Indoor Air Quality in K-12 Schools
Layered Risk (Dose) Reduction Amidst COVID-19

Richard L. Corsi, Ph.D., P.E.

H. Chik M. Erzurumlu Dean

Maseeh College of Engineering & Computer Science

Portland State University

@CorsIAQ

www.corsiaq.com

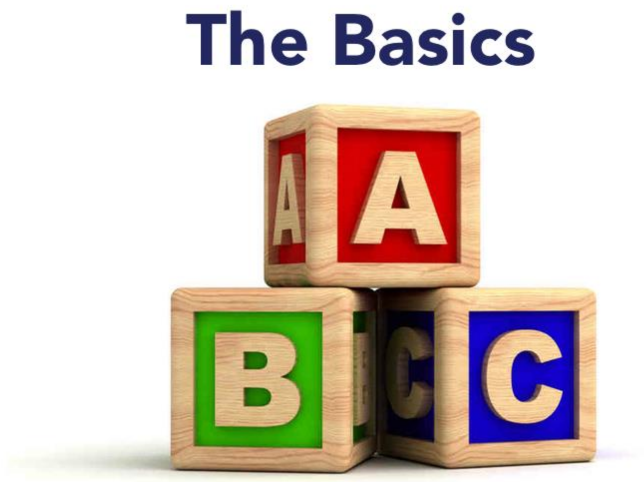
Schools & School Environments Matter

- 1 in 5 Americans in schools each workday
- ≈ 58 M students (K-12: 1.6 to 1.8 yr *inside* schools)
  - Mental, social, physical development
  - Performance, illness, absence

- ≈ 3.7 M teachers + similar support staff
  - Teachers; elevated work-related respiratory problems

    Tak, S., et al. *Journal of School Health*, 2011.
- > \$13,000/student-year US Census Bureau (2020), NEA (2020), educationdata.org

Some Fundamentals



Sources of Emissions

- Breathing
- Speaking
- Singing
- Coughing
- *Flushing?*
- *Resuspending?*

- Virus not naked (embedded in particles)
- Particles = combo of mucous & saliva
- Small fraction of viruses infectious

Particles & Viruses

Particle size important

- Deposition onto indoor surfaces
- Removal in filters / masks
- Deposition in respiratory system
  - How much and where

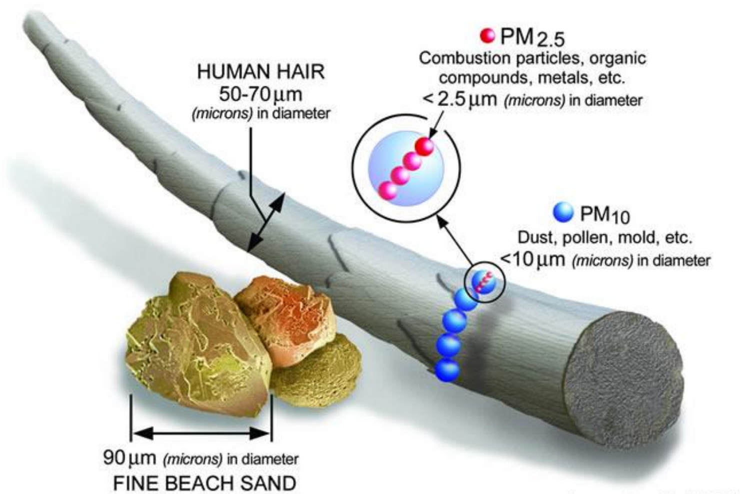
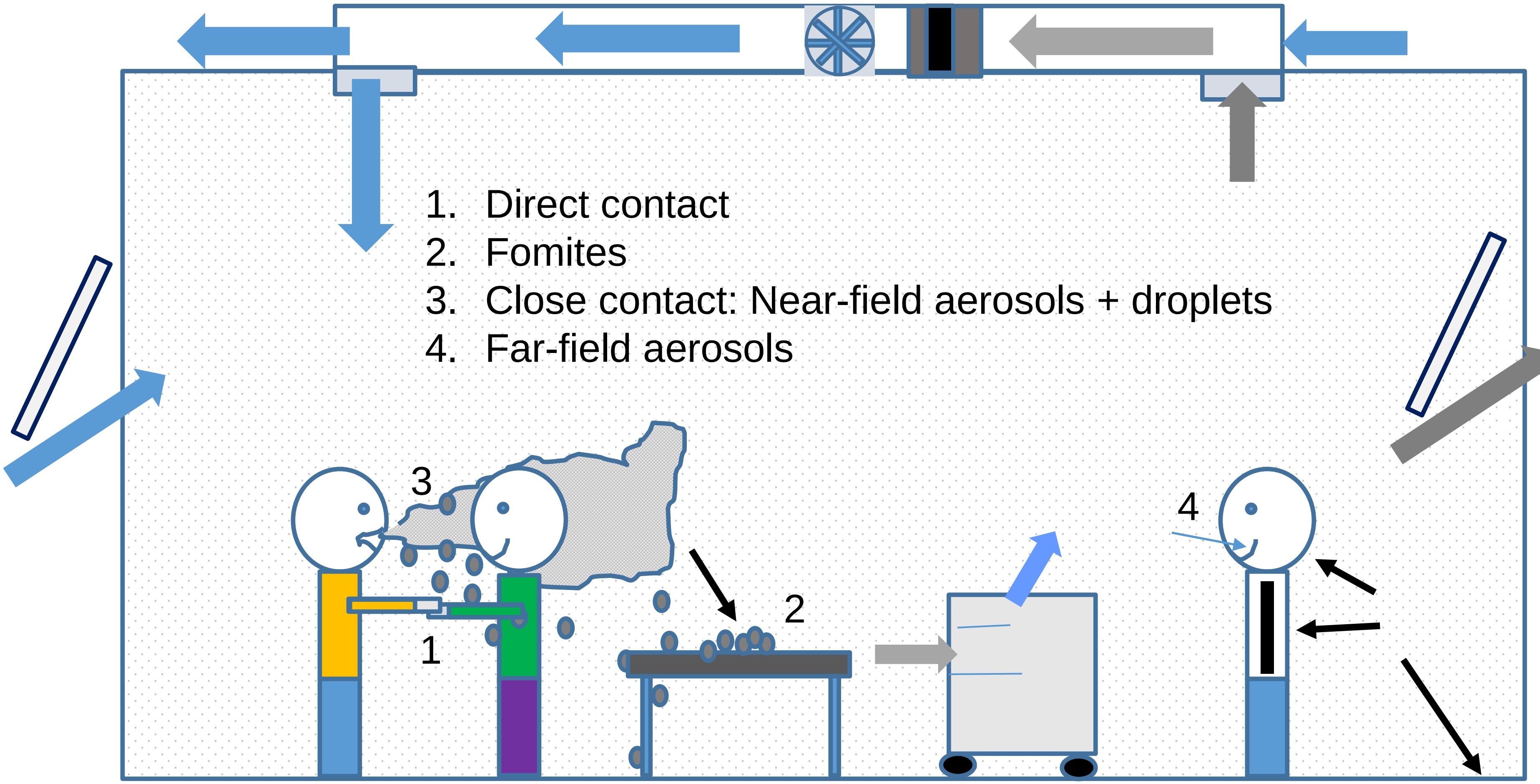


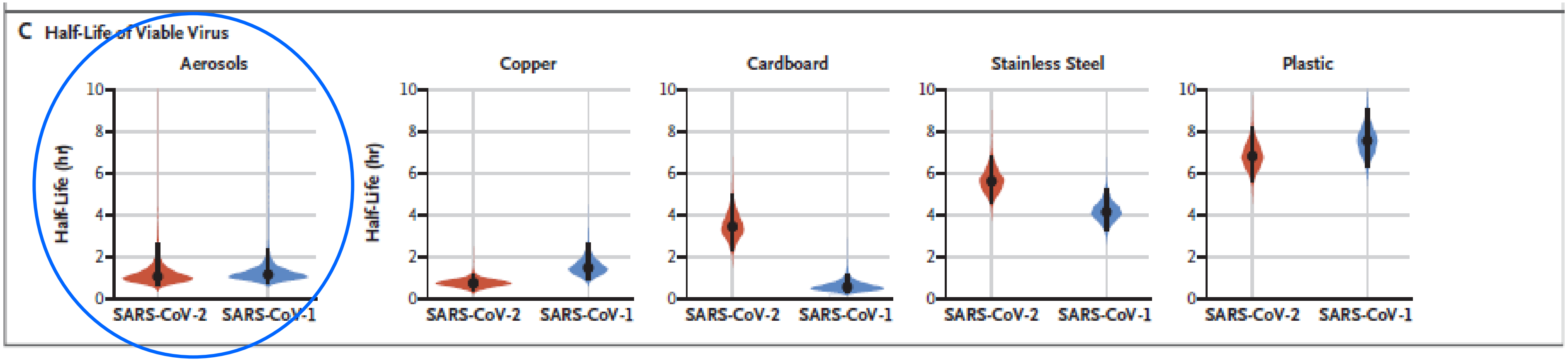
Image courtesy of the U.S. EPA

- Virus ≈ 0.12 µm diameter
- Embedded in particles
- Emitted particles (< 0.3 - 200 µm)
- Particle diameter > virus
- Particle volume >> virus
- V_{part}/V_{virus}
  - 1 µm 600 x
  - 2.5 µm 9,000 x
  - 10 µm 580,000 x

Exposure Pathways & Fate

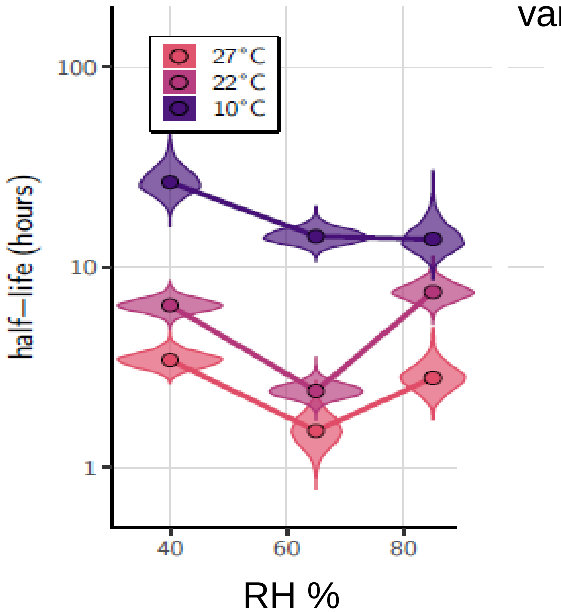


Inactivation of SARS-CoV-2 in Aerosol Particles



van Doremalen, et al., NEJM, March 17, 2020

> Fears, A.C., et al.



Morris, D.H., et al., bioRxiv, posted October 16, 2020. https://doi.org/10.1101/2020.10.16.341883

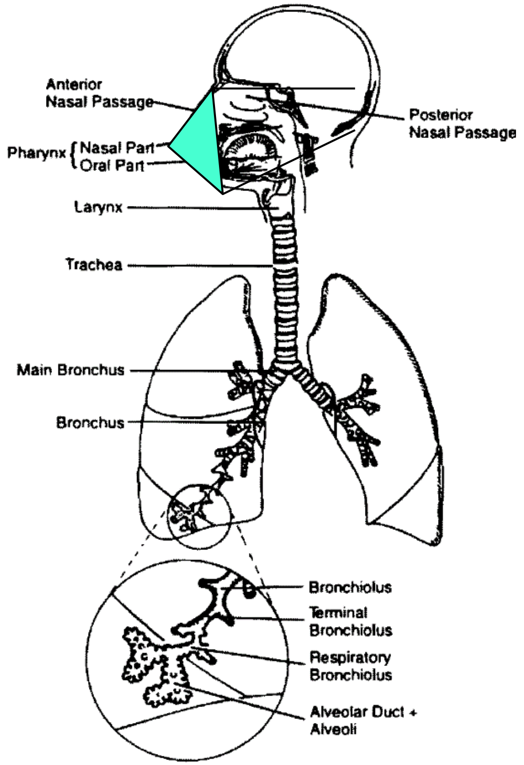
- Inactivation rate in aerosol particles
  - < ventilation + filtration + deposition
- Assume no inactivation (safety factor)

- Lower RH = shift to smaller particles
- Less deposition to indoor surfaces
- Deeper into respiratory system

Inhaled Deposited Dose

$$\text{Dose}_{inhal,i} = C_i \text{ (\#/L)} \times B \text{ (L/min)} \times t \text{ (min)} \times f_{dep,i}$$

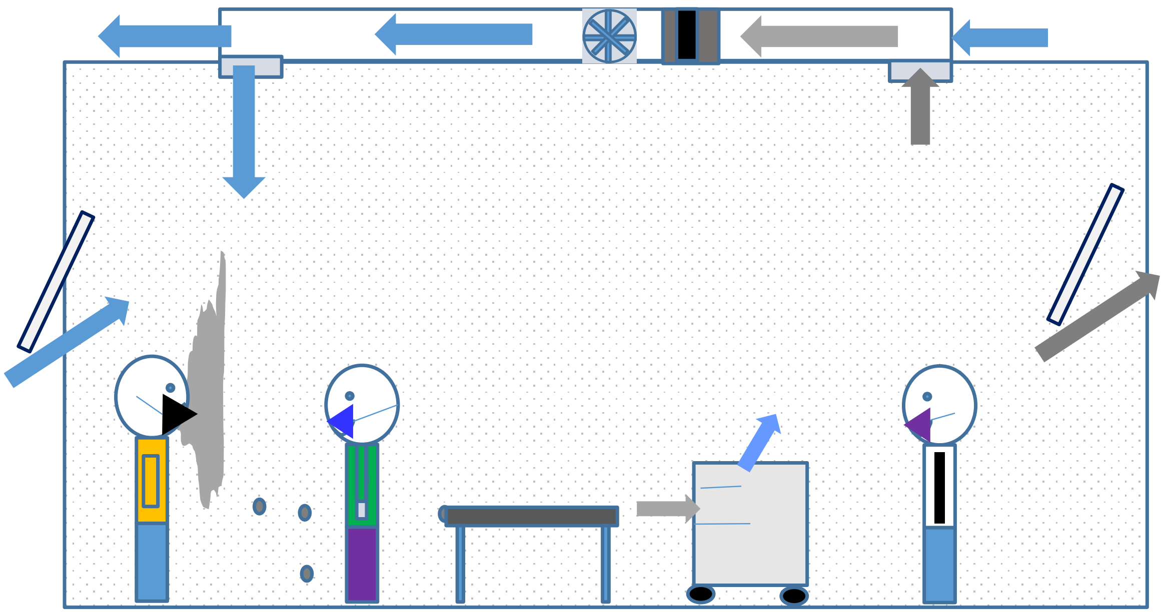
- **C_i = concentration of particles of size i**
  - emissions; mask; ventilation; control; deposition
  - time infector is in space
- **B = Respiratory minute volume**
  - activity (can vary significantly)
- **t = Time in space with an infector**
- **$f_{dep,i}$ = Deposition of particles** of size i in resp
  - particle size; breathing mode; activity; (location)



Convert # deposited to volume

Layered Risk (Dose) Reduction Strategy (LRRS)

- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate



- LRRS can lead to dose reduction > 95%

Reduce Source

"If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure." - **Max von Pettenkofer** (1858)

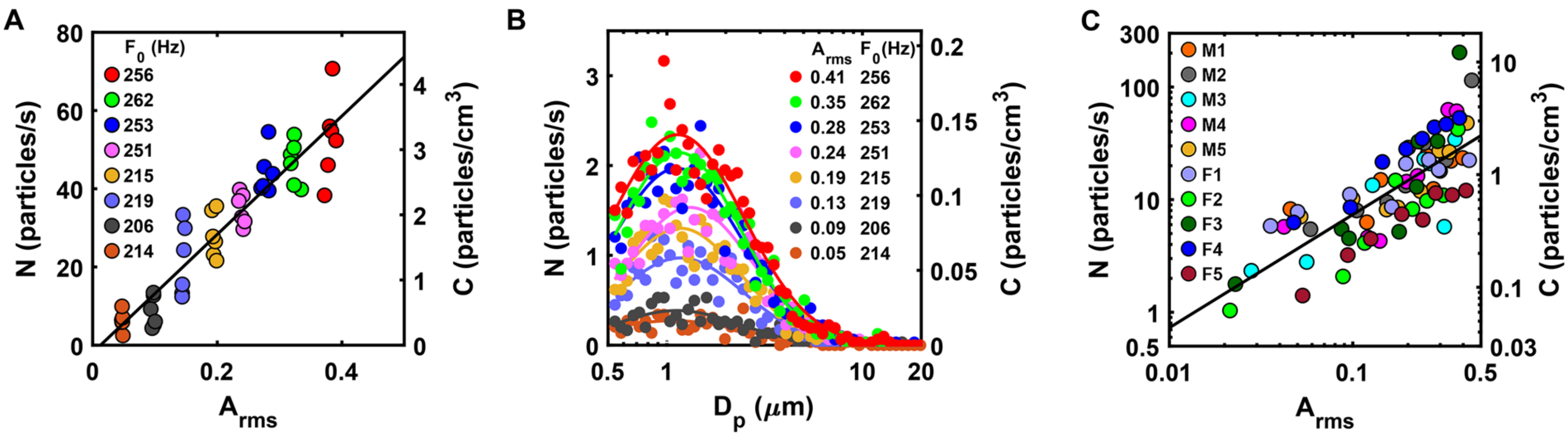
$$\text{Dose}_{inhal,i} = \mathbf{C_i}\ (\#/L) \times \mathbf{B}\ (L/min) \times \mathbf{t}\ (min) \times \boldsymbol{f}_{dep,i}$$

Reduce source
Require masks indoors
Distance from source
Ventilate
Filter
Disinfect (air & surfaces)
Make Use of Time
Educate

- Test & isolate
- Require masks (for all)
- De-densify (less occupants; innovate)
- Eliminate certain activities (singing, aerobics)
- Reduce speaking to extent possible

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

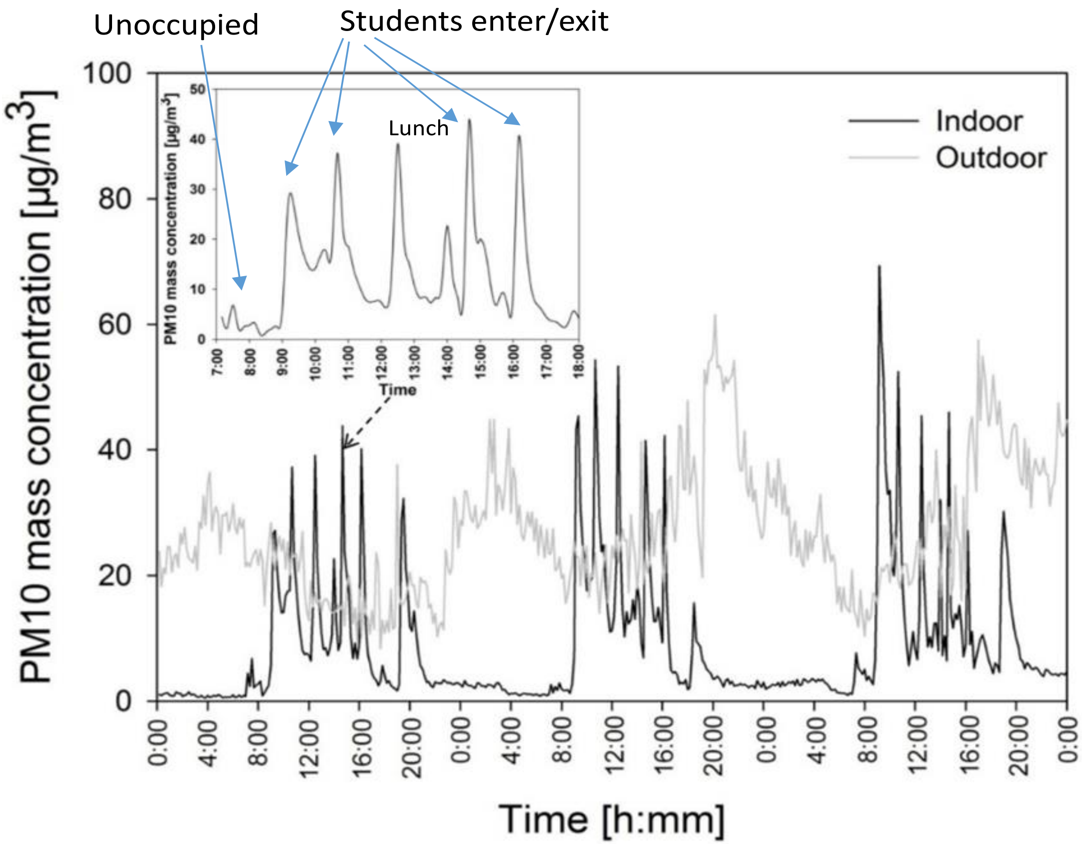
Reduce Source: Speaking



Asadi, S. *et al*. *Scientific Reports*, *9:2348 (2019)* doi.org/10.1038/s41598-019-38808-z

- Breathing ≈ order of magnitude lower than average speaking

Possible Source: Resuspension of Particles



Ren, J. *et al*. *Building & Environment* (accepted)

Re-suspension as source: VCT < Carpet

Require Masks

$$\text{Dose}_{inhal,i} = C_i\ (\#/L) \times B\ (L/min) \times t\ (min) \times f_{dep,i}$$

- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate

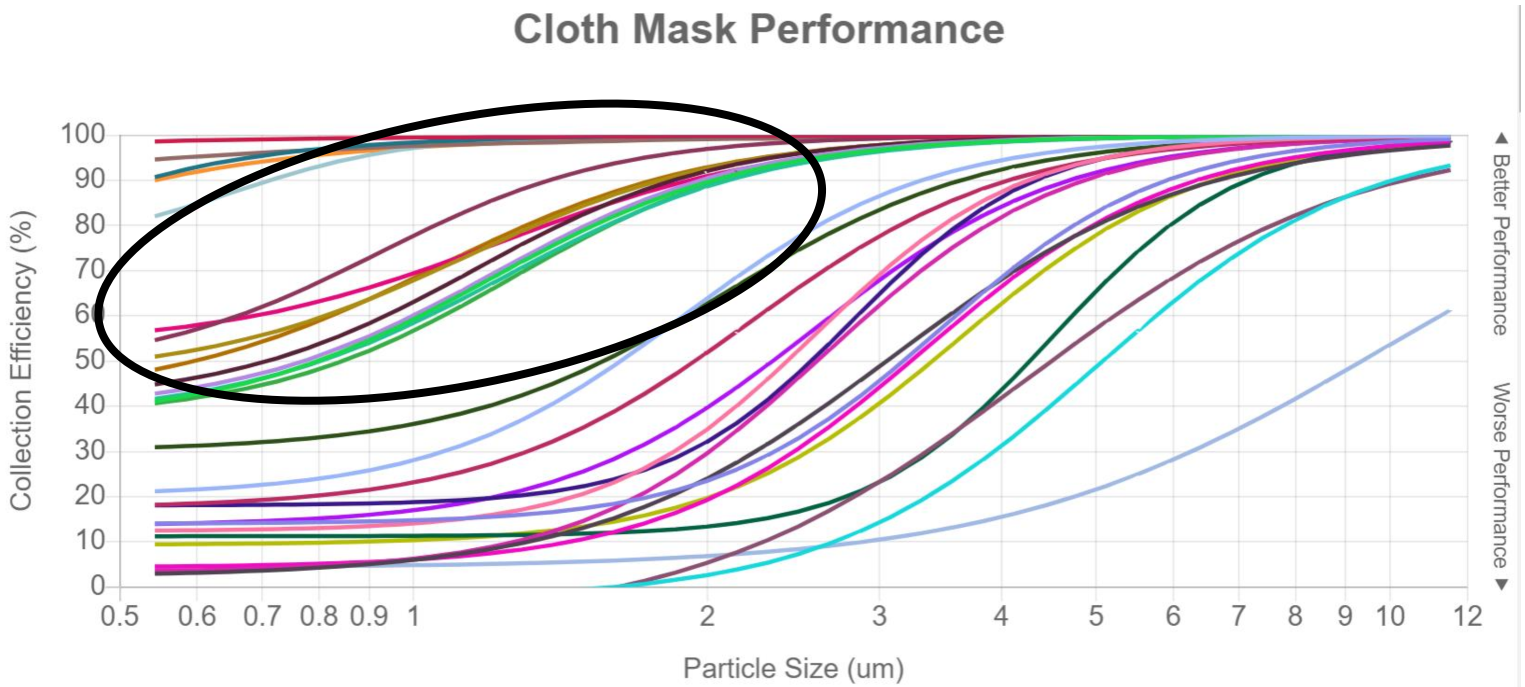
- Universal mask wearing to capture infector
- Dual benefits
  - 30% (I) & 30% (R) = 51% dose reduction
  - 60% x 60% = 84% risk reduction

Problem = all masks off, e.g., lunch

- Outdoors if possible
- Quiet lunch (only teacher speaks)
- Rotating pods (teams) for mask off
- Mask down, eat, Mask up, next team up!

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Cloth Mask Performance



- Performance = strong function of material(s) & fit
- Particle size dependent
- Nice resource
  - Select materials (includes data on breathability)

http://jv.colostate.edu/masktesting/

Drs. John Volcken & Christian L'Orange

Distance from Source (everyone)

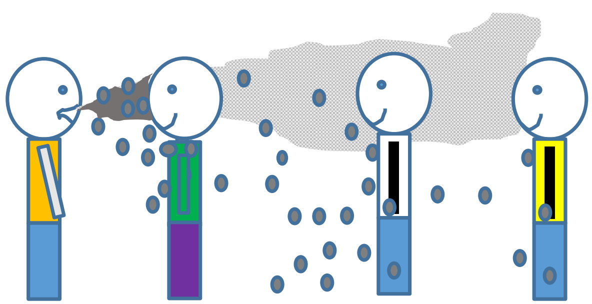
$$\text{Dose}_{inhal,i} = C_i \downarrow (\#/L) \times B\ (L/min) \times t\ (min) \times f_{dep,i}$$

- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate

Horizontal distance traveled to settle 1.5 m
At free-stream air speed of 5 cm/s

d_p (μm)	t (1.5 m)	x (m)
0.5	56 hr	10000
1	14 hr	2500
5	33 min	100
10	8 min	25
20	2 min	6
50	20 sec	1

50 -100 μm particles can travel > 6 ft (jet)



Distancing?

- With masks
- Without masks
- Age / grades

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Ventilate

$$Dose_{inhal,i} = C_i\ (\#/L) \times B\ (L/min) \times t\ (min) \times f_{dep,i}$$

- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate

- Best = outdoors
- Mechanical (controlled)
- Natural (design openings)
- Infiltration

https://www.nytimes.com/2020/07/17/nyregion/coronavirus-nyc-schools-reopening-outdoors.html

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Ventilate

ASHRAE 62.1- 2019 ***Ventilation for Acceptable Indoor Air Quality*** *(Pre-COVID)*

5 L/s-person; 0.6 L/s-m^2

If 24 students + 1 teacher in 60 m^2 classroom = 5 x 25 + 0.6 x 60 = 161 L/s

161 L/s = 576 m^3/hr; AER = 576 m^3/hr / (60 m^2 x 2.8 m) = **3.4/hr**

ASHRAE Position Document on Infectious Aerosols
Approved by ASHRAE Board of Directors - April 14, 2020

The following modifications to building HVAC system operation should be considered:

- Increase outdoor air ventilation (disable demand-controlled ventilation and open outdoor air dampers to 100% as indoor and outdoor conditions permit).
- Additional recommendations on filtration, portable air cleaners, UVGI, T & RH, etc.

https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf

Ventilate

- Many schools under-ventilated or inappropriately ventilated

Absenteeism (Simons et al., *Am. J. Public Health*, 2010)

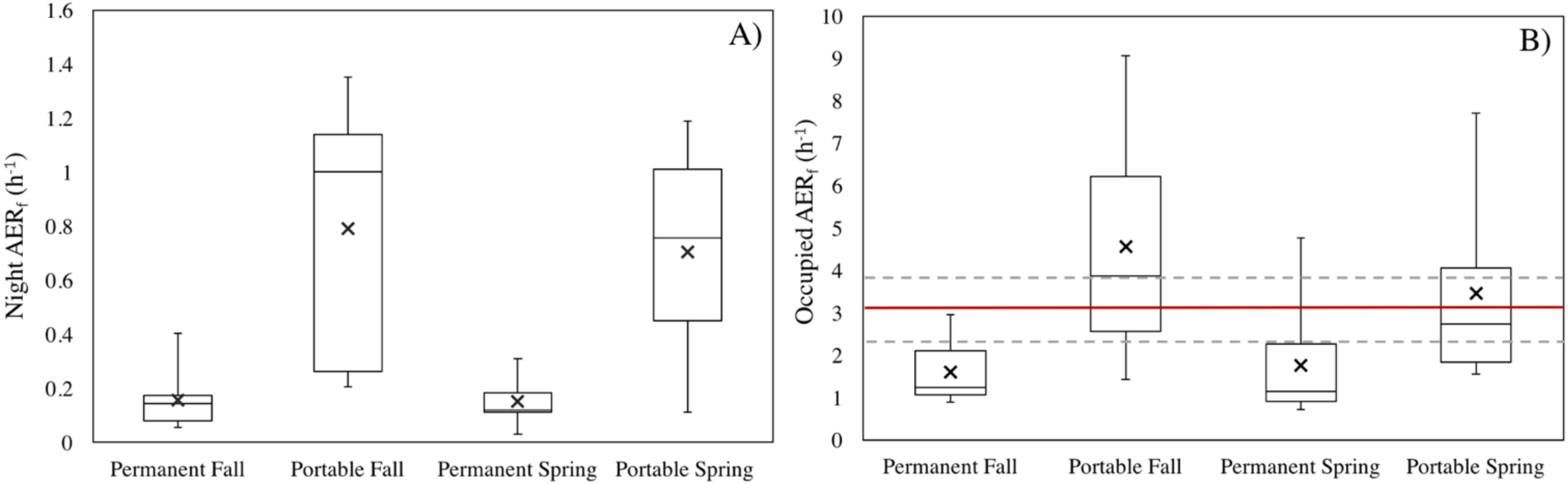
- Association: under-ventilation & absenteeism
- Strongest association: young students

Performance (Haverinen-Shaughnessy et al., *Indoor Air*, 2011)

- 100 southwestern schools/classrooms
- 87% w/ less ventilation than ASHRAE 62.1
- Each 1 L/s-student increase in ventilation:
    - 2.9% increase math; 2.7% read

Ventilation matters (COVID-19 or not)

Air Exchange Rates: Central Texas High Schools



Lesnick, L.A. et al., *ASHRAE Transactions* (2017)

- Permanent classrooms severely under-ventilated (Median < ½ ASHRAE 62.1)
- Generally higher ventilation in portable classrooms (but high variability)
- Portable classrooms – directly connected to outdoors
- Portable classrooms – more natural ventilation opportunities + infiltration

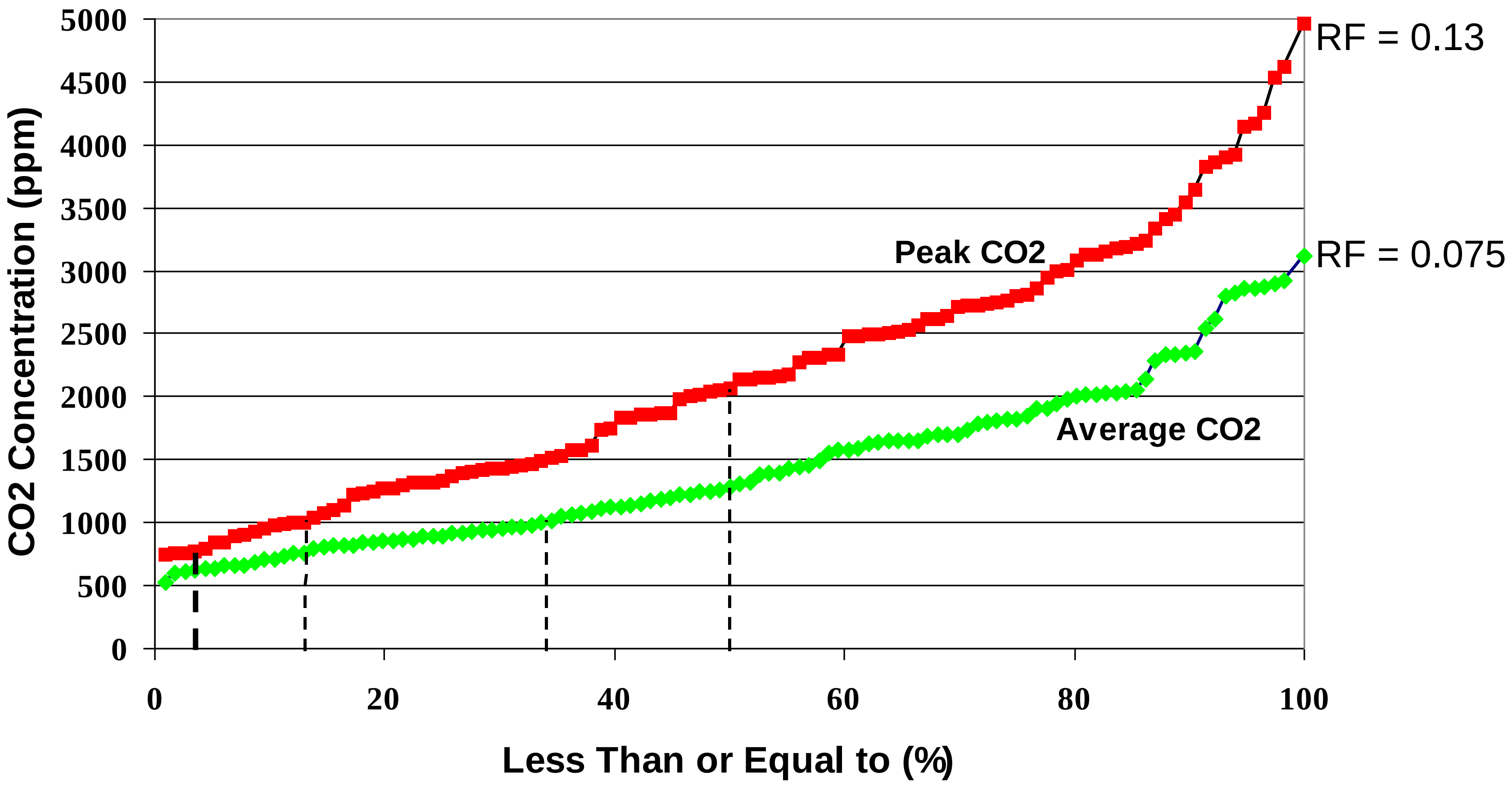
Carbon Dioxide as Surrogate

- **Elevated CO_2 = inadequate ventilation**
- Accumulation of pollutants, body odors
- Productivity decrements
- Increased absences (e.g., Shendell et al., *Indoor Air*, 2004)
  - Δ 1,000 ppm = 0.5-0.9% decrease in annual average daily attendance
- Elevated rebreathed fraction ➡ $RF = (CO_{2,in} – CO_{2,out}) / CO_{2,breath}$
- Greater probability of respiratory infections

- Lower CO_2 (or RF): lower occupancy; increased ventilation

CO_2: Cumulative Distributions

115 K-8 classrooms; all day sampling; two school districts

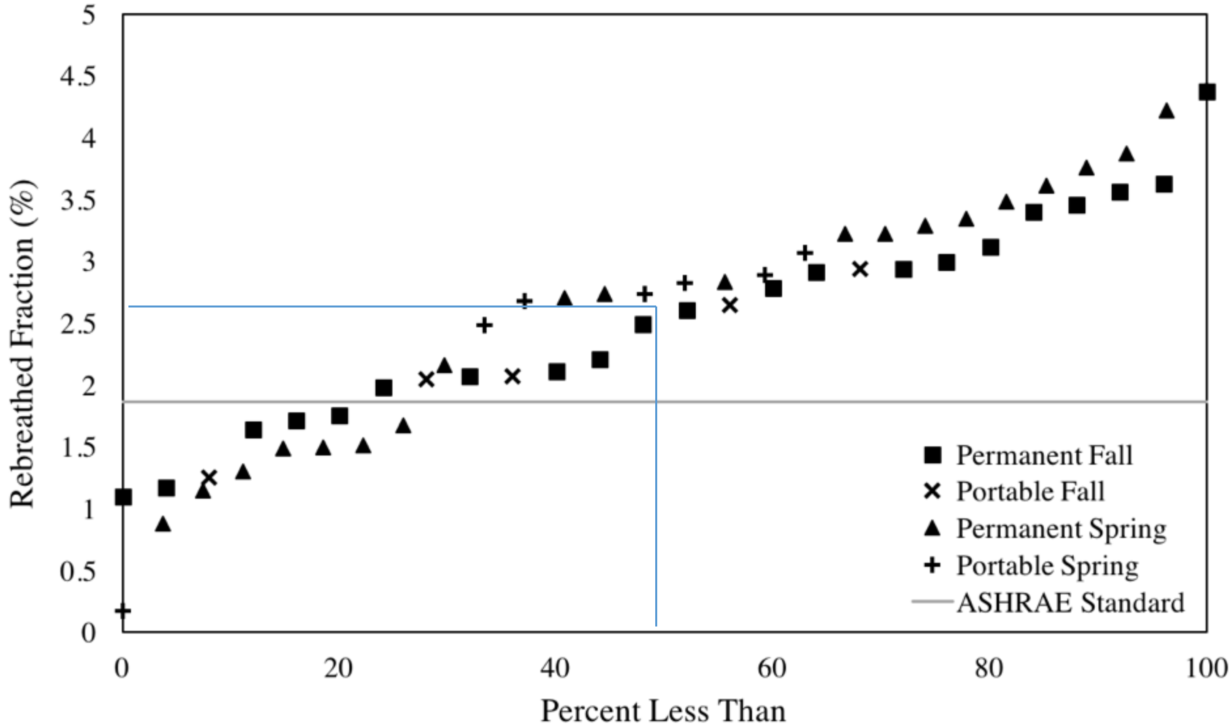


Median average RF = 0.025 (2.5%); Median peak RF = 0.044 (4.4%)

< 15% with average RF < 0.01; < 5% with peak RF < 0.01

Rebreathed Fraction

Central Texas High Schools (Year 1)

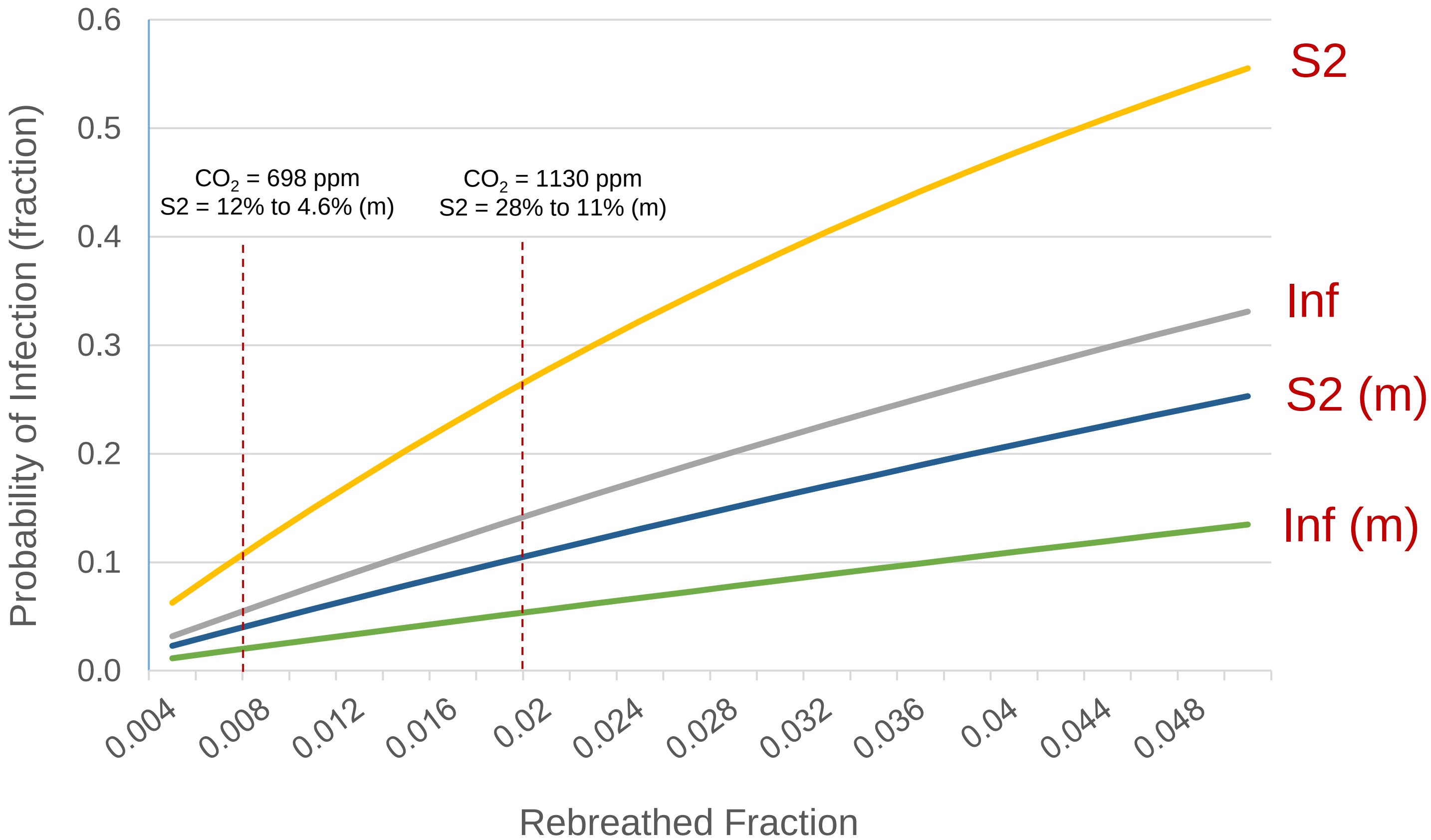


Lesnick, L.A. et al., *ASHRAE Transactions* (2017)

Median RF = 0.025 to 0.027 (2.5 to 2.7%)

Similar to previous K-8 results

Estimates: Probability of Infection



Rudnick-Milton model w/ 1 infector (m = adjusted for masks = 64% dual effectiveness)

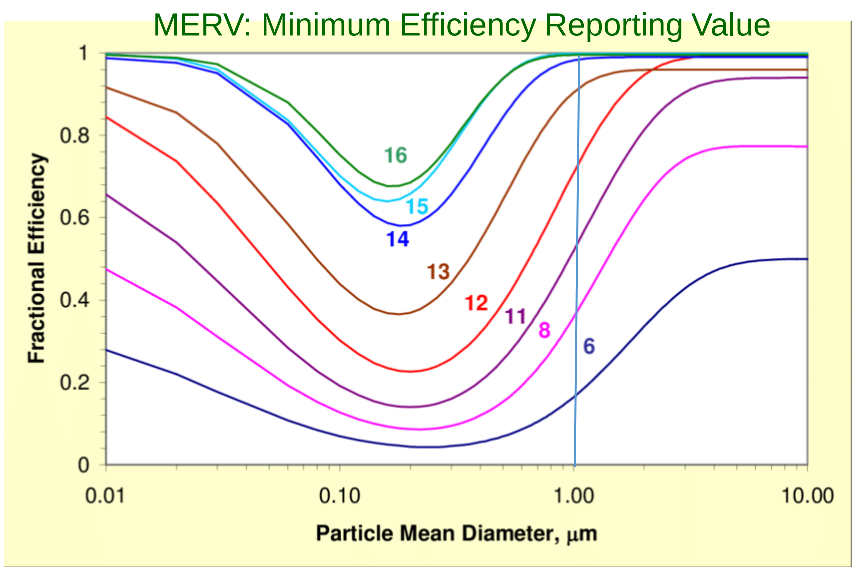
Quanta generation rate: 67/hr for influenza; 135/hr for SARS-CoV-2

Filter

$$\text{Dose}_{inhal,i} = C_i\ (\#/L) \times B\ (L/min) \times t\ (min) \times f_{dep,i}$$

- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate

"Improve central air and other HVAC filtration to MERV-13 or the highest level achievable."
ASHRAE Position Document on Infectious Aerosols (2020)

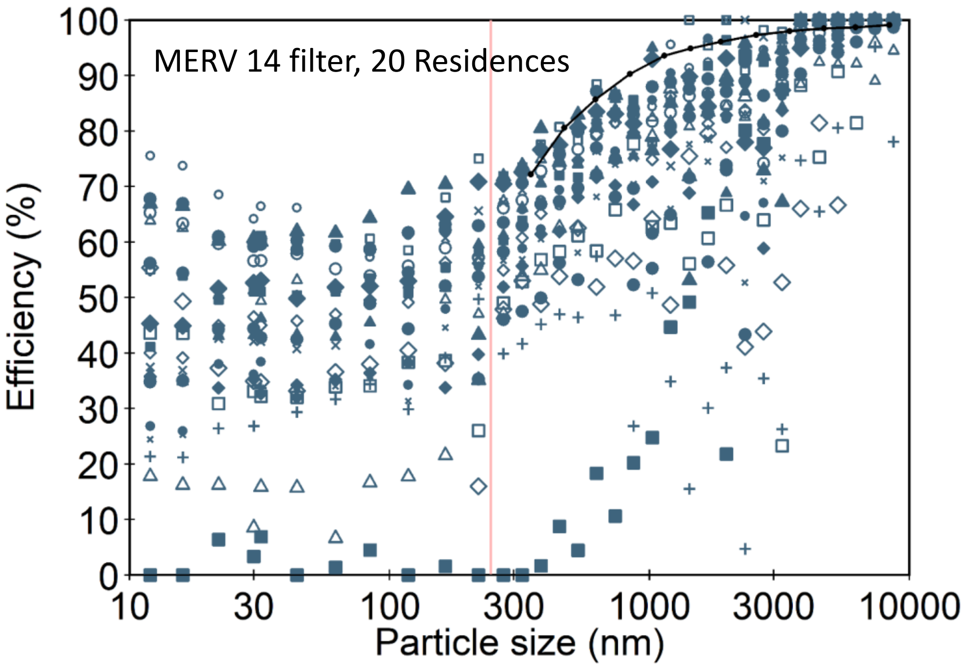


Kowalski & Bahnfleth (2002)
https://www.researchgate.net/figure/Composite-of-all-MERV-filter-models-based-on-initial-conditions_fig3_237558312

- Theoretical
- Can be worse
- System problems?

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Theory & Lab ≠ Practice



Li and Siegel, *Indoor Air* (2020)

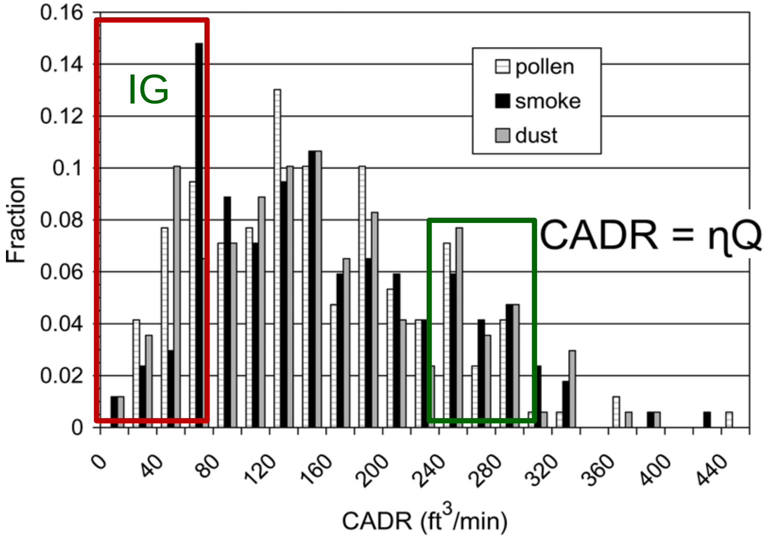
Courtesy of Dr. Jeffrey Siegel, U Toronto

Courtesy of Dr. Atila Novoselac, UT Austin
(not a MERV 13 or 14)

Important to inspect for by-pass

Portable Air Cleaner (PAC)

- Proven: HEPA-based portable air cleaner
- **H**igh **E**fficiency **P**articulate **A**ir
- Key: Clean Air Delivery Rate (CADR)
- CADR = η x Q
  - η = single pass removal fraction (-)
  - Q = volumetric flowrate (ft^3/min)
- Example: η = 0.5; Q = 500 ft^3/min
- CADR = 250 ft^3/min



Shaughnessy, R.J., and Sextro, R.G., *J of Occupational and Environmental Hygiene*, 3: 169–181(2006)

EPA.gov

Portable Air Cleaner (PAC)

- Equivalent air changes per hour = EqACH = **CADR/V**
- Example: V = 600 ft^2 x 8 ft = 4,800 ft^3
- CADR = 300 ft^3/min
- **EqACH** = 300 ft^3/min/4,800 ft^3 = 0.0625/min (or x 60 = **3.8/hr**)

$$C_i = \frac{E_i/\forall}{\lambda + CADR/\forall + k_{d,i}}$$

At steady-state

If λ = 2/hr

2 + 3.8 = 5.8/hr

66% reduction

Add to 64% masks = 88%!

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Filter Microbiomes

- Filters have microbiomes (e.g., fungi growth on filter cake)
- Respiratory viruses have been found on filters
- Take precautions when changing filters (central or PAC)
- Do not agitate
- Mask / goggles
- Gloves / hand hygiene
- Bag it

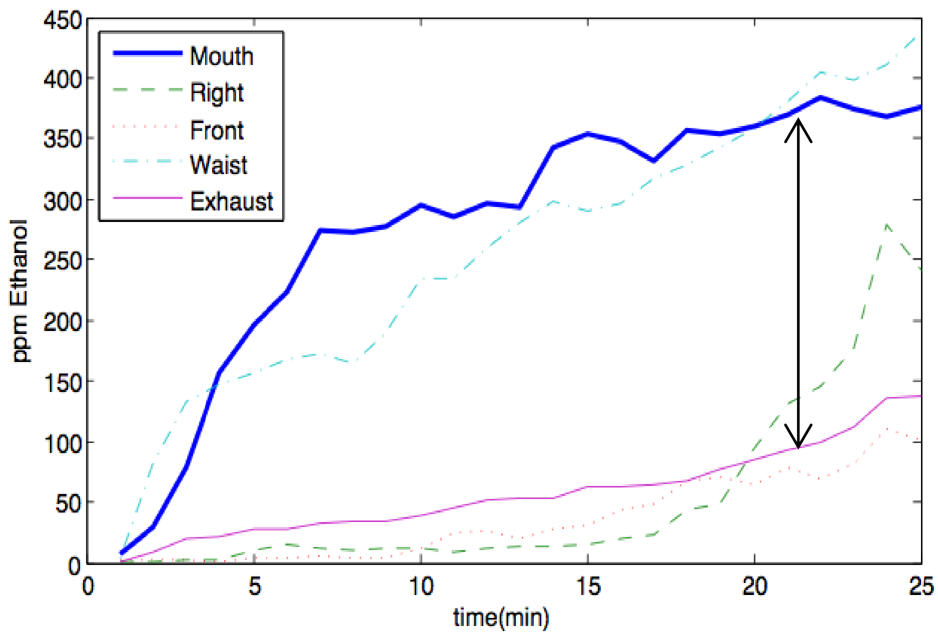
Disinfect (Air & Surfaces)

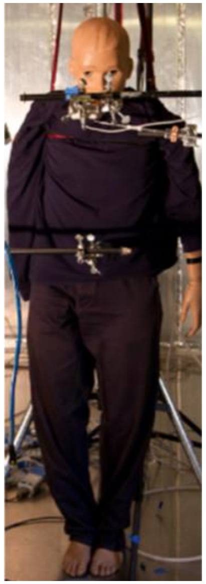
Air: UVGI (can be very effective if done right)

Surfaces (wide range): residual, reaction by-products, worker exposure

Work-related asthma assoc w/ cleaning products

Rosenman et al., *J. Occup. & Environ. Medicine* (2003)





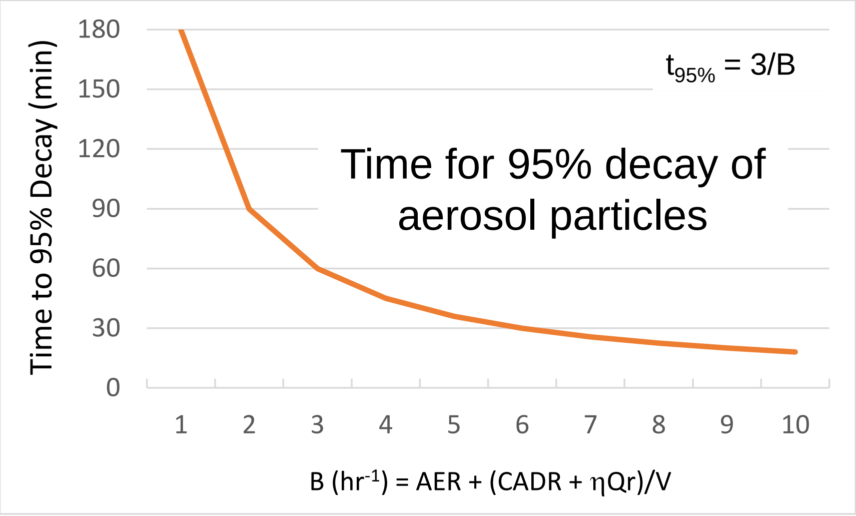
Dissertation: Dr. Clive (Matt) Ernest, UT Austin

Make Use of Time

$$Dose_{inhal,i} = C_i \,(\#/L) \times B\,(L/min) \times t\,(min) \times f_{dep,i}$$

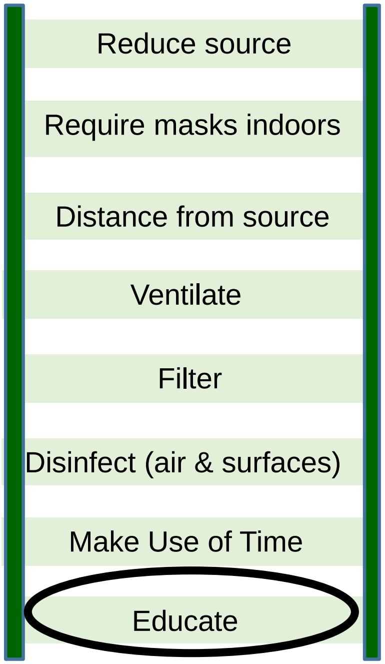
- Reduce source
- Require masks indoors
- Distance from source
- Ventilate
- Filter
- Disinfect (air & surfaces)
- Make Use of Time
- Educate

- Reduce continuous time indoors
- Reduce time w/ mask down at lunch
- Outdoor calm time after physical activity
- Classroom particle decay periods



Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Educate



- Entire school community
    - Admin, teachers, staff, students, parents
- Target modes of communication
    - People absorb differently
- English & Spanish
- Make use of existing tools – explore & educate
    - Slides added to end of presentation

SAFE AIR SPACES COVID-19 Risk Estimator

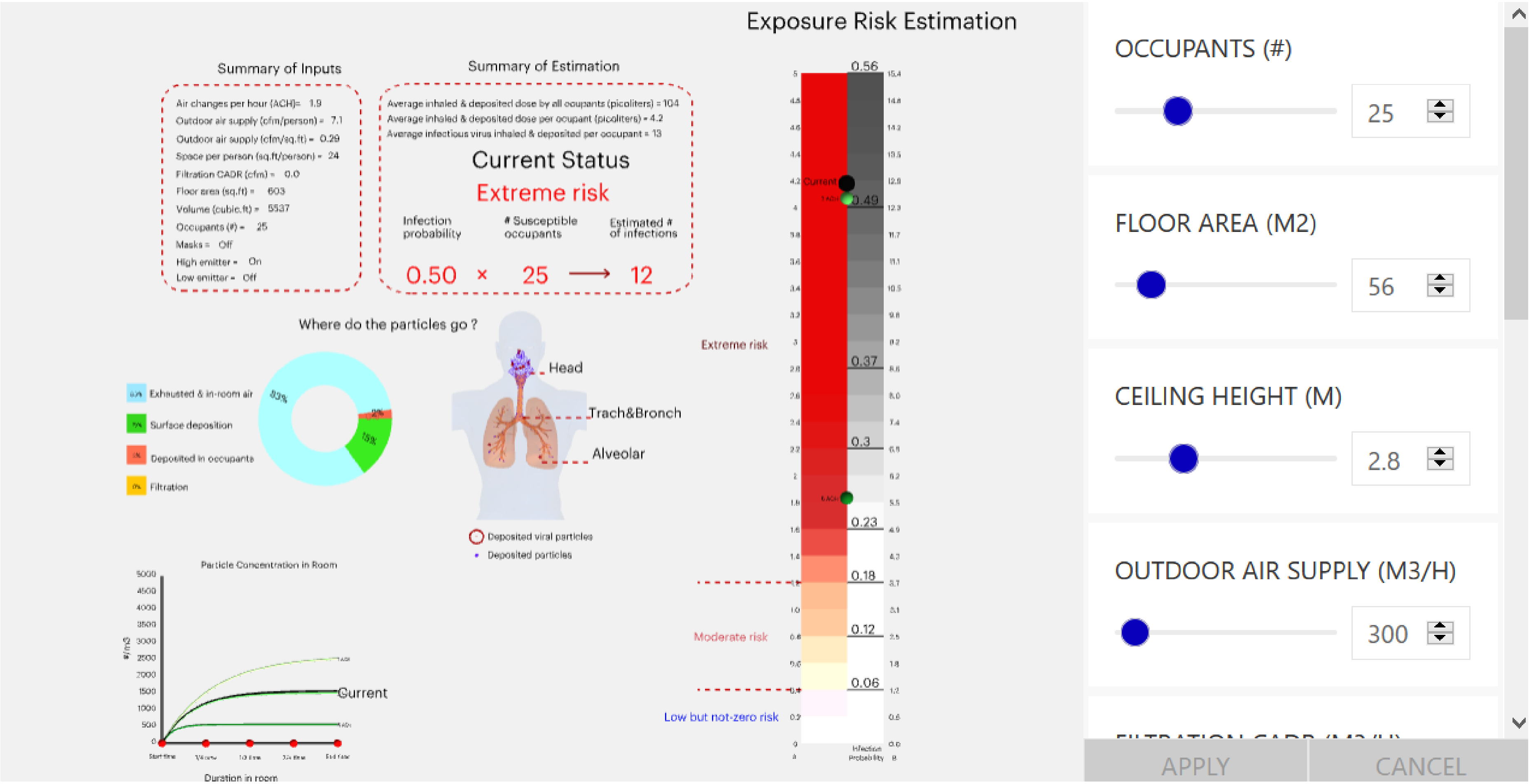
Joint effort between
U of Oregon & Portland State

www.safeairspaces.com

- Educational tool (layered risk reduction)
- Respiratory deposition & risk
- **Factors**: emissions, surface deposition
  ventilation, filtration, masks
  time in space, area & height
- Single zone (multiple coming)
- Far-field (working on near-field)
- Adaptable

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

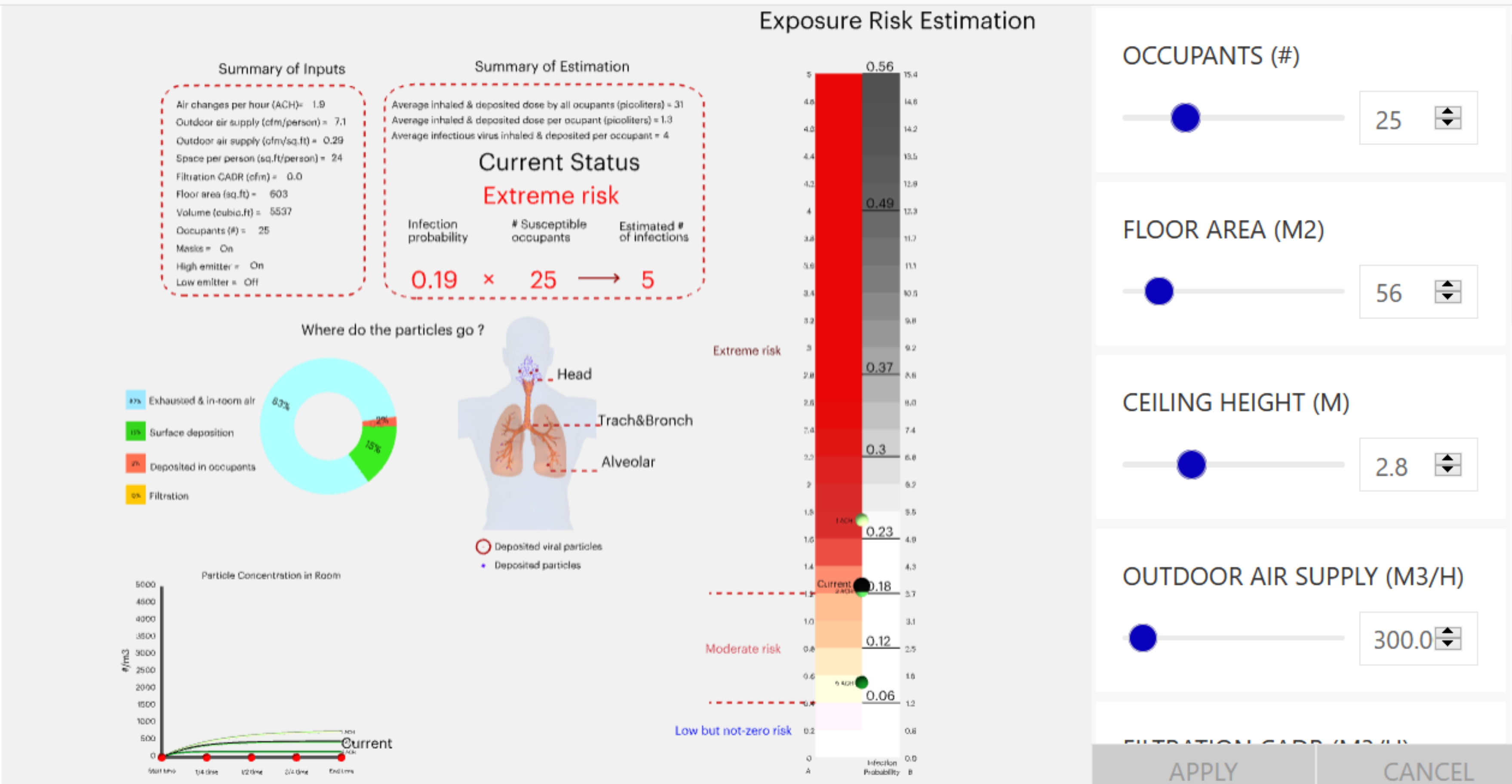
Scenario 1 – No Masks & Under-Ventilated



No masks; < ASHRAE 62.1; No filtration; High emitter; 2.5 hr exposure

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

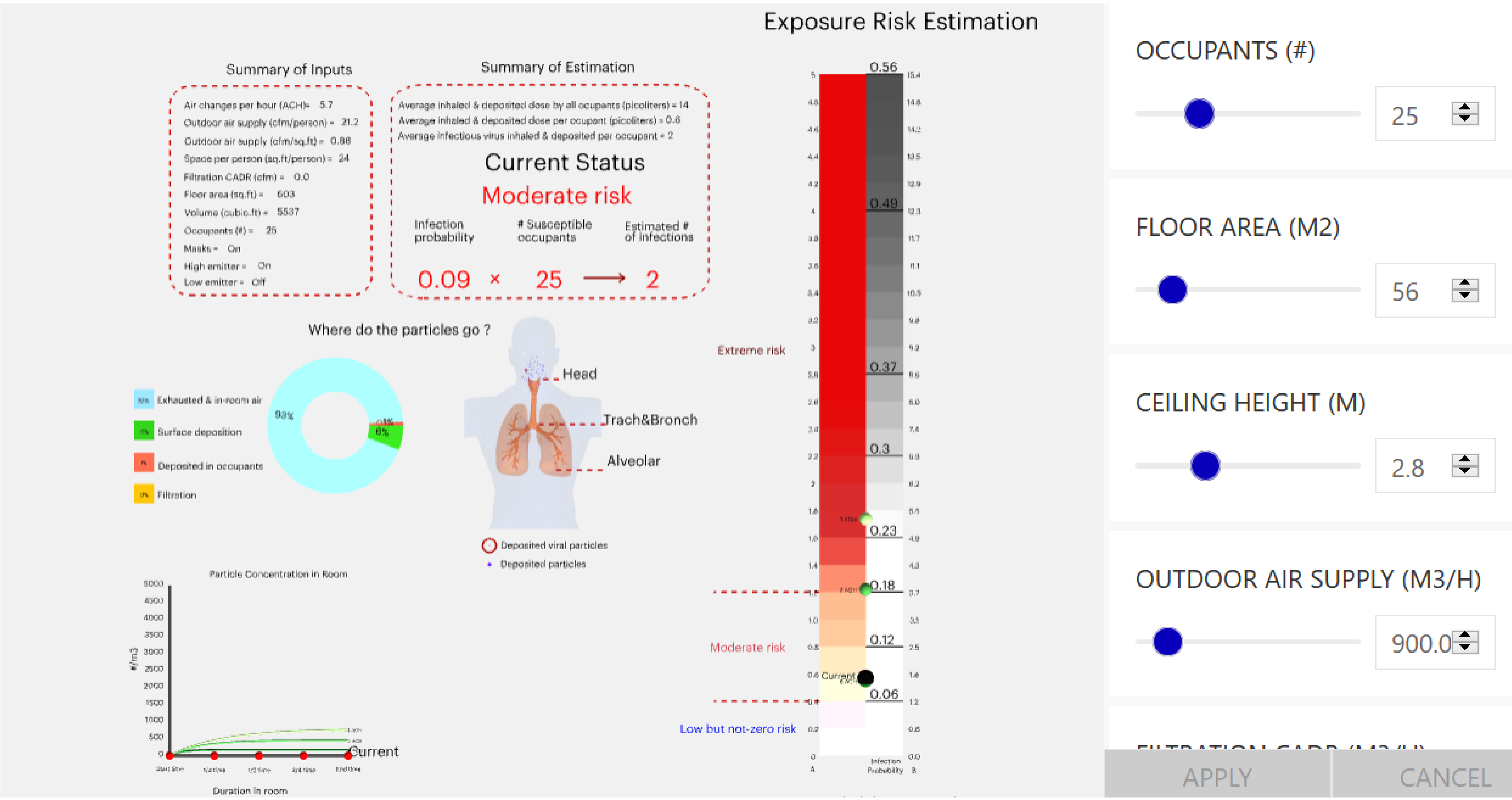
Scenario 2 – Masks & Under-Ventilated



Masks for all; < ASHRAE 62.1; No filtration; High emitter; 2.5 hr exposure

Risk Reduction = 62%

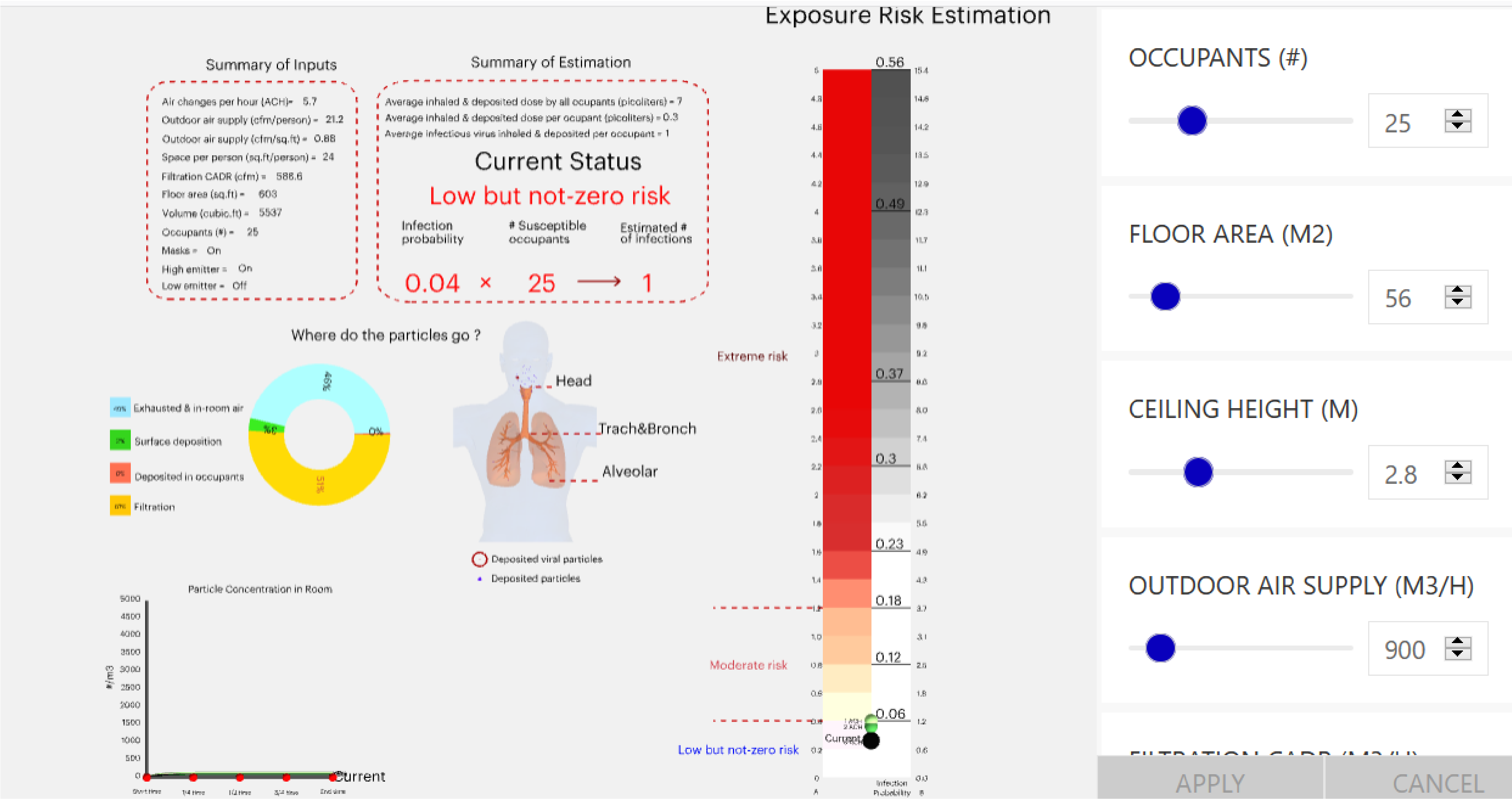
Scenario 3 – Masks + Increased Ventilation



Masks for all; > ASHRAE 62.1; No filtration; High emitter; 2.5 hr exposure

Risk Reduction = 82%

Scenario 4 – Masks + Increased Ventilation + Filtration + Outdoor Mask Break (20 min)

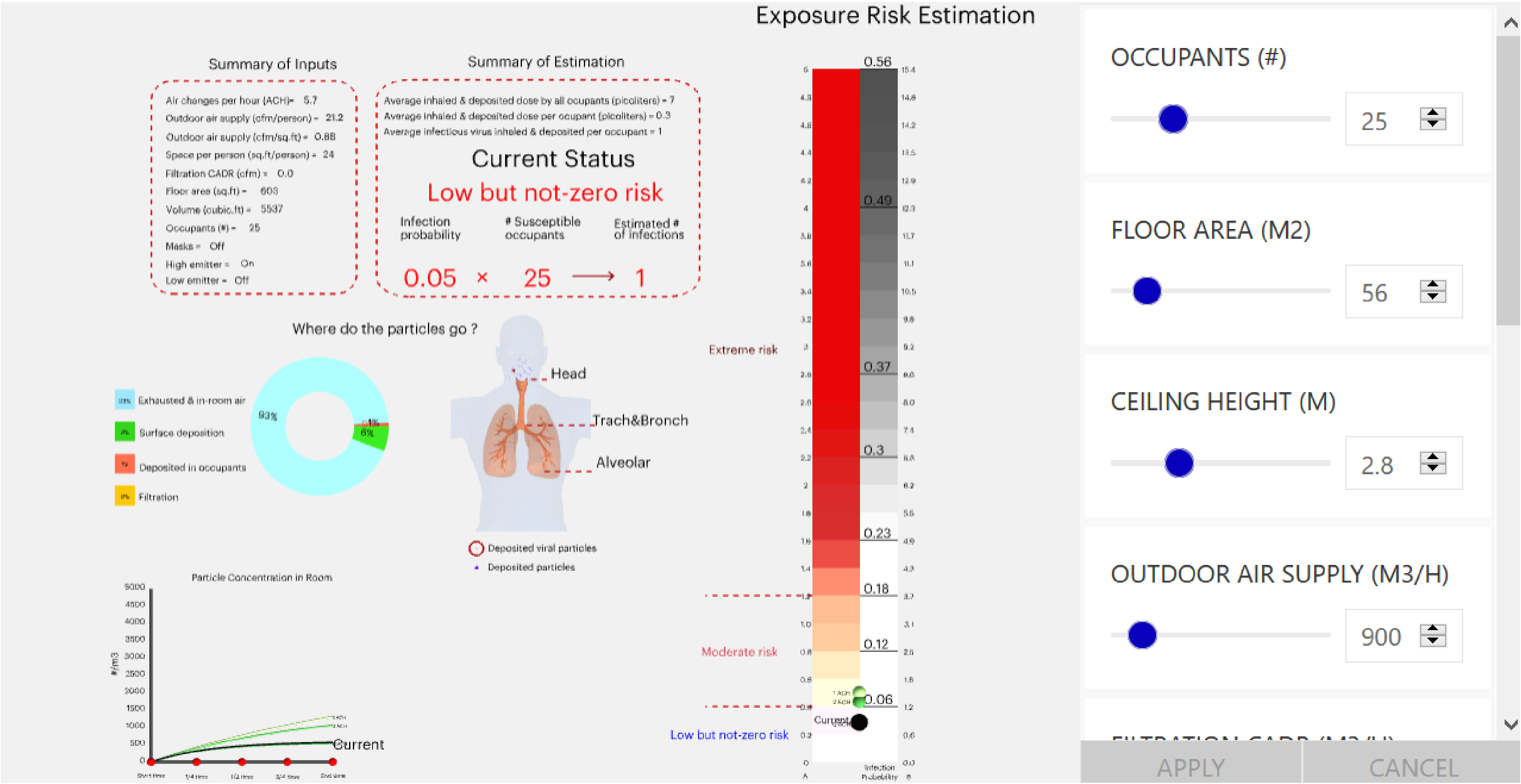


Masks for all; > ASHRAE 62.1; Filtration; High emitter; 2.5 hr exposure

Risk Reduction = 92%

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Scenario 5 – 30 Minute Lunch w/o Masks

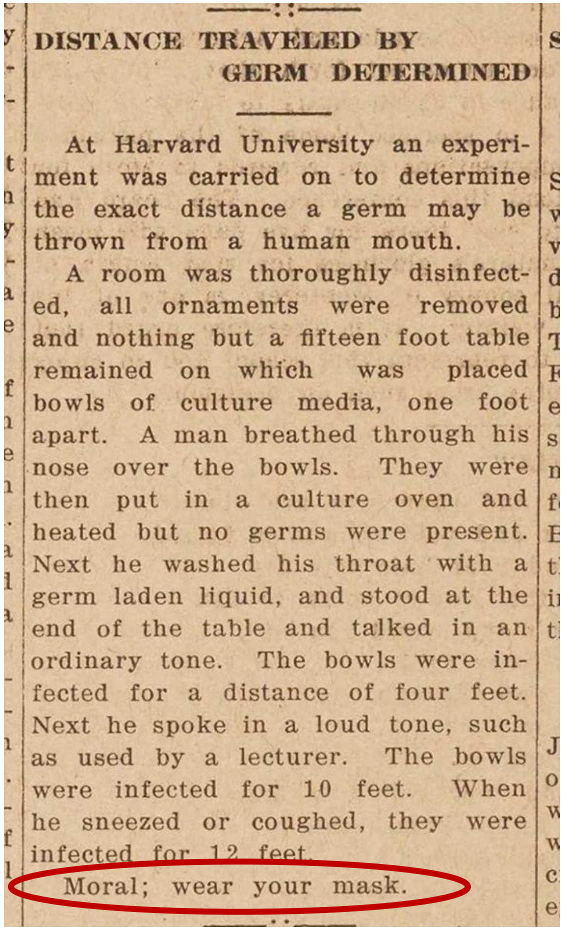


Lunch in classroom: No Masks; > ASHRAE 62.1; No Filtration; High emitter; 0.5 hr

Relatively low risk in far field; near field (close contact) likely larger risk for scenario

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Closure



DISTANCE TRAVELED BY GERM DETERMINED

At Harvard University an experiment was carried on to determine the exact distance a germ may be thrown from a human mouth.

A room was thoroughly disinfected, all ornaments were removed and nothing but a fifteen foot table remained on which was placed bowls of culture media, one foot apart. A man breathed through his nose over the bowls. They were then put in a culture oven and heated but no germs were present. Next he washed his throat with a germ laden liquid, and stood at the end of the table and talked in an ordinary tone. The bowls were infected for a distance of four feet. Next he spoke in a loud tone, such as used by a lecturer. The bowls were infected for 10 feet. When he sneezed or coughed, they were infected for 12 feet.

Moral; wear your mask.

- Schools critical for EVERYBODY
- Multiple benefits for children
- Need schools to be safe as possible
- Layered dose (risk) reduction works
- Use tools to educate and plan*

* Understand that estimation tools are valuable to show trends, relative risks, & not necessarily exact numbers

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Acknowledgements

- International Society of Indoor Air Quality And Climate (ISIAQ)
- American Industrial Hygiene Association (AIHA)
- United States Environmental Protection Agency (USEPA)

Modeling partners:
Kevin Van Den Wymelenberg & Hooman Parhizkar (both U Oregon)

Additional colleagues who provided information for this presentation:
Jose Jimenez (CU Boulder), Atila Novoselac (UT Austin), Jeffrey Siegel (U Toronto)

Ex-students who did the work to generate data used in this presentation:
Matt Ernest, Sangeetha Kumar, Leigh Lesnick (all UT Austin)

My Executive Assistant for help with logistics: Brandi Cobb (Portland State)

Some Additional Resources & Tools

ASHRAE Epidemic Task Force - Schools

https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-reopening-schools-and-universities-c19-guidance.pdf

EPA Tools for Schools, etc.

Environmental Topics | Laws & Regulations | About EPA | Search EPA.gov

CONTACT US SHARE

Creating Healthy Indoor Air Quality in Schools

Promote a healthy learning environment at your school to reduce absenteeism, improve test scores and enhance student and staff productivity.

EPA Supports Healthy Indoor Environments in Schools During COVID-19 Pandemic

Adopting IAQ Best Practices

- Why It's Important
- Take Action to Improve IAQ in Schools
- Framework for Healthy Indoor Environments

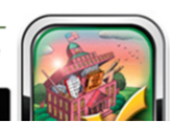
Learning and Training

- On-Demand Training Webinars
  - IAQ Knowledge-to-Action Professional Training Webinar Series

- **Indoor Air Quality Home Page**
- **Frequently Asked Questions**

SUBSCRIBE Subscribe to IAQ and Schools Email Updates

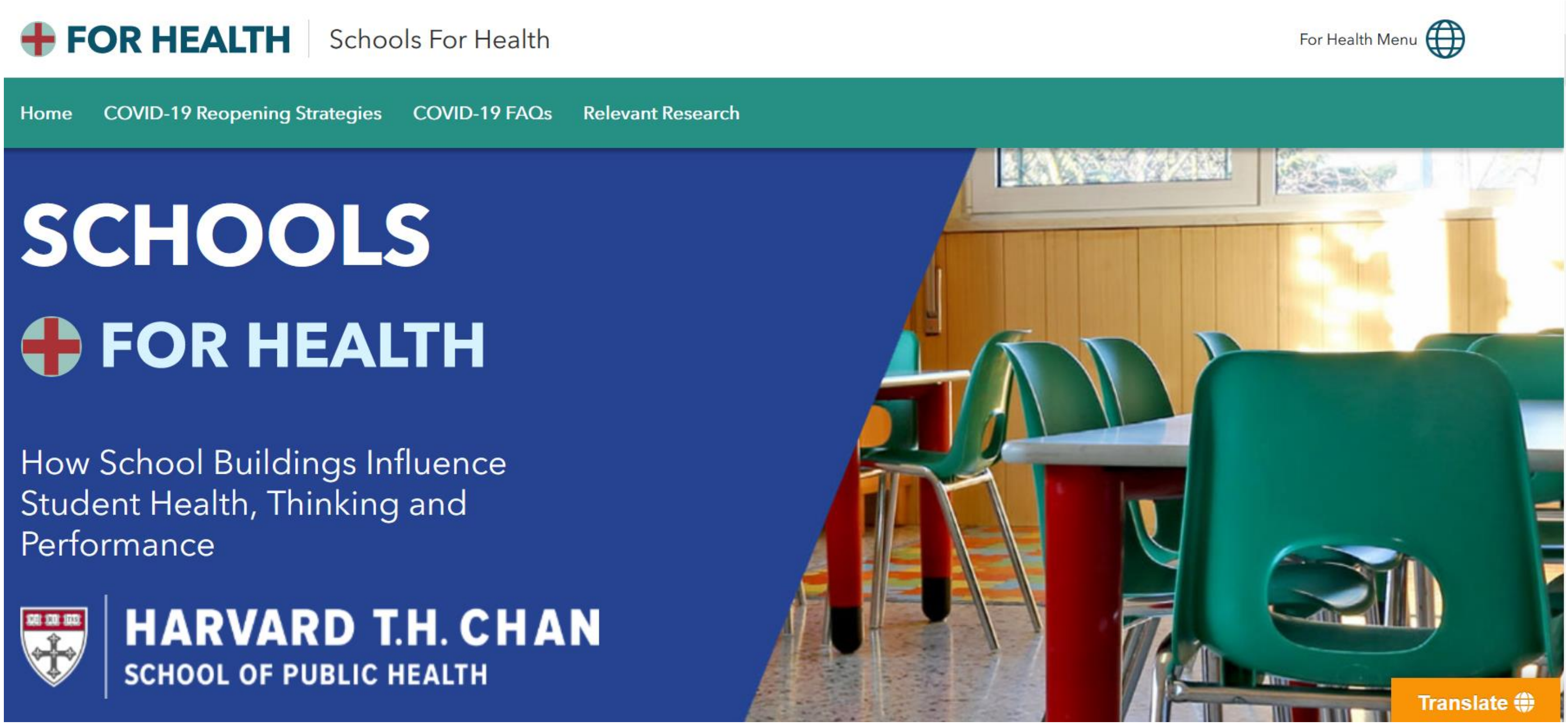
School IAQ
Assessment Mobile App
Assess, then address — EPA has made it easy!
Download on the App Store



https://www.epa.gov/iaq-schools

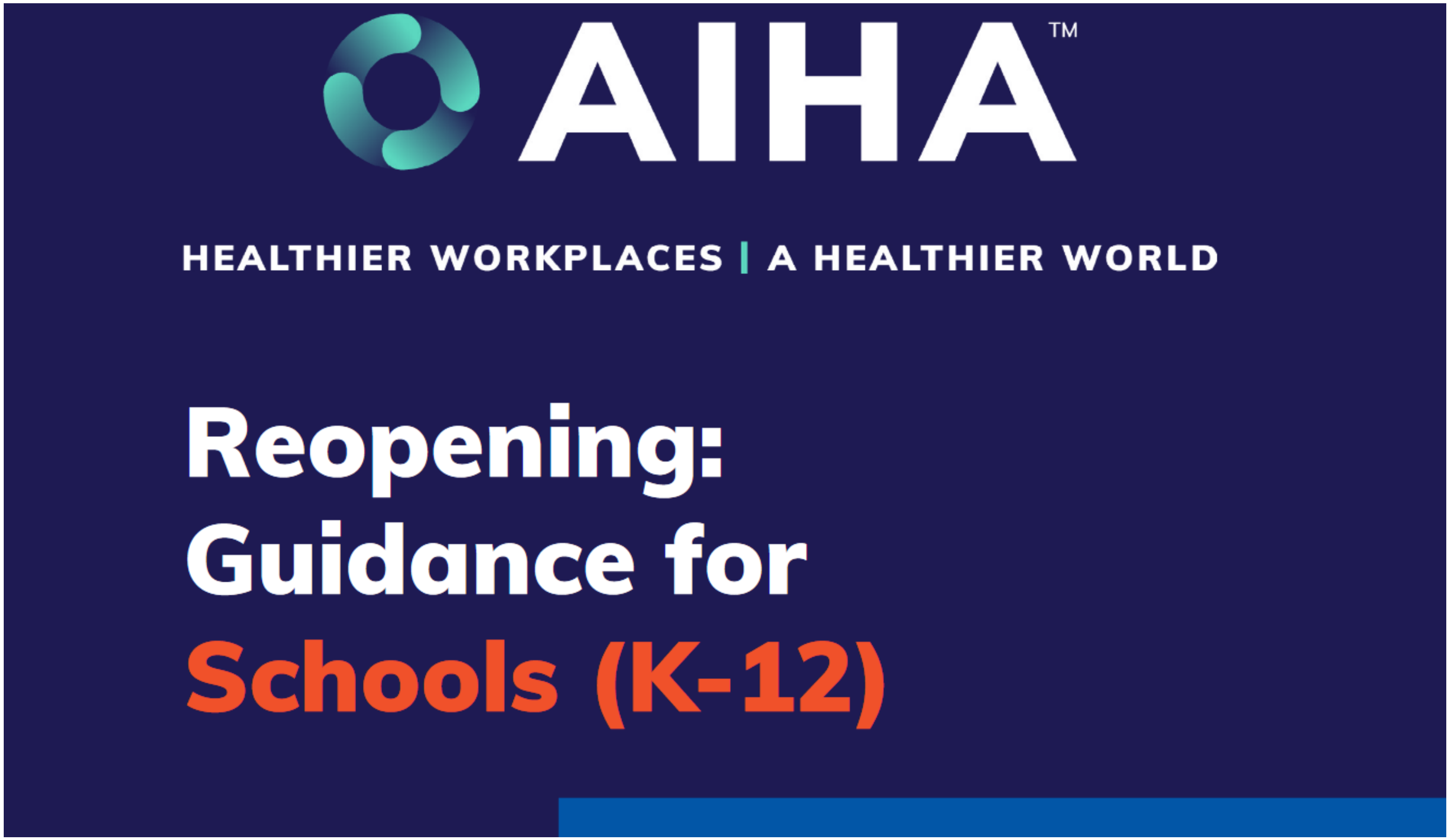
Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Harvard T.H. Chan School of Public Health



https://schools.forhealth.org

AIHA – Reopening Guidance



https://aiha-assets.sfo2.digitaloceanspaces.com/AIHA/resources/Reopening-Guidance-for-Schools-K-12_GuidanceDocument.pdf

FATIMA Model (NIST)

NIST

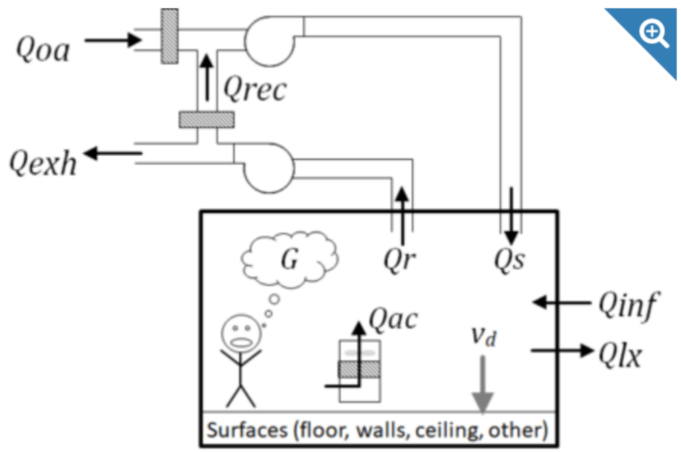
Search NIST

Menu

SOFTWARE

FaTIMA

The web-based tool *Fate and Transport of Indoor Microbiological Aerosols* (FaTIMA) allows for the determination of the indoor fate of microbiological aerosols associated with ventilation, filtration, deposition and inactivation mechanisms. FaTIMA provides a representation of a single, well-mixed zone that is served by a mechanical ventilation system and incorporates particle source and removal mechanisms. The simple mechanical ventilation system model



'/www.nist.gov/sites/default/files/images/2020/05/12/FaTIMA.png

Type of Software
Web Application

Last Updated
2020-09-04

NIST Author
William Stuart Dols

Brian Polidoro

https://www.nist.gov/services-resources/software/fatima

CU Boulder Aerosol Transmission Estimator

University of Colorado Boulder

Aerosol Transmission Estimator

http://tinyurl.com/covid-estimator

A	B	C	D	E	F	G
Estimation of COVID-19 aerosol transmission: master spreadsheet, adapt this one to your case - Default values are for						
This is a general spreadsheet applicable to any situation, under the assumptions of this model - *See notes specific to this case (if applicable) at the very bottom*						
Important inputs as highlighted in orange - change these for your situation						
Other, more specialized inputs are highlighted in yellow - change only for more advanced applications						
Calculations are not highlighted - don't change these unless you are sure you know what you are doing						
Results are in blue -- these are the numbers of interest for most people						
Environmental Parameters						
	Value			**Value in other units**		**Source / Comments**
Length of room	25	ft		7.6	m	Can enter as ft or as m (once entered as m, changing in ft does
Width of room	20	ft	=	6.1	m	Can enter as ft or as m (once entered as m, changing in ft does
	500	sq ft		47	m2	Can overwrite the m2 one. If you want to enter sq ft, enter "=B1
Height	10	ft	=	3.1	m	Can enter as ft or as m (once entered as m, changing in ft does
Volume				142	m3	Volume, calculated. (Can also enter directly, then changing dim
Pressure	0.95	atm				Used only for CO2 calculation
Temperature	20	C				Use web converter if needed for F --> C. Used for CO2 calcula
Relative Humidity	50	%				Not yet used, but may eventually be used for survival rate of vir
Background CO2 Outdoors	415	ppm				See readme
Duration of event	50	min		0.8	h	Value for your situation of interest
Number of repetitions of event	180	times				For e.g. multiple class meetings, multiple commutes in public tr

- Tutorials in English & Spanish: https://www.youtube.com/channel/UChUCsAMXy8f01R3rWqj4z6A
- Many calculators inspired in this one or derived independently, all consistent to my knowledge

69

Courtesy Jose L. Jimenez

Aerosol Science & Indoor Air Researchers

http://tinyurl.com/preguntas-espanol

https://tinyurl.com/FAQ-aerosols

FAQs on Protecting Yourself from COVID-19 Aerosol Transmission

Shortcut to this page: https://tinyurl.com/FAQ-aerosols
Version: 1.65, 15-Sep-2020

If you want to jump over other details and go straight to the recommendations, click here.

Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University