Understanding and reducing the spread of respiratory pathogens through the air

Lidia Morawska

Queensland University of Technology, Australia

University of Surrey, UK

World Health Organization
Collaborating Centre for Air Pollution and Health

Thrive
QUT

This presentation

1. Generation of infectious respiratory particles

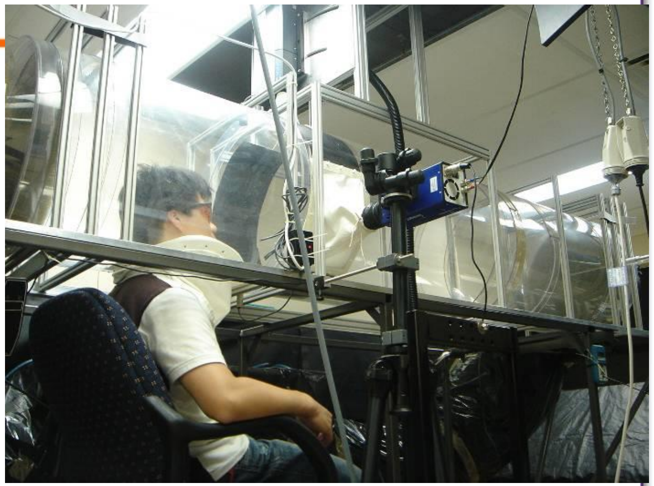
2. Spread of the particles through the air

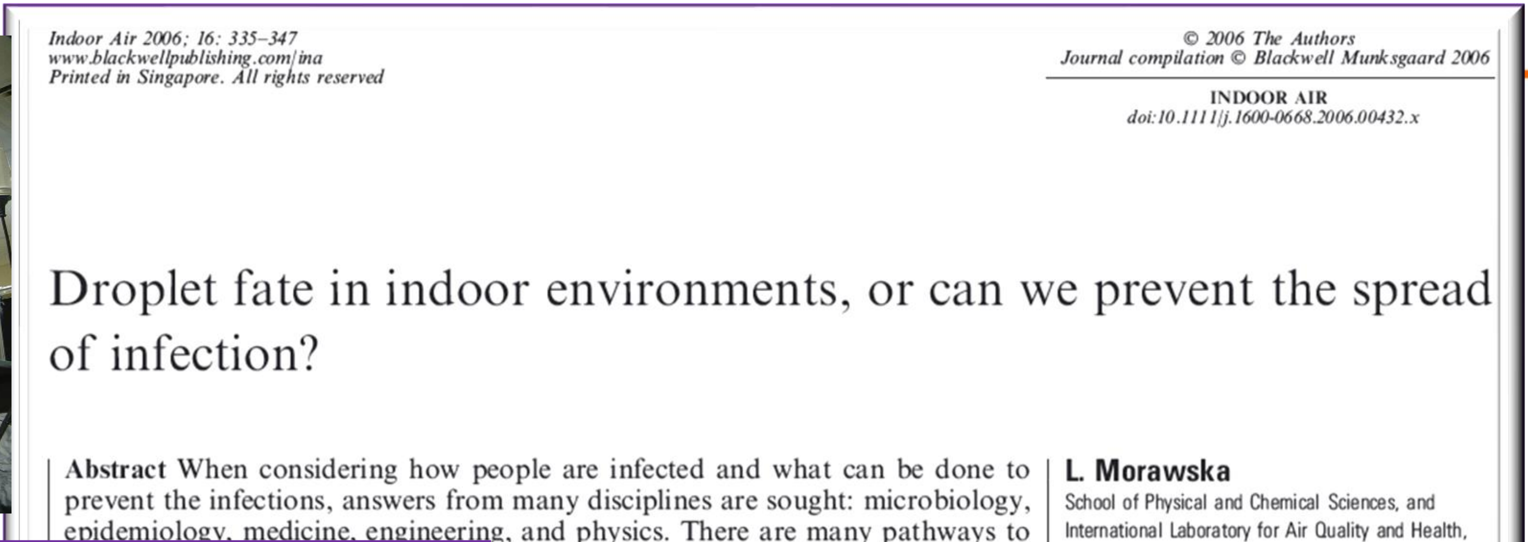
3. Reducing the spread: lessons learned

4. Reducing airborne pathogens as part of achieving clean indoor air

Generation of infectious respiratory particles

Physics of respiratory infection transmission

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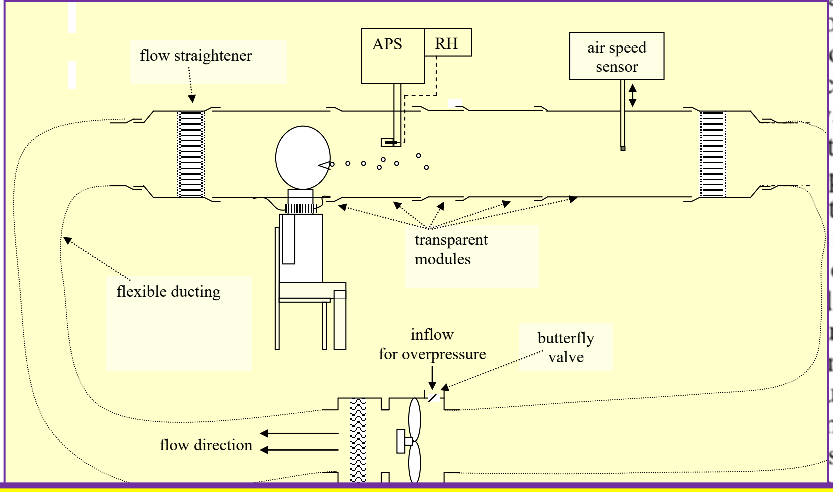
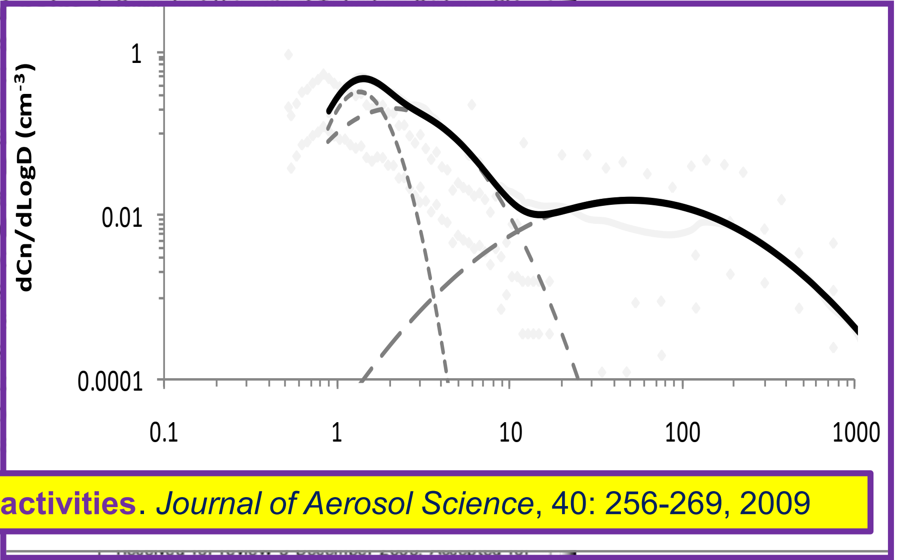
INDOOR AIR
doi:10.1111/j.1600-0668.2006.00432.x

Droplet fate in indoor environments, or can we prevent the spread of infection?

Abstract When considering how people are infected and what can be done to prevent the infections, answers from many disciplines are sought: microbiology, epidemiology, medicine, engineering, and physics. There are many pathways to ...ost significant from the epidemiologica... ...oorganisms can become airborne whe... ...ch, coughing, sneezing, vomiting, or a... ...al. The fate of the droplets is governed ...th droplet size being the most importa... ...position on surfaces and determining ...the droplets. In addition, physical cha... ...as well as the design and operation o... ...critical importance. Do we understan... ...can we quantify the droplet dynamics ...nately no, as this aspect of infection ...ntific interest. However, investigations ...umber of people were infected show h... ...n spread can be. This paper reviews th... ...s of droplet spread and solutions avail...

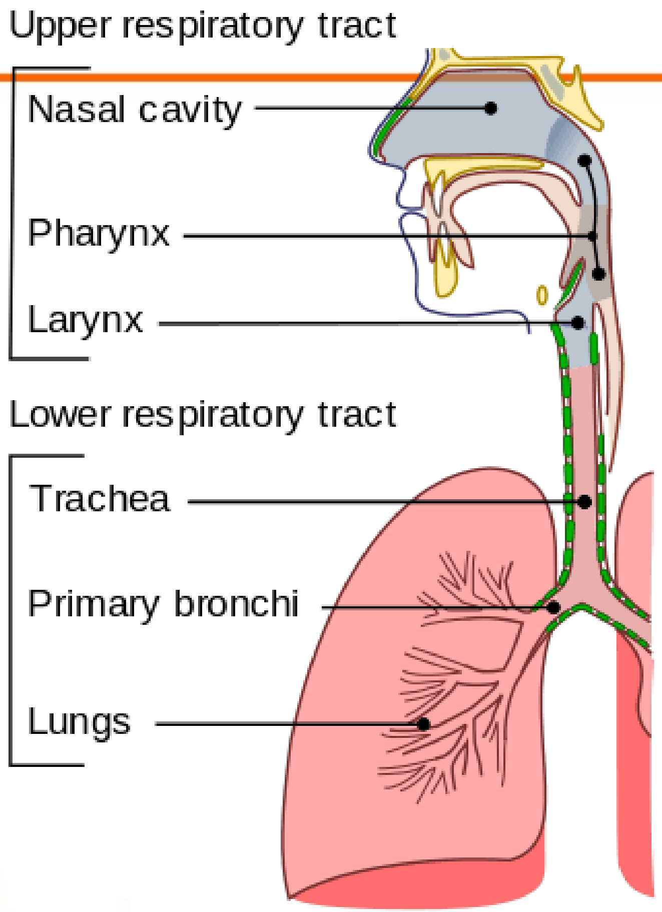
L. Morawska
School of Physical and Chemical Sciences, and
International Laboratory for Air Quality and Health,





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

Generation of respiratory particles



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

Fluid bathing the larynx is aerosolised 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 emitted

Deposition – changing initial size distribution

Viruses and bacteria in the particles?

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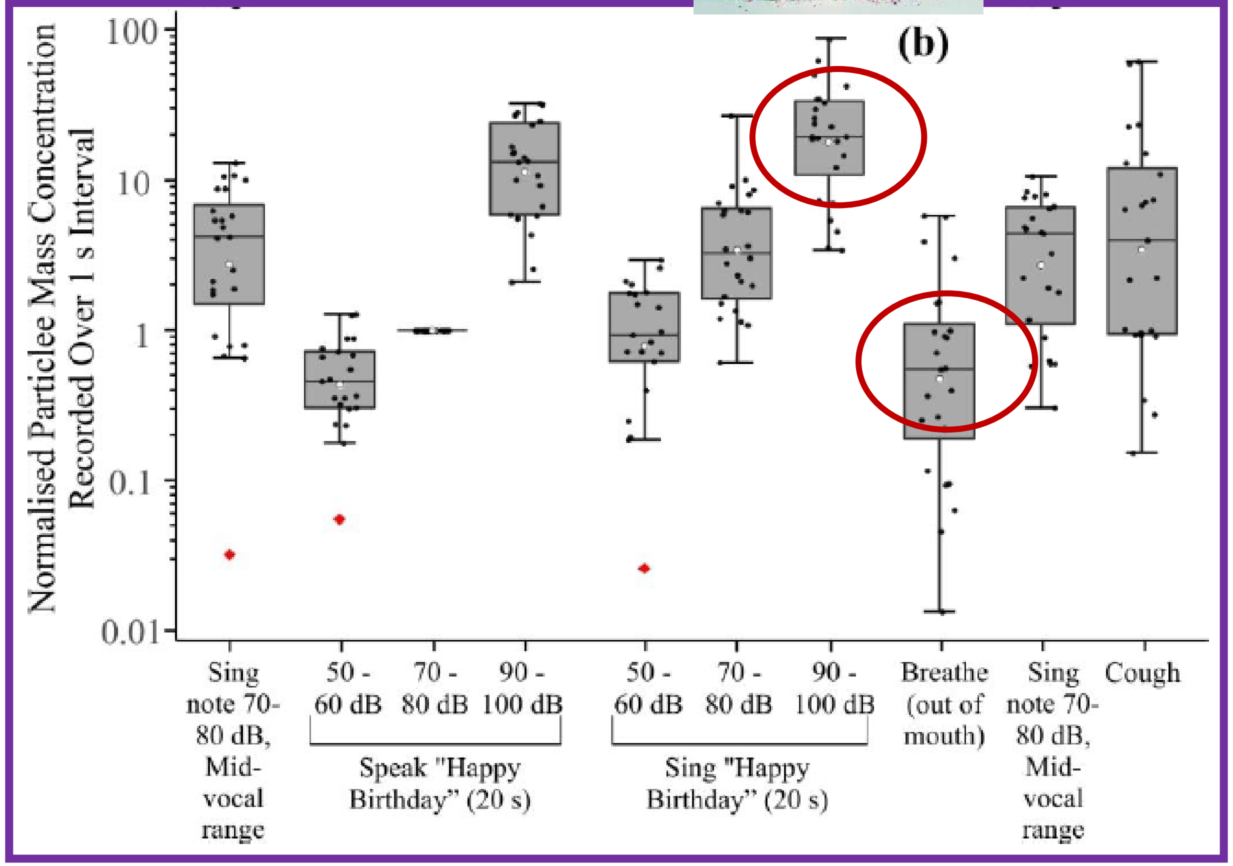
Johnson, G.R. and Morawska, L. The Mechanism of Breath Aerosol Formation. Journal of Aerosol Medicine and Pulmonary Drug Delivery, 22: 229-237, 2009.

Morawska, L., Buonanno, G., Mikszewski, A. And Stabile, L. The physics of respiratory particle generation, fate in the air, and inhalation. *Nature Physics Reviews*, 31:1-2, 2022.

Happy Birthday!



Gregson et al., Comparing the Respirable Aerosol Concentrations and 1 Particle Size Distributions Generated by Singing, Speaking and Breathing. *Aerosol Science and Technology,* 55(6): 681-691, 2021

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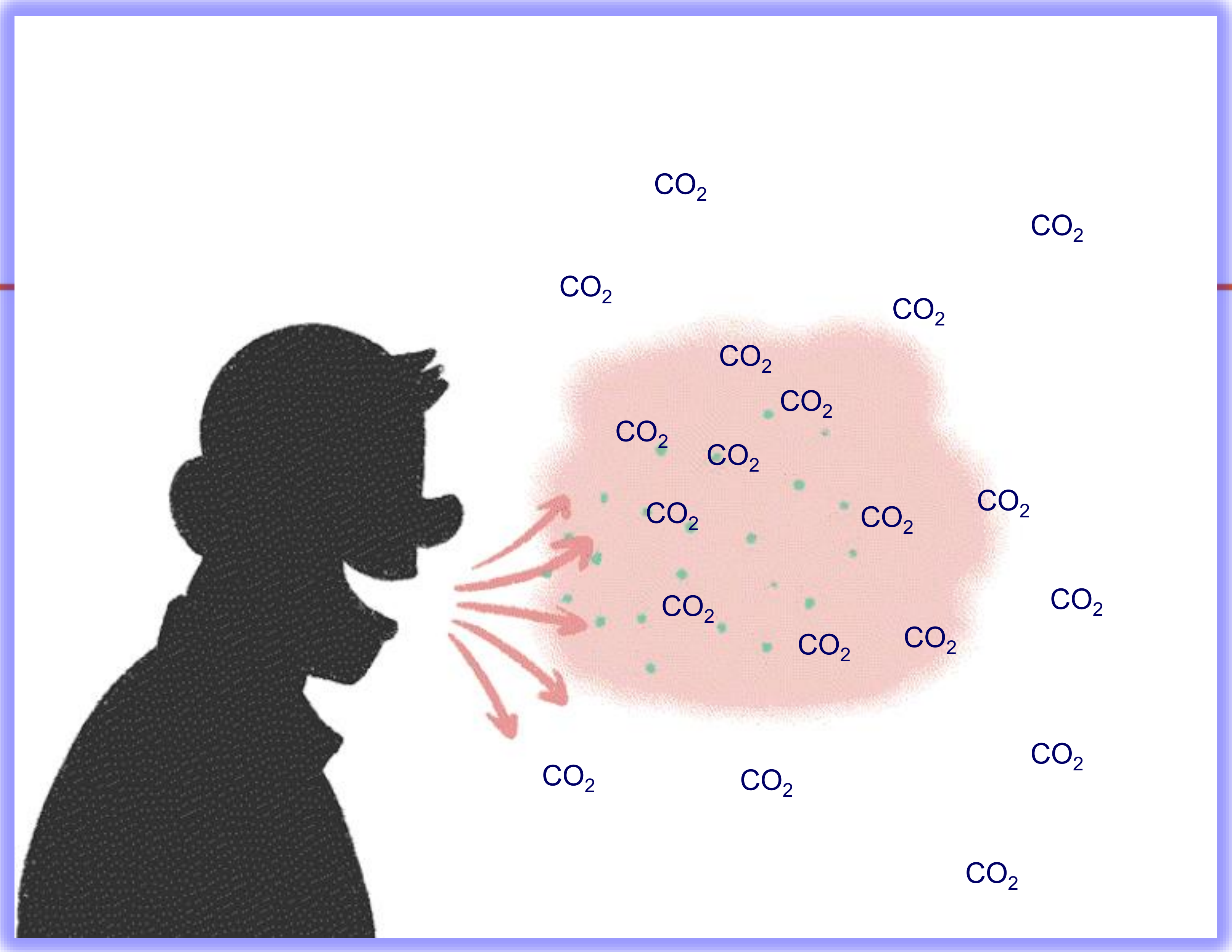
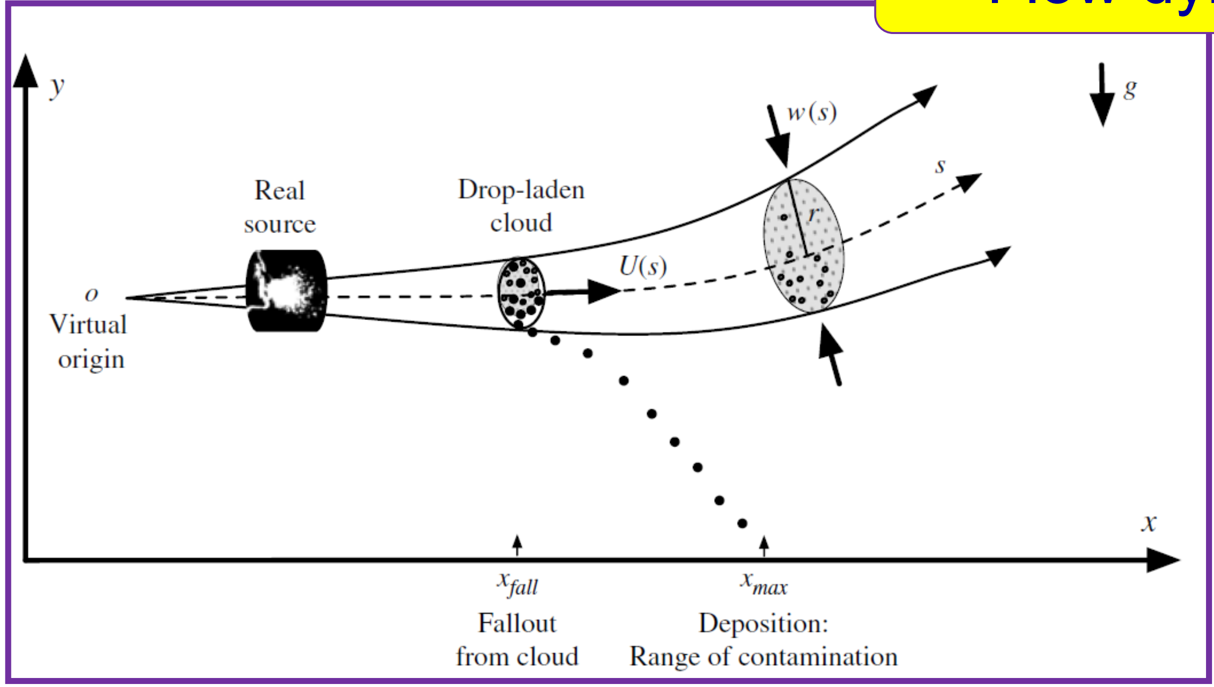
Spread of pathogens through the air



Morawska, L. Australia must get serious about airborne infection transmission. Here's what we need to do. *The Conversation,* 26 July 2021. Published Online: https://theconversation.com/australia-must-get-serious-about-airborne-infection-transmission-heres-what-we-need-to-do-164622

How do particles from respiratory activities travel through the air?

Flow dynamics



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

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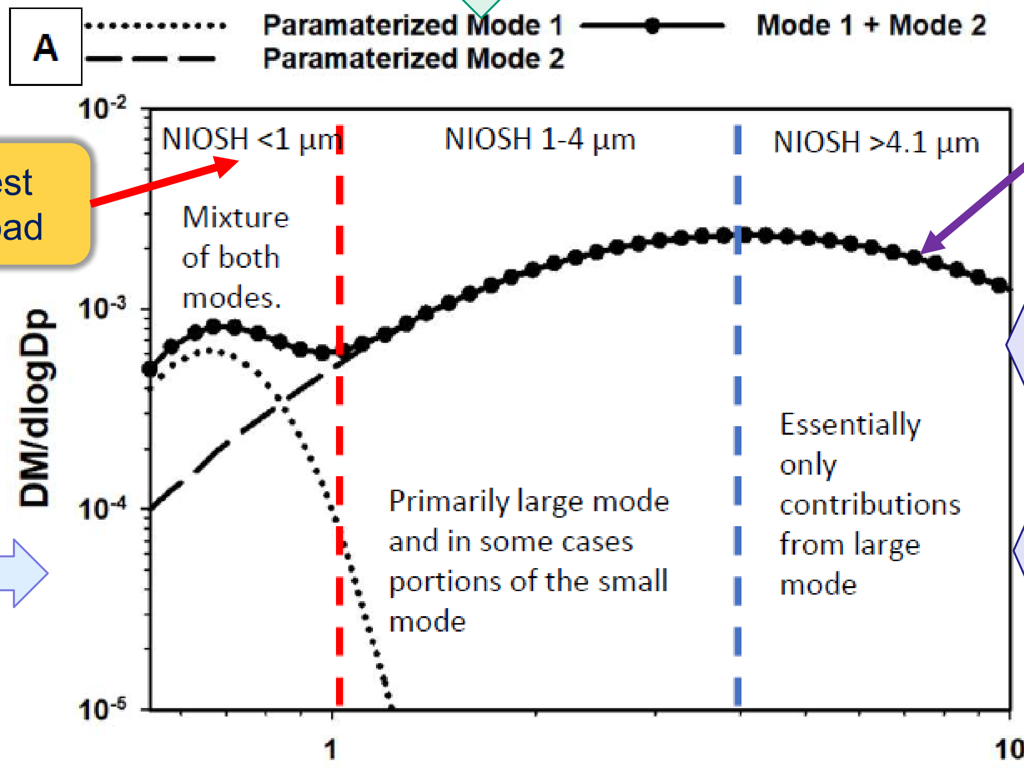
Mass size distributions - mixed acuity COVID-19 rooms

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., The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. *Journal of Exposure Science & Environmental Epidemiology*, p.1-6, 2021.

State of the knowledge: particles

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 and travel long distances

Minutes?

Hours?

Meters (m)?

Tens of m?

- **All respiratory activities** (including breathing) generate particles, but vocalization ⇨ higher emissions than other activities

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State of the knowledge: virus-laden particles

Virus in the particles

- Overall, smaller particles ⇨ contain higher loads (of SARS-CoV-2 but not only)
- 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

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Significance of the indoor environment:
impact on pathogen stability

Reducing the spread: lessons learned

Epidemics and pandemics of the past

Of respiratory infections

Spanish flu

The Conservations, March 27, 2021

What lessons have we learned?

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REVIEW

Lessons from the COVID-19 pandemic for ventilation and indoor air quality

Lidia Morawska[1,2]†, Yuguo Li[3]†, Tunga Salthammer[1,4]*†

through ventilation, filtration, or inactivatio ultraviolet (UV) C radiation. It has been 165 y since Florence Nightingale explained the role of environmental conditions in the spread of diseases (6), and hygienic reformers, including Florence Nightingale and Max von Pettenkofer, demonstrated empirically that the risk of infection in hospitals can be lowered through an

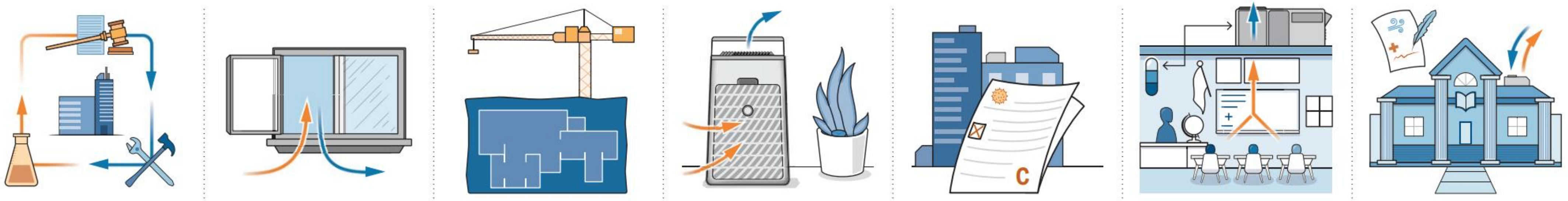

Fig. 1. Key findings and lessons from the COVID-19 pandemic regarding the reduction viral loads through ventilation in the indoor environment.

hundred years ago. Never before in history has it been possible to develop and mass-produce a vaccine in less than a year from when a new virus was first identified (3). However, similar to the misconception about the mode of respiratory virus transmission in the Middle Ages, at the beginning of the COVID-19 pandemic, there was a misconception about how severe acute respiratory syndrome coronavirus 2 (SARS-

in general, and especially in relation to the role of ventilation, it is necessary to identify not only the lessons learned and how society can implement these learnings but also who it was that learned them: health authorities, experts on the subject, scientists and engineers, and/or society in general. As part of our scientific and advisory activities during the pandemic, we have identified seven lessons of particular im-

instead of ventilation, filtration, face-masking, and deactivation of airborne virus (20). Even in the middle of the pandemic, there were controversial discussions in Central and Northern Europe, for example, about whether ventilation makes sense given possible heat loss and the risk of colds.

The main issue behind such a debate is the definition of "expert knowledge." Officials at

Morawska, L., Li, Y. and Salthammer, T. **Lessons from the COVID-19 pandemic for ventilation and indoor air quality.** *Science*, 385(6707): 396-401, 2024. *https://doi.org/10.1126/science.adp2241*

Lesson 1

Interdisciplinary expert knowledge should be the guiding factor in infection risk control and indoor air quality management in general.

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Morawska, L., Li, Y. and Salthammer, T. Lessons from the COVID-19 pandemic for ventilation and indoor air quality. Science, 385(6707): 396-401, 2024. https://doi.org/10.1126/science.adp2241

Old dogmas

Scientific understanding of the role and mechanisms of airborne infection transmission was *well advanced* before the COVID-19 pandemic

Received: 12 November 2021 | Revised: 25 May 2022 | Accepted: 30 May 2022
DOI: 10.1111/ina.13070

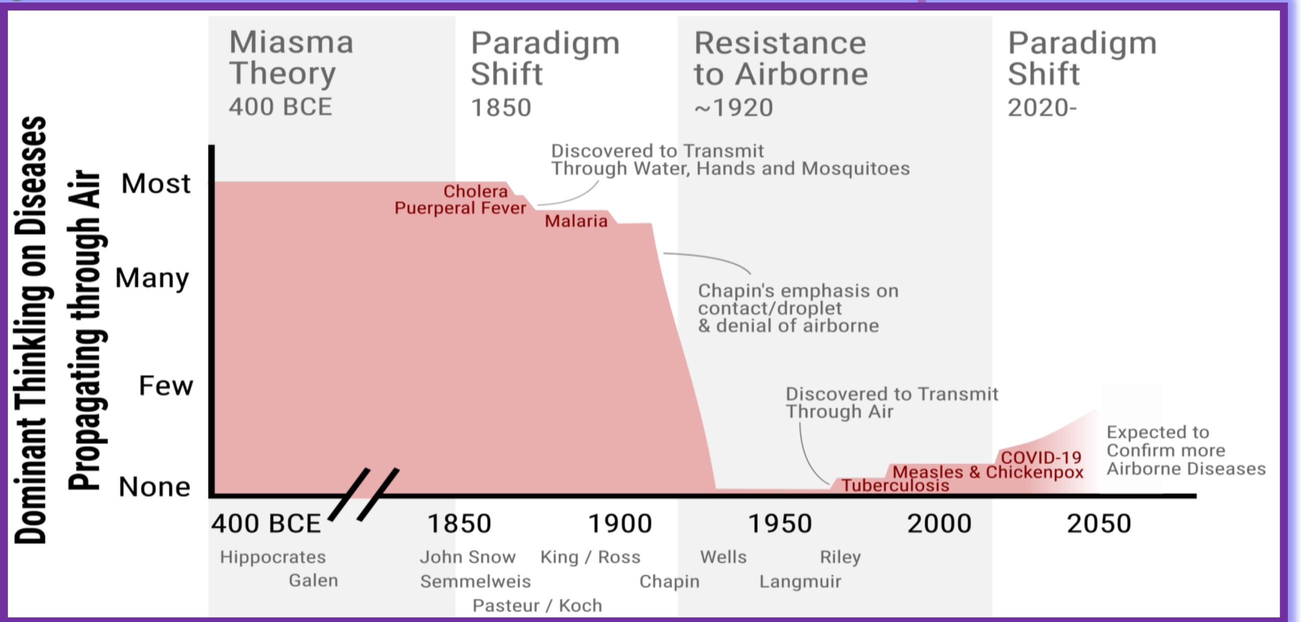
REVIEW

WILEY

What were the historical reasons for the resistance to recognizing airborne transmission during the COVID-19 pandemic?

Jose L. Jimenez[1] | Linsey C. Marr[2] | Katherine Randall[3] | Edward Thomas Ewing[4] | Zeynep Tufekci[5] | Trish Greenhalgh[6] | Raymond Tellier[7] | Julian W. Tang[8] | Yuguo Li[9] | Lidia Morawska[10] | Jonathan Mesiano-Crookston[11] | David Fisman[12] | Orla Hegarty[13] | Stephanie J. Dancer[14] | Philomena M. Bluyssen[15] | Giorgio Buonanno[16] | Marcel G. L. C. Loomans[17] | William P. Bahnfleth[18] | Maosheng Yao[19] | Chandra Sekhar[20] | Pawel Wargocki[21] | Arsen K. Melikov[21] | Kimberly A. Prather[22]

[1]Department of Chemistry and Coop
[2]Department of Civil and Environme
[3]Department of English, Virginia Tec
[4]Department of History, Virginia Tec
[5]School of Journalism, Columbia Uni
[6]Department of Primary Care Health
[7]Department of Medicine, McGill Ur
[8]Department of Respiratory Science
[9]Department of Mechanical Enginee
[10]International Laboratory for Air Qu
[11]Goldman Hine LLP, Toronto, Ontar
[12]Dalla Lana School of Public Health
[13]School of Architecture, Planning &
[14]Department of Microbiology, Hairr
[15]Faculty of Architecture and the Bu
[16]Department of Civil and Mechanic
[17]Department of the Built Environm
[18]Department of Architectural Engir
[19]College of Environmental Sciences
[20]Department of the Built Environm



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Clinical Infectious Diseases

INVITED COMMENTARY

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

Lidia Morawska[1] and Donald K. Milton[2]

[1]International Laboratory for Air Quality and Heath, WHO Collaborating Centre, Queensland University of Technology, Brisbane, Australia, and [2]Institute for Applied Environmental Health, University of Maryland School of Public Health, College Park, Maryland, USA

Group 36

239 scientist from 34 countries

“…this work is considered one of the four key elements in fighting the COVID-19 pandemic and is of immeasurable global significance”.

https://www.washingtonpost.com/opinions/2020/07/14/need-some-good-news-about-covid-19-here-are-six-reasons-optimism

We ... and to the relevant national and international bodies to recognize the potential for airborne spread of coronavirus disease 2019 (COVID-19). There is significant potential for inhalation exposure to viruses in microscopic respiratory droplets (microdroplets) at short to medium distances (up to several meters, or room

VIEWPOINTS

COVID-19 and Airborne Transmission: Science Rejected, Lives Lost. Can Society Do Better?

Lidia Morawska,[1] William Bahnfleth,[2] Philomena M. Bluyssen,[3] Atze Boerstra,[4] Giorgio Buonanno,[5] Stephanie J. Dancer,[6] Andres Floto,[7] Francesco Franchimon,[8] Charles Haworth,[9] Jaap Hogeling,[10] Christina Isaxon,[11] Jose L. Jimenez,[12] Jarek Kurnitski,[13] Yuguo Li,[14] Marcel Loomans,[15]

Lesson 2

Ventilation must go far beyond advice to *"open the window."*

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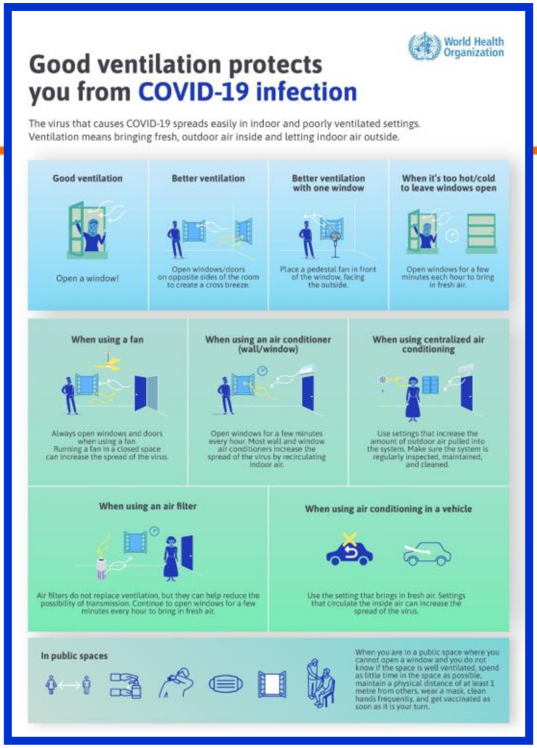
Morawska, L., Li, Y. and Salthammer, T. Lessons from the COVID-19 pandemic for ventilation and indoor air quality. Science, 385(6707): 396-401, 2024. https://doi.org/10.1126/science.adp2241

Natural ventilation

= no ventilation



Homes
Schools
Restaurants
Shops etc.

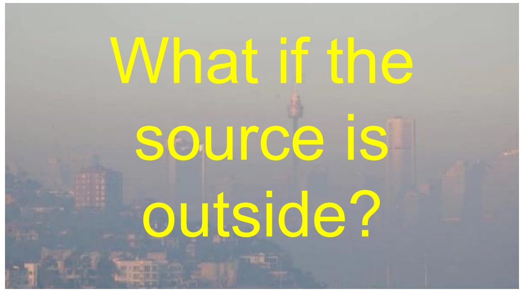
When it is NOT:

- too cold
- too hot
- too noisy

In reality, in most climates,
most of the time it is:

- too cold
- too hot
- too noisy
- too polluted
- too unsafe

NO VENTILATION



Disclaimer:
By "no ventilation" I mean "minimal ventilation".

- The building envelope always leaks.
- Some countries/jurisdictions are more or less sophisticated regarding rules on natural ventilation.

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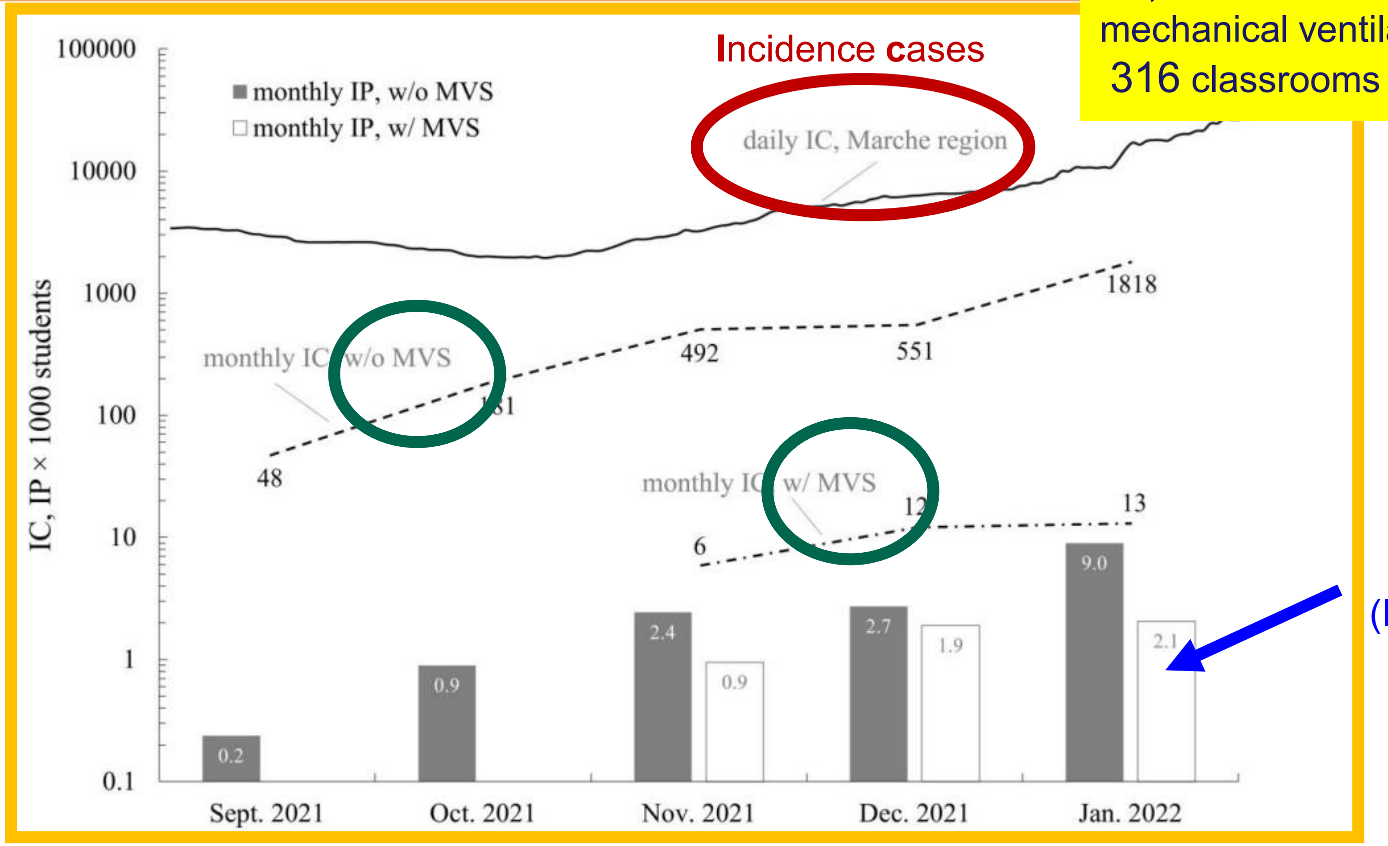
Ventilation reduced COVID-19 cases in schools in the Marche region

10,441 classrooms without (w/o) mechanical ventilation systems (MVSs)
316 classrooms with (w/) MVSs



Ricolfi, L., Stabile, L., Morawska, L. and Buonanno, G., 2022. **Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: a retrospective cohort study in Italy's Marche region**. Frontiers in Public Health, section *Infectious Diseases: Epidemiology and Prevention,* 10: 1087087, 2022.

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Lesson 3

Better building designs that optimize ventilation performance, with indoor air quality as the focus, should be the guiding principle behind the construction of buildings in the future.

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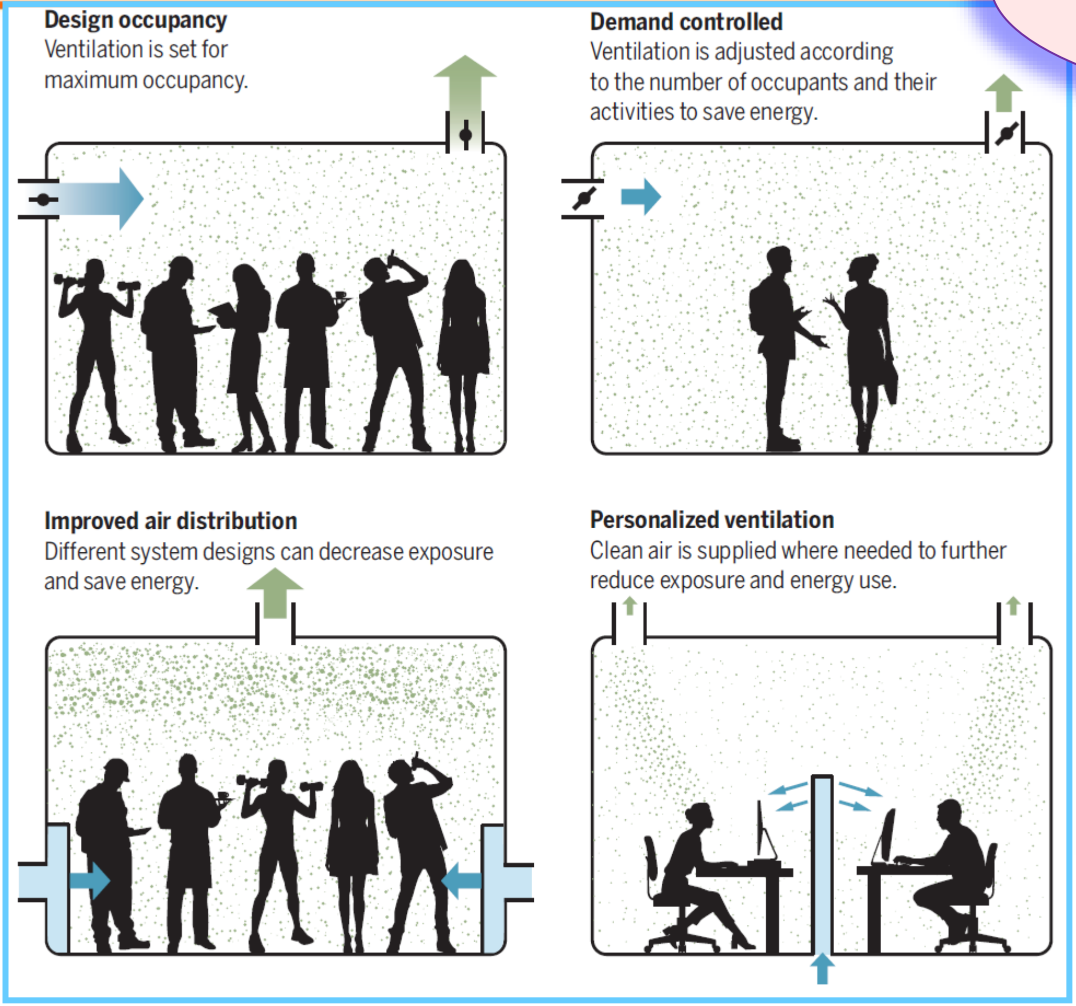
Morawska, L., Li, Y. and Salthammer, T. Lessons from the COVID-19 pandemic for ventilation and indoor air quality. Science, 385(6707): 396-401, 2024. https://doi.org/10.1126/science.adp2241

Do we have the knowledge and technology?



While there are many technological and application complexities…

Knowledge and advanced technologies exist!

But we need *social licence* to use them

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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Lesson 6

Ventilation performance **should be monitored** at all times when buildings are occupied.

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Morawska, L., Li, Y. and Salthammer, T. Lessons from the COVID-19 pandemic for ventilation and indoor air quality. Science, 385(6707): 396-401, 2024. https://doi.org/10.1126/science.adp2241

Monitoring: the most critical step

Addressing actual and community expectations on CO2 concentrations within indoor spaces – A reasonably practicable methodology using CO2 concentration to assess ventilation quality to indoor spaces

Peter McGarry[1*], Lidia Morawska[1,2], Savinda Arambawatta Lekamge[1,2], Simon Witts[3]

Abstract

The ability to quickly assess the performance of a ventilation system to deliver an adequate amount of clean air to the space relative to the number of occupants is important as part of the overall goal of ensuring healthy indoor air. This study investigated the optimal location, number and duration of deployment of carbon dioxide (CO_2) monitors to report in situ CO_2 concentrations as a proxy for ventilation quality and risk of infection. A method for characterising indoor CO_2 concentrations within occupied spaces serviced by heating, ventilation and air conditioning (HVAC) systems was developed and then applied through the deployment of CO_2 sensors within 1439 rooms across 78 mechanically ventilated buildings, with room usage including teaching and teaching support office work. In 1025 (72%) rooms, CO_2 concentration was < 800 ppm, in 267 (18%) it was between 800 ppm and 1000 ppm, while in 147 (10%) of these spaces it exceeded 1000 ppm during room occupancy. We document a method that is demonstrable and is reasonably practicable in terms of instrumentation cost and time to deploy and analyse data to inform the performance of the mechanical ventilation system in replacing inside air with outside air. Reasons for the elevated CO_2 concentrations included undetected malfunctioning ventilation plant, clogged air filters reducing the amount of outside air supplied to spaces, a mismatch between the number of people occupying spaces and the ventilation design occupancy density number, and installation (to larger floor space areas) of additional walled in offices without sufficient air inlet diffusers.

McGarry et al. Addressing actual and community expectations on CO_2 concentrations within indoor spaces – A reasonably practicable methodology using CO_2 concentration to assess ventilation quality to indoor spaces. *Indoor Environments*, 2(3): 100101, 2025.

Reducing airborne pathogens as part of achieving clean indoor air

Lesson 7

Indoor air quality **must be regulated** to protect human health in public spaces.

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Morawska, L., Li, Y. and Salthammer, T. Lessons from the COVID-19 pandemic for ventilation and indoor air quality. Science, 385(6707): 396-401, 2024. https://doi.org/10.1126/science.adp2241

Outdoor versus indoor air quality standards

Outdoor Air
- Emission standards
- Air quality performance standards

Over 200 monitoring stations in Australia

Indoor Air
- National Construction Codes
- Limited emission control standards
- ???

No performance standards, no monitoring

Why do we need IAQ performance standards?

Can IAQ be controlled by a voluntary approach?

It may, but not as a general rule

Cost-benefit of achieving good IAQ :

- new buildings at least 1 to 10
- retrofitting of existing buildings?

Reduced health care costs, cost of infection transmission, of absenteeism, etc.

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Why can’t we monitor indoor air the same way we monitor outdoor air?

Contrast this with outdoor monitoring, which does not have to be conducted on every street corner!

Because …

1. Every indoor space is different, so monitoring is necessary in every public indoor space.

2. We cannot use bulky and expensive compliance monitors for every indoor space.

3. The pathogens responsible for the transmission of indoor airborne infections cannot yet be routinely monitored in real-time.

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INSIGHTS

POLICY FORUM

PUBLIC HEALTH

Mandating indoor air quality for public buildings

If some countries lead by example, standards may increasingly become normalized

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

People living in urban and industrialized societies, which are expanding globally, spend more than 90% of their time in the indoor environment, breathing indoor air (IA). Despite decades of research and advocacy, most countries do not have legislated indoor air quality (IAQ) performance standards for public spaces that address concentration levels of IA pollutants (1). Few building codes address operation, maintenance, and retrofitting, and most do not focus on airborne disease transmission. But the COVID-19 pandemic has made all levels of society, from community members to decision-makers, realize the importance of IAQ for human health, well-being, productivity, and learning. We propose that IAQ standards be mandatory for public spaces. Although enforcement of IAQ performance standards in homes is not possible, homes must be designed and equipped so that they could meet the standards.

in the derivation procedure; the complex political, social, and legislative situation rega ing IAQ; the lack of an open, systematic, harmonized approach (4); and that establ ing an IAQ standard is always the resul a compromise between scientific knowle and political will (5). Because of the hete enous landscape of approaches needed, s barriers remain intact despite the consi able IAQ research and evidence base de oped over the past decades.

CHALLENGES

Source contributions

IA pollution originates from sources indoors (including humans) and outdoors and from chemical reactions between pollutants in IA (6). Compliance with IAQ standards (that refer to the concentrations of indoor pollutants) would require controlling indoor emission sources (such as combustion, building products, and cleaning products) and mini-

is different and is used differently, and we

of monitoring IAQ parameters in buildings depends on the size, cost, robustness, and silent operation of the sensor or monitor; calibration; and ease of interpreting data. But routine, real-time monitoring of indoor pathogens is currently infeasible. In the absence of information on the concentrat of pathogens in IA, the question is wh proxy parameter or pollutant should be basis for legislation that targets airborne fection transmission.

Canberra, August 2024

Scientific consensus of a large, interdisciplinary and international group of experts.

Morawska, L., et al., Mandating indoor air quality for public buildings. *Science*, 383: 6690, 2024. https://doi.org/10.1126/science.adl0677

Proposed IAQ standards

Do you know the basis for these values?

	Level	Averaging time or setpoint
$PM_{2.5}$, μg/m³	15[i]	1-hour
CO_2, ppm	800 (absolute value)[ii]	threshold
	350 (delta)[iii]	threshold
CO, mg/m³	100[iv]	15 minutes[iv]
	35[iv]	1 hour[iv]
	10 [iv]	8 hours[iv]
Ventilation (L/s/person)	14[v]	When the space is occupied

Based on:

WHO AQG

Scenario:
- 25 students
- 1 infected

WHO AQG

Scenario (as above)
$R_0 < 1$

(i) 2021 AQG 24-h level; (ii) when 100% of air delivered to the space is outdoor air, assuming that outdoor CO_2 concentration is 450ppm. It is calculated based on a classroom scenario as described in the Supplement; (iii) Delta (Δ) is the difference between the actual CO_2 concentration and the CO_2 concentration in the supply air (iv) 2010 IAQG level; only including the 8h averaging time; (v) clean air supply rate in the breathing zone, where clean air is as defined earlier in section 3 (Allen et al. 2022). At 25°C and 1 atm (standard atmospheric pressure) for CO 1 ppb = 1.15 μg/m³. Threshold is the concentration level of CO_2 that must not be exceeded.

Morawska, L., et al., 2024. Mandating indoor air quality for public buildings. *Science*, 383(6690), pp.1418-1420

We have the framework for change

Chadwick’s transformation of sanitation infrastructure in the UK in 19th century was a paradigm change.

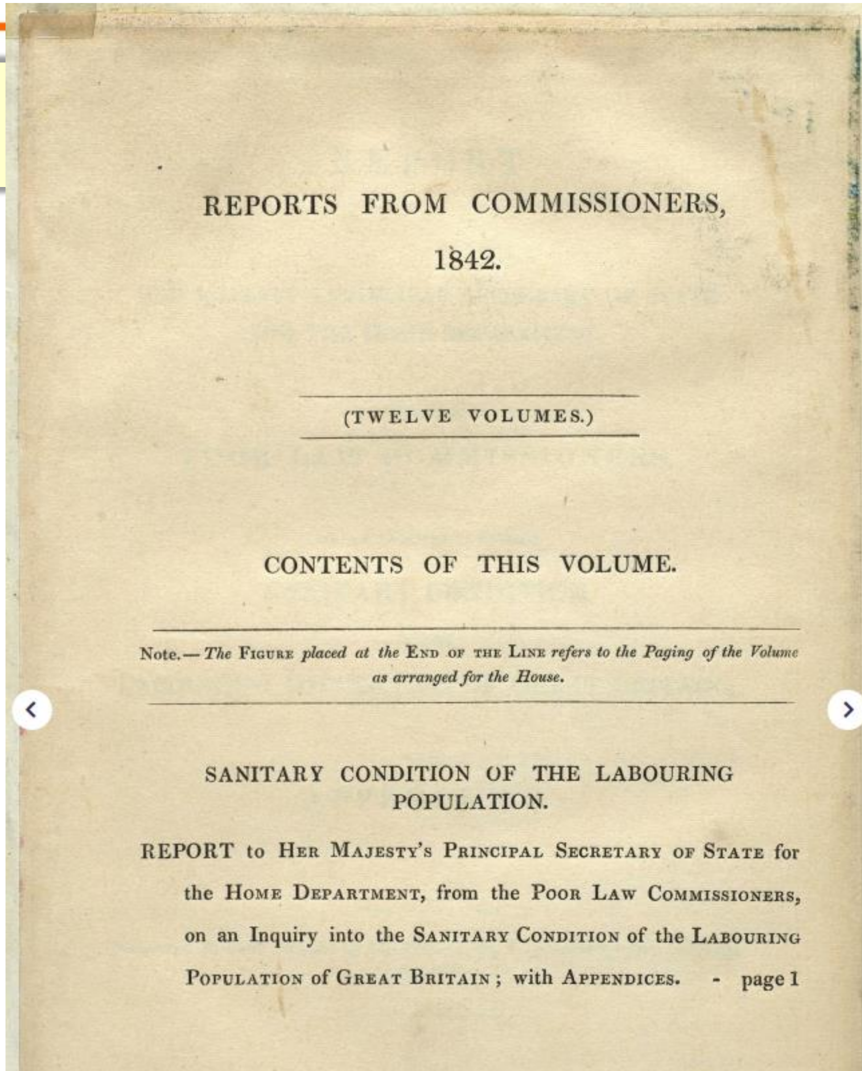
- Changing the paradigm and modernising buildings to improve indoor air quality would produce benefits on a similar scale
- **But the effort and investment required for modernisation will be much lower.**

Why?

Because we (Australia, USA, EU, etc) already have:

- **sophisticated building infrastructure**
- **public health regulatory frameworks**
- **workplace safety and public health law mechanisms**

to support the required advances.



REPORTS FROM COMMISSIONERS,

1842.

(TWELVE VOLUMES.)

CONTENTS OF THIS VOLUME.

Note.—*The Figure placed at the End of the Line refers to the Paging of the Volume as arranged for the House.*

SANITARY CONDITION OF THE LABOURING POPULATION.

REPORT to Her Majesty's Principal Secretary of State for the Home Department, from the Poor Law Commissioners, on an Inquiry into the Sanitary Condition of the Labouring Population of Great Britain; with Appendices. - page 1

Our goal:
to make clean indoor for all the norm!

Have we learned the lessons already?

Thank you!

l.morawska@qut.edu.au

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