INDOOR AIR QUALITY IN SCHOOLS AND CHILDCARE FACILITIES DURING COVID-19

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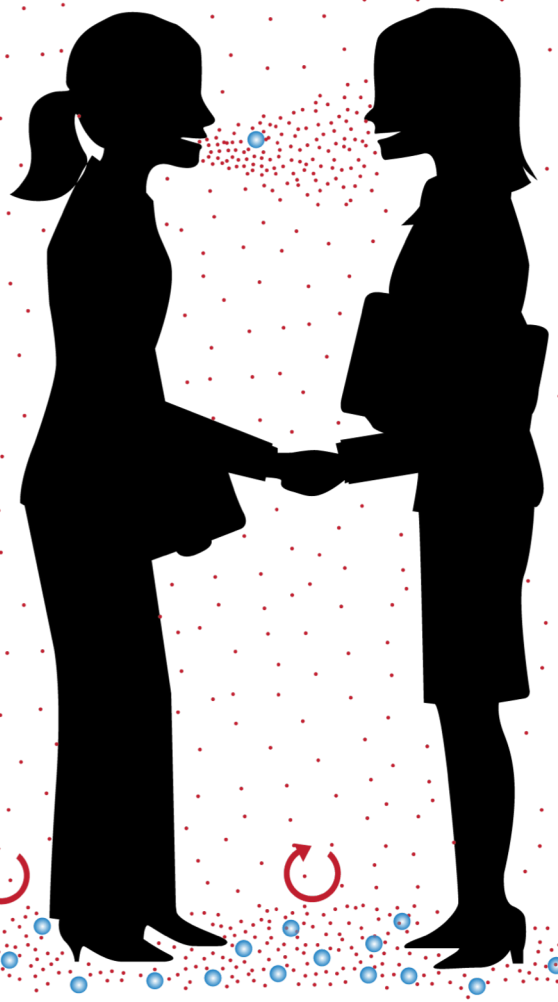
Mechanical Engineering
University of Colorado Boulder

Recommendations

Also suggest adding CO_2 monitors indoors

Short-range airborne transmission

Results in a few cases



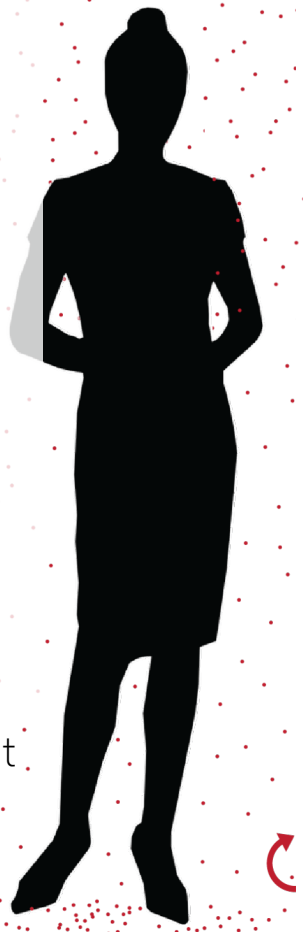
- Provide 3-ply surgical masks weekly to all staff and students, mandate wearing at all times in building
- Implement strict social distancing policies
  - e.g. no eating together in lunch room
- Implement strict quarantine

Long-range airborne transmission

Results in superspreading

In addition to strategies for short-range…

- Aggressively increase ventilation rates to at least 5, ideally 6 air changes per hour outside air
  - Windows/doors open
- Mandate additional air cleaning in every space that is occupied for > 1 hour by > 10 occupants
  - Room size key: 600-1000 ft^2 with 8-10 ft ceilings utilize stand alone HEPA air cleaners
  - Larger rooms with higher ceilings use upper room germicidal ultraviolet light

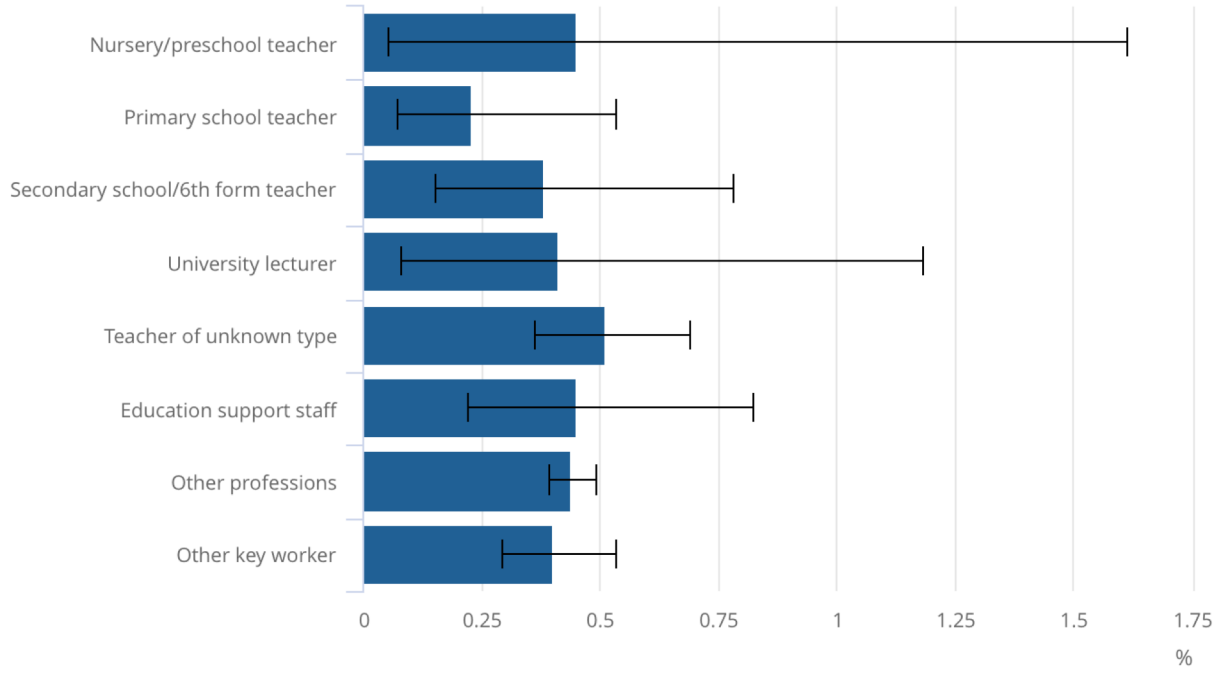


Slides courtesy adapted from Linsey Marr

SCHOOL TRANSMISSIONS

Figure 12: Since the start of the school year there is no evidence of difference in the positivity rate between teachers and other key workers

Unweighted estimates of those in teaching, keyworker and other occupations testing positive for the coronavirus (COVID-19) on nose and throat swabs, 2 September to 16 October 2020, England



What does the data say?

In the UK no evidence of difference in positivity rate between primary and secondary school teachers and their households, other key workers and their households, and other professions and their households

https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurveypilot/6november2020#analysis-of-the-number-of-school-workers-key-workers-and-other-professions-in-england-who-had-covid-19

"There is no consistent pattern. It's not that closing schools leads to a decrease in cases, or that opening schools leads to a surge in cases." – Insights for Education

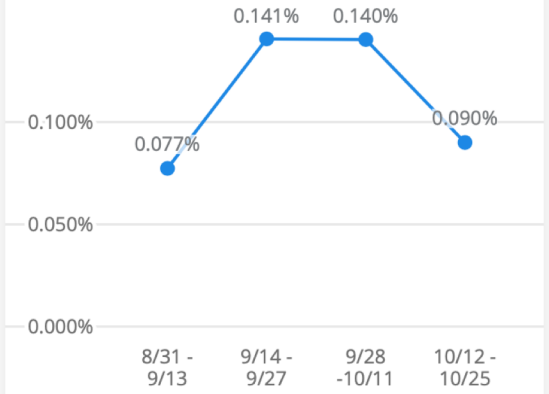
- Susceptibility for children aged <10y is relatively low; susceptibility in adults aged >60y is higher; mitigation measures should be implemented when opening schools, particularly secondary/high schools (Goldstein)
- In England summer school session 0.51 outbreaks for each infection per 100,000 in community; infections and outbreaks uncommon across all educational settings; staff members had increased risk compared to students, majority of cases linked to outbreaks were in staff. The probable transmission direction for the 30 confirmed outbreaks was: staff-to-staff (15), staff-to-student (7), student-to-staff (6) and student-to-student (2) (Ismail)
- Main factors whether child care worker got sick overall level of community transmission in county where lived and race/ethnicity – Black, Latino, Native American people more likely to test positive or be hospitalized. Both policy and social context affect people's risks and outcomes (Gilliam)

Goldstein, E., Lipsitch, M., & Cevik, M. (n.d.). On the effect of age on the transmission of SARS-CoV-2 in households, schools and the community. *The Journal of Infectious Diseases*. Accepted.
Gilliam, W. S., Malik, A. A., Shafiq, M., Klotz, M., Reyes, C., Humphries, J. E., Murray, T., Elharake, J. A., Wilkinson, D., & Omer, S. B. (2020). COVID-19 Transmission in US Child Care Programs. *Pediatrics*, e2020031971.
Ismail, S. A., Saliba, V., Bernal, J. A. L., Ramsay, M. E., & Ladhani, S. N. (2020). SARS-CoV-2 infection and transmission in educational settings: Cross-sectional analysis of clusters and outbreaks in England. Preprint.

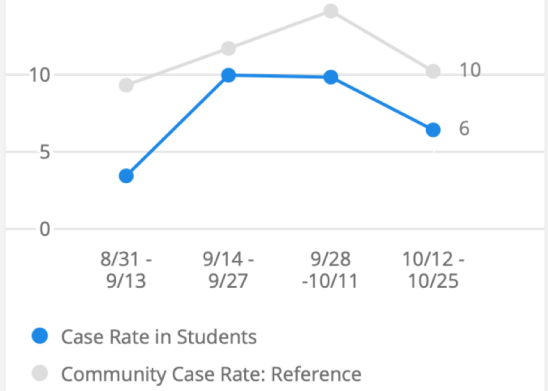
COVID-19 School Response Dashboard – Brown University (self report)

Student Confirmed Infection Rate

Percent of Students with Confirmed Case

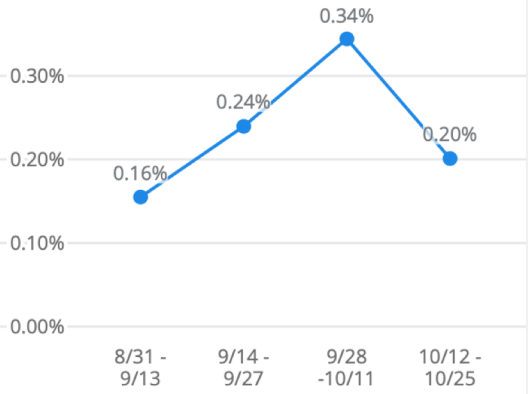


Daily Case Rate Per 100,000 Students

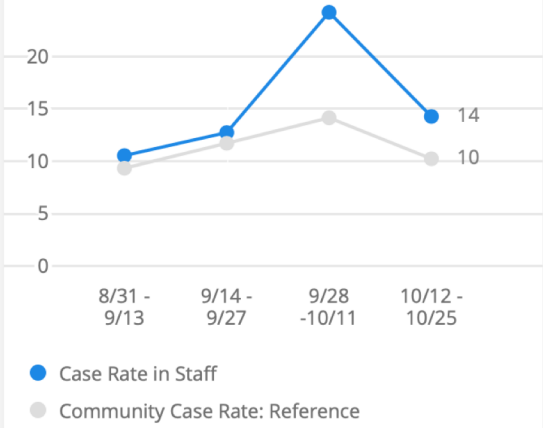


Staff Confirmed Infection Rate

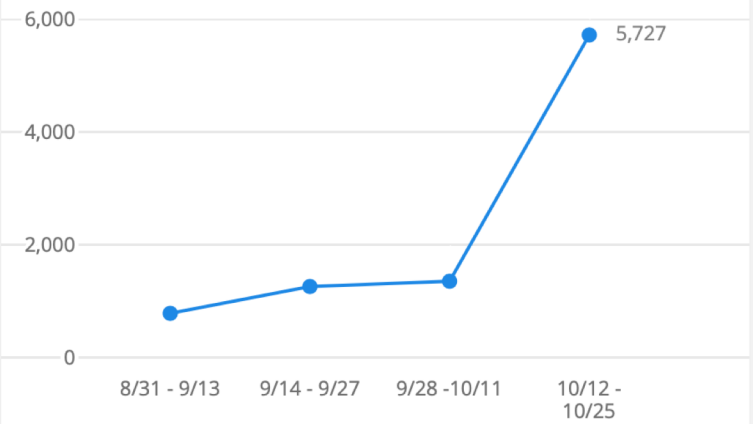
Percent of Staff with Confirmed Case



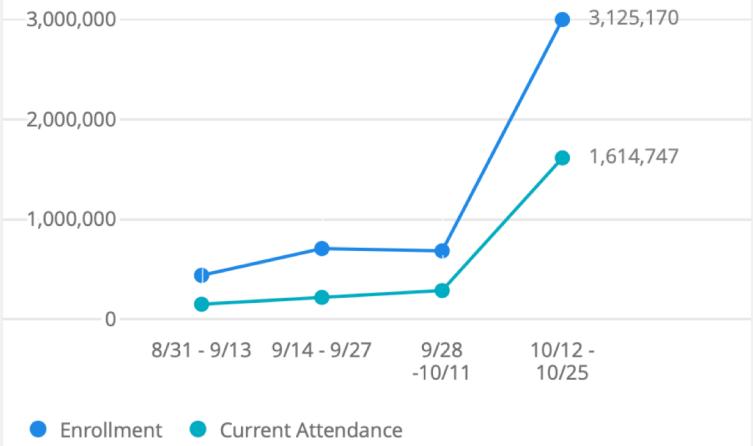
Daily Case Rate Per 100,000 Staff



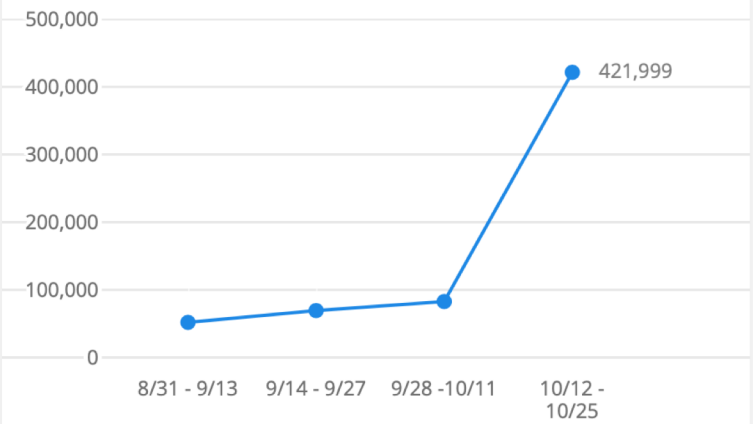
Schools Reporting



Students Represented in Dataset



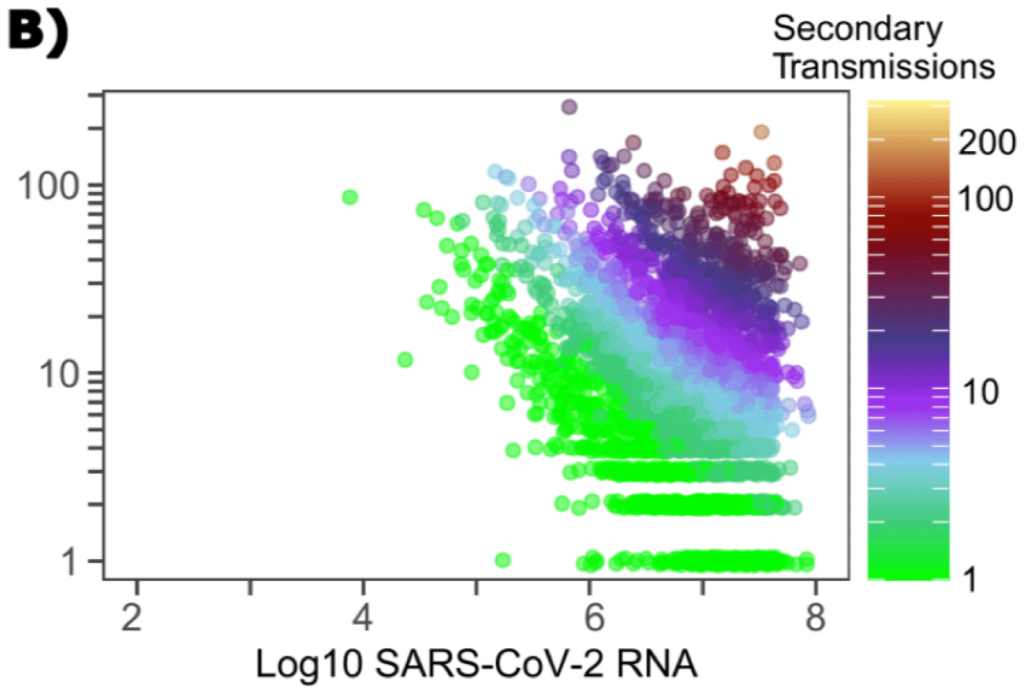
Staff Counts

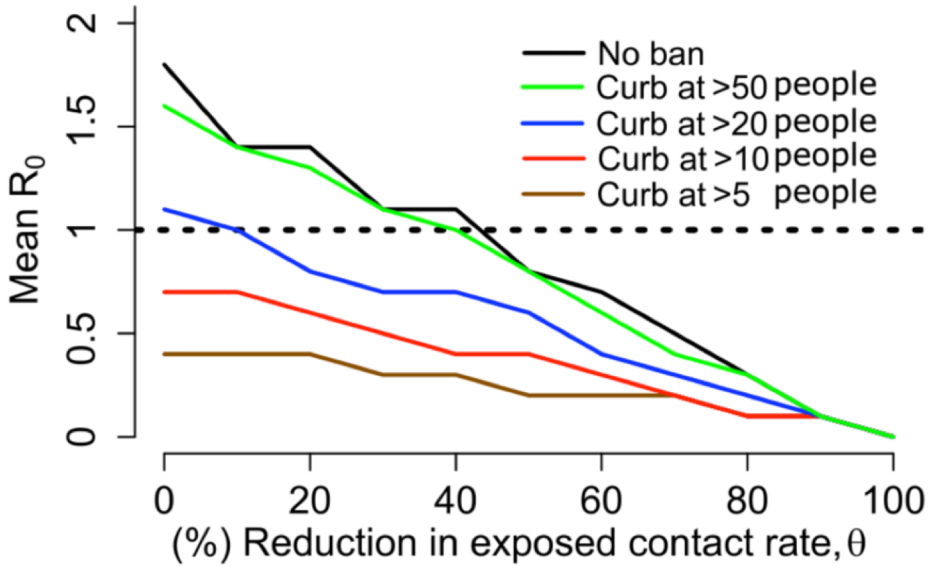


SUPERSPREADING

Superspreading

- As few as 10-20% of infected people transmit 80-90% of the infections; many people barely transmit, asymptomatic/pre-symptomatic
- super-spreader w/ >10 infections occur when infected is shedding very high viral load & has a high concurrent number of exposed contacts





Goyal, A., Reeves, D. B., Cardozo-Ojeda, E. F., Schiffer, J. T. & Mayer, B. T. Wrong person, place and time: viral load and contact network structure predict SARS-CoV-2 transmission and super-spreading events. *medRxiv* (2020).

Lloyd-Smith JO, Schreiber SJ, Kopp PE, Getz WM. Superspreading and the effect of individual variation on disease emergence. *Nature*. 2005;438(7066):355-359. doi:10.1038/nature04153

Skagit Valley Chorale Rehearsal Outbreak

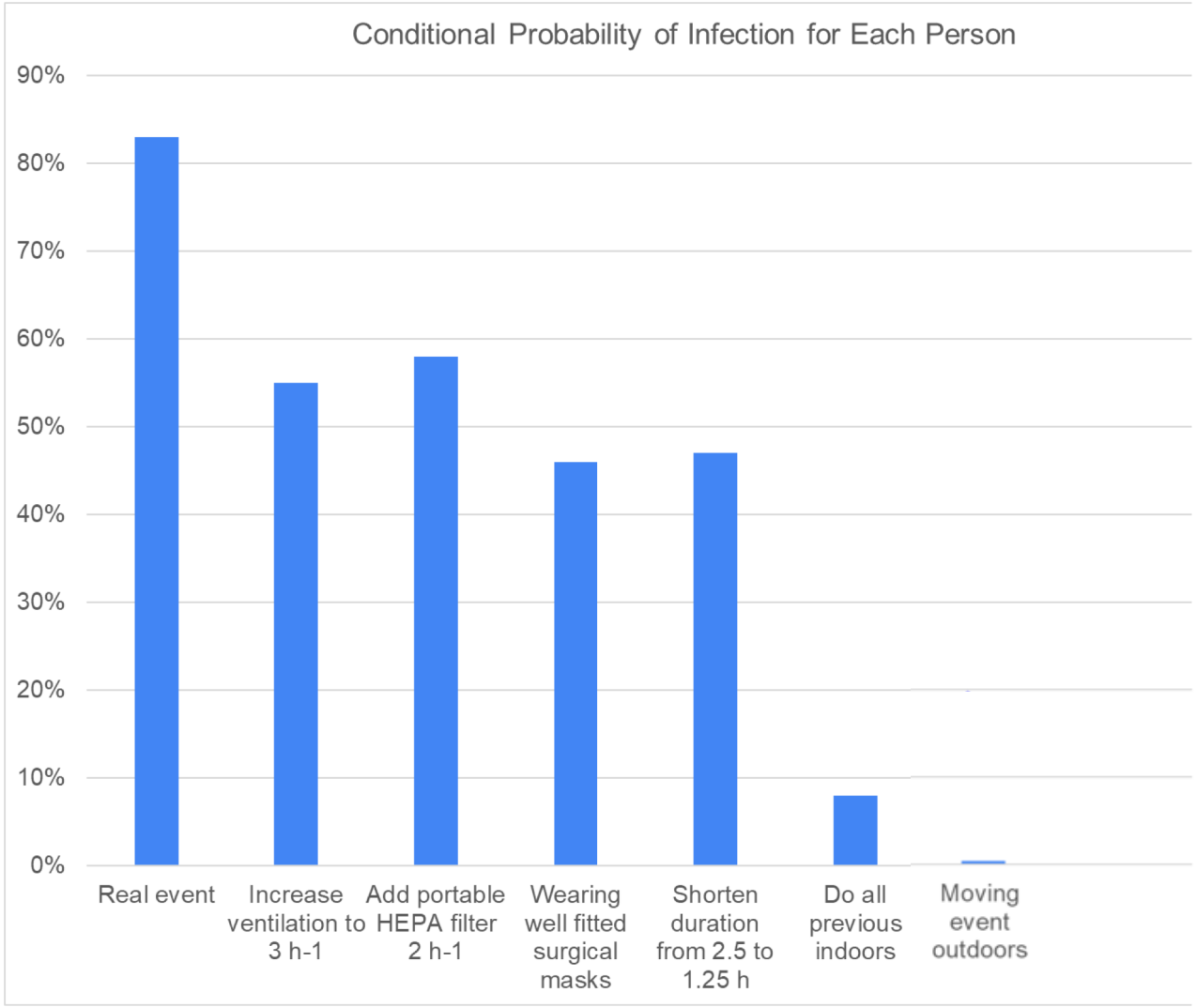
Goal 1: estimate average emission rate of infectious airborne dose

Goal 2: explore how changes in ventilation or duration of event would alter infection risk

Miller, S. L., Nazaroff, W. W., Jimenez, J. L., Boerstra, A., Buonanno, G., Dancer, S. J., Kurnitski, J., Marr, L. C., Morawska, L., & Noakes, C. (2020). Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air*, ina.12751.

Indoors never totally safe, can mitigate

- What happens if we could change conditions?
- All are changing only 1 thing, except "do all previous indoors"



Calculated with: https://tinyurl.com/covid-estimator

Slide courtesy of Prof. Jose Jimenez

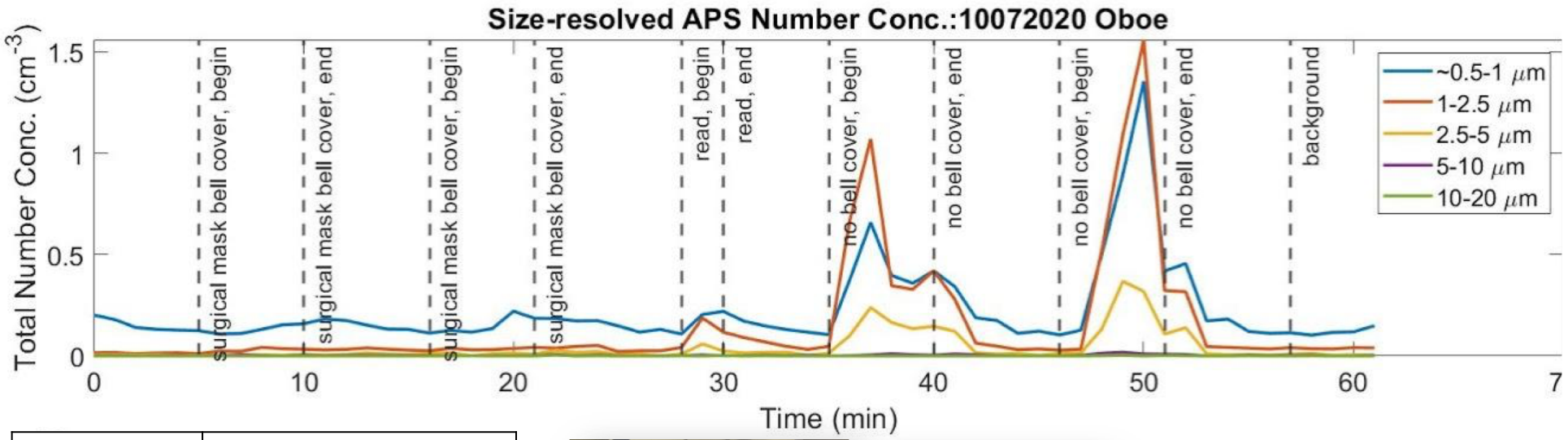
MUSICIANS AND PERFORMERS STUDY

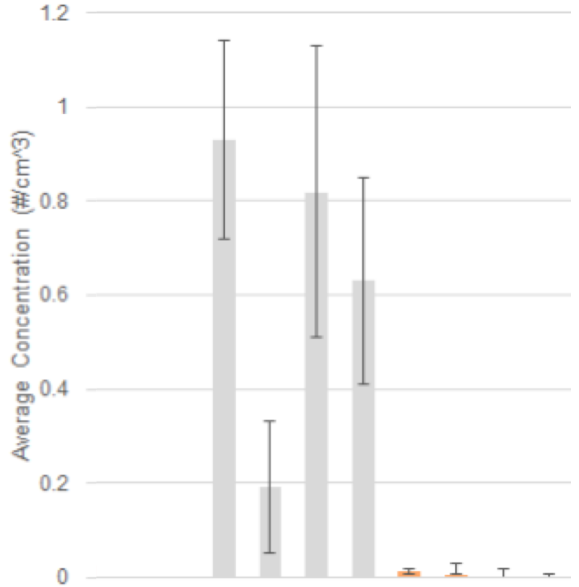
"Let's Save Music"

Study Chairs: NFHS Weaver and Clemson Spede

CU Boulder Research Team: Miller, Vance, Hertzberg, Toohey, Stockman, Patel, Kumar, Bower, Nelson

U of Maryland Team: Srebric, Milton, Zhu

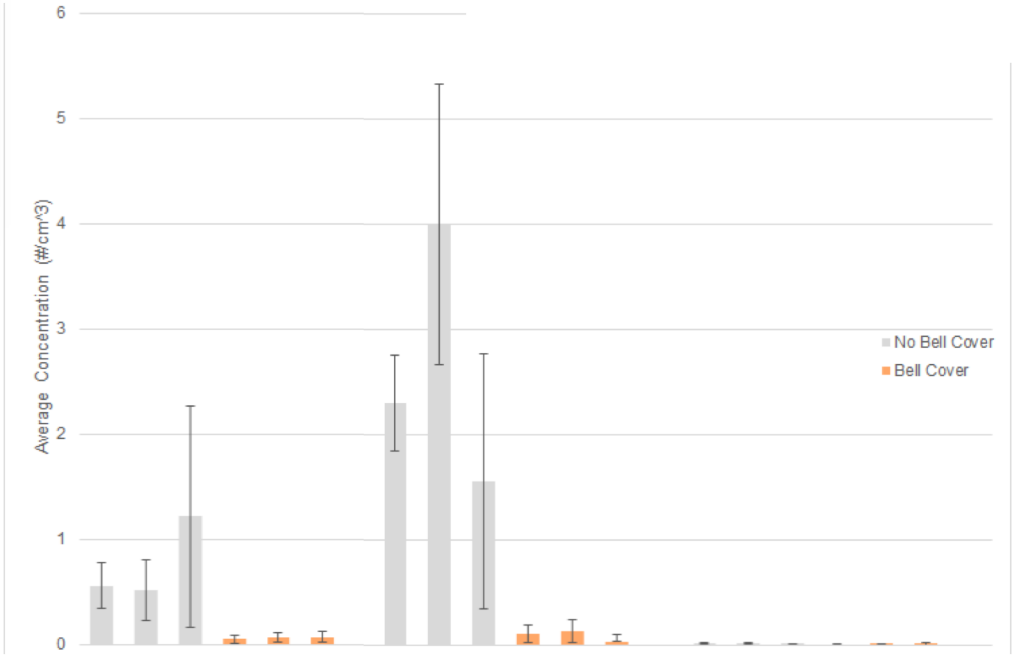




Soprano Singer

Instrument	Bell Cover Efficiency, Sampled at Bell
Clarinet	87%
Bassoon	89%
Saxophone	64%
Oboe	96%
Flute	67%
Trombone	89%
Trumpet	92%
French Horn	95%

Performer	Mask Efficiency, Sampled in Front of Mouth
Theater 1	80%
Theater 2	88%
Soprano Singer	98%
Baritone Singer	79%

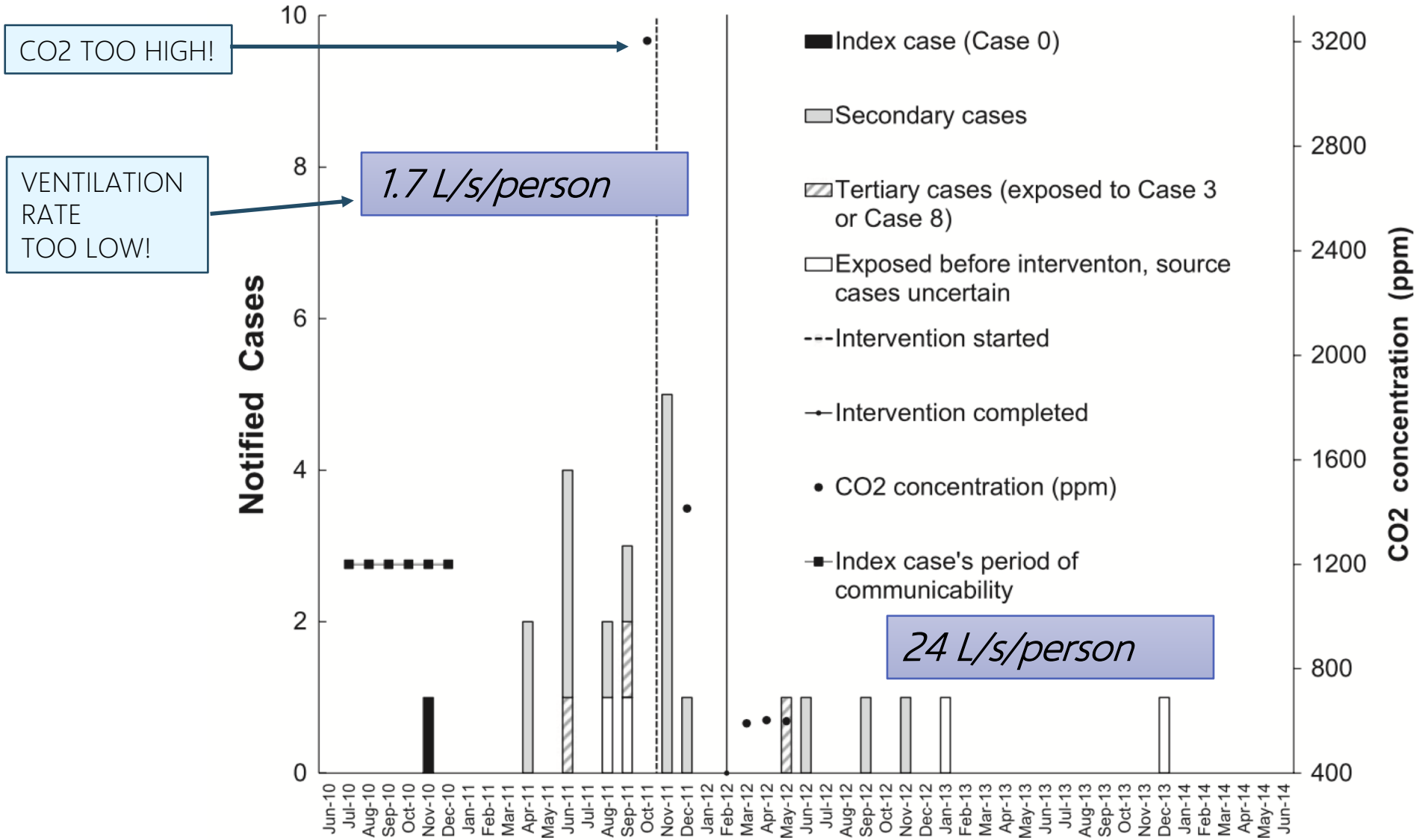


Clarinet Oboe Flute

Music and Performance Specific Recommendations

VENTILATION

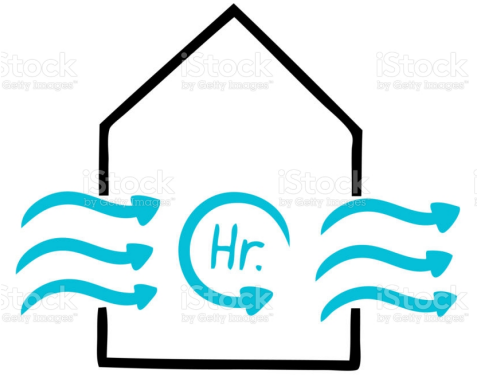
Ventilation Rate and CO_2 in a tuberculosis outbreak



Du C-R, Wang S-C, Yu M-C, et al. Effect of ventilation improvement during a tuberculosis outbreak in underventilated university buildings. *Indoor Air*. 2020;30(3):422-432.

How Air Change Rates Work

measure of the outside **air** volume added to a space divided by the volume of that space



Varies a lot during the day and from one environment to the next!

ASHRAE recommends: *6.7 L/s/person (or 13 cfm/p) outside air*

Occupancy is 35 students/1000 ft²

Design Ventilation Rate: (13 cfm/p) x 35 students = 455 cfm

Air Change Rate? 455 cfm ÷ (10,000 ft³) x (60 m/h)

= 3 air changes per hour (ACH)

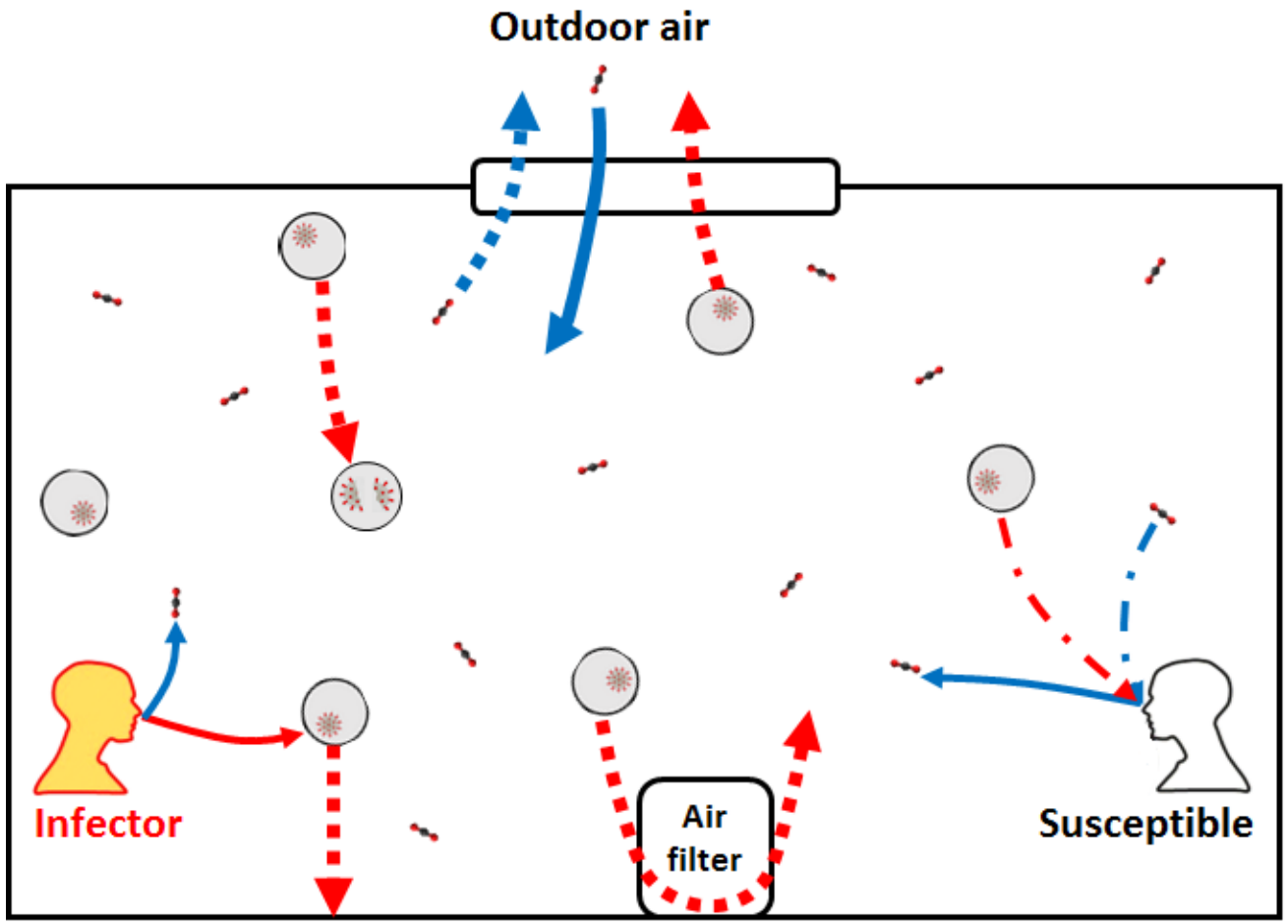
Time for 60% of the room air to be exchanged with outside air?

= 20 min

Time for all of the room air to be exchanged with outside air?

= 60 min

Using CO_2 as an Analog for Ventilation Rate



SARS-CoV-2-containing aerosol

Aerosol containing decayed SARS-CoV-2

SARS-CoV-2-containing aerosol exhalation

SARS-CoV-2-containing aerosol inhalation

SARS-CoV-2-containing aerosol loss (ventilation, deposition, decay, and filtering)

CO_2

CO_2 exhalation

CO_2 inhalation

CO_2 ventilation (out)

CO_2 ventilation (in)

Slide from Dr. Zhe Peng

CO_2 Outdoors and in a Car

Outdoors

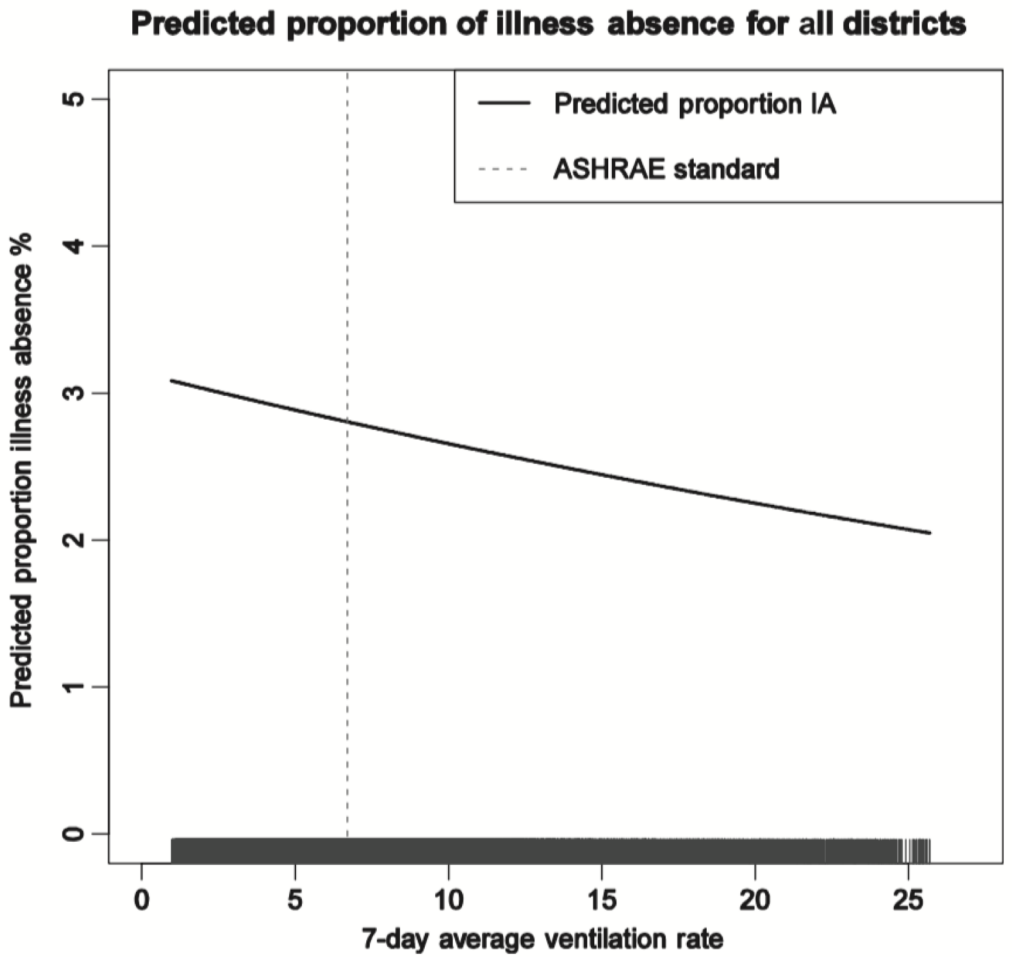
In car, 2 people + child

Windows, closed, recirculated air →

Windows closed, ventilation system w/ outdoor air →

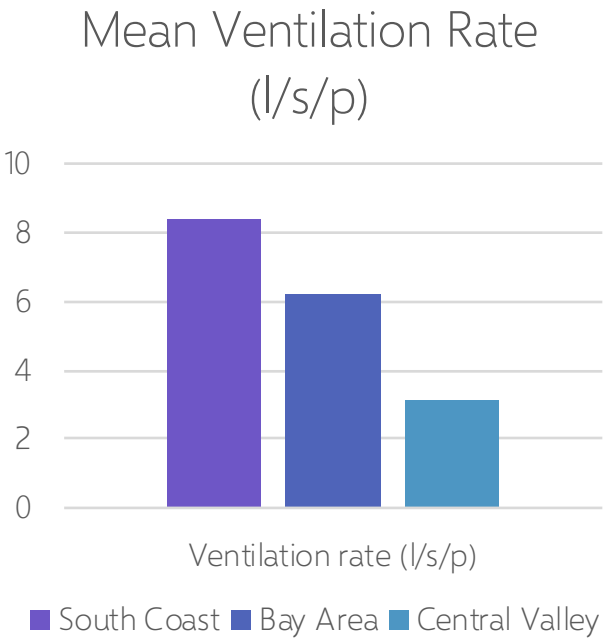
Slide from Dr. Jose Jimenez

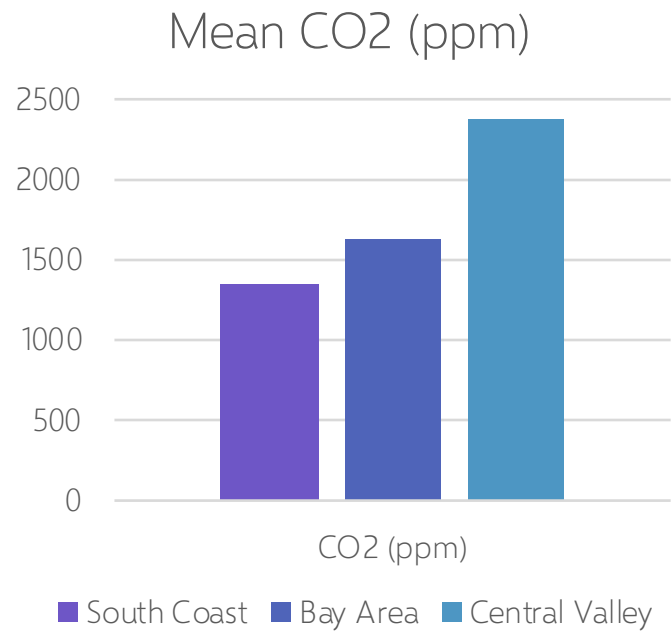
Classroom Ventilation and Illness Absence



Increasing VR from current mean of 4 to CA std of 7 l/s/p would reduce IA by 3-5%

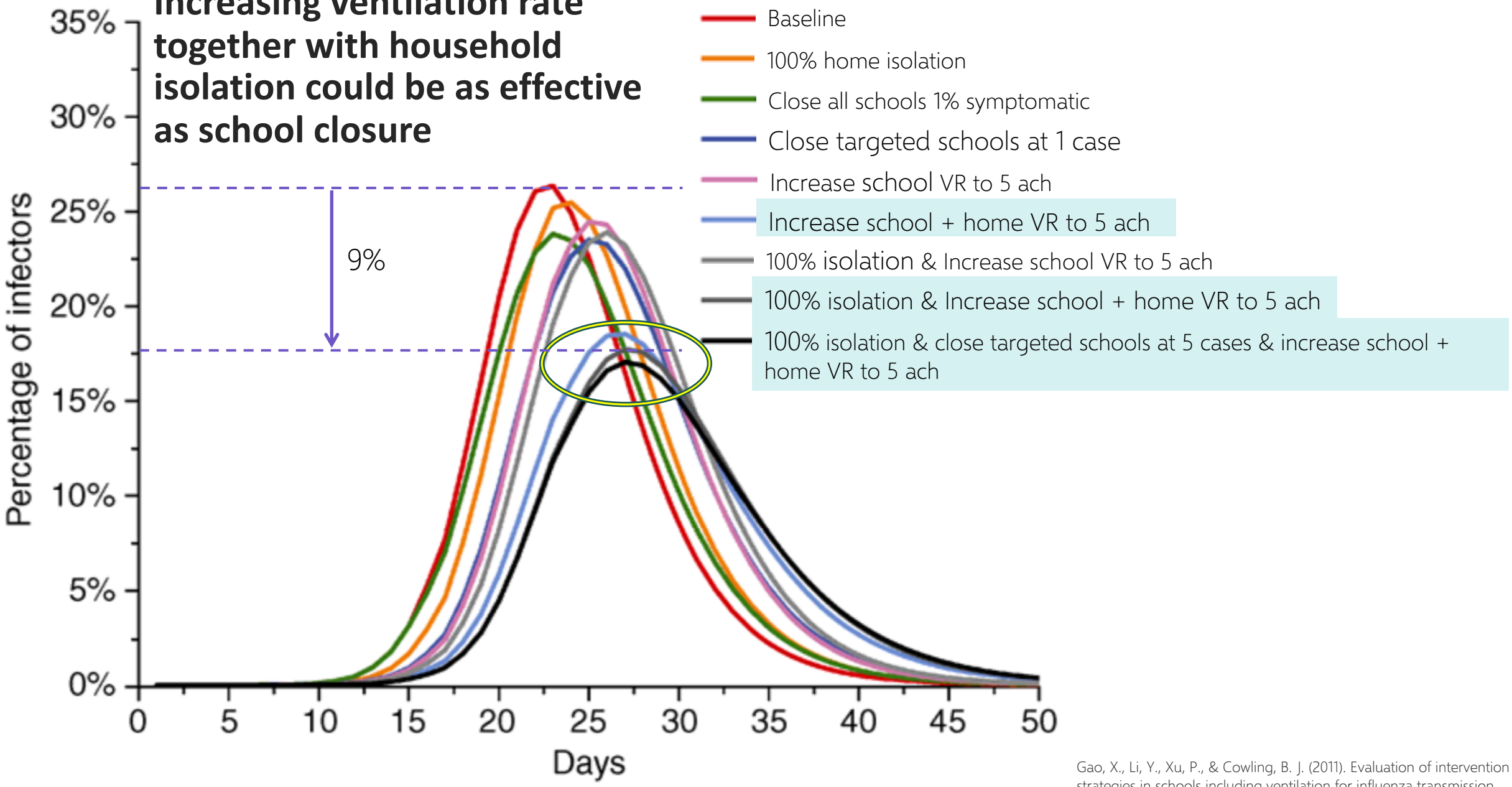
Increasing to 9.4 l/s/p would reduce IA by 7-10%



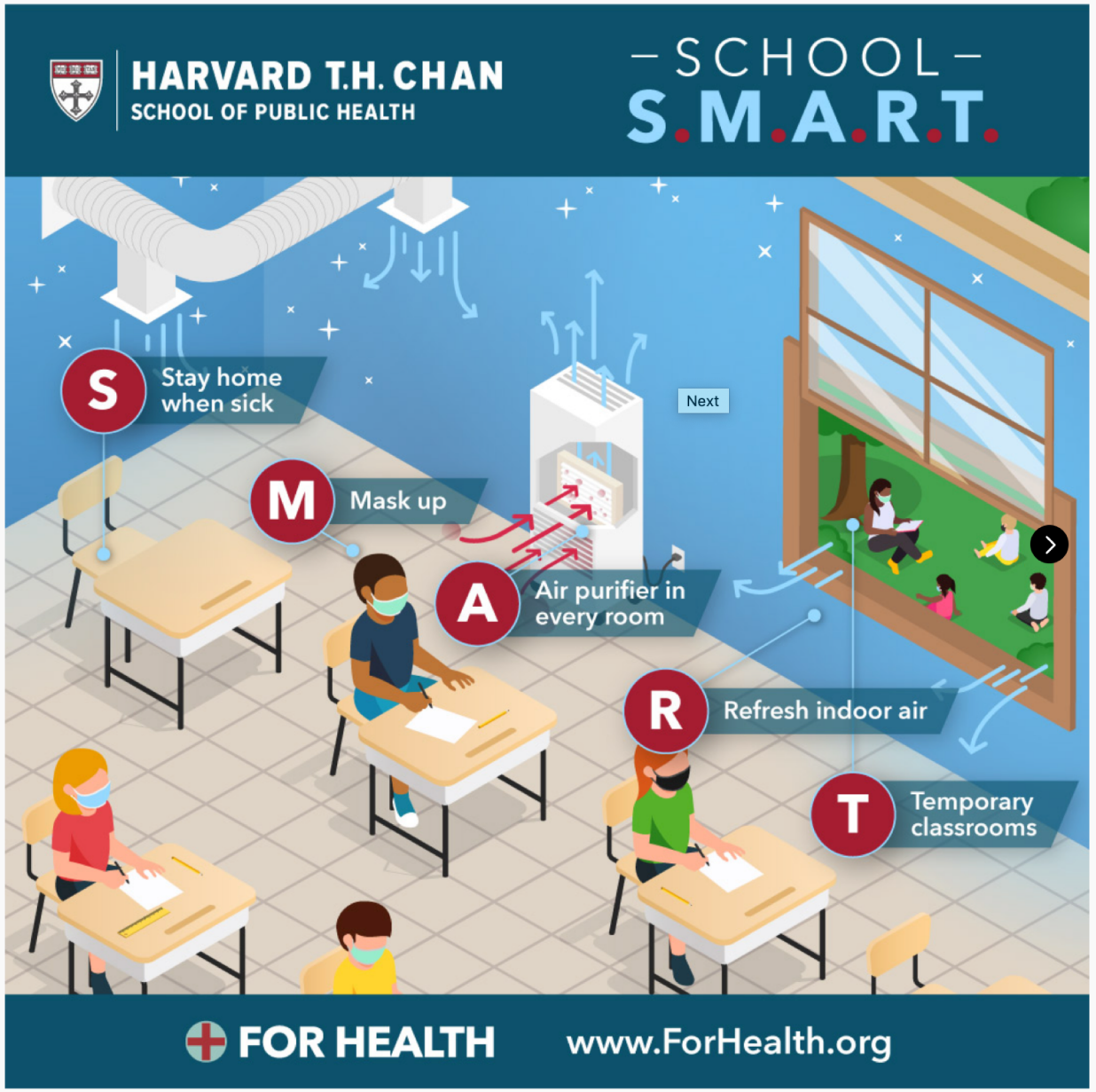


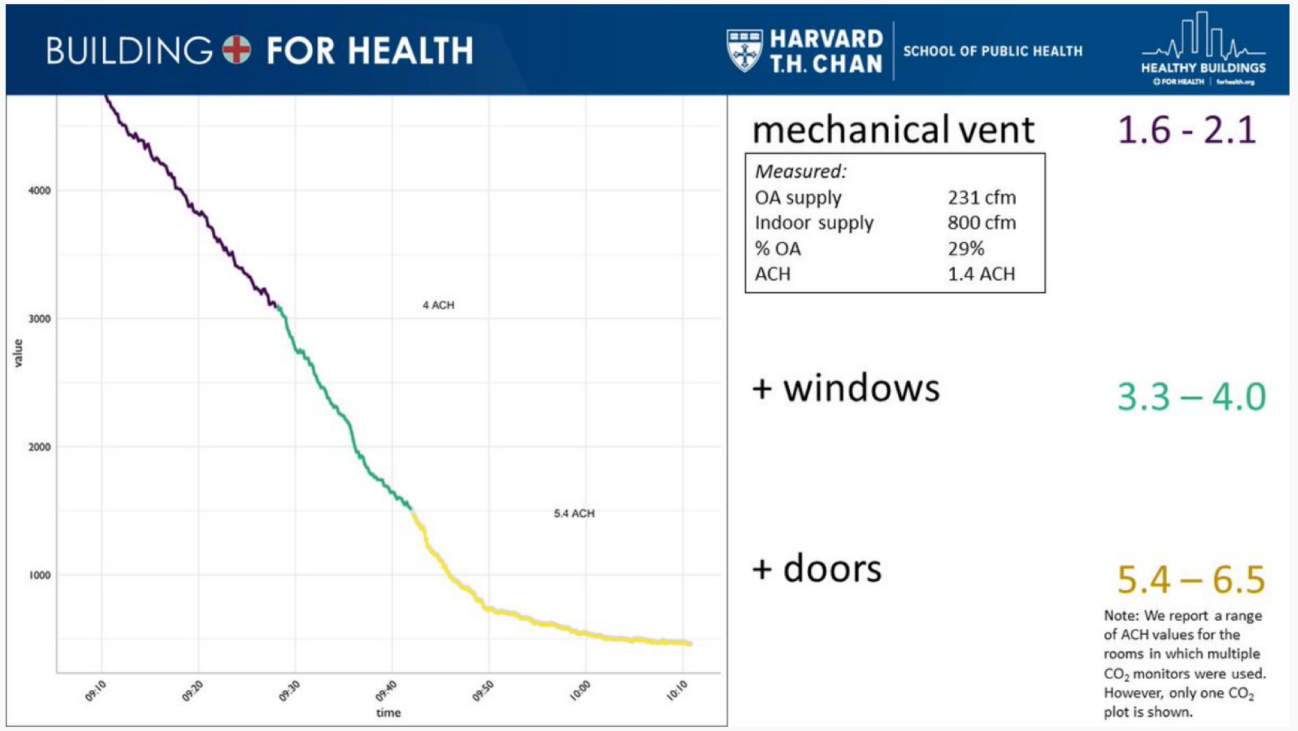
Mendell, M. J., et al. (2013). Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air*, *23*(6), 515–528.

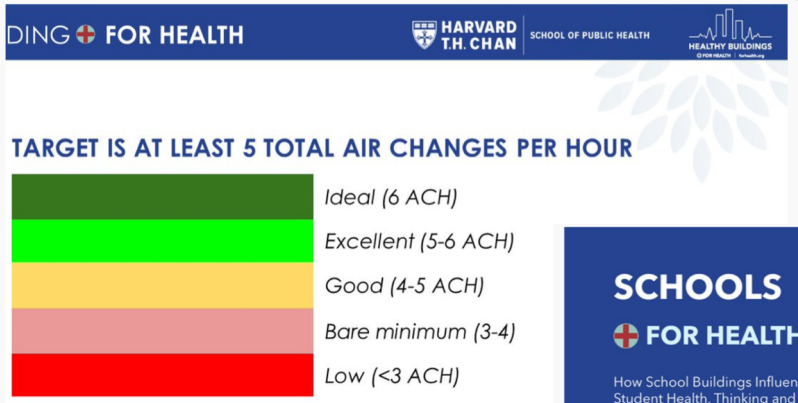
Increasing ventilation rate together with household isolation could be as effective as school closure

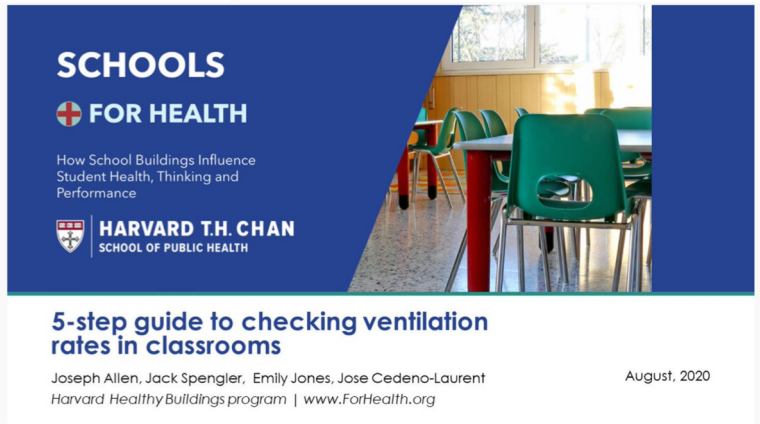


Gao, X., Li, Y., Xu, P., & Cowling, B. J. (2011). Evaluation of intervention strategies in schools including ventilation for influenza transmission control. *Building Simulation*, *5*(1), 29–37.


HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH
– SCHOOL –
S.M.A.R.T.
S
Stay home when sick
M
Mask up
A
Air purifier in every room
R
Refresh indoor air
T
Temporary classrooms
Next
FOR HEALTH
www.ForHealth.org


BUILDING FOR HEALTH
HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH
HEALTHY BUILDINGS
4000
3000
2000
1000
value
4 ACH
5.4 ACH
09:10
09:20
09:30
09:40
09:50
10:00
10:10
time
mechanical vent
1.6 - 2.1
Measured:
OA supply 231 cfm
Indoor supply 800 cfm
% OA 29%
ACH 1.4 ACH
+ windows
3.3 – 4.0
+ doors
5.4 – 6.5
Note: We report a range of ACH values for the rooms in which multiple CO_2 monitors were used. However, only one CO_2 plot is shown.


DING FOR HEALTH
HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH
HEALTHY BUILDINGS
TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR
Ideal (6 ACH)
Excellent (5-6 ACH)
Good (4-5 ACH)
Bare minimum (3-4)
Low (<3 ACH)

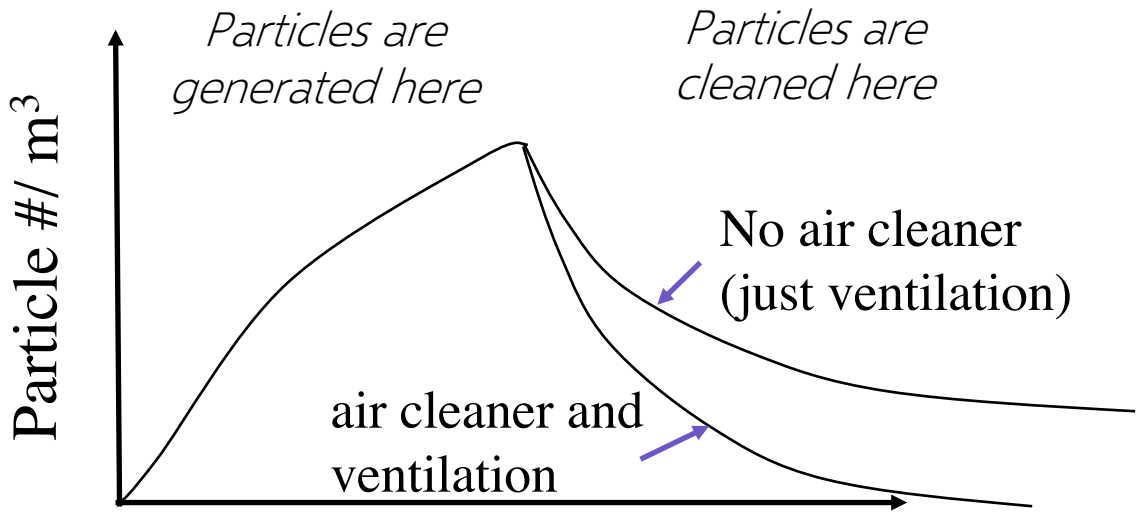

SCHOOLS
FOR HEALTH
How School Buildings Influence Student Health, Thinking and Performance
HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH
5-step guide to checking ventilation rates in classrooms
Joseph Allen, Jack Spengler, Emily Jones, Jose Cedeno-Laurent
Harvard Healthy Buildings program | www.ForHealth.org
August, 2020

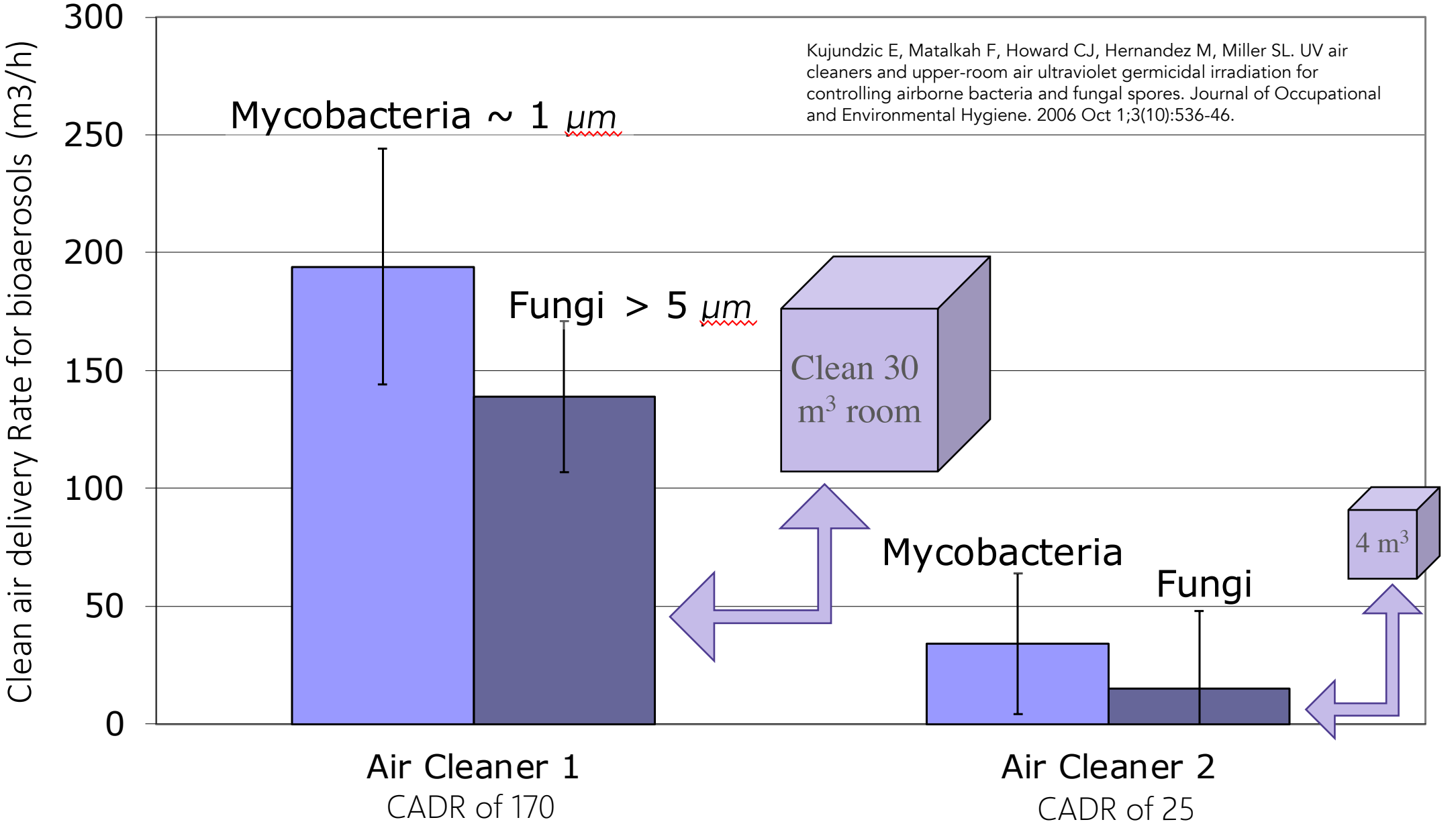
FILTRATION

Air Cleaning

Quantifying air cleaner performance

What is the airflow rate that represents the effective amount of particle-clean air produced by the device? This is the CLEAN AIR DELIVERY RATE - CADR




Clean air delivery Rate for bioaerosols (m3/h)
300
250
200
150
100
50
0
Mycobacteria ~ 1 μm
Fungi > 5 μm
Kujundzic E, Matalkah F, Howard CJ, Hernandez M, Miller SL. UV air cleaners and upper-room air ultraviolet germicidal irradiation for controlling airborne bacteria and fungal spores. Journal of Occupational and Environmental Hygiene. 2006 Oct 1;3(10):536-46.
Clean 30 m3 room
Mycobacteria
Fungi
4 m3
Air Cleaner 1
CADR of 170
Air Cleaner 2
CADR of 25

Harvard CU-Boulder Portable Air Cleaner Tool

SIMPLE TOOL FOR SCHOOLS FOR SELECTING PORTABLE AIR CLEANER FOR ROOMS (input fields are bright yellow)

STEP 1 HOW BIG IS THE ROOM?

Select units of preference	feet	
How big is your room?	500	*Input your room size here in square feet*
How tall are your ceilings?	8	*Input your room size here in feet*

STEP 2 WHAT IS THE 'CLEAN AIR DELIVERY RATE' OF THE AIR PURIFER? (you get this from the manufacturer)

What is the clean air delivery rate of the air cleaner?	300	*Find the CADR from the manufacturer in units of cubic feet per minute, or cfm; if they report multiple*

STEP 3 HOW MUCH OUTDOOR AIR VENTILATION DO YOU HAVE?

How is the ventilation in my school?	Low ventilation	Good ventilation	3	ACH	*This is the approximate minim*
		Enhanced ventilation	4	ACH	*Select this only if your school h*
		Typical school	1.5	ACH	*This is an approximate averag*
		Low ventilation	1	ACH	*Select this if your school has pc*

STEP 4 COMBINING AIR CLEANING AND VENTILATION, IS YOUR ROOM MEETING THE TARGET?

Air changes from outdoor air ventilation	1
Air changes from air cleaner	4.5
Total air changes in the room per hour	**5.5**

TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR

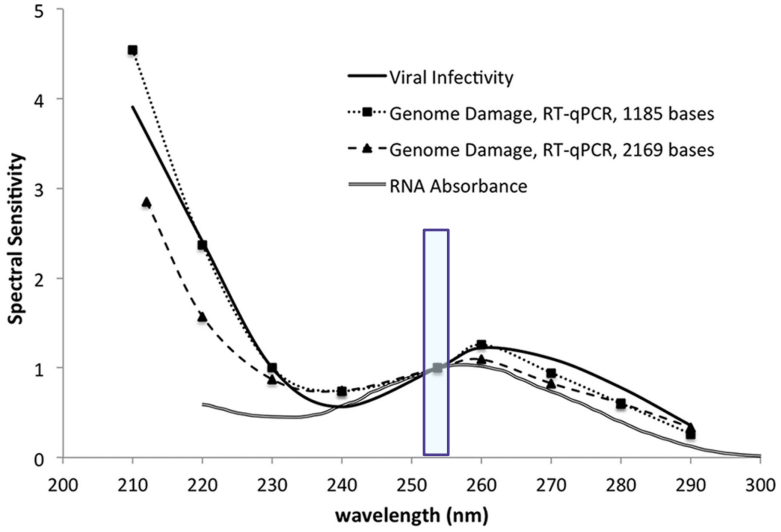
	Ideal (6 ACH)
	Excellent (5-6 ACH)
	Good (4-5 ACH)
	Bare minimum (3-4 ACH)
	Low (<3 ACH)

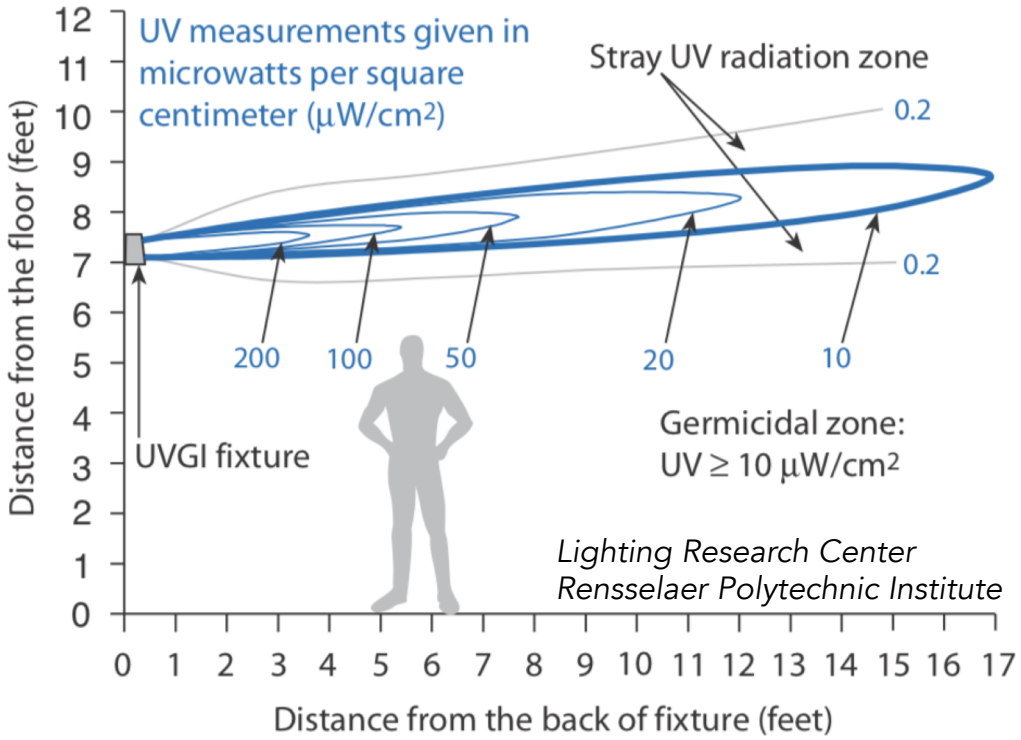
STEP 5 WHAT SIZE ROOM WILL WORK FOR THIS PORTABLE AIR CLEANER?

Cubic feet per minute (cfm) of clean air from cleaner	300	*This is from the manufacturer (see cell 'c10')*
Cubic feet per minute (cfm) of outdoor air from ventilation	67	*This is calculated from air changes per hour and volume of room*
Total cfm of air cleaning and ventilation	**367**	
Recommended room size for this air cleaner (in square feet)	**550**	*This is the recommended maximum size of the room for this air cleaner to achieve 5 total ACH*

GERMICIDAL ULTRAVIOLET LIGHT

Upper-Room Germicidal UV

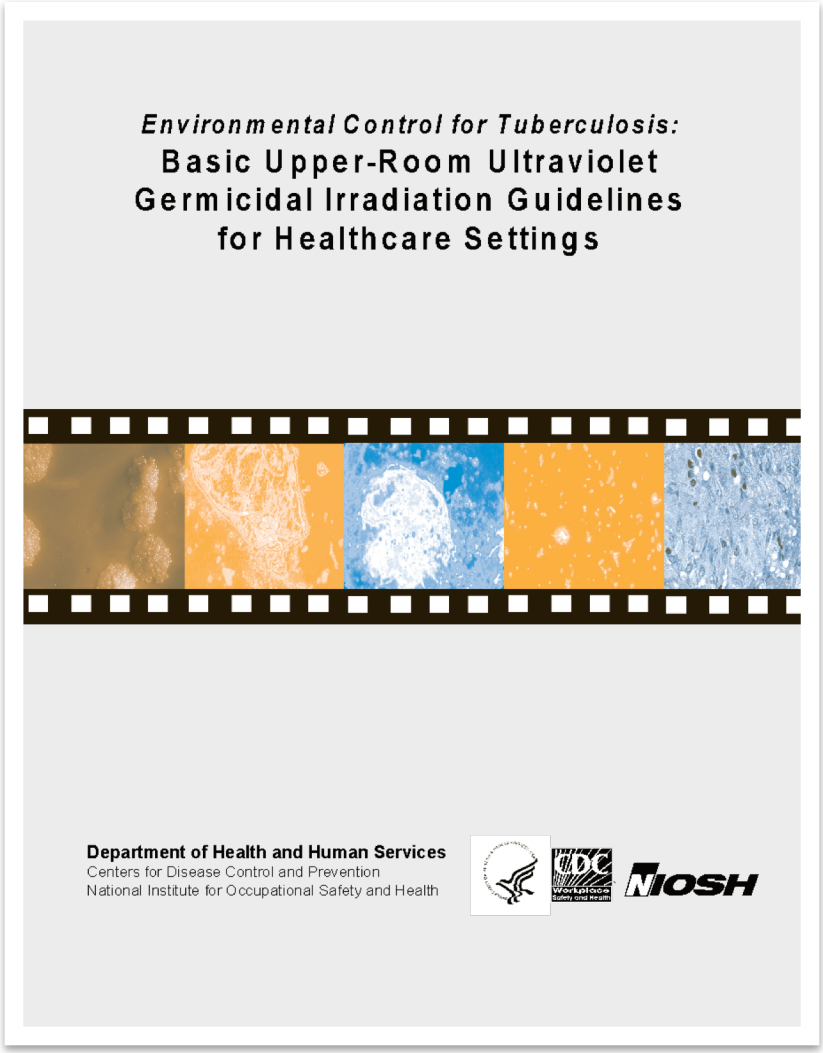




Crowded environments where unsuspected infectious persons may be present (e.g. jails, homeless shelters, hospital waiting rooms)

Beck, S. E., Rodriguez, R. A., Hawkins, M. A., Hargy, T. M., Larason, T. C., & Linden, K. G. (2016). Comparison of UV-induced inactivation and RNA damage in MS2 phage across the germicidal UV spectrum. *Applied and environmental microbiology*, *82*(5), 1468-1474.

CDC NIOSH Upper Room Air Studies



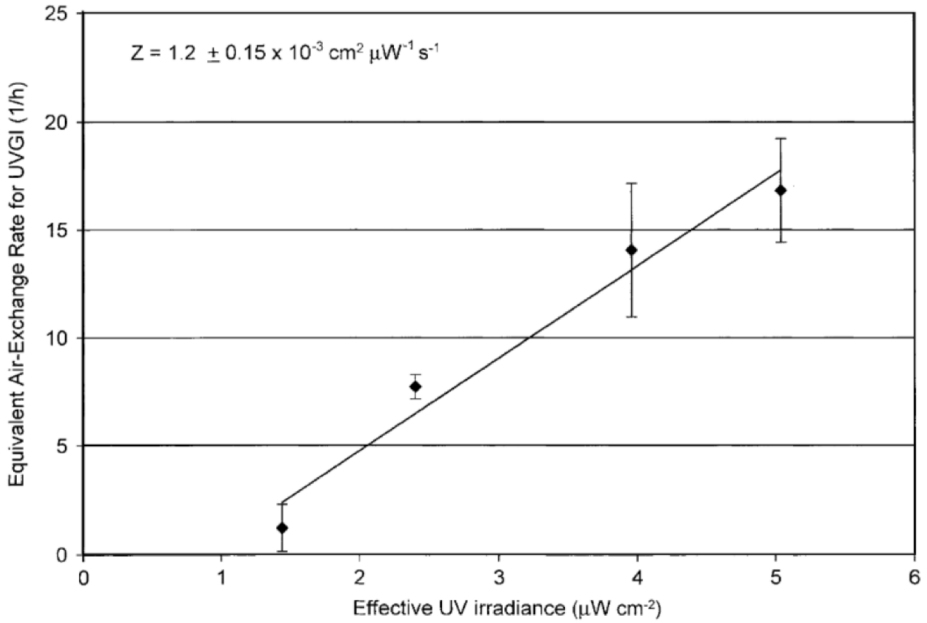


Fig. 7. UVGI inactivation rate as a function of effective UVGI spherical irradiance for *M. parafortuitum*. Effective UVGI spherical irradiance is the irradiance measured by actinometry in the upper-room zone only normalized to the fraction of room volume irradiated by UV (0.3/2.5 m).

We found that among different engineering control measures, UVGI singly is the optimal strategy combined with effective isolation and vaccination interventions for containing influenza, measles, and chickenpox.

Liao et al. 2008

Xu, P. et al. 2003; Xu, P., et al. 2005

CONCLUSIONS

Aggressively focus all resources and efforts on opening schools, reducing community spread with strict mask wearing, limiting gathering sizes, increasing ventilation rates in homes and communities…AND…

THREE IMPORTANT IDEAS

#1	#2	#3
Devastating consequences to keeping kids remote and out of in-person school – national priority	Returning to in-person school should be prioritized over other aspects of economy (last to close; first to reopen)	Cannot be 'schools as usual'; need layered defense risk reduction strategies

The infection fatality rate for kids is very low; overall risk lens has to include #1 above; strategies in #3 are designed to protect both kids AND adults

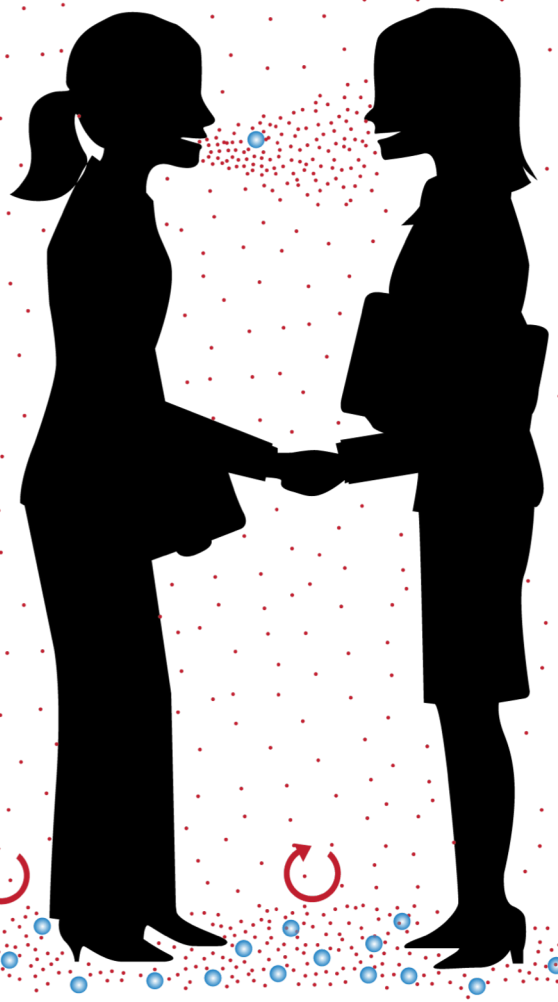
Adapted from Joe Allen

Recommendations

Also suggest adding CO_2 monitors indoors

Short-range airborne transmission

Results in a few cases



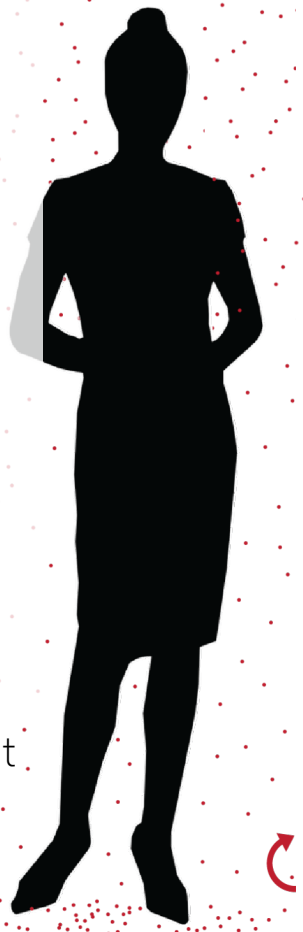
- Provide 3-ply surgical masks weekly to all staff and students, mandate wearing at all times in building
- Implement strict social distancing policies
  - e.g. no eating together in lunch room
- Implement strict quarantine

Long-range airborne transmission

Results in superspreading

In addition to strategies for short-range…

- Aggressively increase ventilation rates to at least 5, ideally 6 air changes per hour outside air
  - Windows/doors open
- Mandate additional air cleaning in every space that is occupied for > 1 hour by > 10 occupants
  - Room size key: 600-1000 ft^2 with 8-10 ft ceilings utilize stand alone HEPA air cleaners
  - Larger rooms with higher ceilings use upper room germicidal ultraviolet light



Slides courtesy adapted from Linsey Marr

ADDITIONAL SLIDES

"There is no consistent pattern. It's not that closing schools leads to a decrease in cases, or that opening schools leads to a surge in cases." – Insights for Education

- **Susceptibility for children aged <10y is relatively low**; susceptibility in adults aged >60y is higher; **mitigation measures should be implemented when opening schools, particularly secondary/high schools** (Goldstein)
- 2ndary transmission very low in Rhode Island child care programs allowed to reopen; **occurred when community transmission increased**; reduced class sizes and use of face masks for adults (Gelles)
- In England summer school session 0.51 outbreaks for each infection per 100,000 in community; **infections and outbreaks uncommon** across all educational settings; staff members had increased risk compared to students, **majority of cases linked to outbreaks were in staff**. The probable transmission direction for the 30 confirmed outbreaks was: staff-to-staff (15), staff-to-student (7), student-to-staff (6) and student-to-student (2) (Ismail)
- Main factors whether child care worker got sick **overall level of community transmission** in county where lived and race/ethnicity – Black, Latino, Native American people more likely to test positive or be hospitalized. **Both policy and social context affect people's risks and outcomes** (Gilliam)

Goldstein, E., Lipsitch, M., & Cevik, M. (n.d.). On the effect of age on the transmission of SARS-CoV-2 in households, schools and the community. *The Journal of Infectious Diseases*. Accepted.
Gelles R, DellaGrotta AL, Molina C, et al. Limited Secondary Transmission of SARS-CoV-2 in Child Care Programs — Rhode Island, June 1–July 31, 2020. MMWR 2020;69:1170–1172
Gilliam, W. S., Malik, A. A., Shafiq, M., Klotz, M., Reyes, C., Humphries, J. E., Murray, T., Elharake, J. A., Wilkinson, D., & Omer, S. B. (2020). COVID-19 Transmission in US Child Care Programs. *Pediatrics*, e2020031971.
Ismail, S. A., Saliba, V., Bernal, J. A. L., Ramsay, M. E., & Ladhani, S. N. (2020). SARS-CoV-2 infection and transmission in educational settings: Cross-sectional analysis of clusters and outbreaks in England. Preprint.

Increase (clean) outdoor air supply

- building ventilation can be as effective as public health interventions
- existing ventilation rates may be too low to prevent or control airborne infectious diseases in indoors
- and might need to be increased by 10x

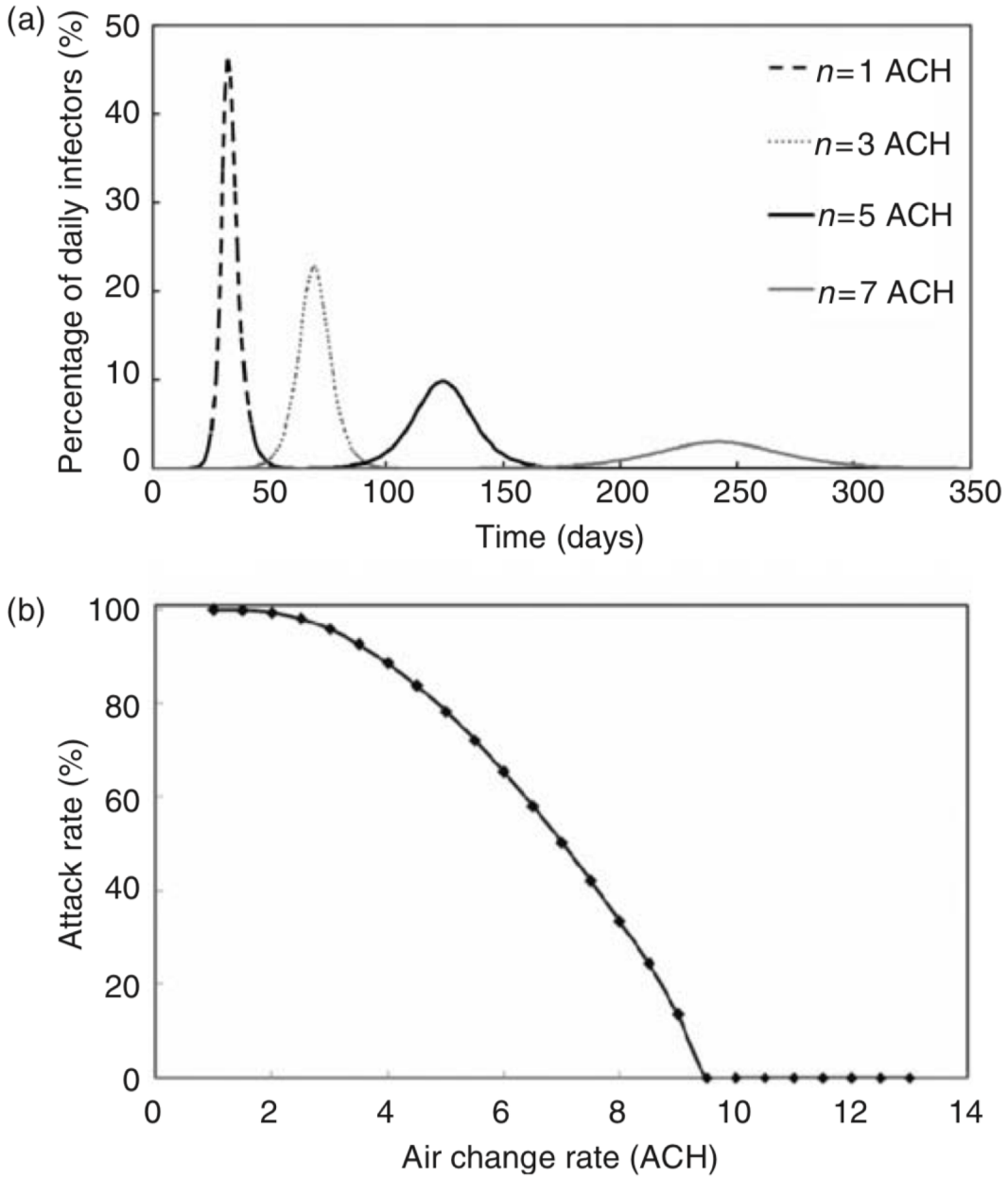


Fig. 2. The effect of increasing ventilation rate: (a) change of daily incidents, (b) change of overall attack rate.

Gao, X., Li, Y. and Leung, G.M., 2009. Ventilation control of indoor transmission of airborne diseases in an urban community. *Indoor and Built Environment*, *18*(3), pp.205-218.