupant activity	Standing, speaking	Resting, oral breathing	Resting, loudly speaking	–
Median ER_q $\log_{10}$ (quanta h^{-1})	0.41	-0.28	1.2	0.44
Natural ventilation AER (h^{-1})	0.5	0.5	0.5	0.5
Mechanical ventilation AER (h^{-1})	2.6	1.4	3.2	2.4
High air quality AER (h^{-1})	6.4	4.7	8.4	6.5
Natural ventilation (L s^{-1} p^{-1})	1.2	1.6	0.89	1.2
Mechanical ventilation (L s^{-1} p^{-1})	6.1	4.4	5.7	5.4
High air quality ventilation (L s^{-1} p^{-1})	15	15	15	15

Theoretical “Herd Immunity” Threshold = $1 - 1/R_0$

Event-specific threshold number of susceptibles = $1/R$

The Vaccination Threshold for SARS-CoV-2 Depends on the Indoor Setting and Room Ventilation

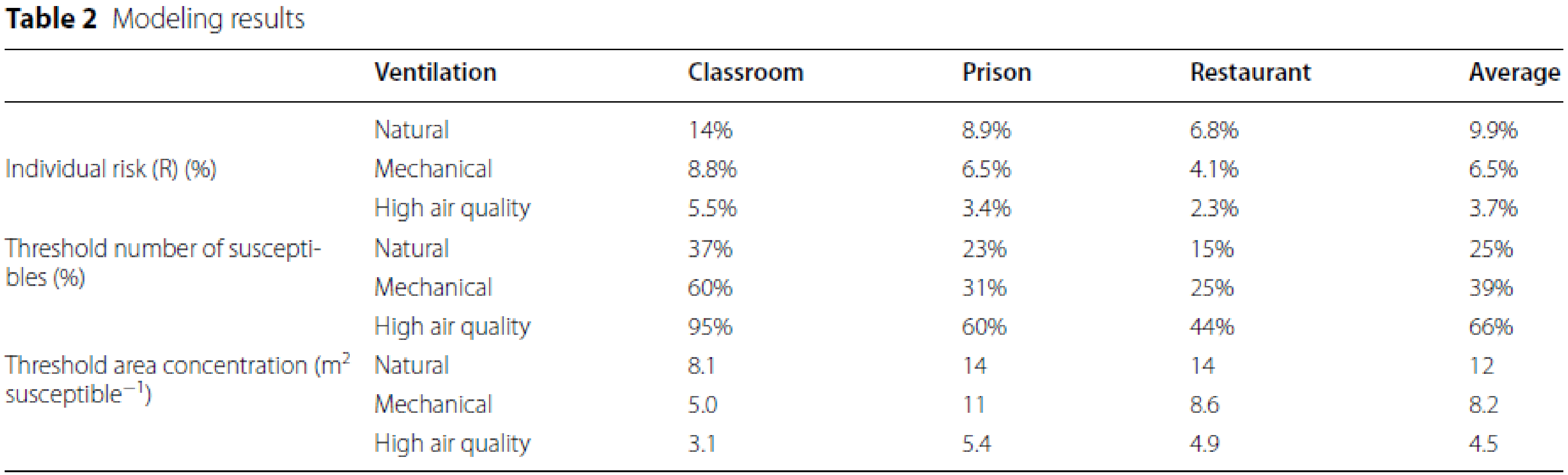


Table 2 Modeling results

	Ventilation	Classroom	Prison	Restaurant	Average
Individual risk (R) (%)	Natural	14%	8.9%	6.8%	9.9%
	Mechanical	8.8%	6.5%	4.1%	6.5%
	High air quality	5.5%	3.4%	2.3%	3.7%
Threshold number of susceptibles (%)	Natural	37%	23%	15%	25%
	Mechanical	60%	31%	25%	39%
	High air quality	95%	60%	44%	66%
Threshold area concentration (m^2 susceptible^{-1})	Natural	8.1	14	14	12
	Mechanical	5.0	11	8.6	8.2
	High air quality	3.1	5.4	4.9	4.5

- For wild-type SARS-CoV-2, required vaccination rates are much higher for a naturally ventilated restaurant (85%) than for a mechanically ventilated classroom (40%);

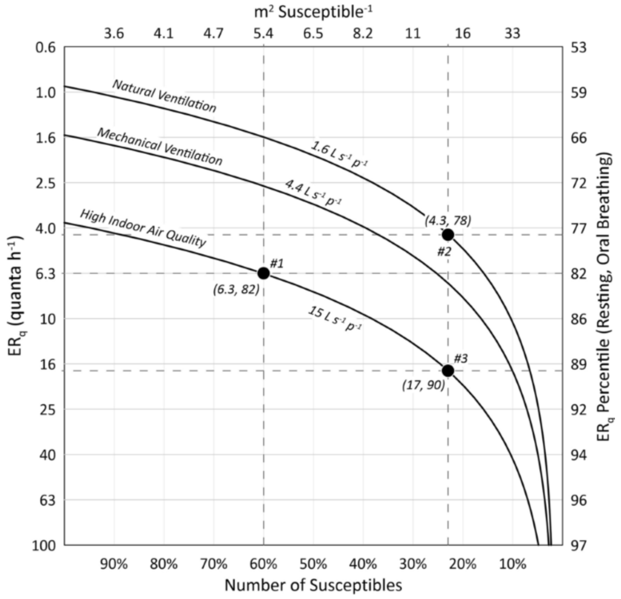
- An average of 10 m^2 per susceptible occupant of an indoor space is more appropriate to reduce wild-type SARS-CoV-2 secondary transmission risk, versus social distancing guidelines of 1-2 m separation distance.

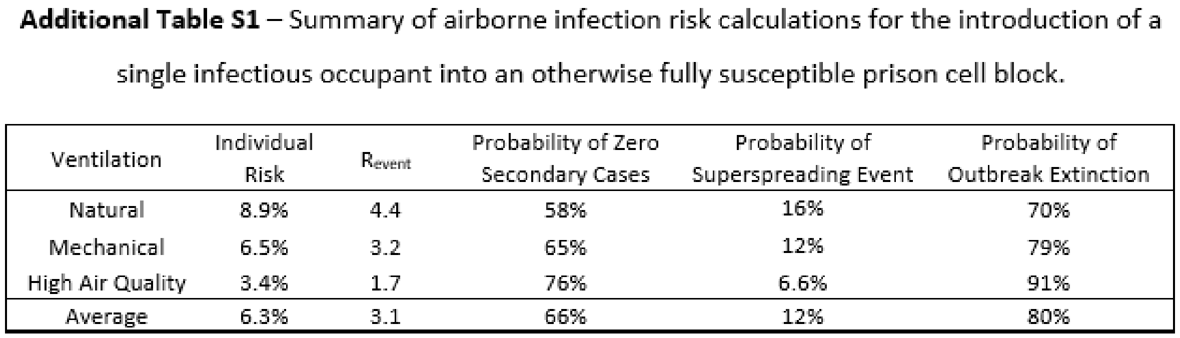
Perspectives Three Years Later

- Study 2 was undertaken prior to the emergence of the Delta and subsequent SARS-CoV-2 variants;
- A time-variable spectrum of susceptibility to SARS-CoV-2 was established, persisting to present day;
- The "vaccination threshold" is better conceptualized as a "susceptibility threshold";
- The relationship between the risk of secondary transmission, the area concentration of susceptibles in a room, and the room ventilation effectiveness remains relevant.

Significance & Implications of the Findings

- A high, comfort-based ventilation rate can provide a substantial downstream epidemiological benefit relative to a poorly ventilated baseline condition;
- Greatest effect for overdispersed pathogens, where most transmission is caused by a minority of infected persons, and increasing ventilation increases the extinction probability of an outbreak.





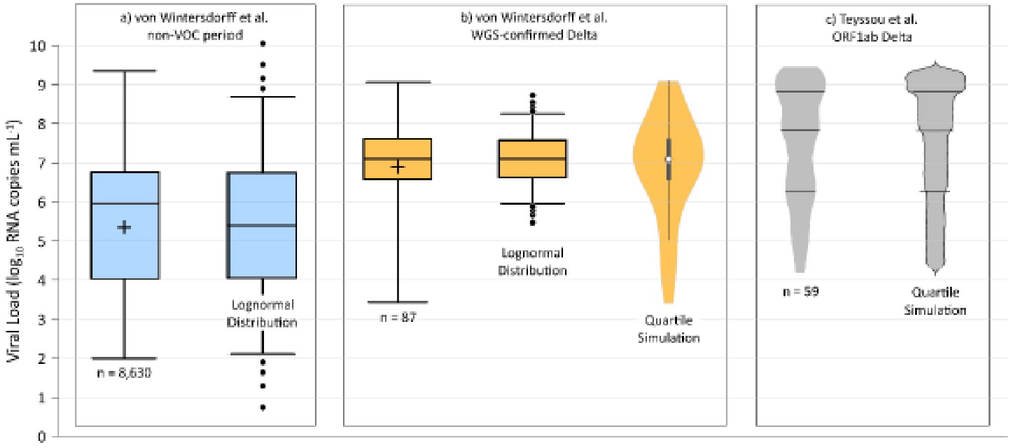
Additional Table S1 – Summary of airborne infection risk calculations for the introduction of a single infectious occupant into an otherwise fully susceptible prison cell block.

Ventilation	Individual Risk	R_{event}	Probability of Zero Secondary Cases	Probability of Superspreading Event	Probability of Outbreak Extinction
Natural	8.9%	4.4	58%	16%	70%
Mechanical	6.5%	3.2	65%	12%	79%
High Air Quality	3.4%	1.7	76%	6.6%	91%
Average	6.3%	3.1	66%	12%	80%

Increased Close Proximity Airborne Transmission of the SARS-CoV-2 Delta Variant; Assessment of SARS-CoV-2 Airborne Transmission Risk in Public Buses

Mikszewski A, Stabile L, Buonanno G, Morawska L. Increased close proximity airborne transmission of the SARS-CoV-2 Delta variant. *Sci Total Environ*. 2022;816:151499. doi:10.1016/j.scitotenv.2021.151499

5. Quantify community spread through close proximity airborne transmission



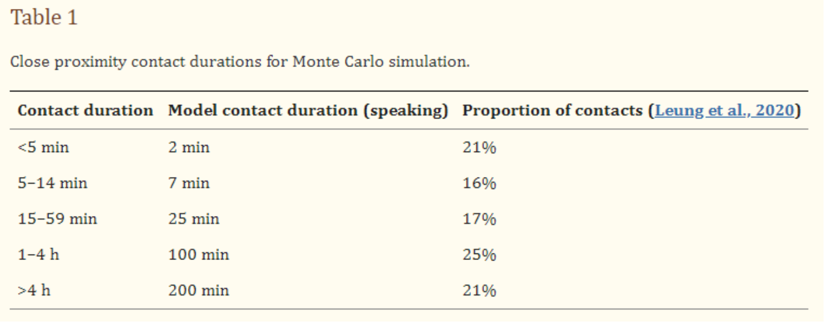
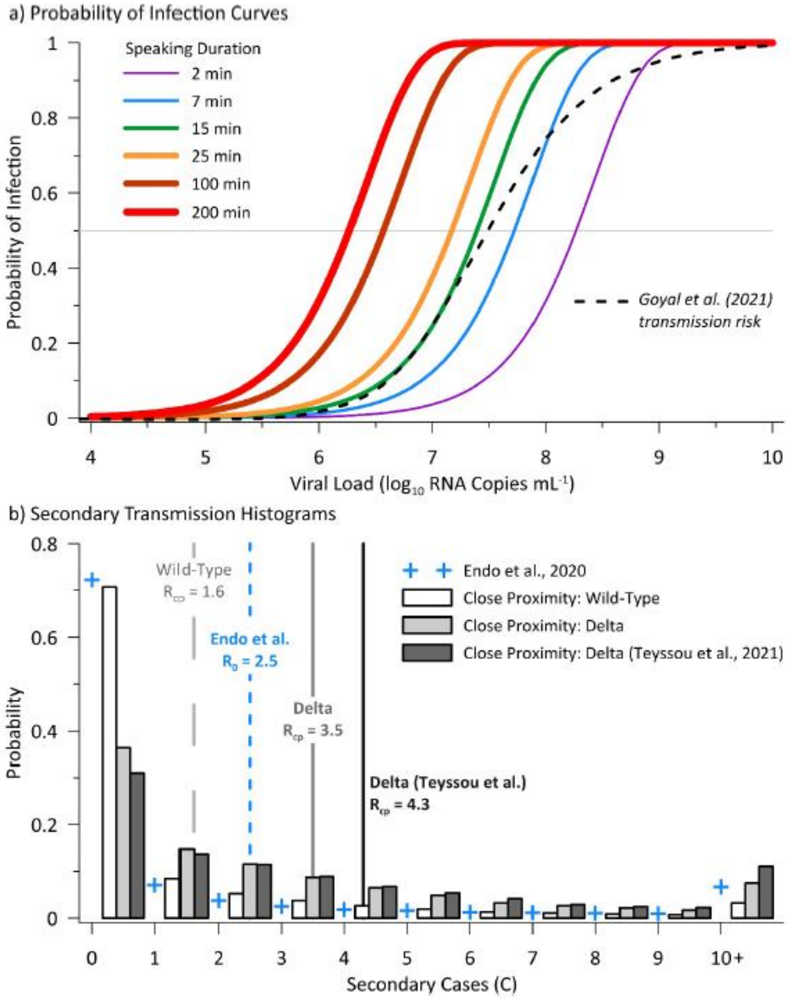


Table 1

Close proximity contact durations for Monte Carlo simulation.

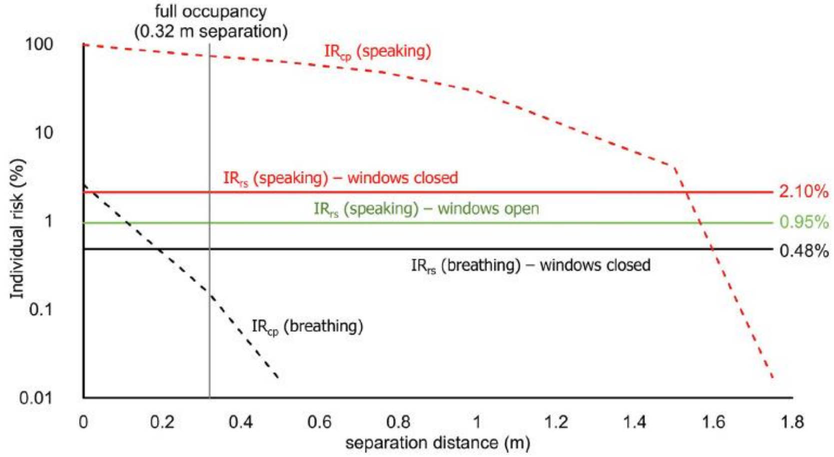
Contact duration	Model contact duration (speaking)	Proportion of contacts (Leung et al., 2020)
<5 min	2 min	21%
5–14 min	7 min	16%
15–59 min	25 min	17%
1–4 h	100 min	25%
>4 h	200 min	21%



Increased Close Proximity Airborne Transmission of the SARS-CoV-2 Delta Variant; Assessment of SARS-CoV-2 Airborne Transmission Risk in Public Buses

Bertone M, Mikszewski A, Stabile L, et al. Assessment of SARS-CoV-2 airborne infection transmission risk in public buses. *Geoscience Frontiers*. 2022;13(6):101398. doi:10.1016/j.gsf.2022.101398

6. Develop a risk assessment methodology to consider both close proximity and room-scale airborne transmission in same setting



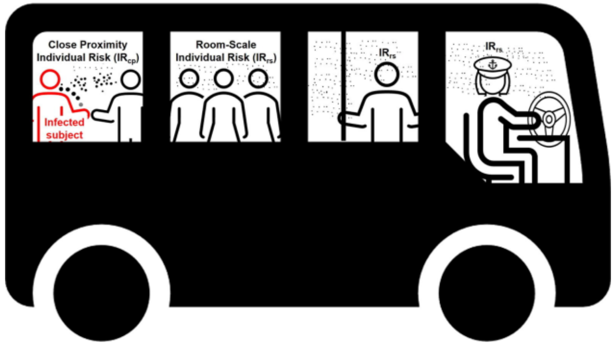
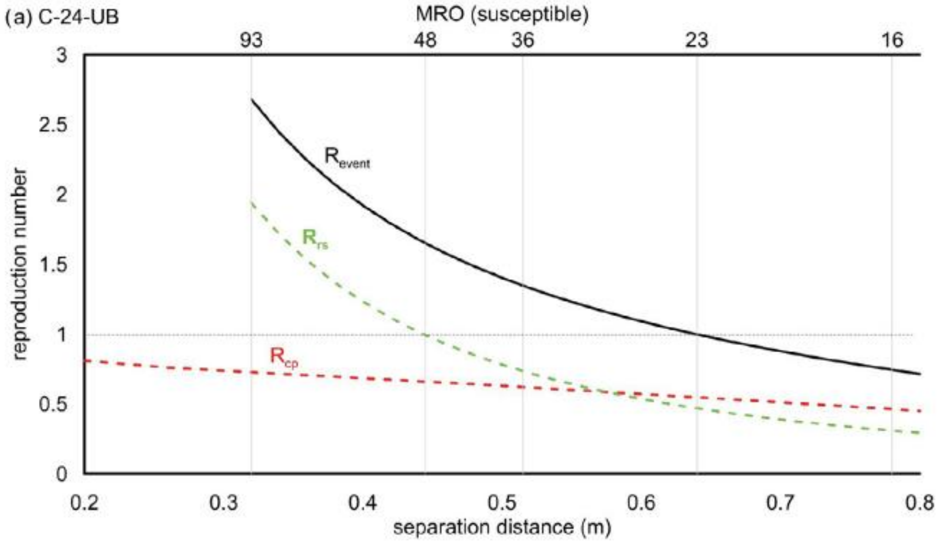


Table 2
Characteristics of the buses in terms of maximum occupancy, volume, crowding index, and ventilation rate.

Bus class	Maximum occupancy suggested by the (ECE-R107, 2015) regulation			Volume (m^3)	Crowding index (person m^{-3})
	Seats	Standees	Tot		
I	36	57	93	63	1.5
III	51	–	51	65	0.8



$$MRO = \frac{1 - IR_{cp}}{IR_{rs}}(\text{susceptibles})$$

Significance & Implications of the Findings

1. Short-range (or close proximity) airborne transmission is likely the dominant mode for SARS-CoV-2.

2. Close proximity airborne transmission does not account for all secondary transmission, indicating a role for longer-range (room-scale) transmission through shared indoor air;

3. Transmission of the Delta variant appears to be more homogeneous, with a higher overdispersion parameter.

1. For the Delta variant, for full occupancy of an urban bus, FFP2 masks are required universally if the infected person is speaking.

2. For a breathing infected subject, the close proximity risk is negligible with limited risk at the room scale

Maintaining silence can be considered an effective intervention at reducing airborne transmission on public transit, or in other environments where possible.

Risk of SARS-CoV-2 in a Car Cabin Assessed Through 3D CFD Simulations

Arpino F, Grossi G, Cortellessa G, et al. Risk of SARS-CoV-2 in a car cabin assessed through 3D CFD simulations. *Indoor Air*. 2022;32(3):e13012. doi:10.1111/ina.13012.

7. Compare risk estimates based on the well-mixed room approach to those made using CFD modeling

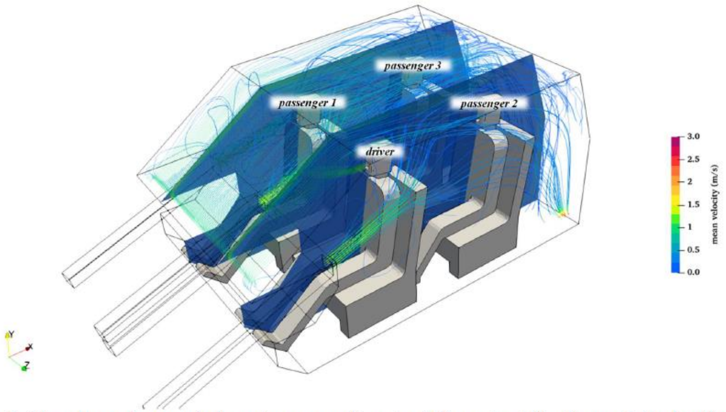


Figure 3 – Streamlines and mean velocity contours on x-y slices at z=-0.38 m and z=0.38 m in case of mixed ventilation mode at 50% ($Q_{50\%}$), speaking activity, driver infected.

$$C = \sum_{S=1}^{S=3} Ber(P_I)_S$$

(secondary cases)

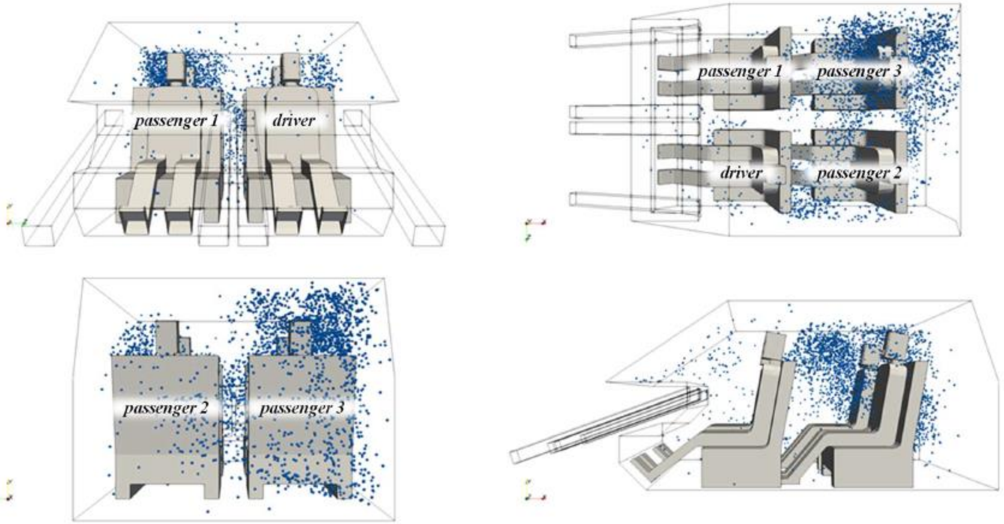
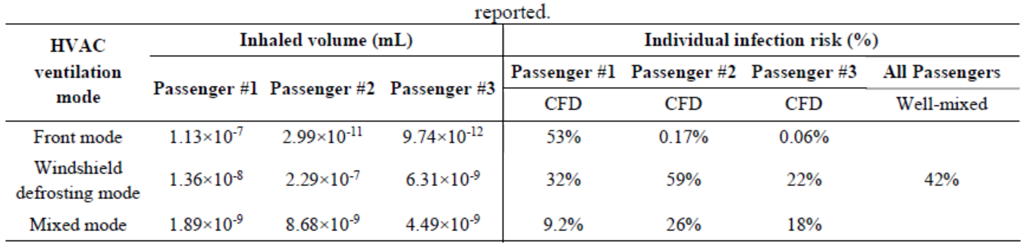


Figure 5 – Spatial particle distribution after 30 min in case of mixed ventilation mode at 50%, speaking activity, passenger #3 infected.

Table 8 - Doses in terms of volume of airborne respiratory particle ($V_{p\text{-}post}$) inhaled by susceptible occupants of the car cabin and their individual infection risk for different HVAC ventilation mode in case of $Q_{50\%}$ flow rate, driver infected, speaking activity, and 30-minute exposure scenario. Infection risks evaluated through the well-mixed approach are also reported.



HVAC ventilation mode	Inhaled volume (mL)			Individual infection risk (%)			
	Passenger #1	Passenger #2	Passenger #3	Passenger #1	Passenger #2	Passenger #3	All Passengers
				CFD	CFD	CFD	Well-mixed
Front mode	1.13×10^{-7}	2.99×10^{-11}	9.74×10^{-12}	53%	0.17%	0.06%	42%
Windshield defrosting mode	1.36×10^{-8}	2.29×10^{-7}	6.31×10^{-9}	32%	59%	22%	
Mixed mode	1.89×10^{-9}	8.68×10^{-9}	4.49×10^{-9}	9.2%	26%	18%	

Significance & Implications of the Findings

1. In a small, confined space such as a passenger car, CFD approaches are needed for most accurate estimation

2. The well-mixed (zero-dimensional) approach resulted in the highest predicted number of secondary transmissions of all scenarios modeled, indicating that the mean risk was overestimated compared to the more accurate CFD estimates.

Use of zero-dimensional approaches therefore may represent an upper bound.

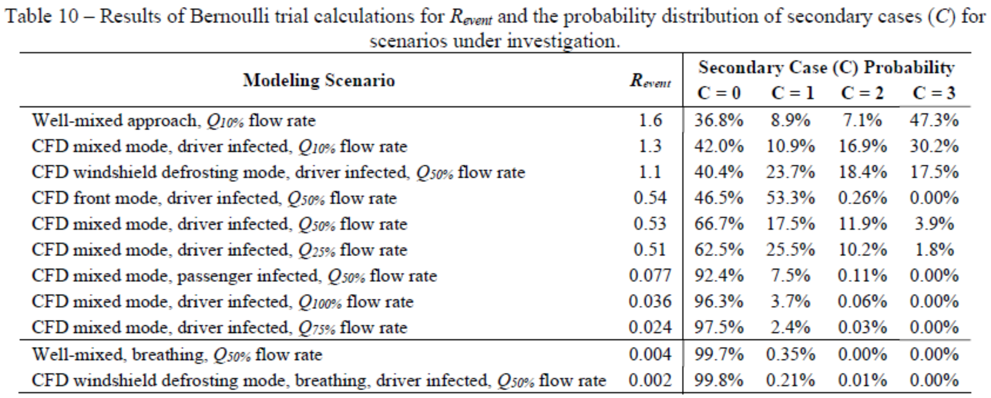


Table 10 – Results of Bernoulli trial calculations for R_{event} and the probability distribution of secondary cases (C) for scenarios under investigation.

Modeling Scenario	R_{event}	Secondary Case (C) Probability			
		C = 0	C = 1	C = 2	C = 3
Well-mixed approach, $Q_{10\%}$ flow rate	1.6	36.8%	8.9%	7.1%	47.3%
CFD mixed mode, driver infected, $Q_{10\%}$ flow rate	1.3	42.0%	10.9%	16.9%	30.2%
CFD windshield defrosting mode, driver infected, $Q_{50\%}$ flow rate	1.1	40.4%	23.7%	18.4%	17.5%
CFD front mode, driver infected, $Q_{50\%}$ flow rate	0.54	46.5%	53.3%	0.26%	0.00%
CFD mixed mode, driver infected, $Q_{50\%}$ flow rate	0.53	66.7%	17.5%	11.9%	3.9%
CFD mixed mode, driver infected, $Q_{25\%}$ flow rate	0.51	62.5%	25.5%	10.2%	1.8%
CFD mixed mode, passenger infected, $Q_{50\%}$ flow rate	0.077	92.4%	7.5%	0.11%	0.00%
CFD mixed mode, driver infected, $Q_{100\%}$ flow rate	0.036	96.3%	3.7%	0.06%	0.00%
CFD mixed mode, driver infected, $Q_{75\%}$ flow rate	0.024	97.5%	2.4%	0.03%	0.00%
Well-mixed, breathing, $Q_{50\%}$ flow rate	0.004	99.7%	0.35%	0.00%	0.00%
CFD windshield defrosting mode, breathing, driver infected, $Q_{50\%}$ flow rate	0.002	99.8%	0.21%	0.01%	0.00%

3. A novel Bernoulli-trial based approach was developed to calculate discrete numbers of secondary cases for each modeled scenario and simulation.

This enables more accurate quantification of the probability of specific numbers of secondary cases, which may be more useful than the mean R_{event} estimate (further exploration is needed on this).

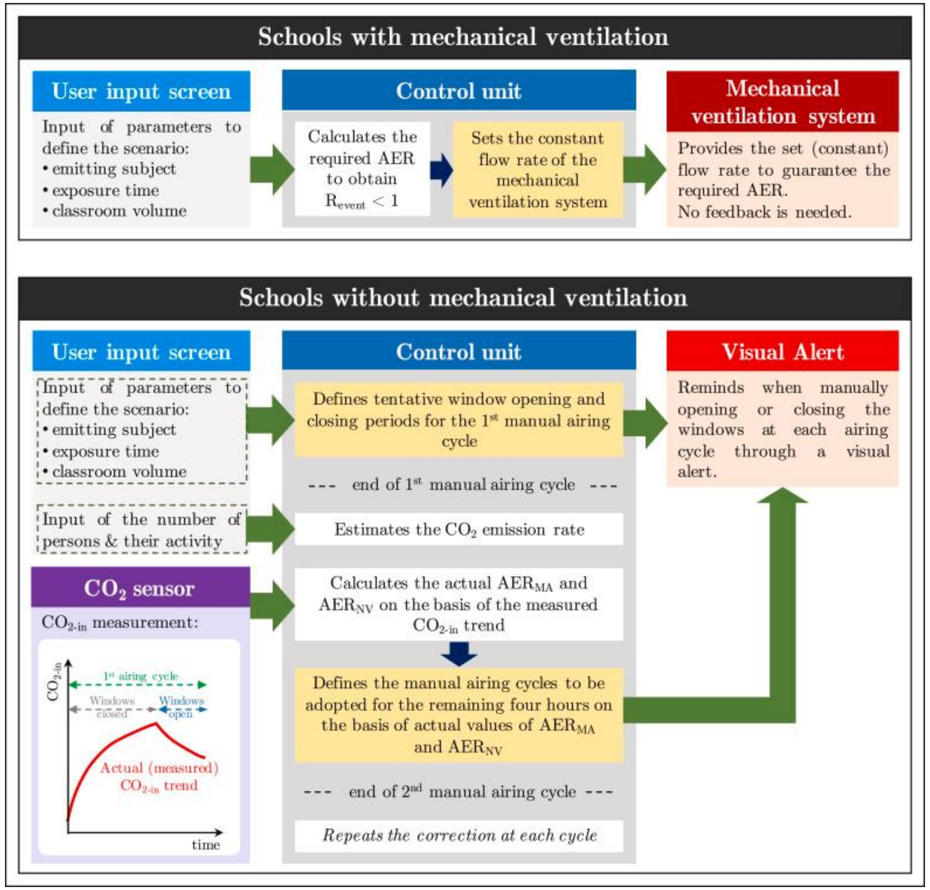
Ventilation procedures to minimize the airborne transmission of viruses in classrooms

Stabile L, Pacitto A, Mikszewski A, Morawska L, Buonanno G. Ventilation procedures to minimize the airborne transmission of viruses in classrooms. *Build Environ*. 2021;202:108042. doi:10.1016/j.buildenv.2021.108042.

1. Required air exchange rates for infection control cannot be prescribed as fixed numbers.

2. Airing schedules can be adjusted in near real-time based on monitoring of CO_2 concentrations, with the goal of maintaining less than one secondary transmission on the average for the scenario in question (i.e., an R_{event} below 1).

3. Adopting a CO_2 concentration threshold as a direct proxy for virus transmission can be misrepresentative and yield inaccurate risk estimates.



Schools with mechanical ventilation

User input screen

Input of parameters to define the scenario:
- emitting subject
- exposure time
- classroom volume

Control unit

Calculates the required AER to obtain $R_{event} < 1$

Sets the constant flow rate of the mechanical ventilation system

Mechanical ventilation system

Provides the set (constant) flow rate to guarantee the required AER.
No feedback is needed.

Schools without mechanical ventilation

User input screen

Input of parameters to define the scenario:
- emitting subject
- exposure time
- classroom volume

Input of the number of persons & their activity

CO_2 sensor

$CO_{2\text{-in}}$ measurement:

Control unit

Defines tentative window opening and closing periods for the 1st manual airing cycle

--- end of 1st manual airing cycle ---

Estimates the CO_2 emission rate

Calculates the actual AER_{MA} and AER_{NV} on the basis of the measured $CO_{2\text{-in}}$ trend

Defines the manual airing cycles to be adopted for the remaining four hours on the basis of actual values of AER_{MA} and AER_{NV}

--- end of 2nd manual airing cycle ---

Repeats the correction at each cycle

Visual Alert

Reminds when manually opening or closing the windows at each airing cycle through a visual alert.

8. Document and compare how airborne transmission risk assessment tools were used during the COVID-19 pandemic

Study 8: *Case studies using a simple airborne infection risk calculator to minimize COVID-19 infection risk*

Linge, K.L., Chen, J., Mikszewski, A. et al. Case studies using a simple airborne infection risk calculator to minimize COVID-19 infection risk: a review of common approaches and challenges. Manuscript submitted for publication and under review (2023).

Study 8 documented case studies from Australia and New Zealand using the Airborne Infection Risk Calculator (AIRC), describing how the AIRC was used to assess COVID-19 risk in different indoor settings and how users customized the tool for their own purposes.

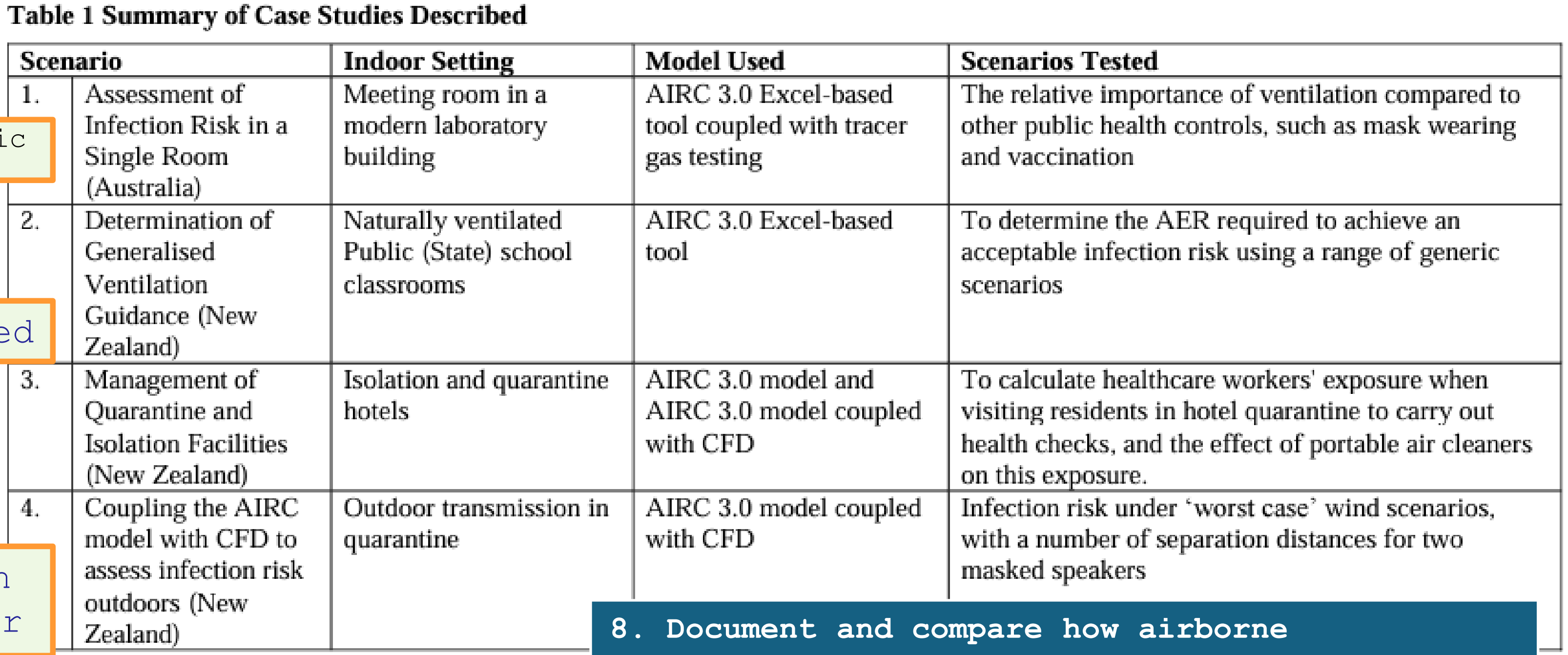


Table 1 Summary of Case Studies Described

Scenario		Indoor Setting	Model Used	Scenarios Tested
1.	Assessment of Infection Risk in a Single Room (Australia)	Meeting room in a modern laboratory building	AIRC 3.0 Excel-based tool coupled with tracer gas testing	The relative importance of ventilation compared to other public health controls, such as mask wearing and vaccination
2.	Determination of Generalised Ventilation Guidance (New Zealand)	Naturally ventilated Public (State) school classrooms	AIRC 3.0 Excel-based tool	To determine the AER required to achieve an acceptable infection risk using a range of generic scenarios
3.	Management of Quarantine and Isolation Facilities (New Zealand)	Isolation and quarantine hotels	AIRC 3.0 model and AIRC 3.0 model coupled with CFD	To calculate healthcare workers' exposure when visiting residents in hotel quarantine to carry out health checks, and the effect of portable air cleaners on this exposure.
4.	Coupling the AIRC model with CFD to assess infection risk outdoors (New Zealand)	Outdoor transmission in quarantine	AIRC 3.0 model coupled with CFD	Infection risk under 'worst case' wind scenarios, with a number of separation distances for two masked speakers

Room-specific

Generalized

Companion calculator

8. Document and compare how airborne transmission risk assessment tools were used during the COVID-19 pandemic

Study Limitations

1. Very limited data on viral load, dose-response relationship, and concentrations of viable viruses in exhaled particles versus in sputum/mucus/saliva

2. Studies do not stochastically consider variation in particle emissions between individuals, which may be extreme

3. Completely mixed room neglects higher risk within the respiratory jet – further work needed on combined approaches (as in Study 4)

4. Particle deposition and inactivation rates in ambient air should be adjusted for more detailed site-specific analysis including effects of relative humidity and CO_2 concentration.

5. More sophisticated epidemiological modeling frameworks are needed considering:

- multiple day infectious periods;
- variable social contact networks,
- variable separation distances during close contact,
- cumulative exposure effects.

Scientific Novelty of the Work

- Derived original estimates of quanta emission rates for numerous respiratory pathogens;
- Implemented stochastic treatment of the cumulative emission rate from multiple infected persons in the same room;
- Demonstrated the consistency between the predictive estimation approach and the often-significant individual variation in infectiousness;
- Combined close proximity and room-scale airborne transmission risk assessment methods;
- Compared risk assessment results between zero-dimensional (completely-mixed room) and three-dimensional (CFD) models; and
- Developed a novel Bernoulli-trial based approach to estimate discrete numbers of secondary cases resulting from modeling scenarios.