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INDOOR AIR QUALITY CONTROL AFTER THE COVID-19 PANDEMIC

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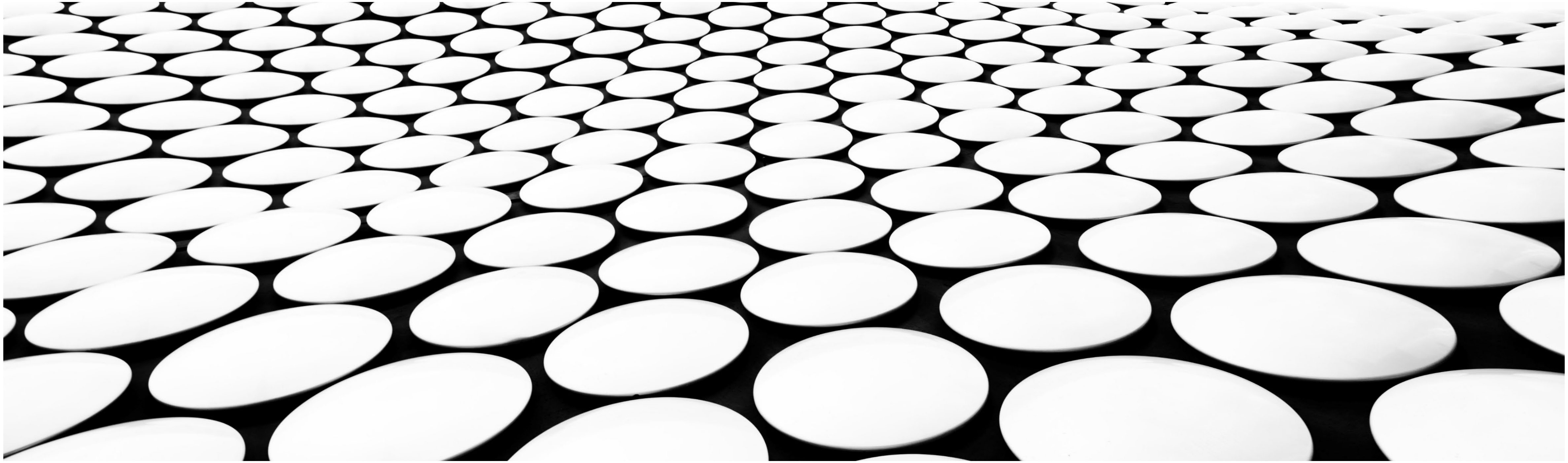
Region XIII CRC

19 August 2022

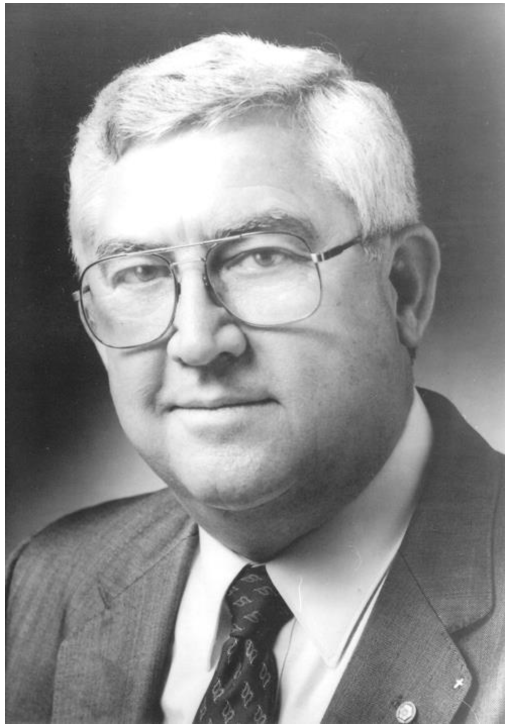


Topics

- IAQ before Covid-19
- What we've learned (and re-learned) from the pandemic
- Requirements for IAQ standards that address infection
- Overcoming the IAQ-energy conflict
- Important knowledge gaps

Before Covid-19

“Indoor air quality has gone from what had been described as a 'non-issue' to what could be the most important health concern we will face for the remainder of the 20th century.”
~Donald Bahnfleth, 1986



Health and productivity loss – known for decades

c. 2000

2020

ASHRAE Journal

How IEQ Affects Health, Productivity

By William J. Fisk, P.E., Member ASHRAE

This article, a summary of Fisk,[1,2] estimates the nationwide improvements in health and productivity potentially attainable by providing better indoor environmental quality (IEQ) in U.S. buildings. Estimates include the potential reductions in three categories of health effects, the associated economic benefits, and the potential direct improvements in productivity not mediated through health.

Potential percentage reductions in health effects from changes in improving IEQ were estimated from the results of epidemiological (i.e., population health) studies that identified risk factors for health effects and quantified the risks. For example, many studies have found that the prevalence of respiratory symptoms associated with asthma are increased by 20% to 100% among occupants of houses with moisture problems, implying that elimination of these moisture problems would diminish symptoms by 17% to 50% in these occupants (e.g., 20% ÷ 120% = 17%).

These risk factor reductions through practical measures were estimated from published data using engineering judgments. For example, it was considered technically feasible and practical, but not necessarily easy or inexpensive, to double ventilation rates in offices or improve prevention and expedite repair of water leaks in buildings. Consequently, the "potential" reductions in risk factors are those considered both technically feasible and practical, recognizing that implementation costs and other barriers will sometimes make these gains difficult.

To calculate health benefits, potential percentage reductions in health effects were multiplied by the size of the affected population or by the number of health effects experienced. To estimate economic benefits, the percentage reductions in health effects were multiplied by the annual costs of the health effects. The costs in the U.S. of acute respiratory illnesses and of allergies and asthma were based on published estimates with direct health-care costs and indirect productivity costs (e.g., value of lost work).

Estimating the costs of sick building syndrome (SBS) symptoms was more difficult and produced more uncertain estimates. No comprehensive data were available on the costs of SBS-related investigations, remediations, or litigation. However, three studies have measured small but statistically significant decreases in worker performance linked to SBS symptoms. Therefore, the estimated cost of SBS symptoms was based on these measured decreases in work performance (adjusted downward[1]) and on the economic output of office workers, since SBS is most commonly reported for office workers.

A similar procedure was used to estimate the potential direct productivity gains from improved indoor temperature control and better lighting quality. All estimates were adjusted to 1996 U.S. dollars and to the size of the U.S. population in 1996.

Acute Respiratory Illness

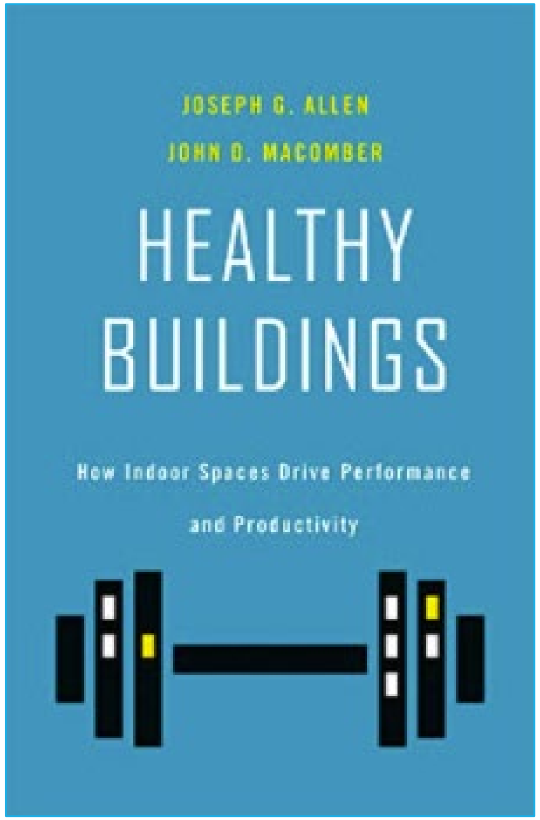
No high quality studies identified failed to find a link between building characteristics and acute respiratory illnesses (ARIs) such as influenza and common colds. Eight studies reported statistically significant 23% to 76% reductions in ARIs among building occupants with higher ventilation rates, reduced space sharing, reduced occupant density, or irradiation of air with ultraviolet light. These changes were considered technically feasible and practical, given sufficient benefits.

One study found a 35% reduction in short-term absence, a surrogate for ARI, in buildings with higher ventilation rates. Because some studies took place in buildings such as barracks and a jail, reductions in ARIs were adjusted downwards, and ranged from 9% to 20%. Mul-

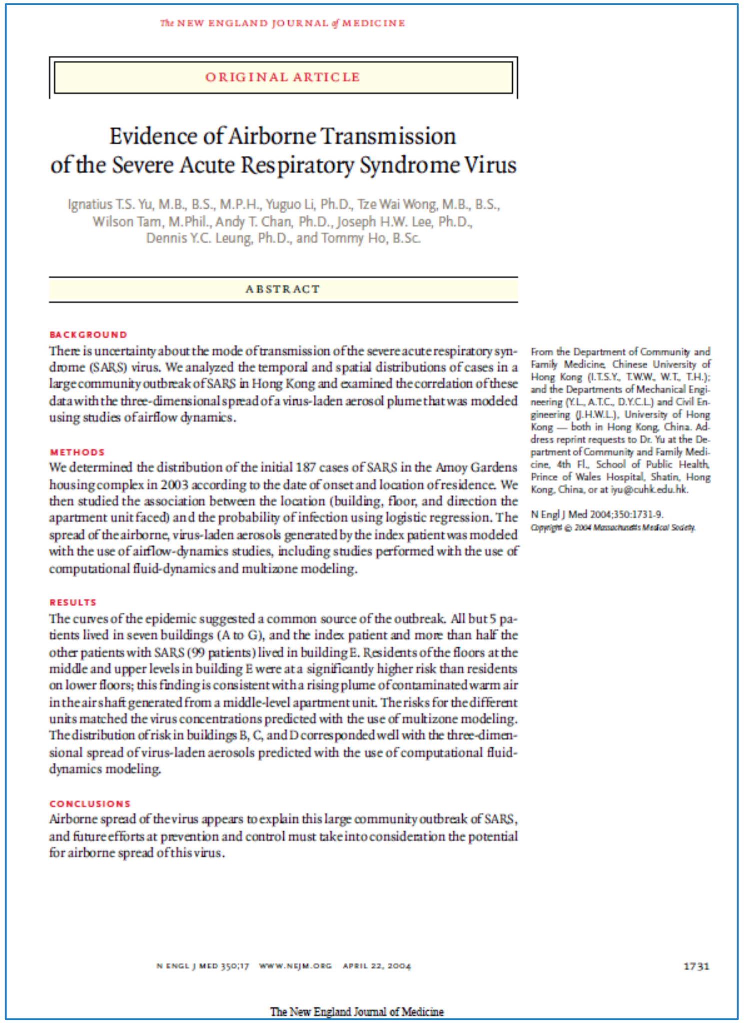
About the Author
William J. Fisk, P.E., is staff scientist and department head, Indoor Environment Department, at Lawrence Berkeley National Laboratory, Calif.

Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (1996 U.S. $)
Reduced Respiratory Illness	16 Million to 37 Million Avoided Cases of Common Cold or Influenza	$6 Billion to $14 Billion
Reduced Allergies And Asthma	8% to 25% Decrease in Symptoms within 53 Million Allergy Sufferers and 16 Million Asthmatics	$1 Billion to $4 Billion
Reduced Sick Building Syndrome Symptoms	20% to 50% Reduction in SBS Health Symptoms Experienced Frequently at Work by ~15 Million Workers	$10 Billion to $30 Billion
Improved Worker Performance from Changes in Thermal Environment and Lighting	Not Applicable	$20 Billion to $160 Billion

Table 1: Estimated potential productivity gains.



Lesser epidemics – influenza, SARS, MERS…


The NEW ENGLAND JOURNAL of MEDICINE

ORIGINAL ARTICLE

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

Ignatius T.S. Yu, M.B., B.S., M.P.H., Yuguo Li, Ph.D., Tze Wai Wong, M.B., B.S., Wilson Tam, M.Phil., Andy T. Chan, Ph.D., Joseph H.W. Lee, Ph.D., Dennis Y.C. Leung, Ph.D., and Tommy Ho, B.Sc.

ABSTRACT

BACKGROUND

There is uncertainty about the mode of transmission of the severe acute respiratory syndrome (SARS) virus. We analyzed the temporal and spatial distributions of cases in a large community outbreak of SARS in Hong Kong and examined the correlation of these data with the three-dimensional spread of a virus-laden aerosol plume that was modeled using studies of airflow dynamics.

METHODS

We determined the distribution of the initial 187 cases of SARS in the Amoy Gardens housing complex in 2003 according to the date of onset and location of residence. We then studied the association between the location (building, floor, and direction the apartment unit faced) and the probability of infection using logistic regression. The spread of the airborne, virus-laden aerosols generated by the index patient was modeled with the use of airflow-dynamics studies, including studies performed with the use of computational fluid-dynamics and multizone modeling.

RESULTS

The curves of the epidemic suggested a common source of the outbreak. All but 5 patients lived in seven buildings (A to G), and the index patient and more than half the other patients with SARS (99 patients) lived in building E. Residents of the floors at the middle and upper levels in building E were at a significantly higher risk than residents on lower floors; this finding is consistent with a rising plume of contaminated warm air in the air shaft generated from a middle-level apartment unit. The risks for the different units matched the virus concentrations predicted with the use of multizone modeling. The distribution of risk in buildings B, C, and D corresponded well with the three-dimensional spread of virus-laden aerosols predicted with the use of computational fluid-dynamics modeling.

CONCLUSIONS

Airborne spread of the virus appears to explain this large community outbreak of SARS, and future efforts at prevention and control must take into consideration the potential for airborne spread of this virus.

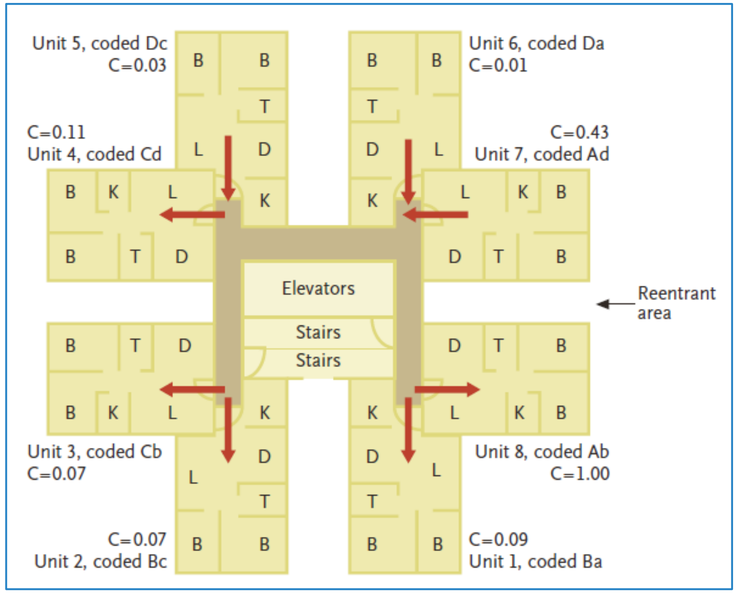
From the Department of Community and Family Medicine, Chinese University of Hong Kong (I.T.S.Y., T.W.W., W.T., T.H.); and the Departments of Mechanical Engineering (Y.L., A.T.C., D.Y.C.L.) and Civil Engineering (J.H.W.L.), University of Hong Kong — both in Hong Kong, China. Address reprint requests to Dr. Yu at the Department of Community and Family Medicine, 4th Fl., School of Public Health, Prince of Wales Hospital, Shatin, Hong Kong, China, or at iyu@cuhk.edu.hk.

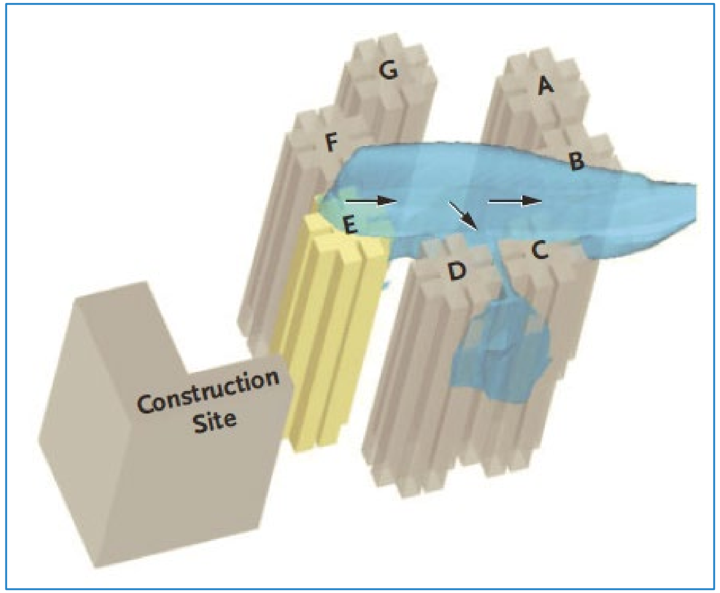
N Engl J Med 2004;350:1731-9.

N ENGL J MED 350;17 WWW.NEJM.ORG APRIL 22, 2004 1731

The New England Journal of Medicine

2003 – SARS Epidemic
Amoy Gardens, Hong Kong

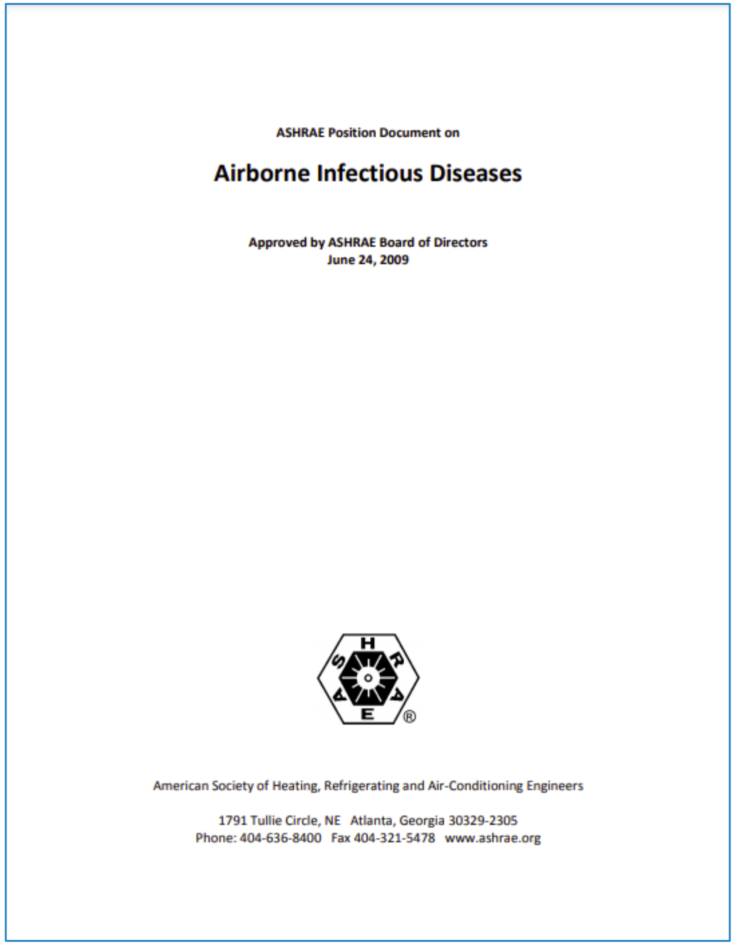




Risk reduction tools were also well-known

- "Many infectious diseases are transmitted through inhalation of airborne infectious particles…"
- "Airborne infectious particles can be disseminated through buildings including ventilation systems"
- Airborne infectious disease transmission can be reduced using **dilution ventilation, specific in-room flow regimes,… room pressure differentials, personalized and source capture ventilation, filtration, and UVGI.**
-

~ASHRAE (2009)



ASHRAE Position Document on

Airborne Infectious Diseases

Approved by ASHRAE Board of Directors
June 24, 2009

American Society of Heating, Refrigerating and Air-Conditioning Engineers

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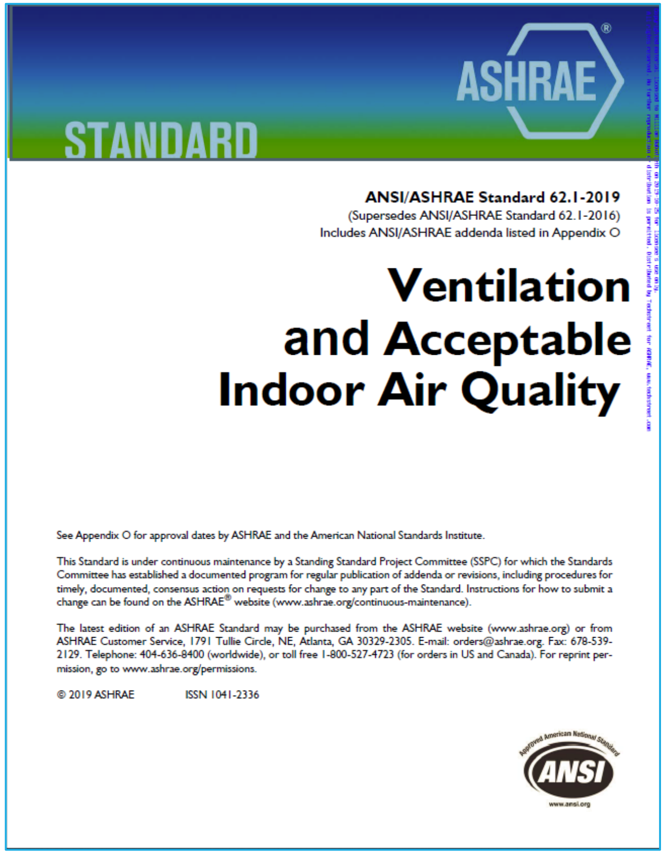
Acceptable IAQ today - *safe and satisfactory*

- (A)ir in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.
- *Harmful concentrations*
  - Levels that cause adverse health effects
  - Does not include pathogens
- *Satisfaction*
  - Perceived air quality
- No explicit consideration of wellness
  - *Not merely the absence of disease or infirmity* (WHO)



STANDARD

ASHRAE

ANSI/ASHRAE Standard 62.1-2019
(Supersedes ANSI/ASHRAE Standard 62.1-2016)
Includes ANSI/ASHRAE addenda listed in Appendix O

Ventilation and Acceptable Indoor Air Quality

See Appendix O for approval dates by ASHRAE and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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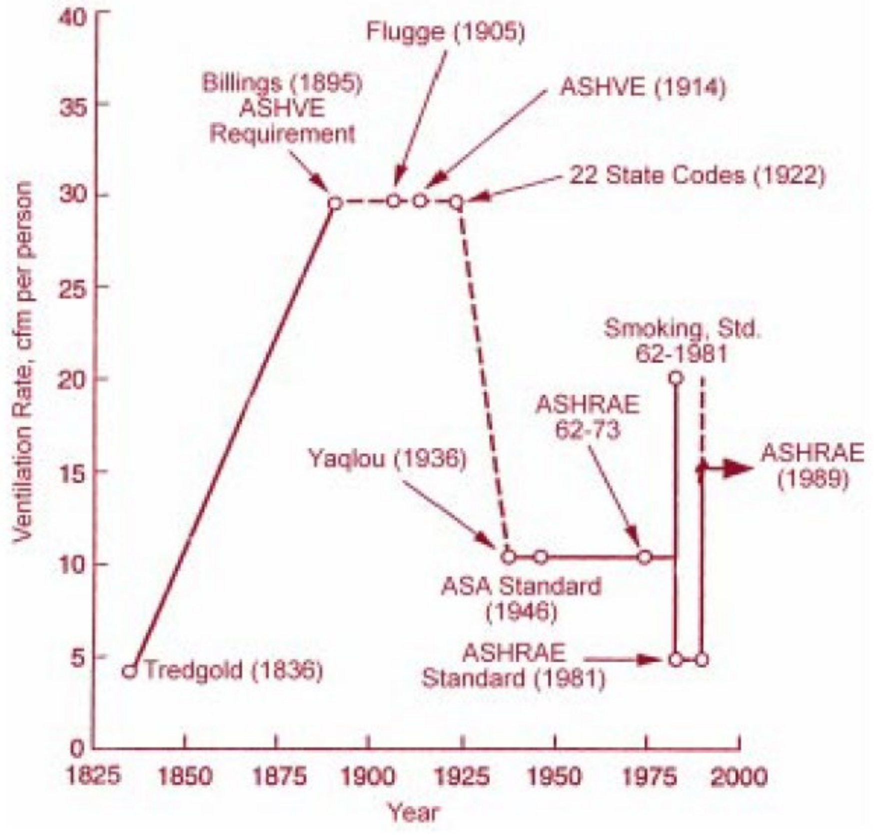
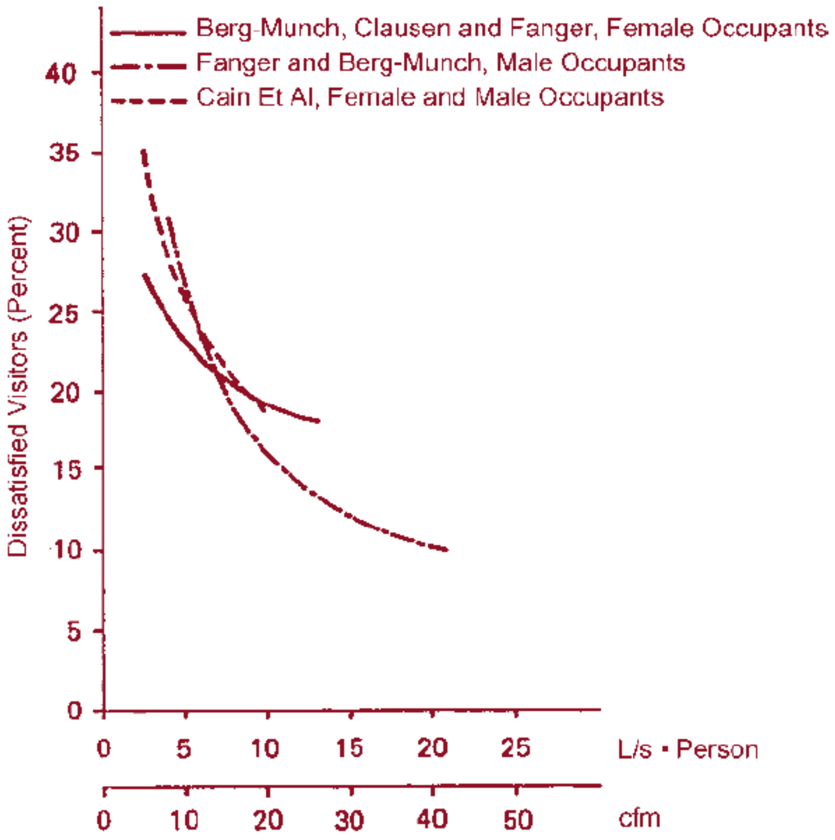
Approved American National Standard ANSI

LONG RUNNING DEBATE – VENTILATE FOR DISEASE OR ODOR CONTROL?





Janssen, J.E., 1999. The history of ventilation and temperature control: The first century of air conditioning. ASHRAE Journal, 41(10), p.48.

Current minimum filtration rates protect equipment, not people

Range	MERV 8
1	N/A
2	≥ 20%
3	≥ 70%

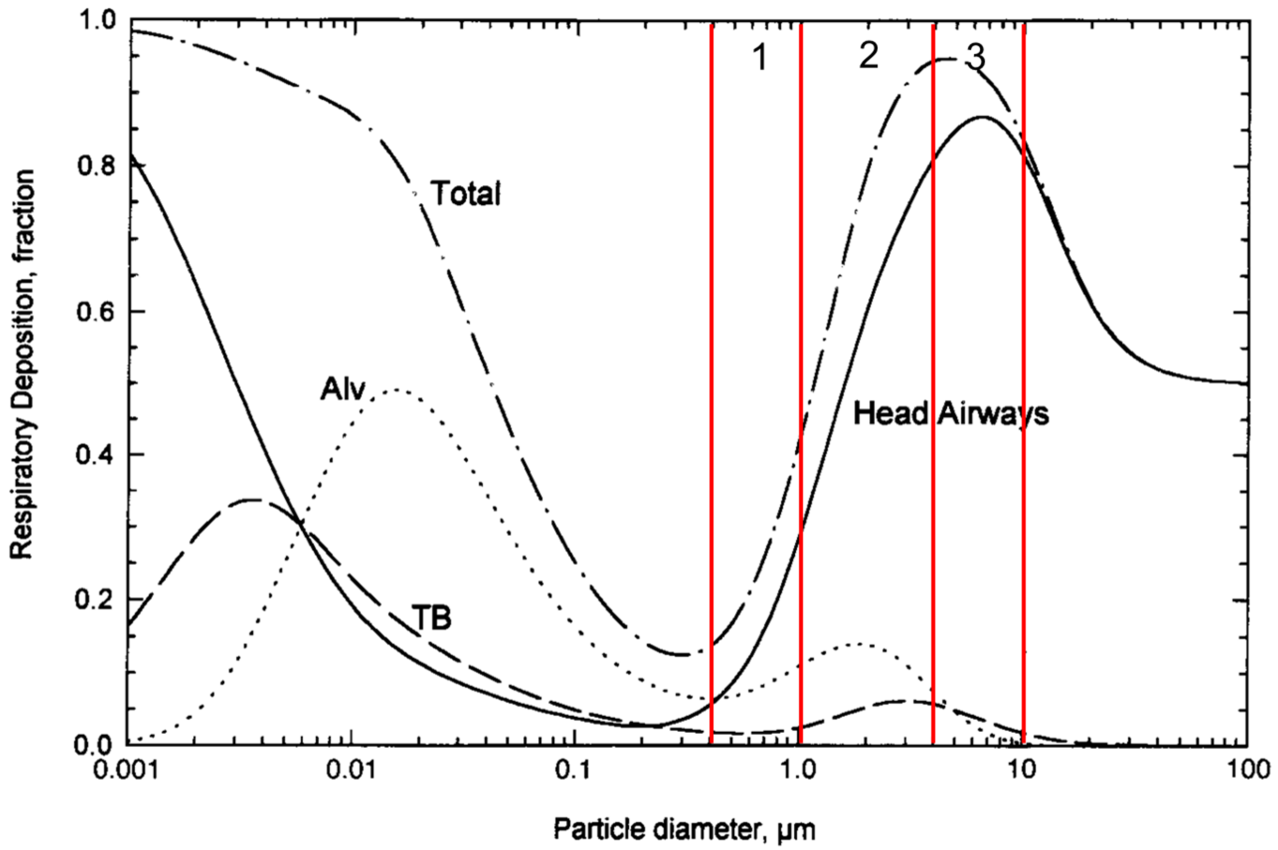


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

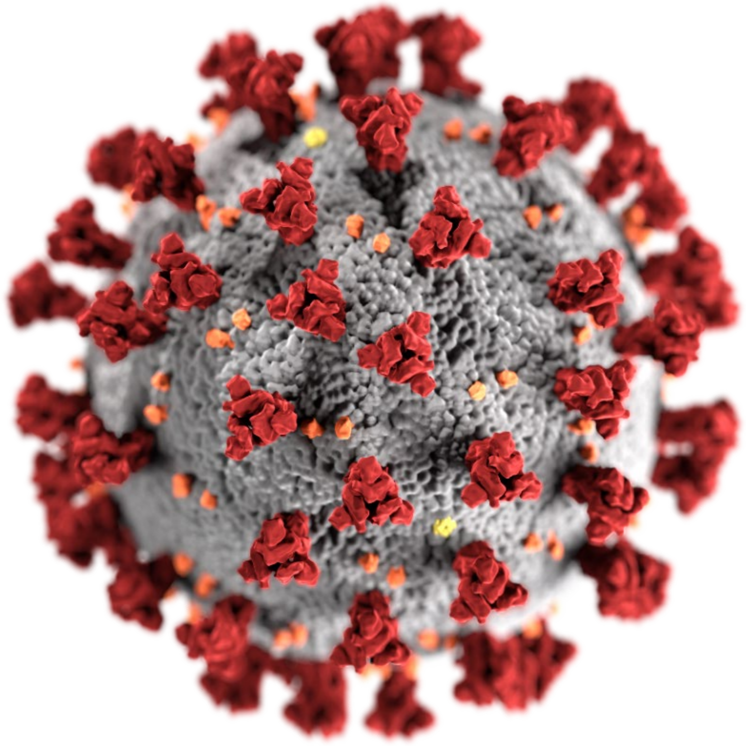
“Acceptable” IAQ doesn’t include wellness

Healthy Buildings

Wellness

“Acceptable” IAQ doesn’t include resilience

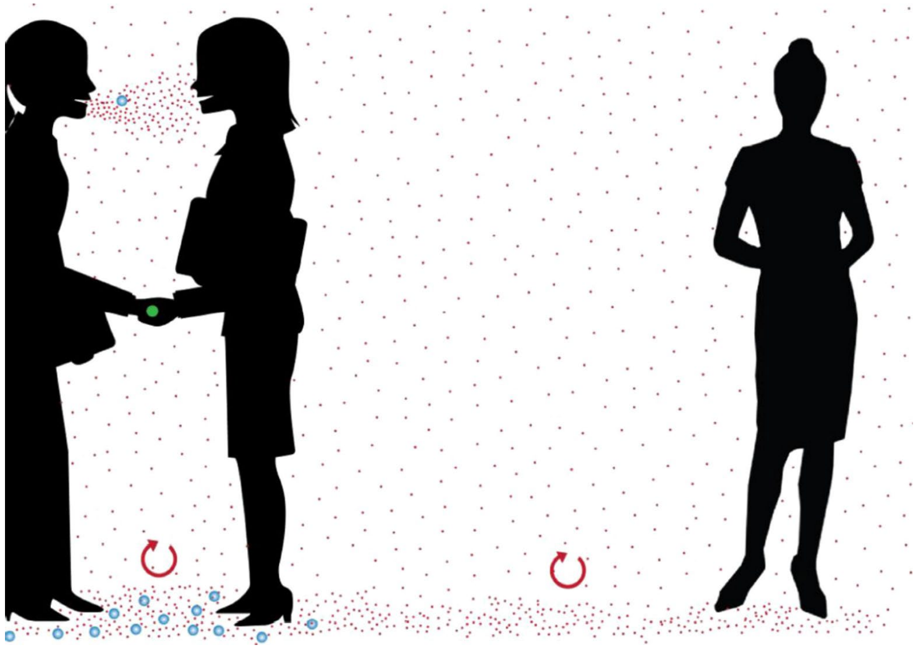
Airborne Infectious Diseases



Ambient Air Quality Emergencies

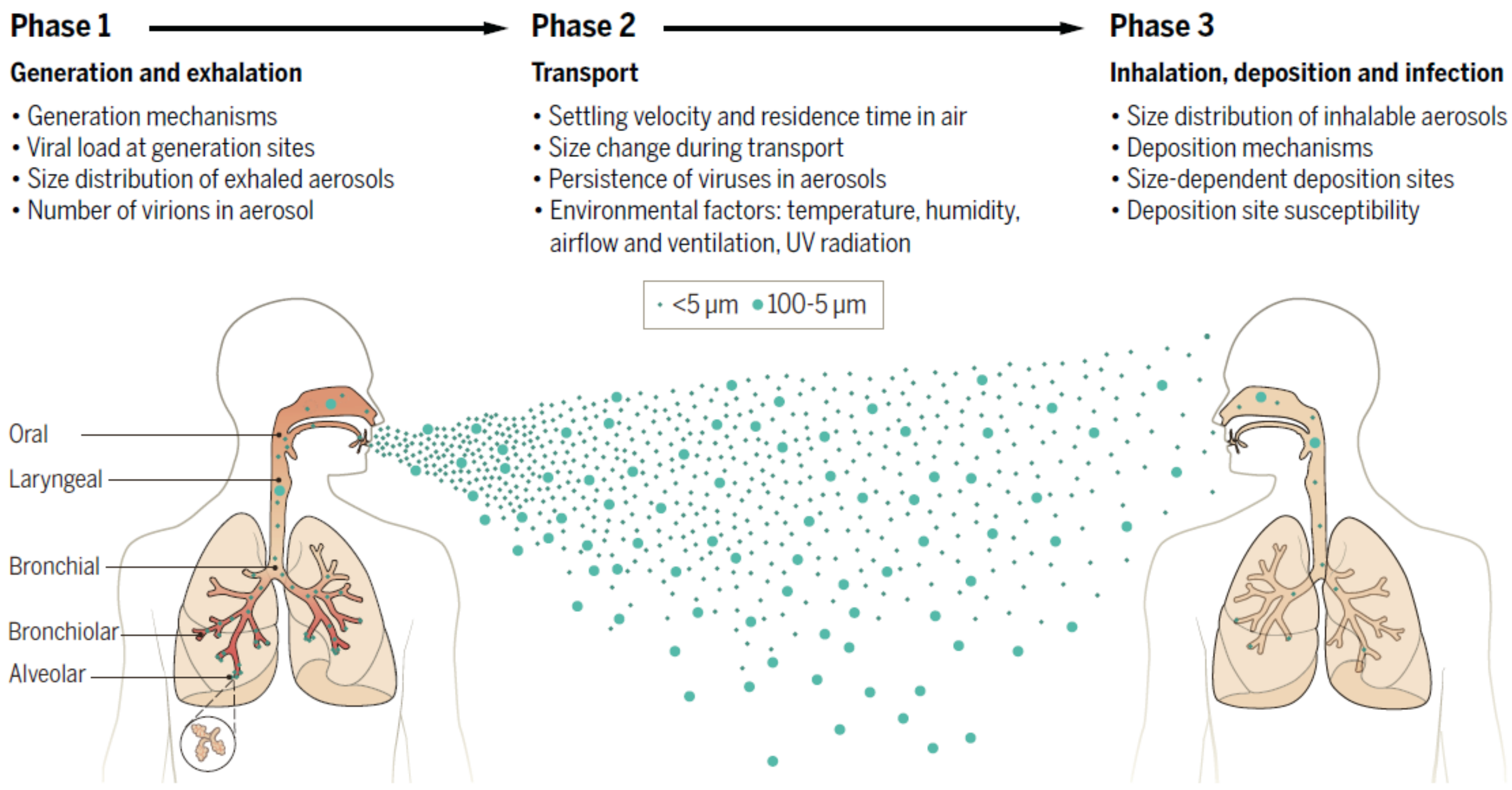
Communicable disease transmission modes

- Inhalation – fine respiratory droplets and aerosol particles
- Deposition – splash or spray of respiratory droplets onto mucous membranes (mouth, nose, eyes)
- Touching – with hands directly contaminated or indirectly by touching contaminated surfaces (fomites)



Tang, J.W., et al., 2021. Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2). *Journal of Hospital Infection*.

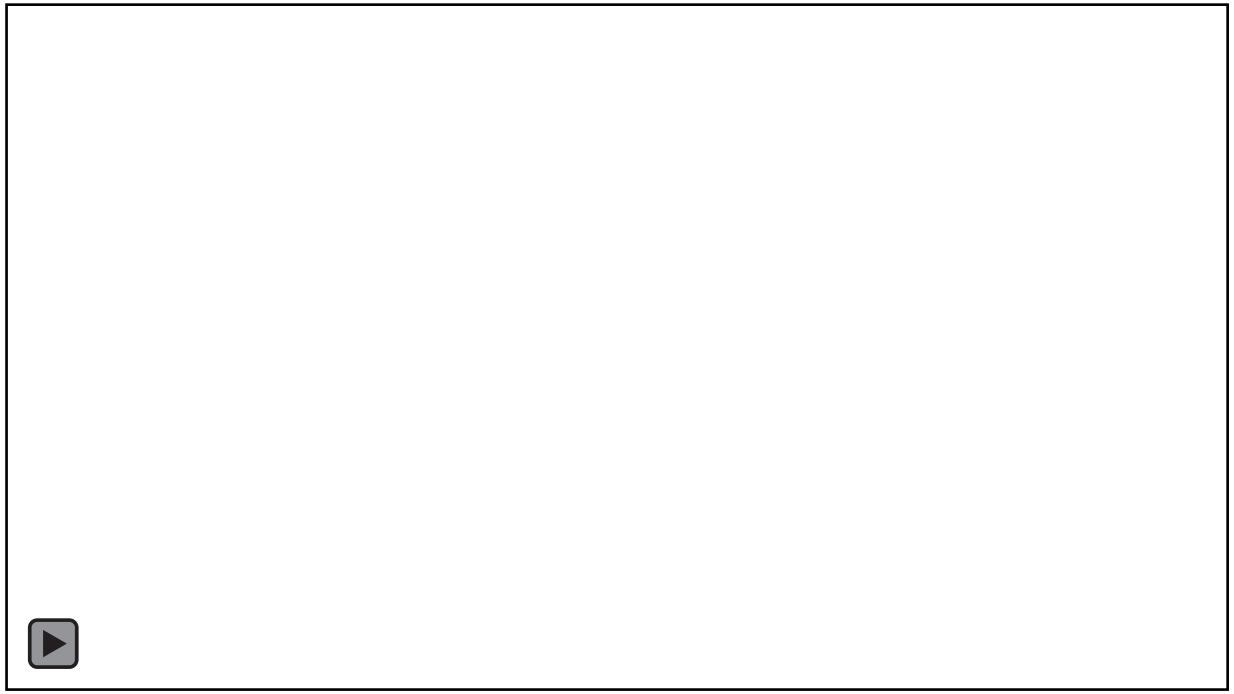
Airborne transmission - complex



Wang et al., Airborne transmission of respiratory viruses Science 373, 981 (2021)
doi.org/10.1126/science.abd9149

Airborne transmission - Guangzhou restaurant

- Low ventilation rate increases infectious aerosol concentration
- Air flow patterns established by ductless split air conditioners determine who is exposed
- Duration of exposure important – only diners infected, not servers



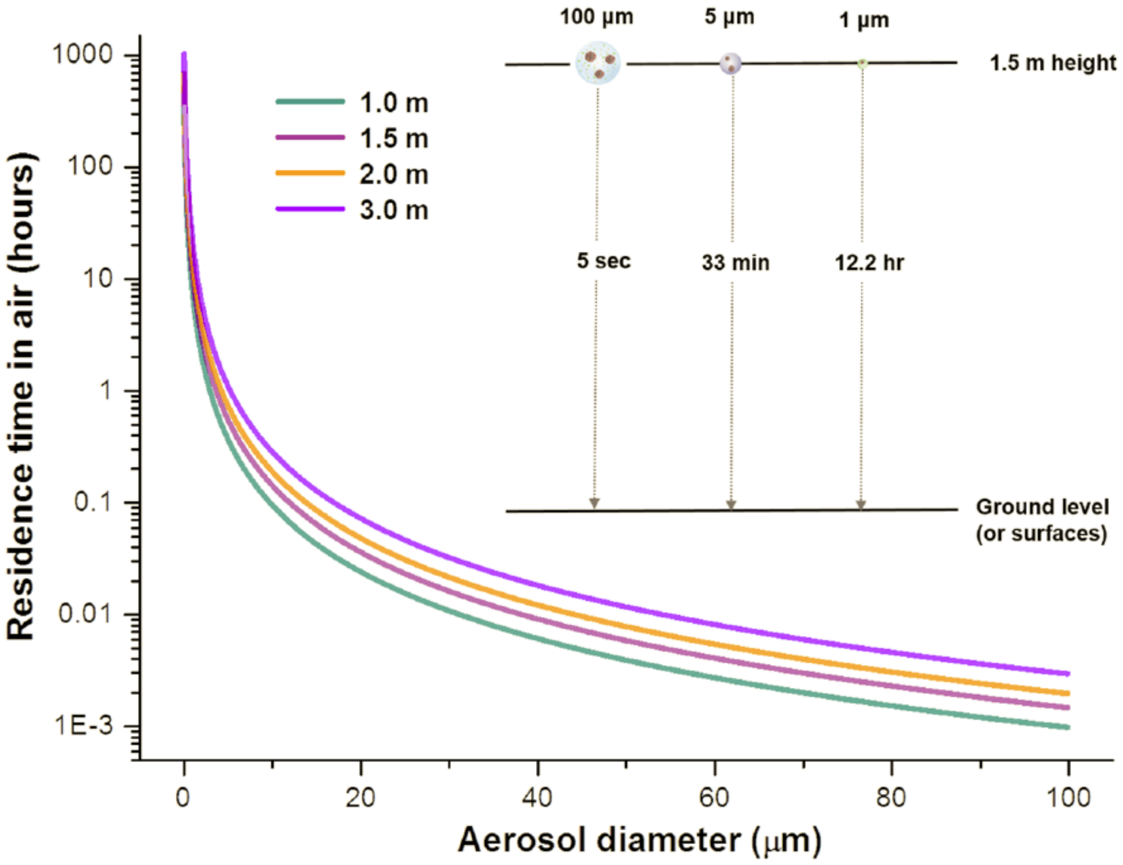
Y. Li, et al. 2021. https://doi.org/10.1016/j.buildenv.2021.107788

Airborne transmission – HVAC systems

- Nursing home in Netherlands
  (De Man, et al. 2021. Clinical Infectious Diseases, 73(1), pp.170-171. doi.org/10.1093/cid/ciaa1270)
  - Seven wards, no infections in six
  - 81% resident infections, 50% healthcare worker infections in the seventh
  - Healthcare workers did not move between wards
  - Residents had private rooms but were mobile, so cannot completely rule out close contact
- Comparison of HVAC systems
  - Six wards had the same system – 100% outdoor air
  - Seventh ward – recirculating CO_2-based demand control (close below 1000 ppm), dust filters

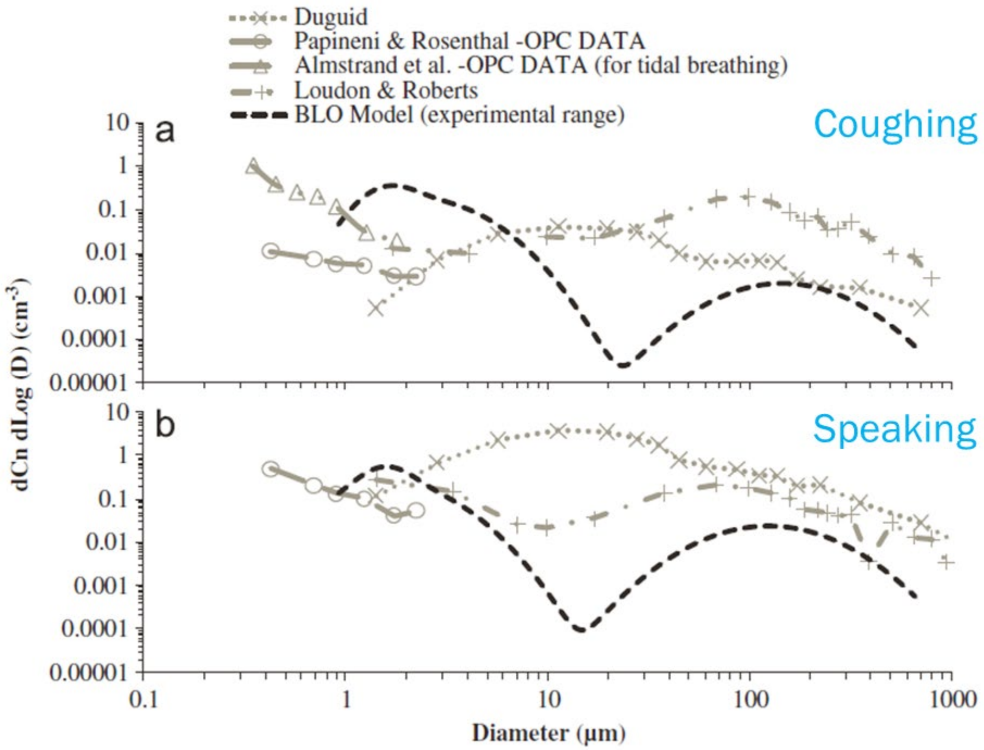
Particle size is important for transmission and risk management

- Aerosols - fine particles that can stay in the air for some period of time
- The smaller a particle is, the longer it is likely to stay airborne
- Particles < ~100 μm important for intermediate/long range transmission
- Smaller particles penetrate more deeply into the respiratory system
- Most of viral load is in particles smaller < 5 μm



Wang et al., Airborne transmission of respiratory viruses Science 373, 981 (2021)
doi.org/10.1126/science.abd9149

Respiratory aerosol generation and deposition



Johnson, et al. 2011. Modality of human expired aerosol size distributions. Journal of Aerosol Science 42:839-851.

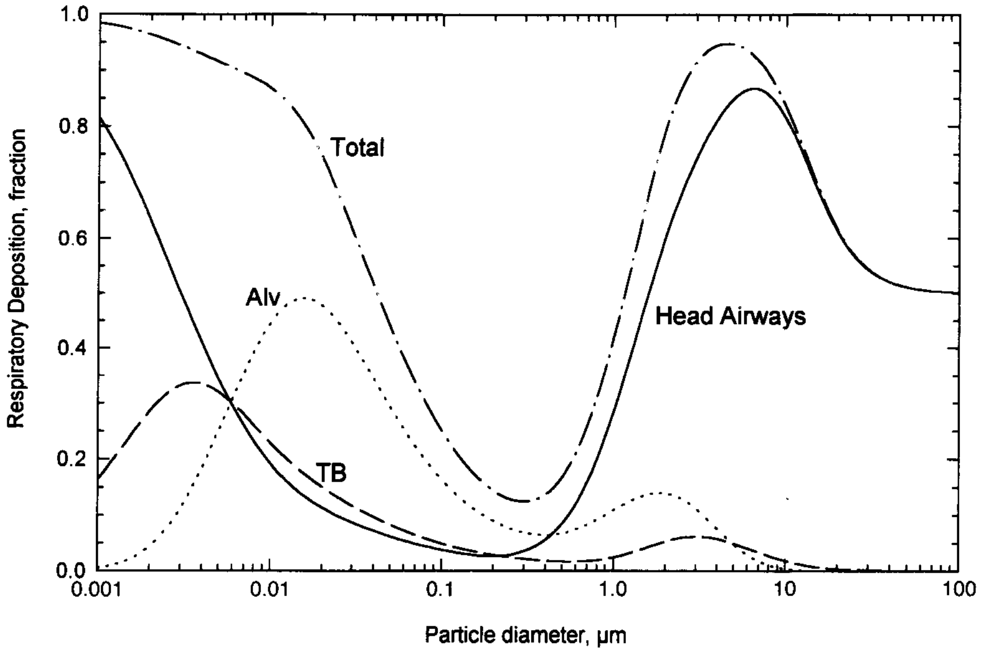


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

Infection risk is a function of exposure (dose)

- Inhaled Dose = Concentration × Volume Inhaled
- Factors affecting concentration
  - Number of infectors
  - Emission rate per infector
  - Removal rate – controls + natural mechanisms
- Factors affecting volume inhaled
  - Age
  - Activity level
  - Duration of exposure

All things are poison, and nothing is without poison, the dosage alone makes it so a thing is not a poison. ~Paracelsus, 1538.

Airborne infection risk – Wells-Riley model

$$P = 1 - \exp\left(-\frac{Iqpt}{Q}\right)$$

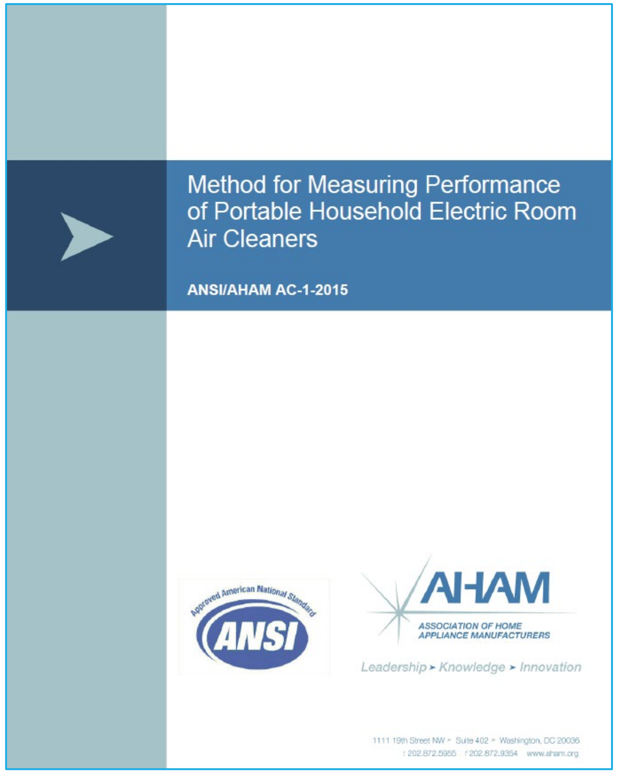
- Steady-state conditions
- Time-dependent risk
- Quanta determined from data

- P = probability of new infections
- I = number of infectors
- q = quanta (infectious dose) emission rate [1/hr]
- p = pulmonary ventilation rate per susceptible [m^3/h]
- t = exposure time [hr]
- Q = flow rate of uncontaminated air [m^3/h]

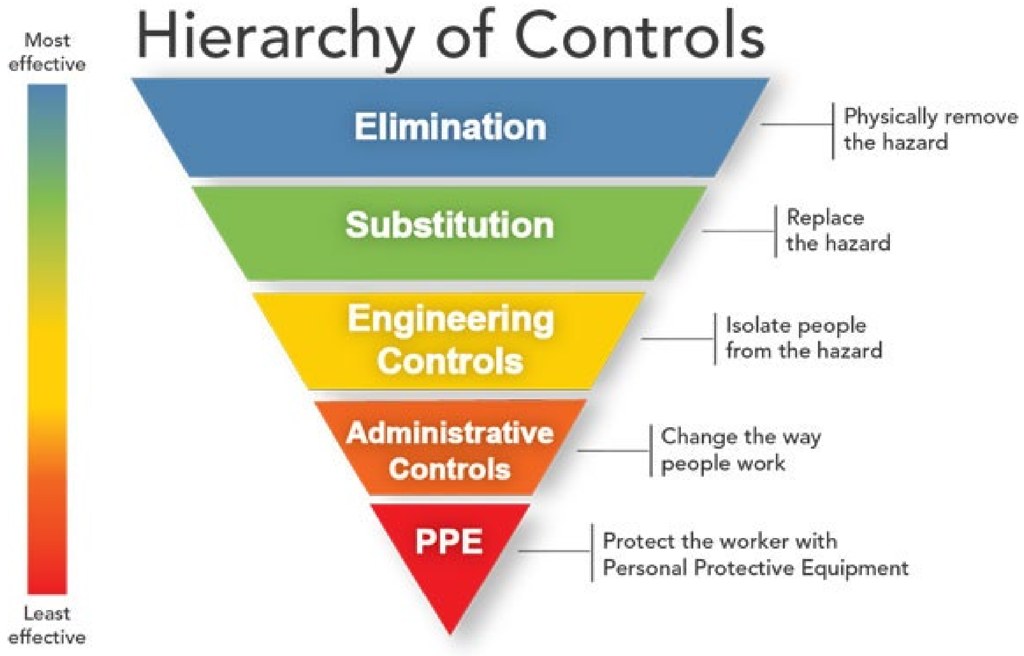
Given source and occupancy characteristics, can calculate required uncontaminated air flow rate

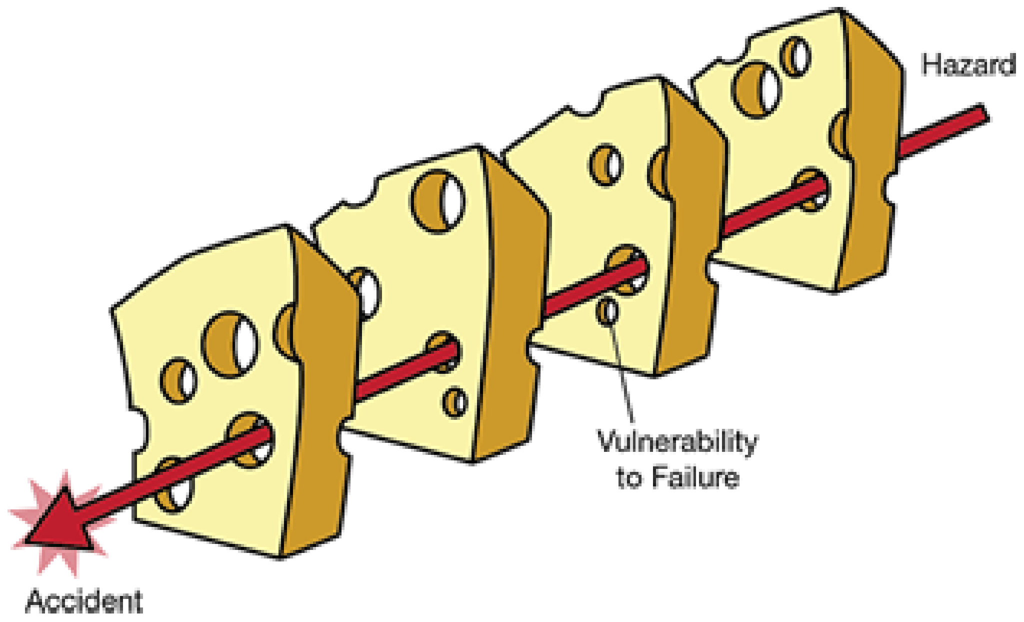
EQUIVALENT OUTDOOR AIR – A BASIS FOR COMBINING CONTROLS

- An equivalent ventilation rate can be determined to each mechanism and summed
  - Dilution ventilation
  - Mechanical filtration
  - Inactivation by air cleaners
  - Natural mechanisms
    - Infiltration
    - Deposition
    - Natural inactivation of viral aerosols



Infection risk management – hierarchy of controls/Swiss cheese



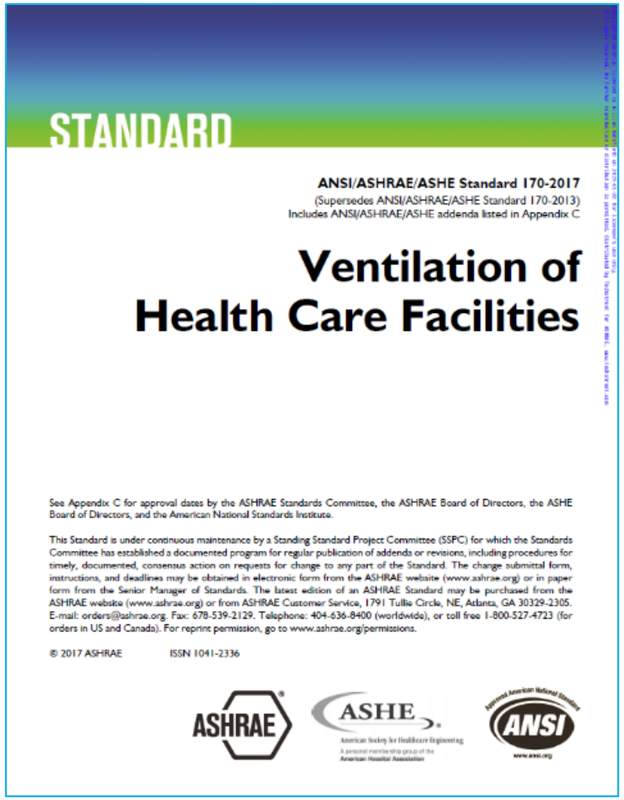


Engineering controls

- Ventilation – dilute contaminants with outdoor air/exhaust contaminated air
- Air Distribution – use airflow to prevent exposure/enhance removal of contaminants
- Mechanical Filtration – capture infectious particles
- Disinfection – inactivate infectious particles

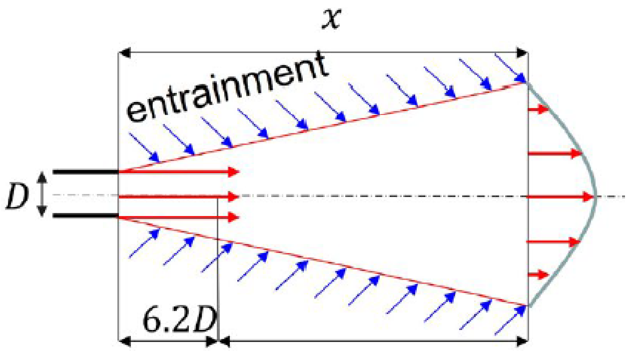
Ventilation – how much?

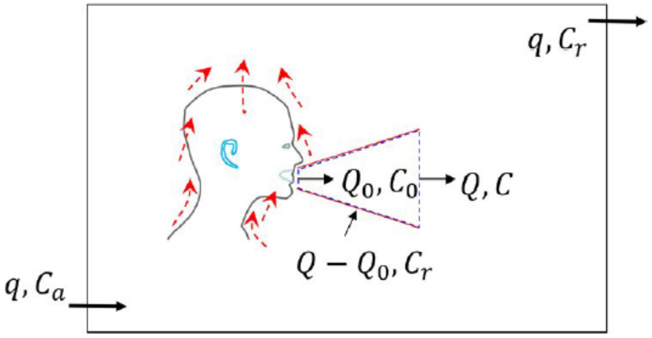
- WHO
  - 10 L/s-person (~21 cfm/pers) for non-healthcare
  - Based on analysis of dilution compared to outdoors
- HSPH and others
  - 4-6 ACH for schools
  - Based on analogy to healthcare ventilation
- Others develop custom rates using Wells-Riley based models

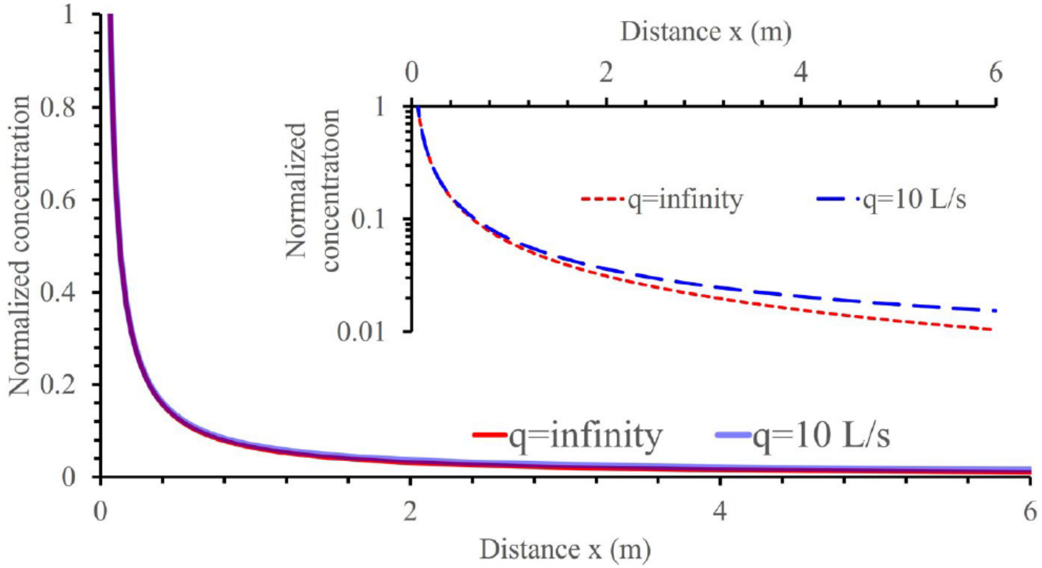


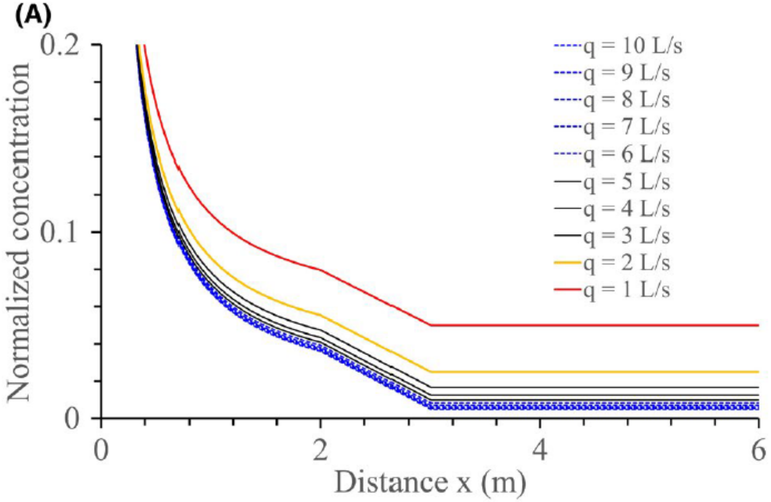
https://www.who.int/publications/i/item/9789240021280

Why 10 L/s per person?





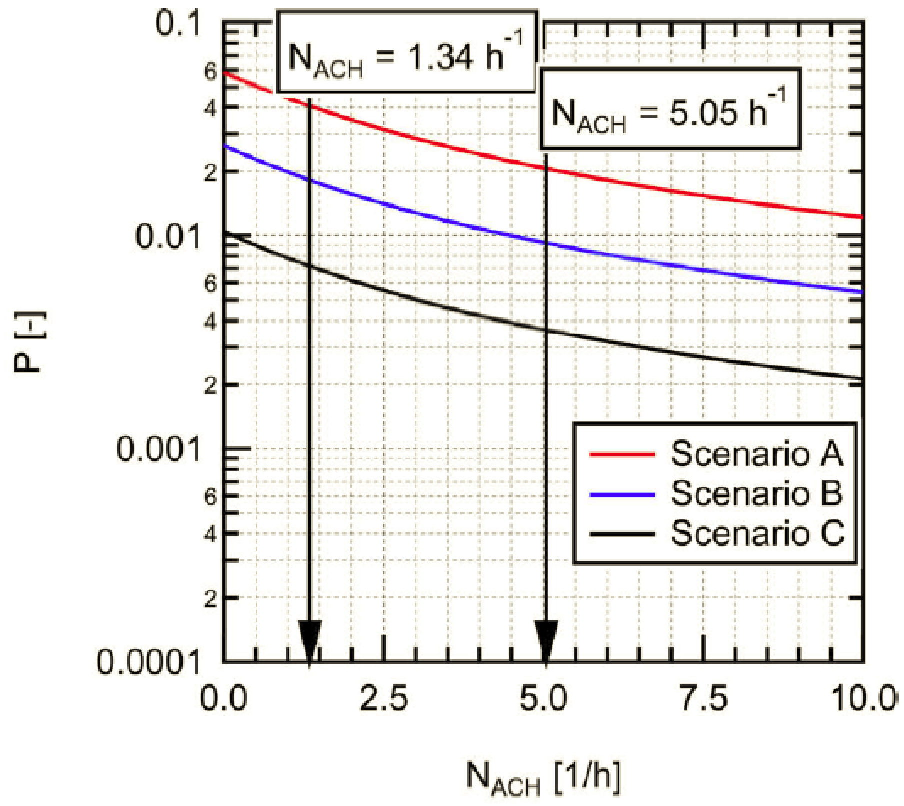




Li, Y., Cheng, P. and Jia, W., 2022. Poor ventilation worsens short-range airborne transmission of respiratory infection. *Indoor air*, *32*(1), p.e12946.

Air change rate as an infection control metric

- Healthcare ventilation standards set requirements for outdoor air and total supply air in ACH
- ASHRAE Standard 170 is the basis of healthcare ventilation design in most states
- 5 – 6 ACH of clean air supply has been suggested as a Covid risk mitigation target for schools by analogy
- Modeling suggests that 5 ACH can lower risk by ~50% compared to 1 ACH



Rothamer, et al. 2021.
doi.org/10.1080/23744731.2021.1944665

Air change rate (ACH) vs. Ventilation rate per person

- Used in healthcare ventilation standards
- Relevant to clearance time
- Ventilation rate per person relevant to steady state
- Has been used to describe air flow requirements for Covid-19

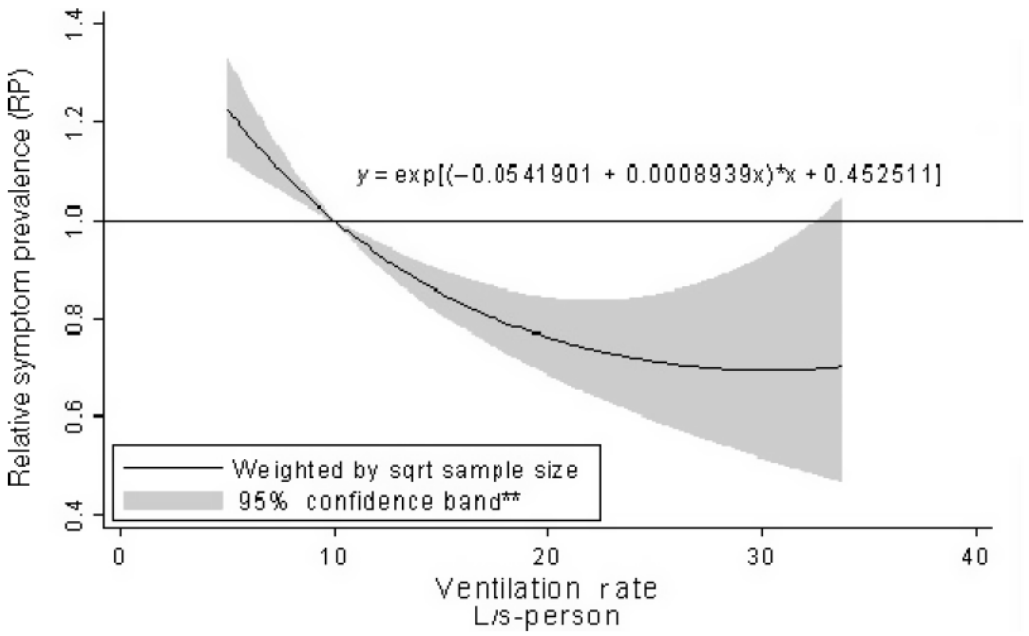
For a space with volume V in cubic feet (L×W×H), and ventilation rate Q in cubic feet per minute

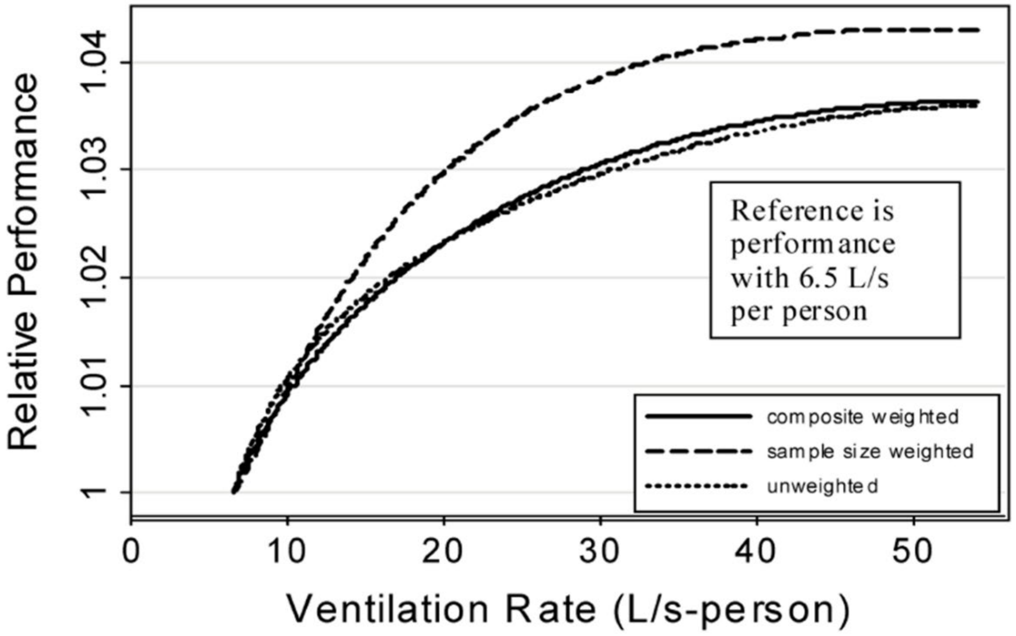
$$ACH\left[h^{-1}\right] = \frac{Q\left[cfm\right]\cdot 60\left[min/hr\right]}{V\left[ft^3\right]}$$

- Can be confusing - may have both good ventilation and low air change rate
- Example -ASHRAE Standard62.1 office space
  - 5 cfm/person + 0.06 cfm/sf
  - Typical density - 5 persons/1000 sf
  - For 1000 sf, need 85 cfm = 17 cfm/pers
  - For 9 foot ceiling height, V = 9000 cubic feet

$$ACH = \frac{Q\cdot 60}{V} = \frac{85\cdot 60}{9000} = 0.47$$

Ventilation rate increases have other benefits



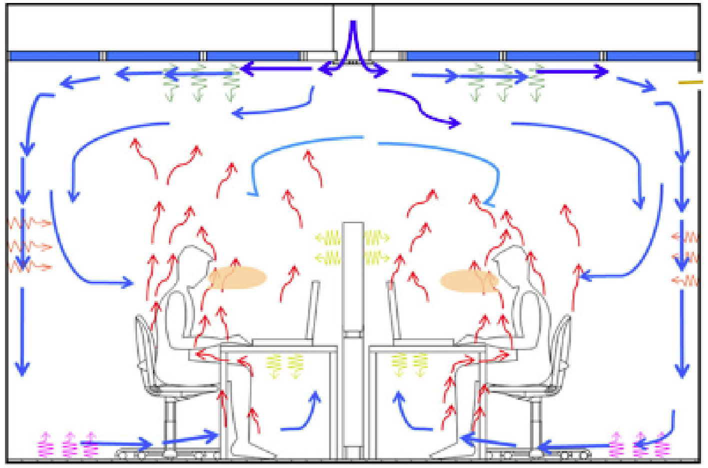


W. Fisk, A Mirer, M. Mendell. 2009. Quantitative relationship of sick building syndrome symptoms with ventilation rates. Indoor Air

Seppänen, O. and W. Fisk. 2006. Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health. HVAC&R Research.

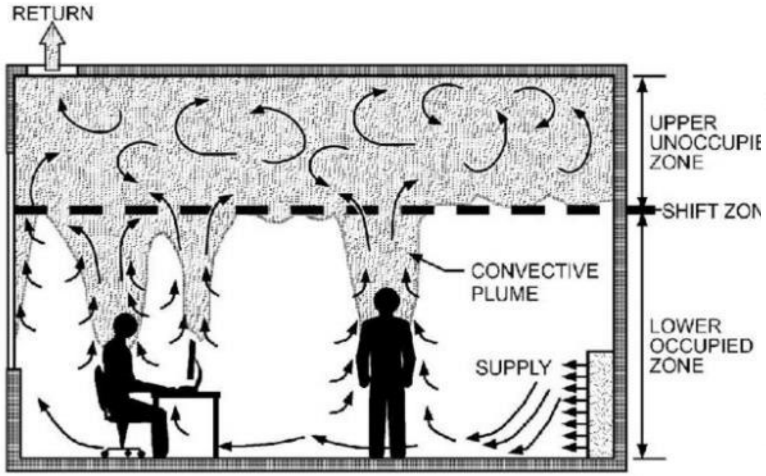
Best approach to air distribution?

Overhead Mixing



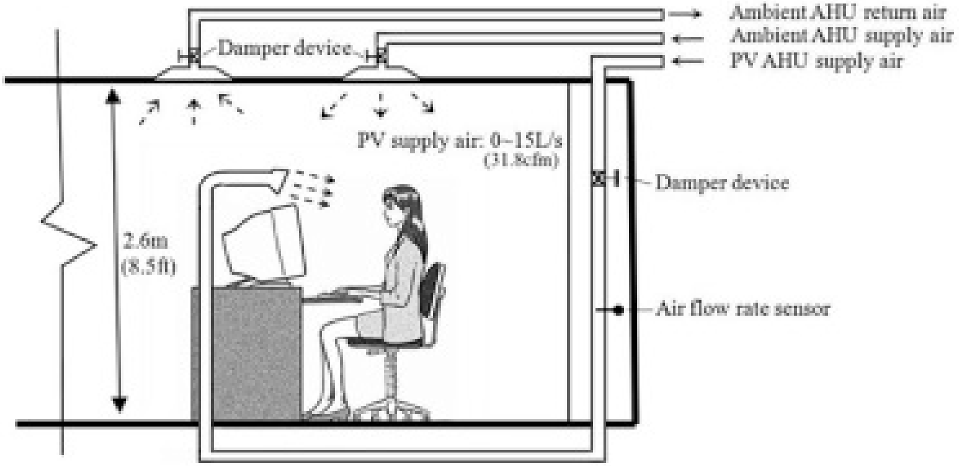
doi:10.1111/ina.12206

Stratified



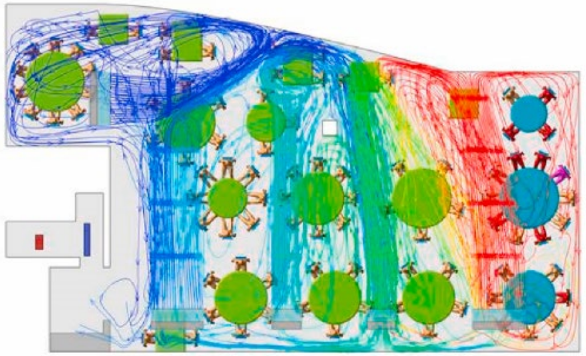
doi: 10.3390/en10020231

Personal



doi.org/10.1016/j.buildenv.2015.11.036

Situationally, any of them may be a good choice – or can fail



Li, Y., et al., 2021. Building and Environment, p.107788.

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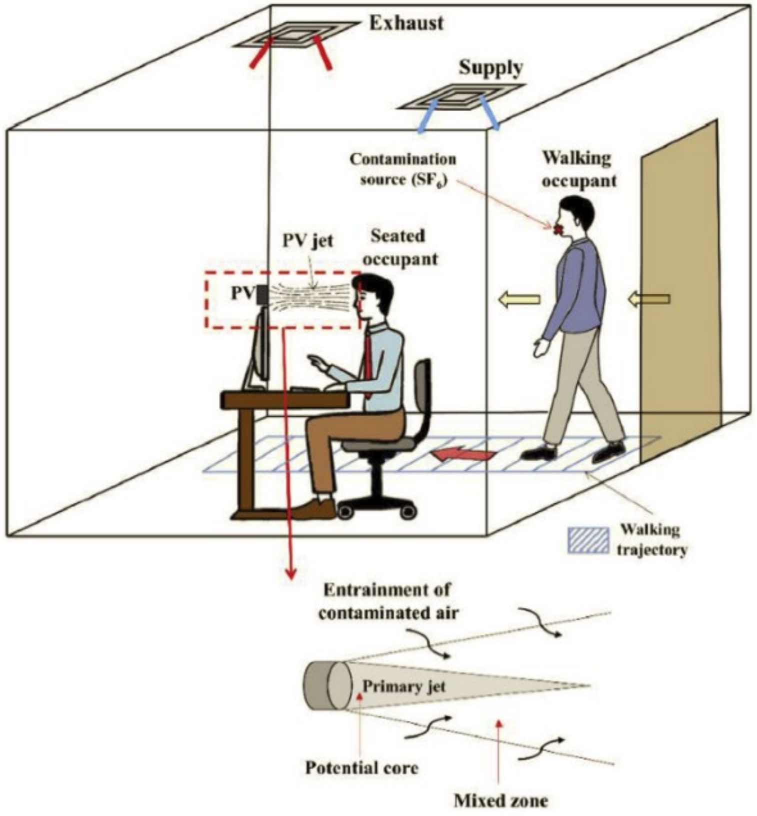
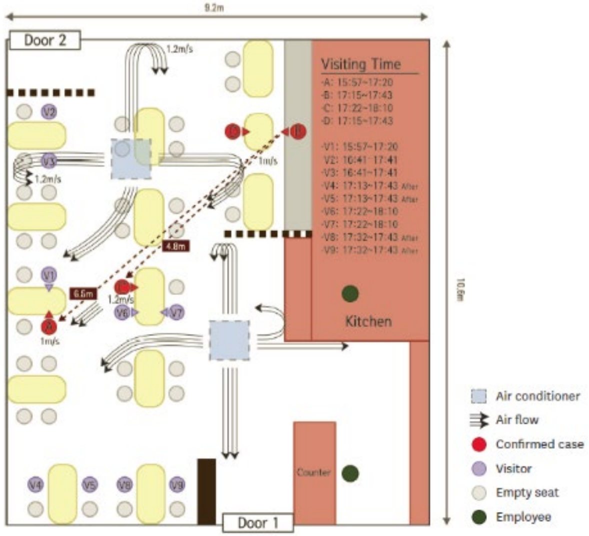


Al Assaad, D., Ghali, K. and Ghaddar, N., 2019. *Building and Environment*, *160*, p.106217.



Kwon, K.S., et al., 2020. Journal of Korean medical science, 35(46).

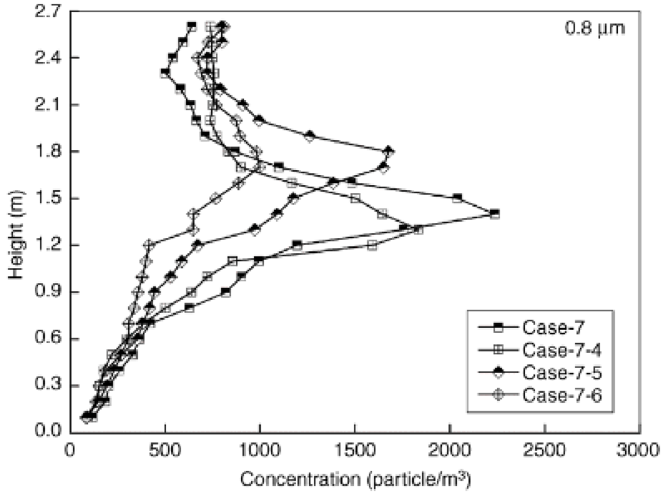
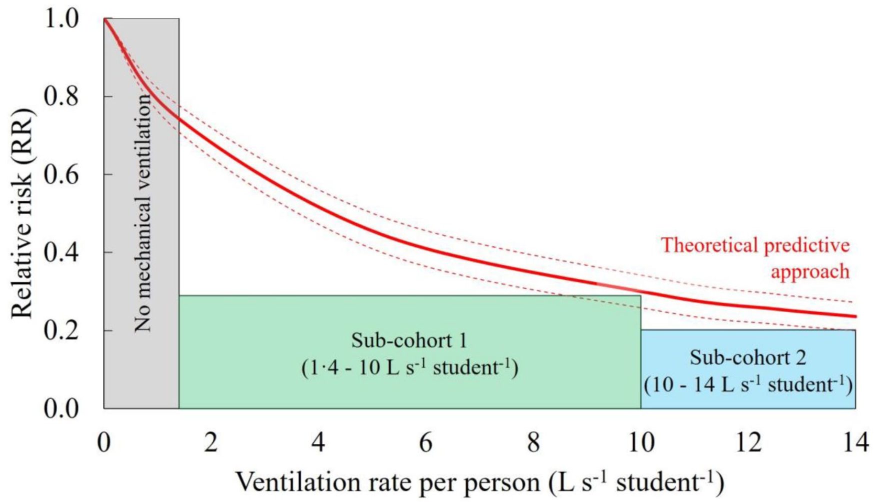


Fig. 10 Average concentrations (0.8 μm) in planes across the room at different height levels

Gao, N., He, Q. and Niu, J., 2012, *Building Simulation* (Vol. 5, No. 1, pp. 51-60).

Mechanical ventilation works, natural ventilation is uncertain

- Italian schools study
  - 10,000+ classrooms
  - 316 retrofitted with mechanical ventilation
  - Covid infection rates 80% lower in mechanically ventilated classrooms with 10 – 14 L/s-pers
  - 12-15% reduction per unit of ventilation



Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: a retrospective cohort study in Italy's Marche region

Luca Ricolfi[a,b], Luca Stabile[c], Lidia Morawska[d], Giorgio Buonanno[c,d,*],

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[c] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, FR, Italy
[d] International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Queensland, Australia

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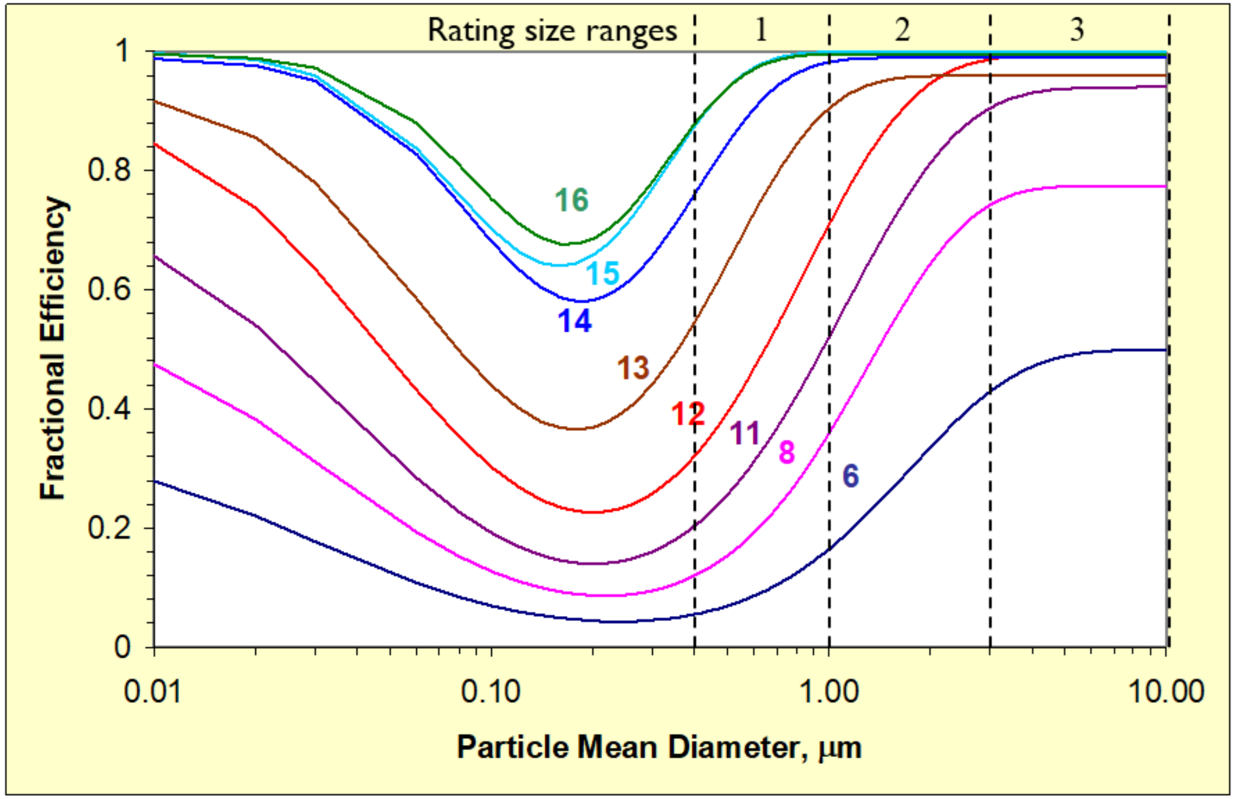
Email: buonanno@unicas.it

Preprint - https://arxiv.org/abs/2207.02678

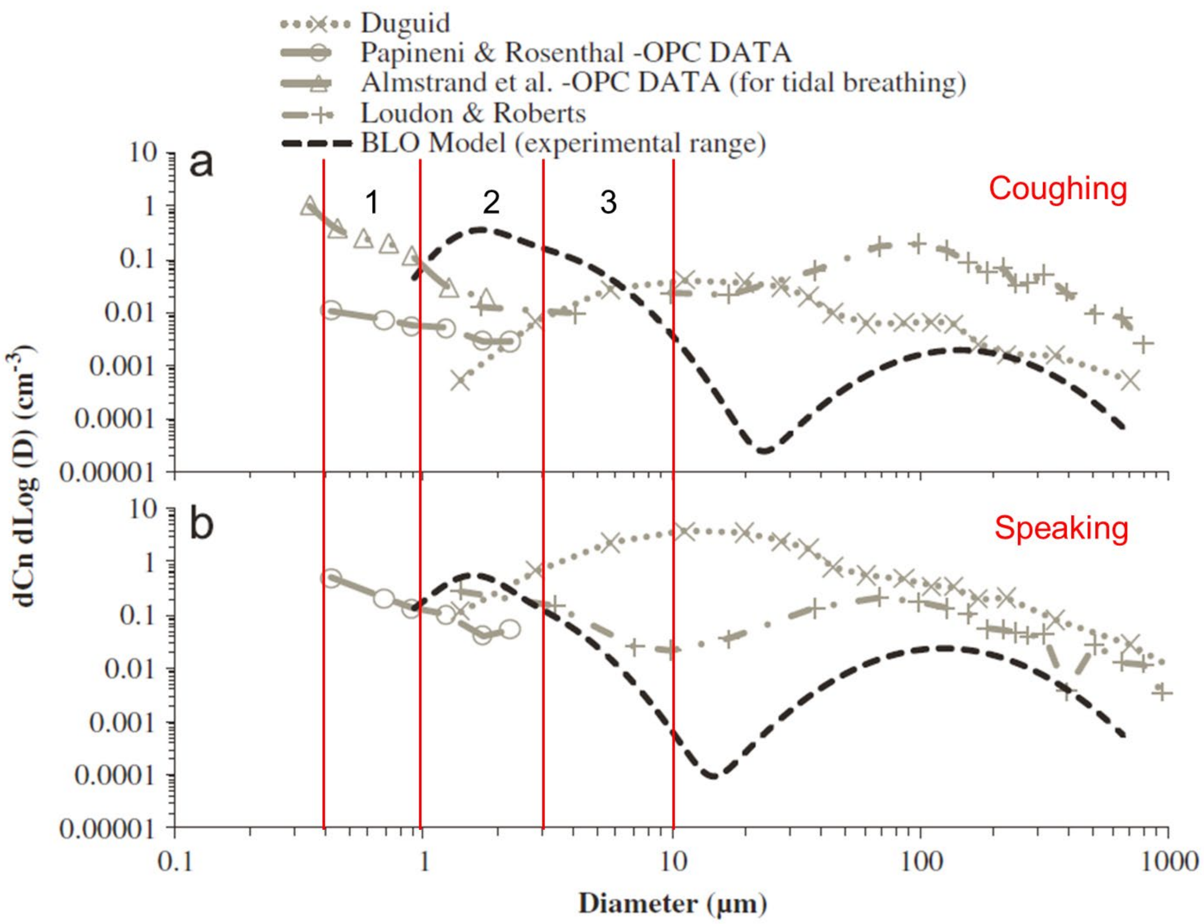
Filter ratings - MERV

- Minimum Efficiency Reporting Value (MERV)
  - ASHRAE Standard 52.2
  - Filters tested in 3 size ranges
    - 0.3 – 1 µm
    - 1 – 3 µm
    - 3 – 10 µm
  - Rating based on minimum efficiency in each range
- Current requirements
  - MERV 8 non-residential (ASHRAE Standard 62.1)
  - MERV 6 residential (ASHRAE Standard 62.2)



Kowalski, W.J. and Bahnfleth, W.P., 2002. MERV filter models for aerobiological applications. Air Media, Summer, 1.

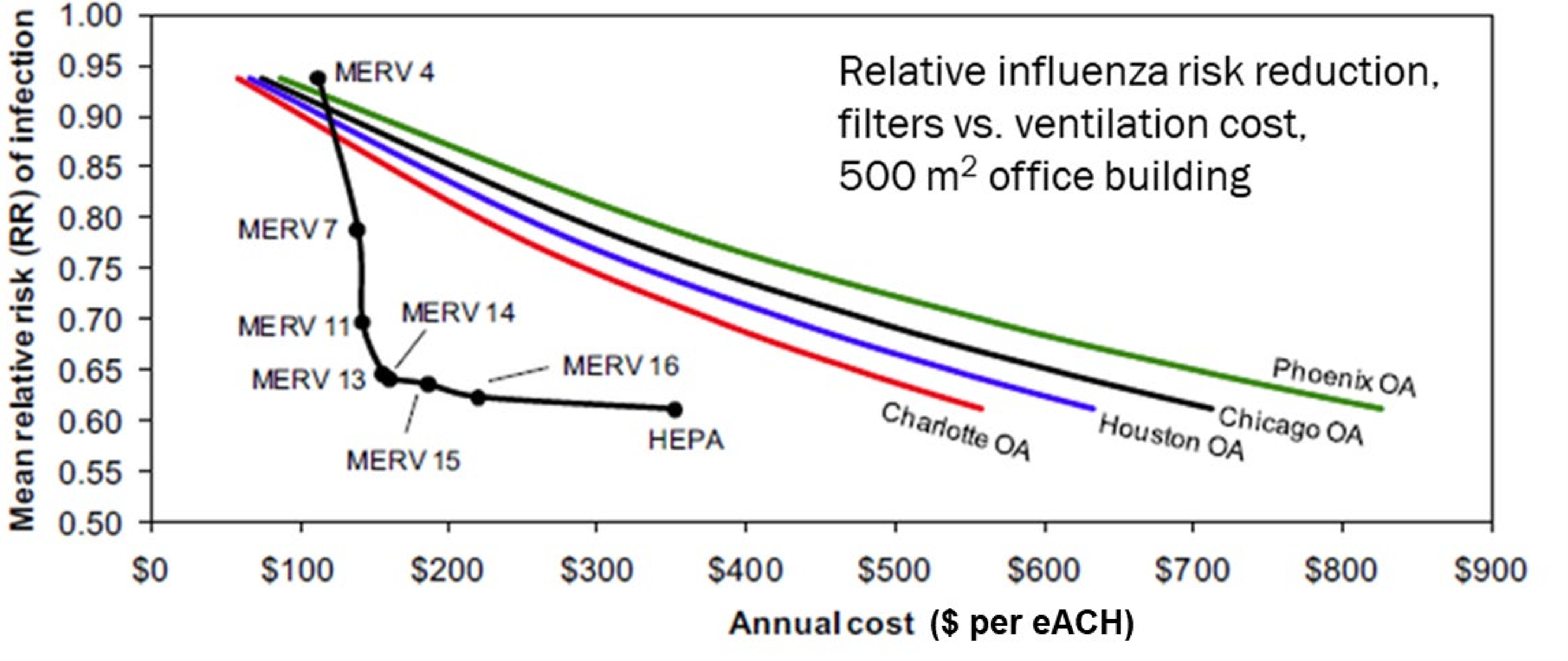
MERV-13 OR HIGHER RECOMMENDED FOR INFECTION CONTROL



	MERV 8	MERV 13
1 (0.3-1μm)	N/A	≥ 50%
2 (1-3 μm)	≥ 20%	≥ 85%
3 (3-10 μm)	≥ 70%	≥ 90%

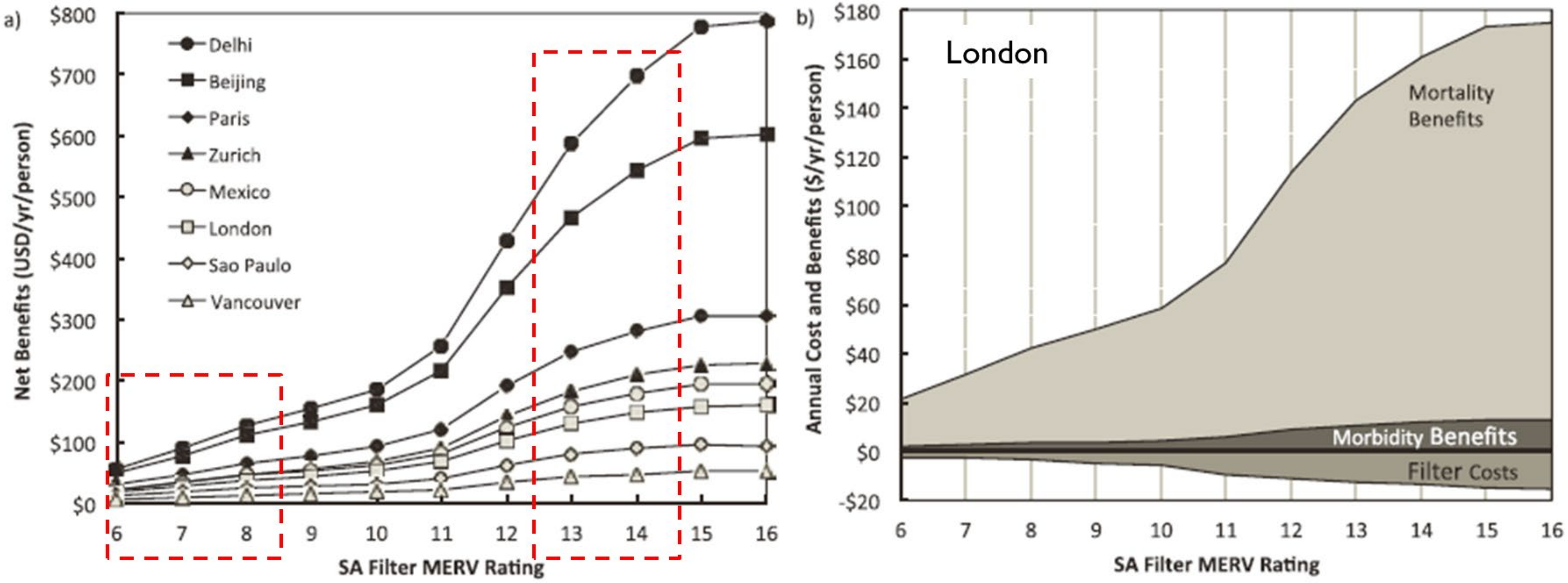
Johnson, et al. 2011. Modality of human expired aerosol size distributions. Journal of Aerosol Science 42:839-851.

MERV-13 near optimal, lower cost than increased ventilation



Azimi, P. and Stephens, B., 2013. HVAC filtration for controlling infectious airborne disease transmission in indoor environments: predicting risk reductions and operational costs. *Building and environment*, *70*, pp.150-160.

Higher performance filtration has significant health and health cost benefits



(Montgomery, J., C. Reynolds, S. Rogak, S. Green. 2015. Financial Implications of Modifications to Building Filtration Systems. Building and Environment 85:17-28.)

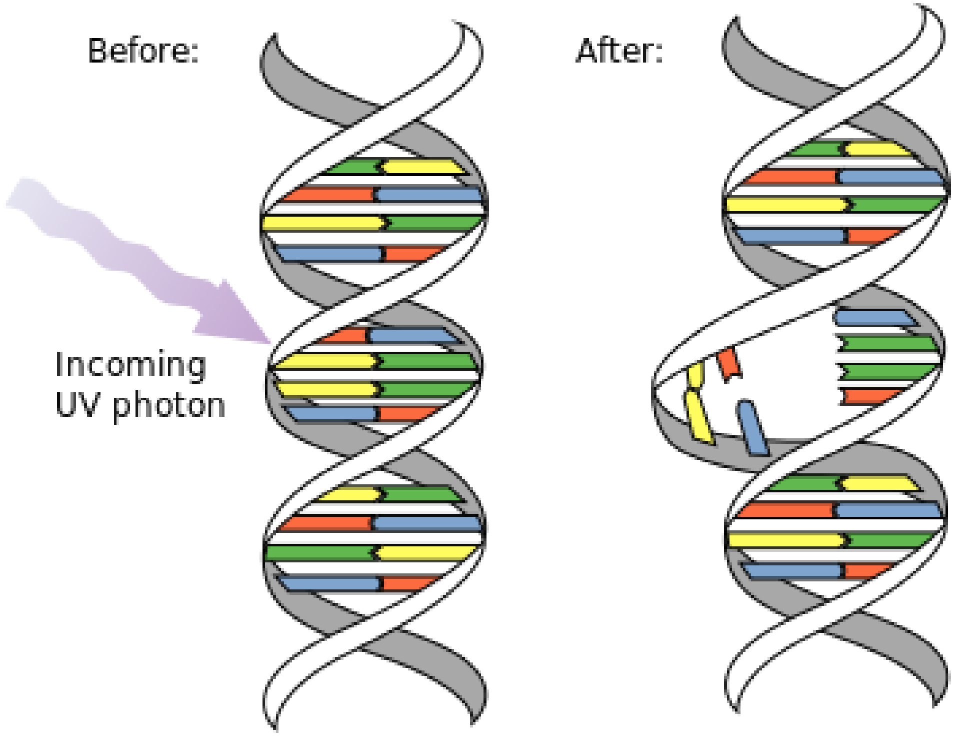
Disinfection

- Destroy or inactivate or destroy microorganisms
- Many technologies in the marketplace
  - Germicidal ultraviolet light (GUV) - damages microbial DNA/RNA
  - Additive air cleaners – add oxidants to air
    - Bipolar ionization
    - Hydrogen peroxide gas
    - Photocatalytic oxidation
    - Triethylene glycol

- GUV is well understood, accepted technology, approved by CDC for tuberculosis control
- Additive air cleaners lack strong evidence basis for effectiveness and safety, do not have consensus methods of test
- Some technologies produce ozone
- A number of recent studies have reported lackluster performance and byproduct generation

GERMICIDAL ULTRAVIOLET LIGHT

- Studied and applied for more than 100 years
  - Operating room air disinfection – 1936
  - School classroom air disinfection - 1937
- Approved for tuberculosis prevention by US CDC
- 254 nm UV-C produced by mercury vapor lamps is most common source – not safe for human exposure
- LEDs and Kr-Cl lamps are making other wavelengths, potentially safer, possible
- Order of 10 – 100 eACH

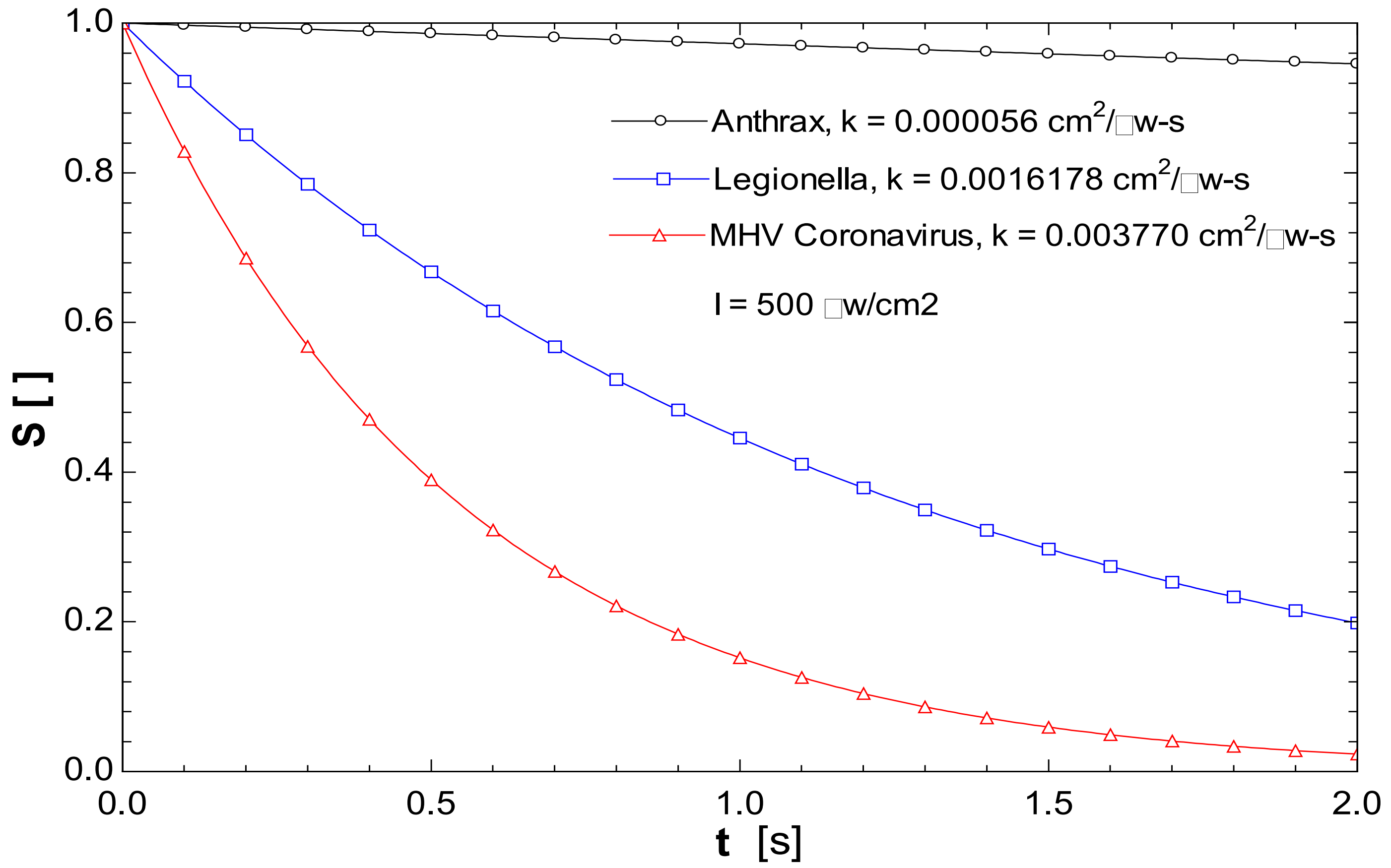


MICROBIAL CHARACTERISTICS INFLUENCE UV-C PERFORMANCE

- Microbial survival after UVC exposure

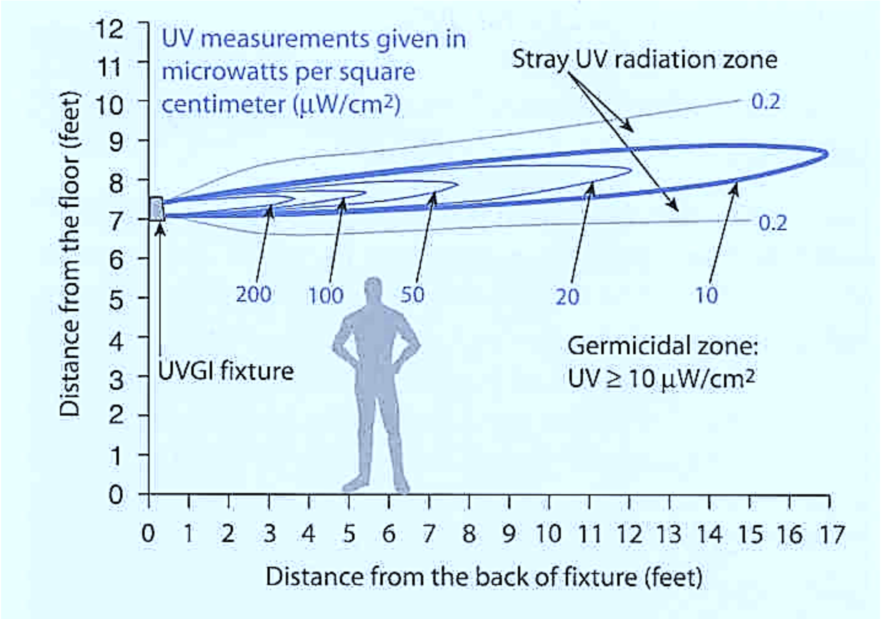
$$S = \exp\left(-kIt\right)$$

  - S = surviving fraction of initial population
  - k = deactivation rate constant (cm^2/μW-s)
  - I = UV fluence (μW/cm^2)
  - t = duration of exposure (s)



GERMICIDAL UV APPLICATIONS

Upper Room UVGI



In-Duct/Coil UVGI

Portable Surface Treatment UVGI

UPPER ROOM PERFORMANCE – PHILADELPHIA SCHOOL STUDY

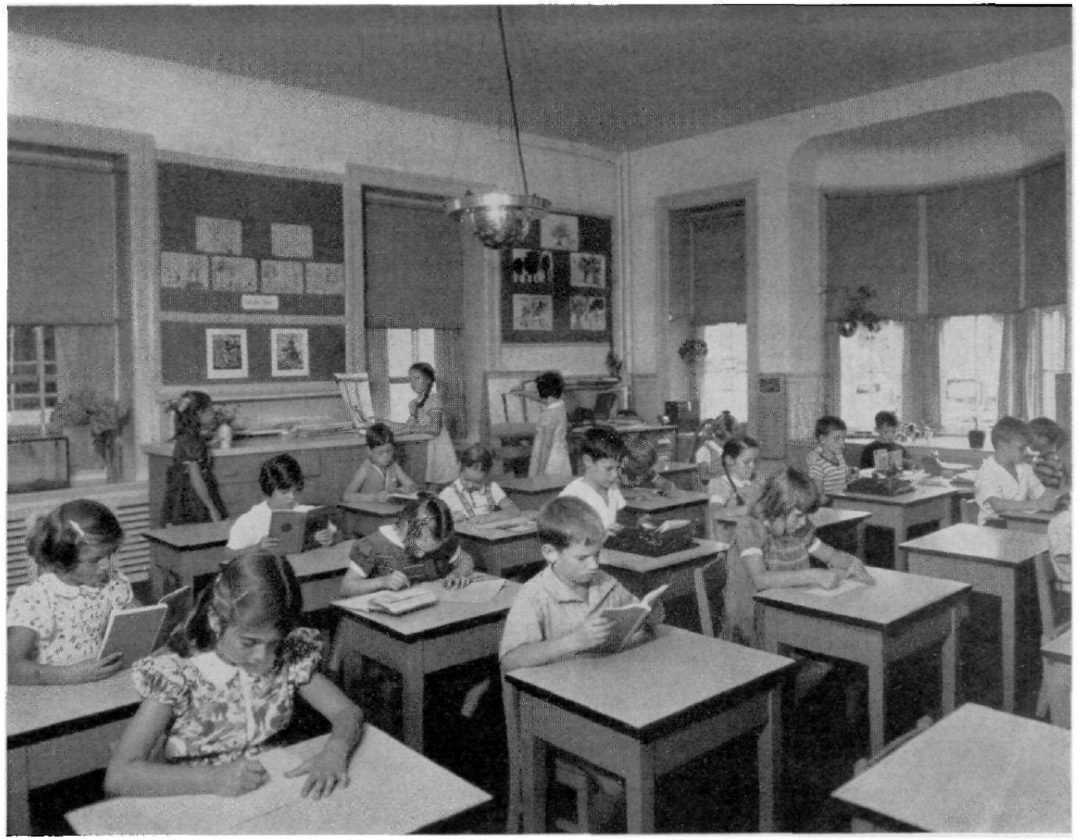
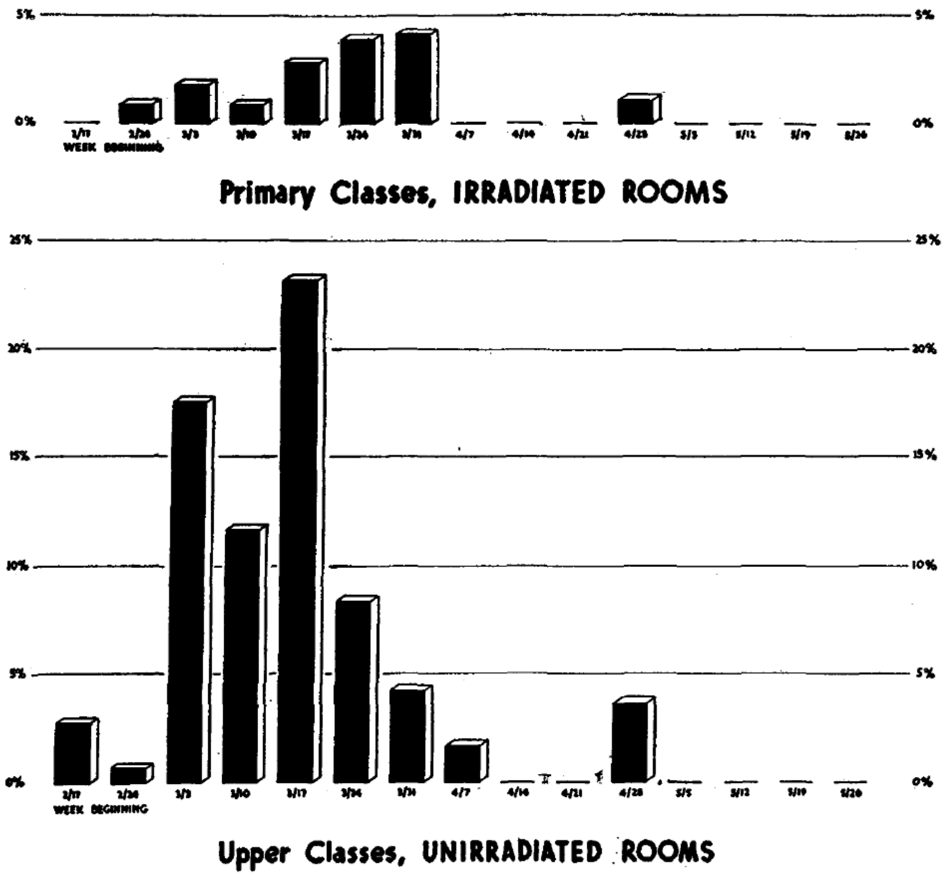


FIGURE 1. Classroom, Germantown Friends School, central radiant sources.

Weekly new measles cases, control and treated



Wells, W.F., Wells, M.W. and Wilder, T.S., 1942. The environmental control of epidemic contagion. I. An epidemiologic study of radiant disinfection of air in day schools Am J Hyg, 35, pp.97-121.

PROMISING RESULTS FOR GERMICIDAL LIGHT AT MULTIPLE WAVELENGTHS

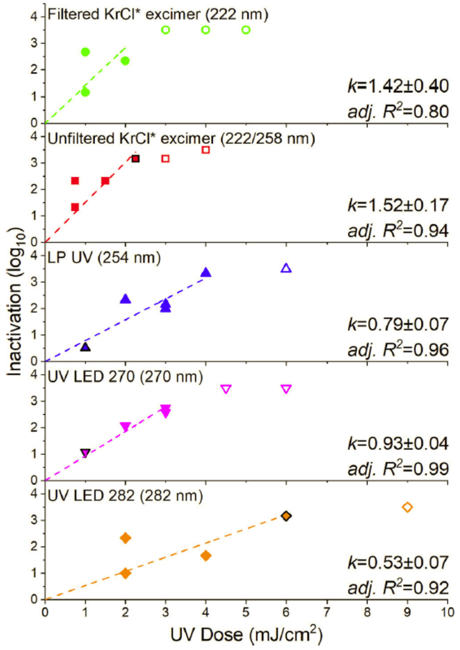
AMERICAN SOCIETY FOR MICROBIOLOGY | Applied and Environmental Microbiology®

PUBLIC AND ENVIRONMENTAL HEALTH MICROBIOLOGY

Check for updates

UV Inactivation of SARS-CoV-2 across the UVC Spectrum: KrCl* Excimer, Mercury-Vapor, and Light-Emitting-Diode (LED) Sources

Ben Ma,[a] Patricia M. Gundy,[b] Charles P. Gerba,[b] Mark D. Sobsey,[c] Karl G. Linden[a]



https://journals.asm.org/doi/full/10.1128/AEM.01532-21

www.nature.com/scientificreports

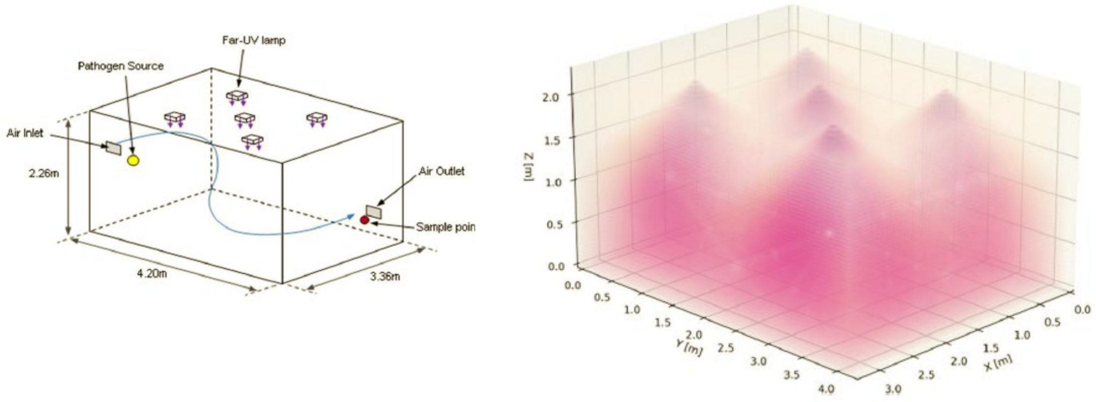
scientific reports

Check for updates

OPEN

Far-UVC (222 nm) efficiently inactivates an airborne pathogen in a room-sized chamber

Ewan Eadie[1✉], Waseem Hiwar[2], Louise Fletcher[2], Emma Tidswell[2], Paul O'Mahoney[1,3], Manuela Buonanno[4], David Welch[4], Catherine S. Adamson[5], David J. Brenner[4], Catherine Noakes[2] & Kenneth Wood[6]



https://www.nature.com/articles/s41598-022-08462-z

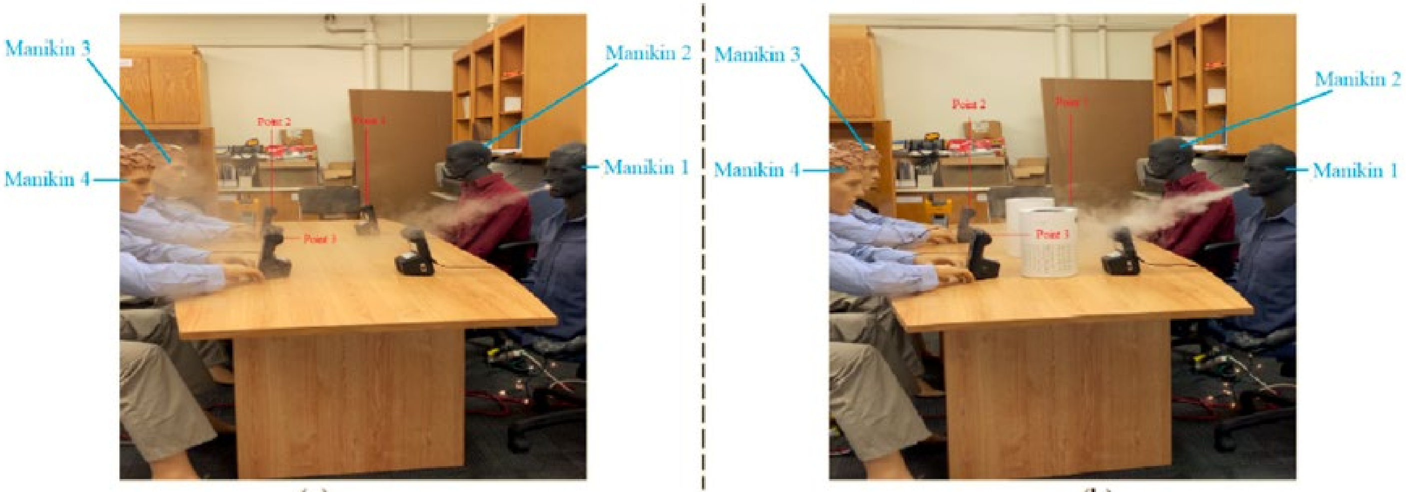
Portable air cleaners

- Standalone engineering controls
- Can incorporate filtration, disinfection technologies for microorganisms
- HEPA filters common – recommended, make other disinfection technologies redundant
- May include other technologies to remove gases from air
  - Activated carbon
- Wide range of costs and capacities

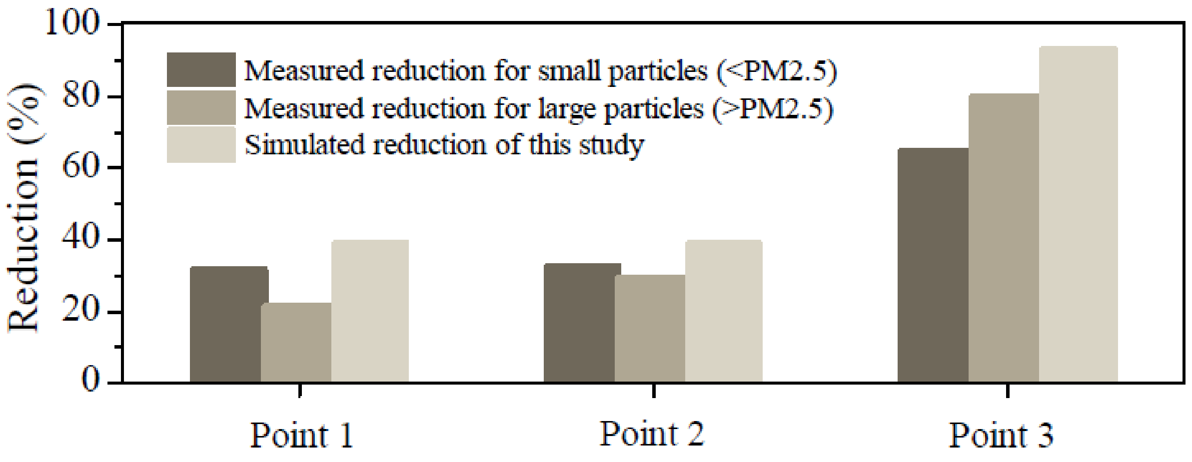
Portable mechanical filtration reduces exposure

- Conway, et al. 2022 *The removal of airborne SARS-CoV-2 and other microbial bioaerosols by air filtration on COVID-19 surge units.* (pre-print) doi.org/10.1101/2021.09.16.21263684

  "Airborne SARS-CoV-2 was detected in the ward on all five days before activation of air/UV filtration, but on none of the five days when the air/UV filter was operational,,,Filtration significantly reduced the burden of other microbial bioaerosols in both the ward (48 pathogens detected before filtration, two after, p=0.05) and the ICU. (45 pathogens detected before filtration, five after p=0.05)."



(a) (b)



Zhai, et al. (2021)
https://doi.org/10.3390/buildings11080329

Future buildings healthy, resilient, sustainable

- Efficient ventilation
  - Energy recovery
  - Efficient air distribution
  - Hybrid ventilation
- Alternatives to ventilation
  - Source reduction
  - Air cleaning
- Combine *Smart* with healthy and resilient
  - Re-imagined demand controls
  - Energy-optimized emergency operating modes

Knowledge gaps…many

- Airborne disease transmission risk assessment – great uncertainty
- Exposure limits and corresponding equivalent clean air delivery requirements
- Application relevant performance characteristics of many technologies – need testing and certification
- Emerging UV technologies
- Impact of air distribution in rooms on effectiveness of air cleaners

…However, we know a lot about which technologies are effective, even if difficult to quantify

Final thoughts

- Built environment has not functioned well to protect us from infection during the pandemic
- There are other, older IAQ problems - In the long term, IAQ improvements should address the range of key exposures
- Ability of buildings to adapt will be key to limiting energy use and operating cost
- Much needs to be done – research, standards, education
- Practice should be science-based – requires proactive effort by researchers

Thank You!

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PennState College of Engineering | ARCHITECTURAL ENGINEERING

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