Fundamentals of Aerosol Transport &
Practical Layered Risk Reduction for Indoor Environments

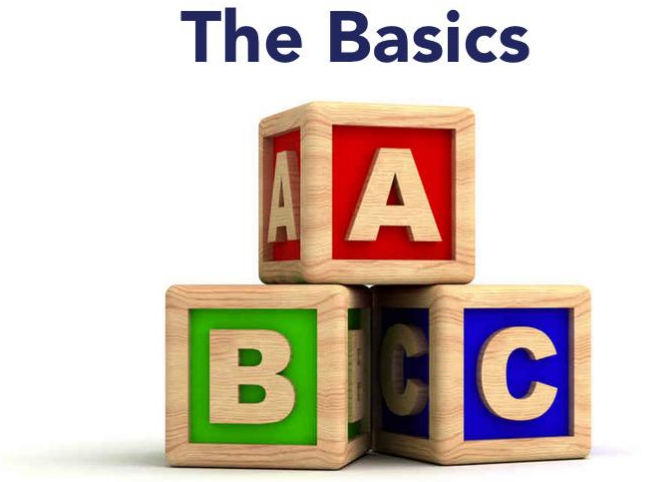
Richard L. Corsi, Ph.D., P.E.
H. Chik M. Erzurumlu Dean
Maseeh College of Engineering & Computer Science

Portland State University

National Tribal Air Association: An Overview of COVID in the Workplace for Tribes: Re-Opening Tribal Buildings September 2020

Fundamentals

- Sources of emissions
- Exposure pathways
- General fate
- Deposited inhalation dose



Layered Risk Reduction Strategy

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

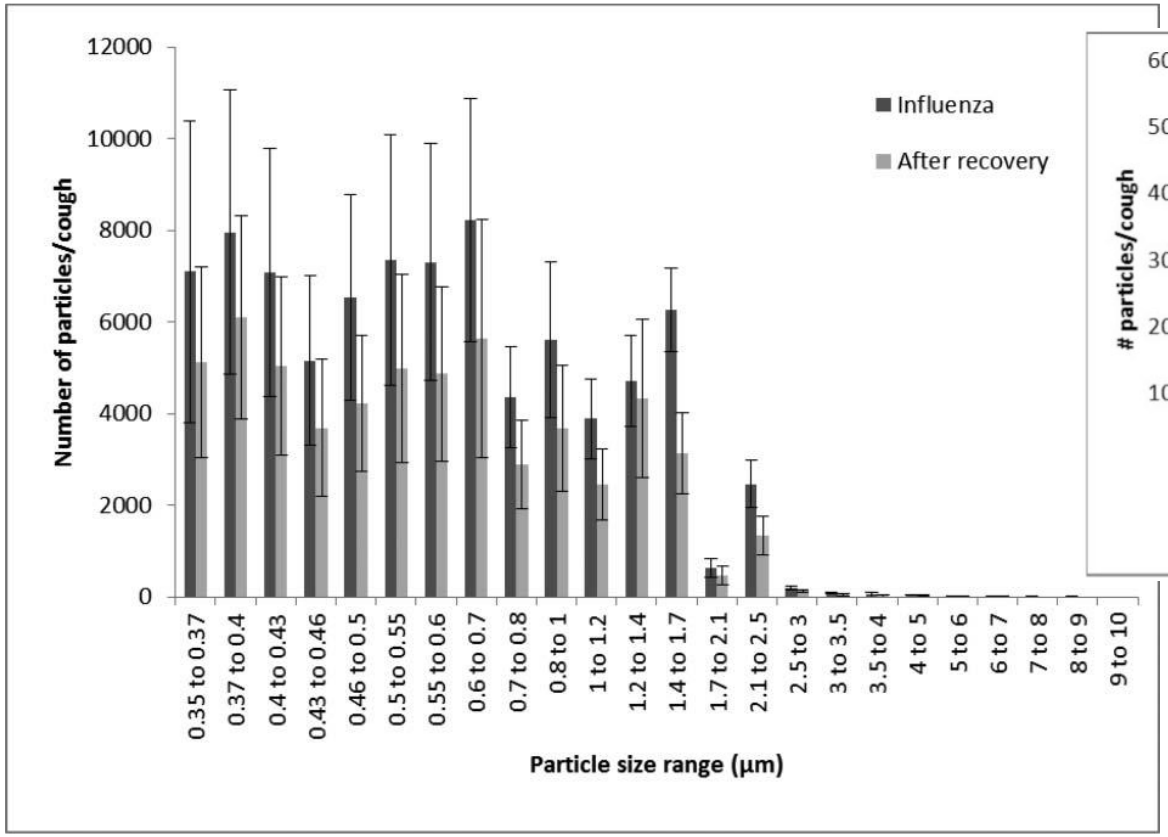
Sources of Emissions

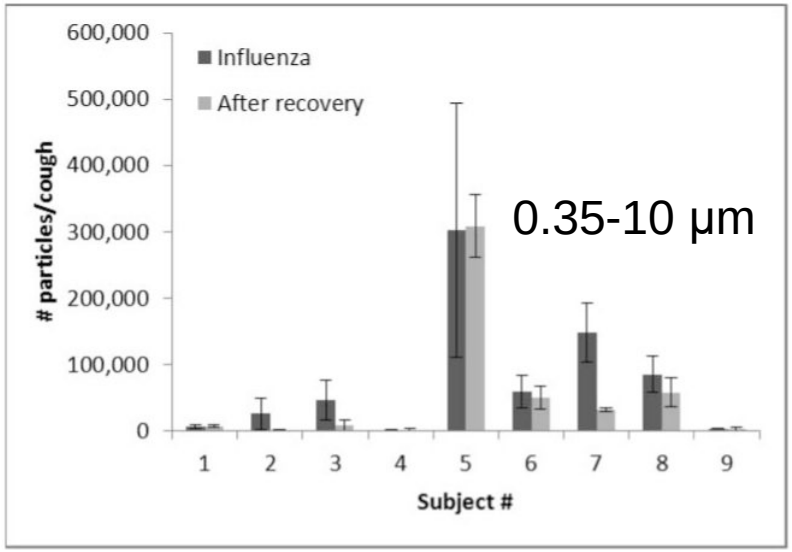
- Breathing
- Speaking
- Singing
- Coughing
- *Flushing?*
- *Resuspending?*

- Virus not naked (embedded in particles)
- Particles = combo of mucous & saliva
- Particle sizes vary widely (< 0.3 μm to 200 μm)
- Small fraction of viruses infectious

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

Coughing



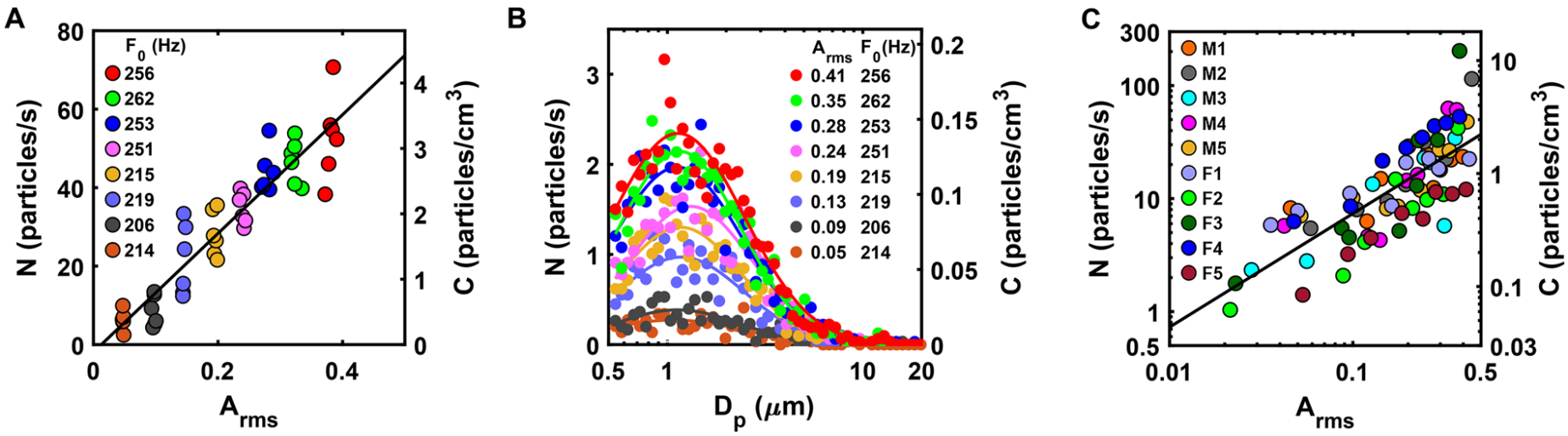


Lindsley, W.J., *et al., J of Occupational and Environmental Hygiene*, 9: 443–449 (2012)

- Mean = 75,400 SD = 97,300 / cough
- Range: 900 – 302,000 / cough

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

Speaking

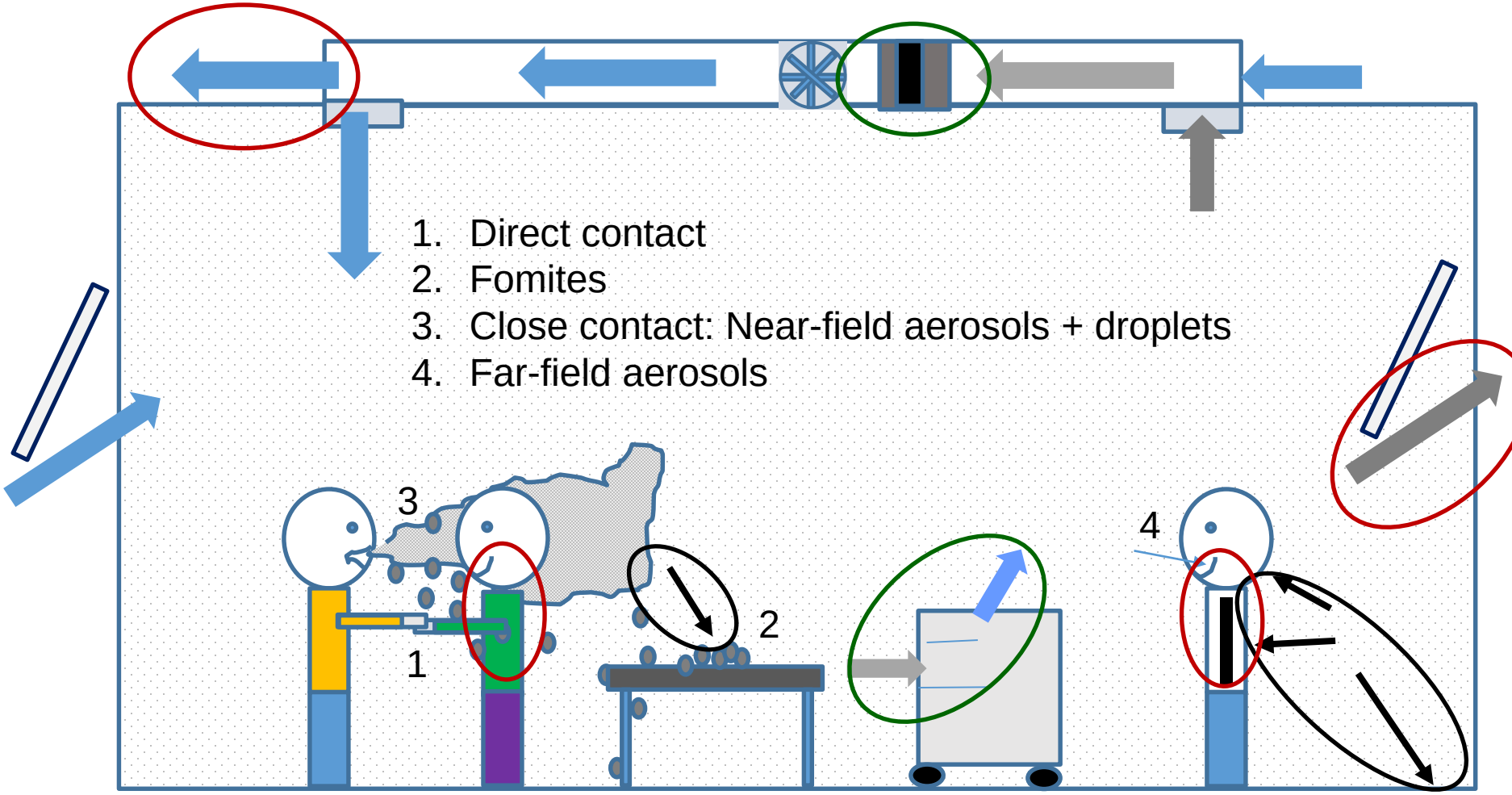


Asadi, S. *et al*. *Scientific Reports*, *9:2348 (2019)* doi.org/10.1038/s41598-019-38808-z

- Reasonable range = 300 to 3,000/min (some super-emitters to 12K/min)
- Super-emitter: 6 min of speaking loudly ≈ mean emission of single cough
- Breathing ≈ order of magnitude lower than average speaking

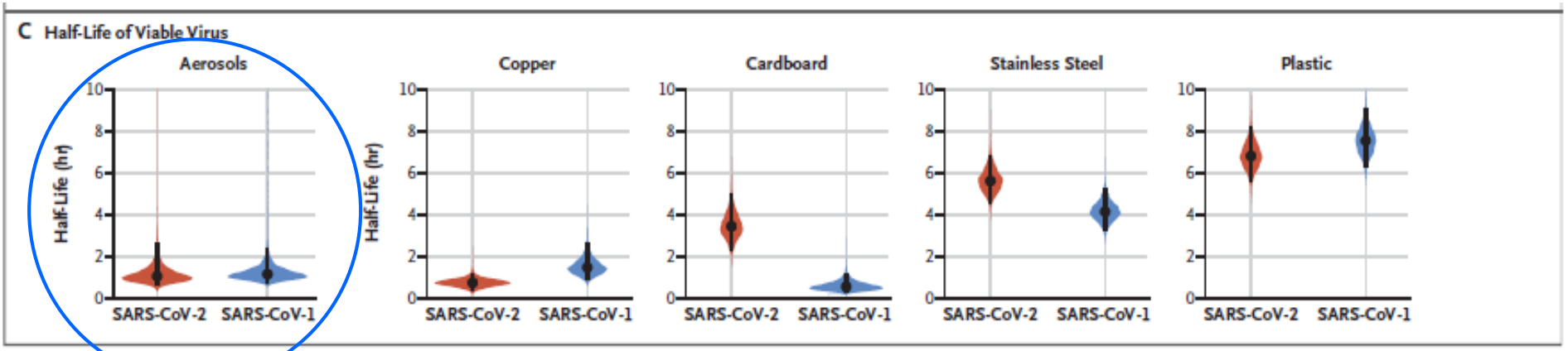
Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

Exposure Pathways & General Fate



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

Inactivation Rates of SARS-CoV-2



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

- $t_{1/2}$ = 1.1 hr ⟶ *decay rate* = 0.63/hr
- "ballpark" of ACH for residential buildings
- lower than many non-residential buildings

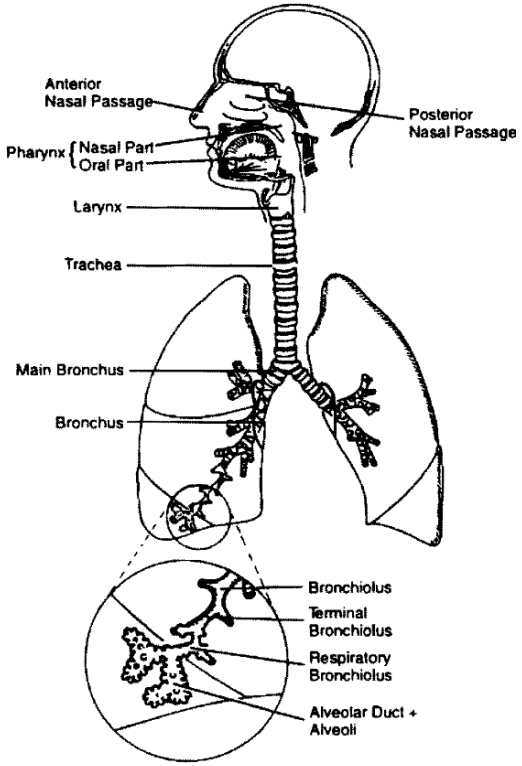
Deposited Inhalation Dose

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

- **C_i = concentration of particles of size i**
  - emissions; mask; deposition; ventilation; control
  - 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

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

Deposition In Respiratory System



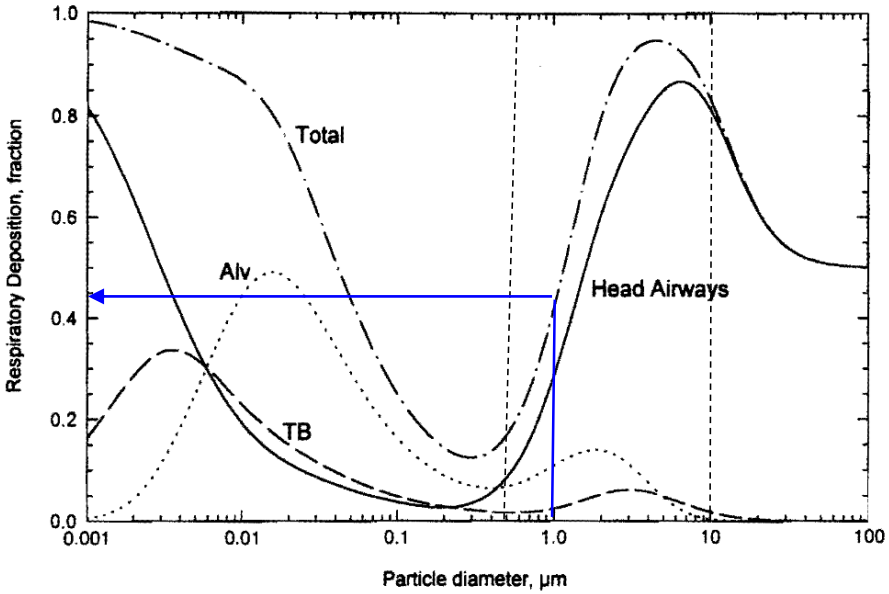


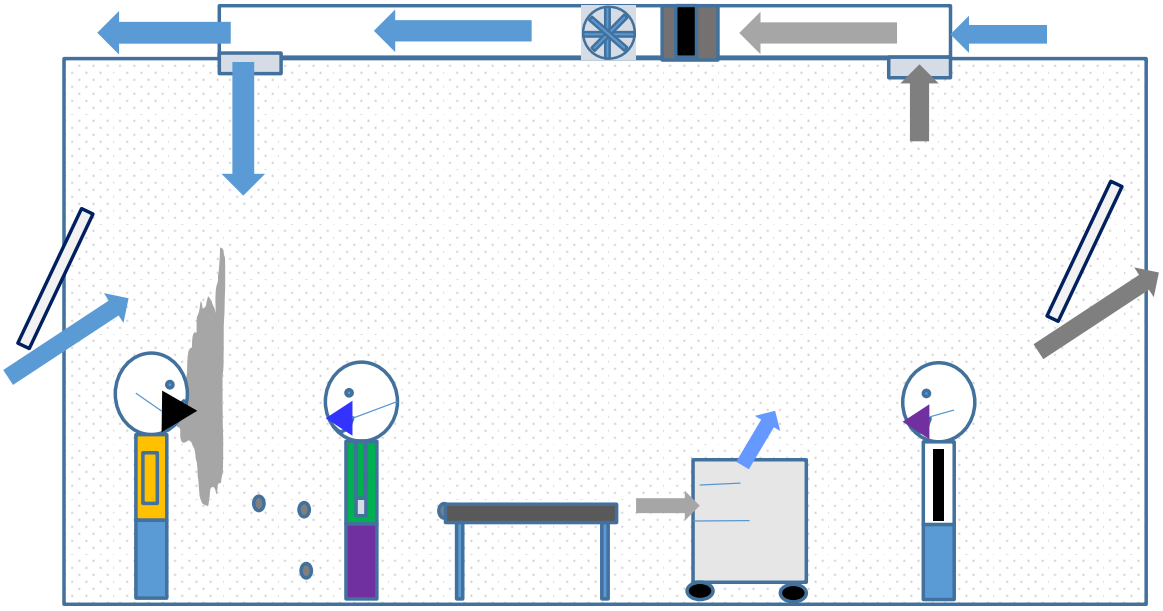
FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

W.C. Hinds, Aerosol Technology, 2nd Ed. 1999, John Wiley & Sons

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

Layered Risk Reduction (LRR) Strategy

- Reduce source
- Require masks indoors
- Distance from source
- Reduce time indoors
- Ventilate
- Filter / Inactivate
- Clean
- Educate



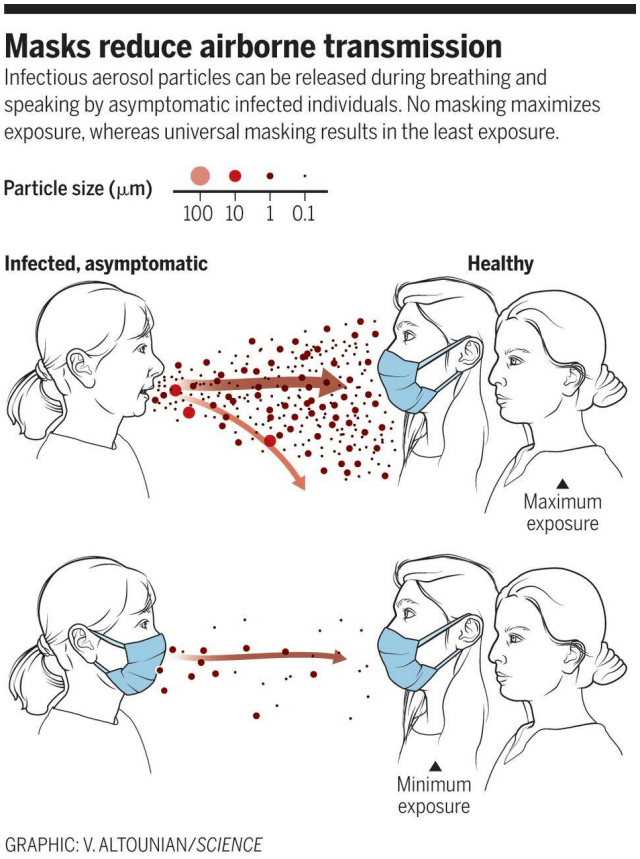
- LRR can lead to risk reduction > 90%

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

Reduce Source / Require Masks

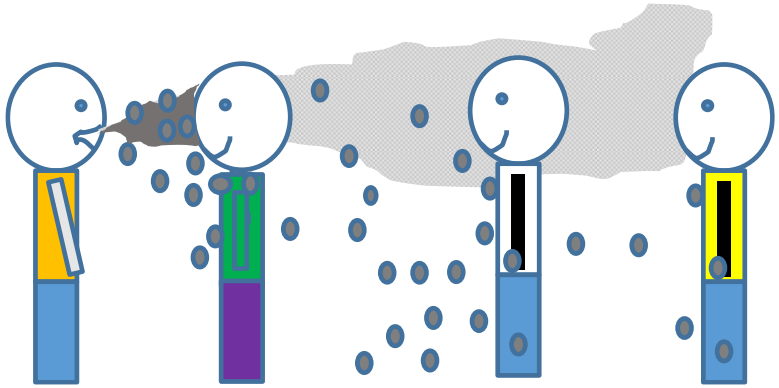
"If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure." - **Max von Pettenkofer** (1858)

- Test & isolate
- De-densify (less occupants)
- Require masks for all
- Reduce speaking to extent possible
- Ban certain activities (singing, aerobics)
- Replace flooring?



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

Distance from Source (others)

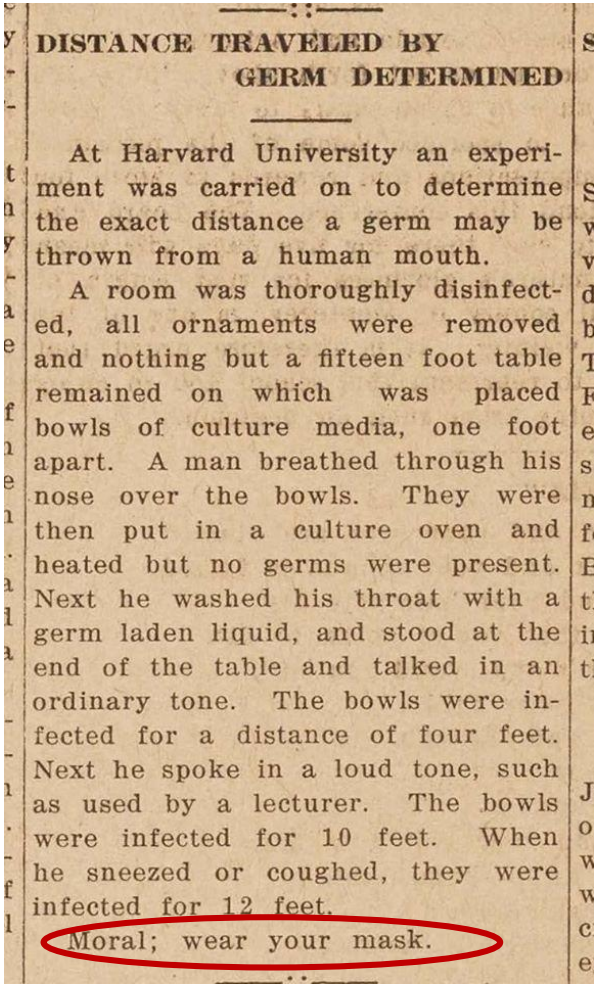


At air speed of 5 cm/s in free stream

d_a (µm)	V_{TS} (m/s)	k_d (1/hr)	$X_{1.5m}$ (m) -GS	$X_{50\%}$(m) - PF
0.5	7.5E-06	0.05	10000	2500
1	3.0E-05	0.1	2500	1200
5	7.5E-04	1.5	100	80
10	3.0E-03	7	25	20
50	7.5E-02	100	1	1

Particles ≤ 10 µm not substantially removed w/in 6 ft

Even 50 to 100 µm particles can travel > 6 ft (warm jet)



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.

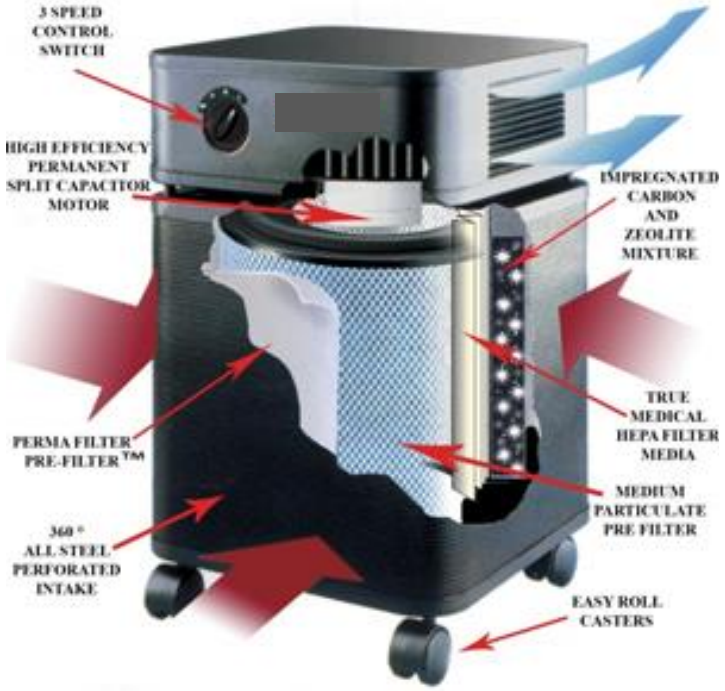
A room was thoroughly disinfected, all ornaments were removed and nothing but a fifteen foot table remained on which was placed bowls of culture media, one foot apart. A man breathed through his nose over the bowls. They were then put in a culture oven and heated but no germs were present. Next he washed 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.

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

Engineering Controls

- Increase outdoor air supply (correctly)
- Centralized or room-specific filtration
- Portable air cleaner
- UVGI: Inactivate (destroy) virus
- Others? (generally not rigorously tested)



http://www.sheffield-pottery.com/

Portable Air Cleaners

- HEPA-based portable air cleaner
- HEPA = High Efficiency Particulate Air
- Key attribute = 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

EPA.gov

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

Portable Air Cleaners

- Equivalent air changes per hour = EqACH = **CADR/V** (V = volume of indoor space)
- Example: V = 600 ft^2 x 8 ft = 4,800 ft^3
- CADR = 300 ft^3/min
- **EqACH** = 300 ft^3/min/4,800 ft3 = 0.0625/min (or x 60 = **3.8/hr**)

$$C_i = \frac{E_i/\lambda V}{1 + k_{d+p,i}/\lambda + \eta_i Q_c/\lambda V}$$

If λ= 0.5/hr 3.8/0.5 = 7.6

1 + 7.6 = 8.6

89% reduction

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

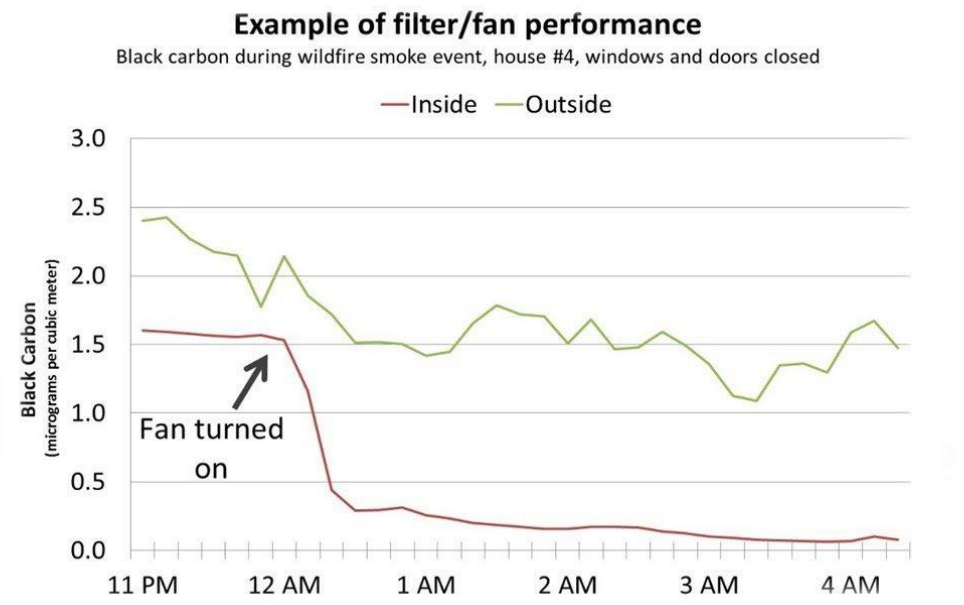
DIY - Portable Air Cleaners

- Box fan sucking through filter
- Multiple filters in parallel (benefits)
- Cost = $30 to $60 (+ filter replacement)
- Some reports of good performance

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

Example: Portable Air Cleaners

@MPHProject



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

Summary

Reduce source

Require masks indoors

Distance from source

Reduce time indoors

Ventilate

Filter / Inactivate

Clean

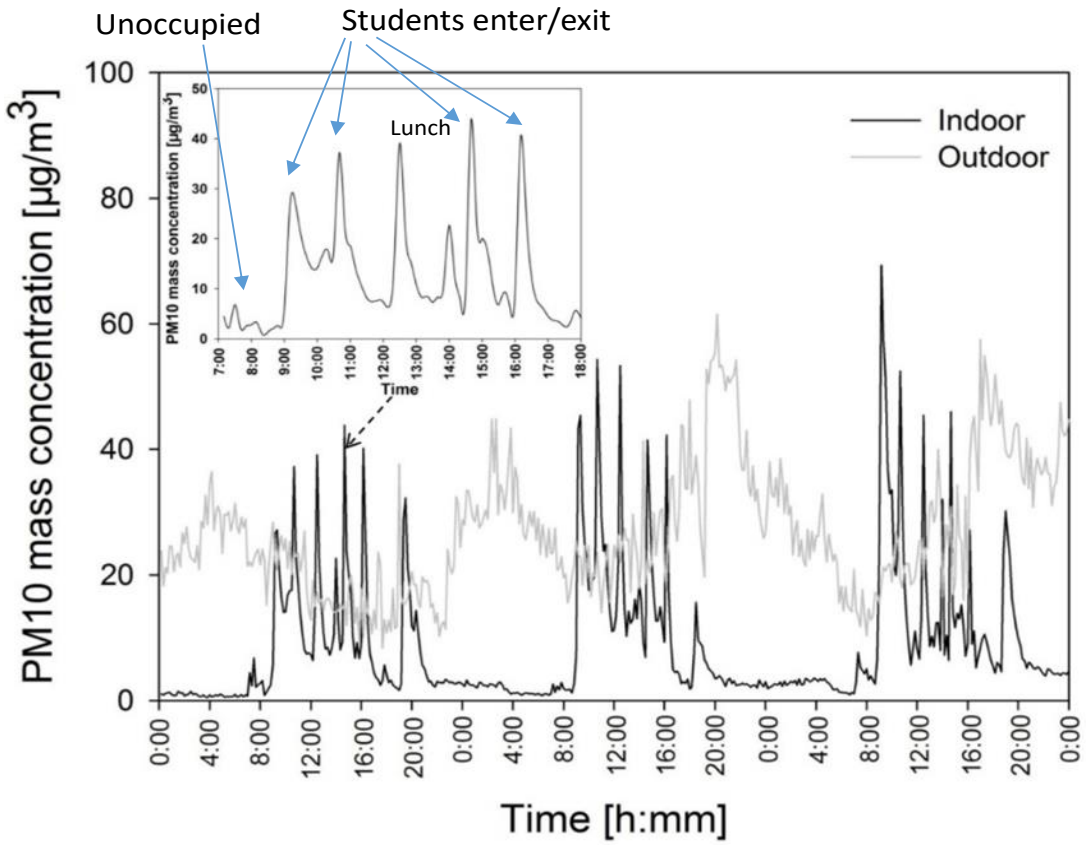
Educate

- Four major transmission pathways
- Known sources of SARS-CoV-2 (high variability)
- SARS-CoV-2 conveyed via aerosols (important)
- Can travel long distances from infector (source)
- Deposited inhaled dose critical: $D = C \times B \times t \times f$
- Layered Risk Reduction Strategy
  - Potential for significant benefit

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

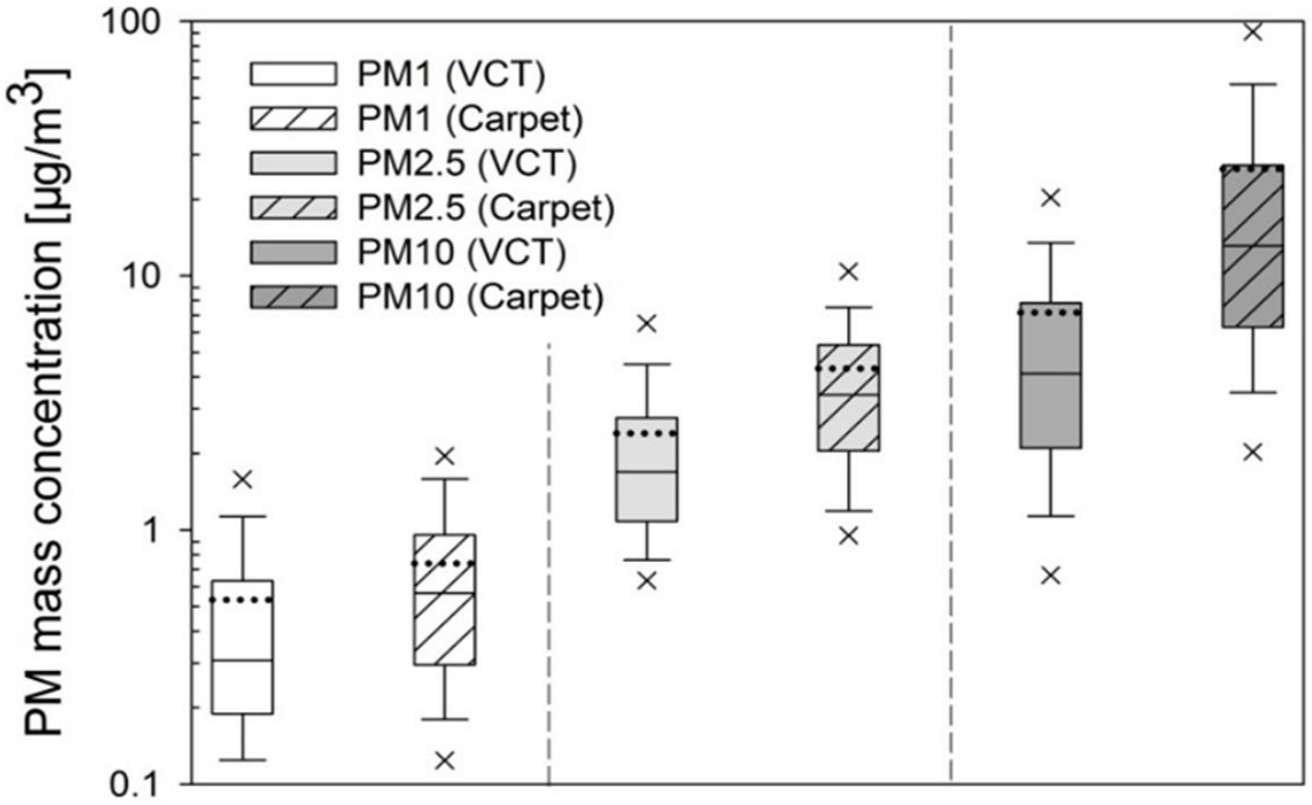
Extra Slides for Discussion

Resuspension of Particles?



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

Influence of Flooring



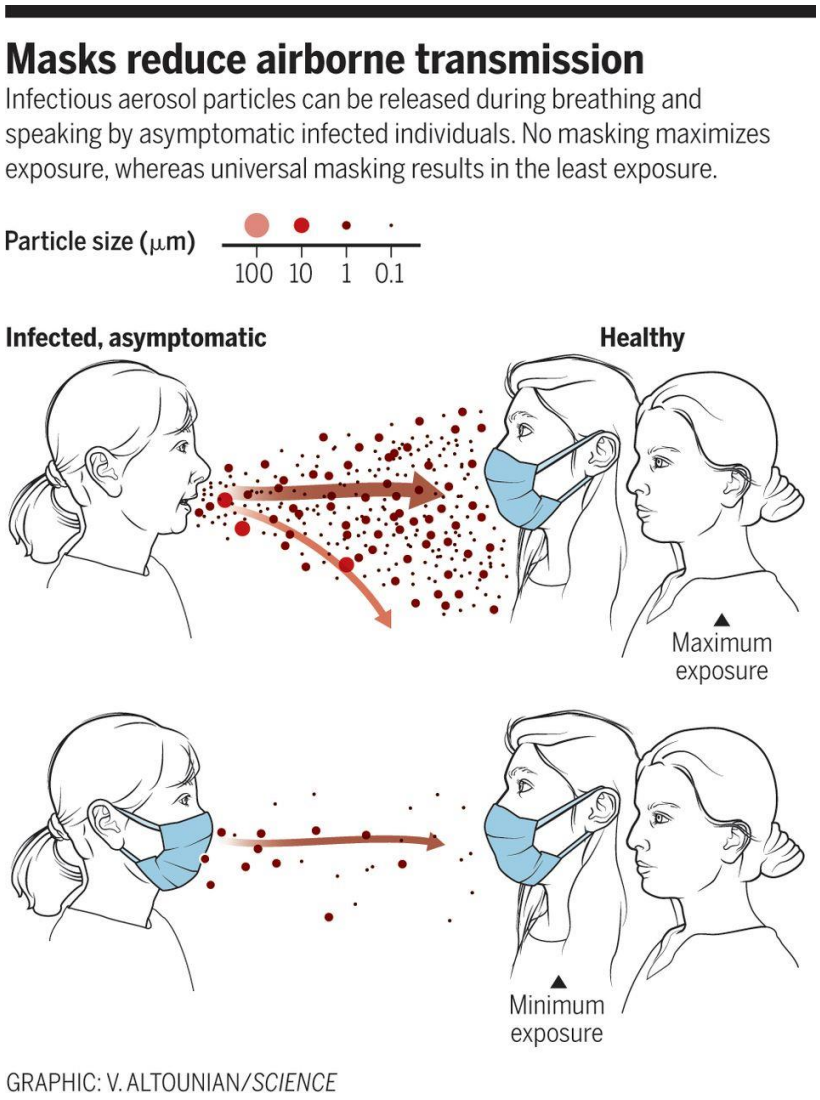
Ren, J. *et al*. *Building & Environment* (accepted)

Should carpet be removed before reopening?

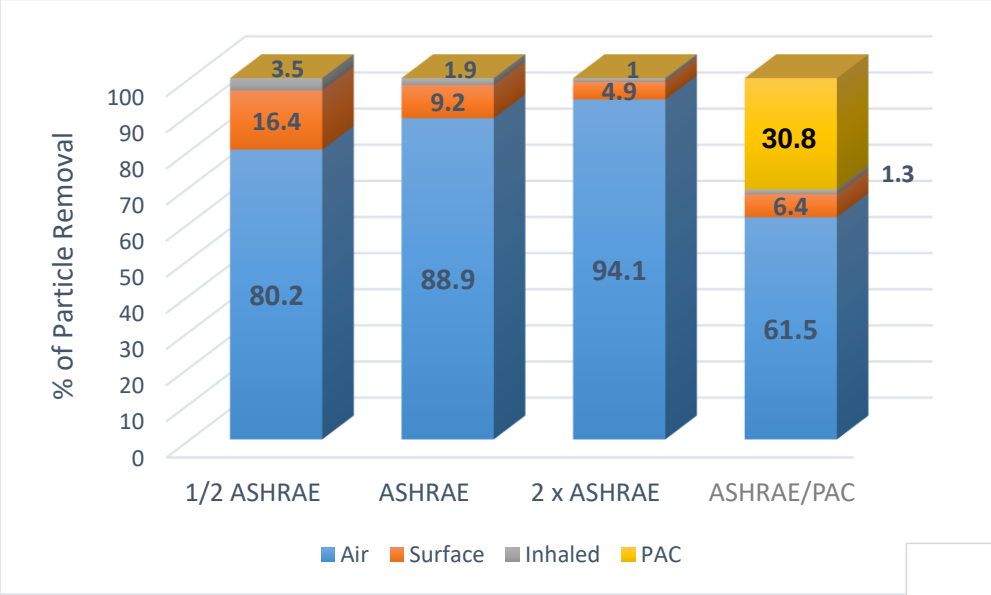
Easier to clean/disinfect impermeable flooring.

Masks

- **Masks protect others***
  - Reduction in large droplets
  - Reduced initial jet distance
- **Masks protect you***
  - Large droplet “projectiles”
  - Small amt of aerosols
- **Want low degree of penetration**
  - Fibrous
  - Random fiber orientation
  - Thicker = better
  - Must be breathable
- **Want low leakage**
  - Minimize “least resistance”
  - Often around crease of nose
  - Separate nose & mouth?



Putting It All Together

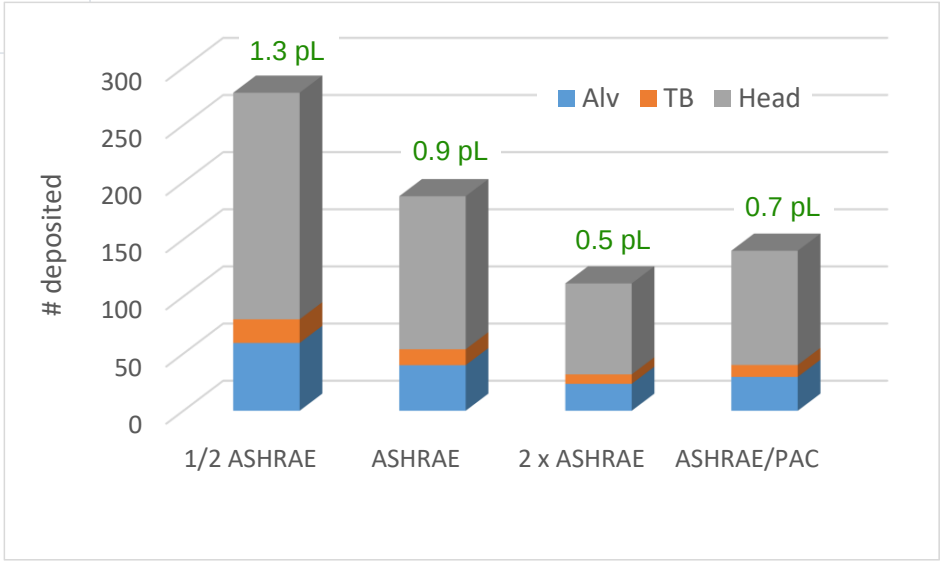


Simulation for university lecture

- 0.5 to 4 μm particles from infector
- Fate: exhaust to outdoors dominates
- Fate: Surface dep up as vent down
- Fate: HEPA-PAC signif

Particle deposition in resp system

- Nose breathers
- Dominated by head region (25% ALV)
- Fate mechs impact volume deposited

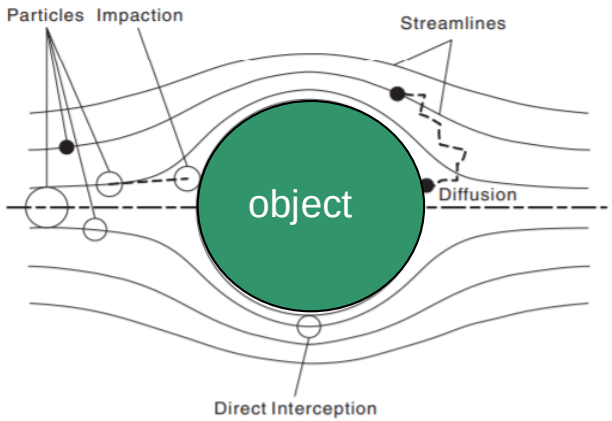


Richard L. Corsi, Ph.D., PE.
Dean, Maseeh College of Engineering & Computer Science, Portland State University

ASHRAE = ASHRAE 62.1 2019

Particle Deposition Mechanisms

Gravitational settling important
Other deposition mechanisms

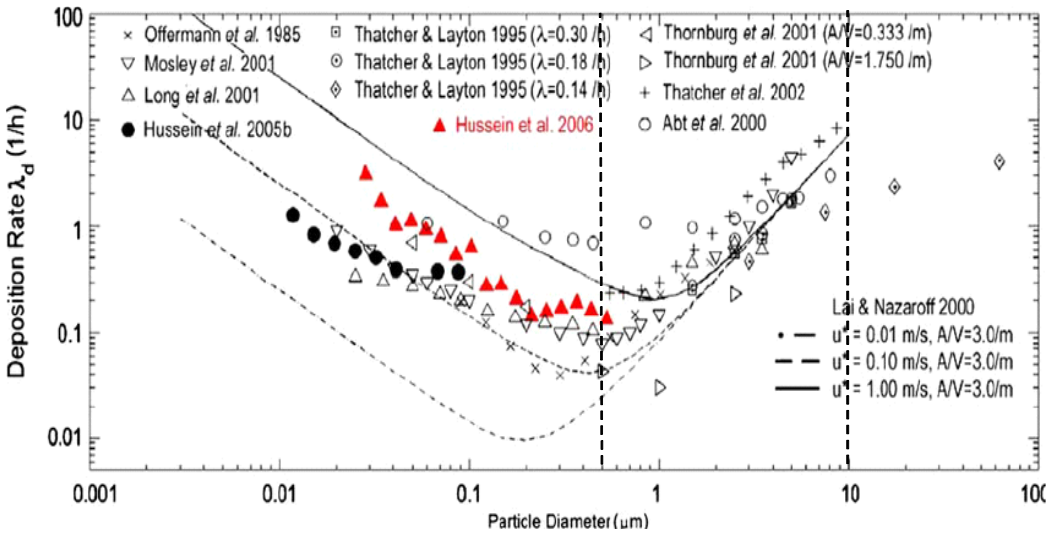


Modified from Wang, W., *et al. Aerosol Sci & Technol*, 46:843–851, 2012

Humans
Furnishings
Fan blades
Fiber in a filter
More "clutter" = more op for removal
More mixing = more op for removal

Electrostatic & thermophoretic effects

$$\beta_i = \lambda + k_{dep,i} + \sum \frac{P_i Q_c}{V} + f_{dep,i} \frac{Q_b}{V} + \ldots$$

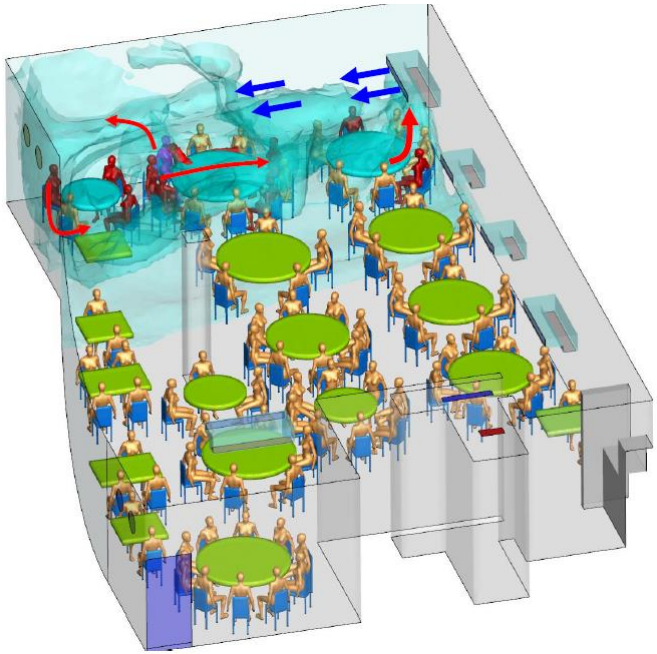


Hussein, T.; Kulmala, M., *Water Air Soil Pollut*. 8:23–34 (2008)

- k_{dep} for 0.5 to 10 μm particles ≈ 0.1 to 7 h^{-1}
- Context: λ ≈ (0.3 to 4 h^{-1})* – fn(type of building)

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

EID Applied to Restaurant X

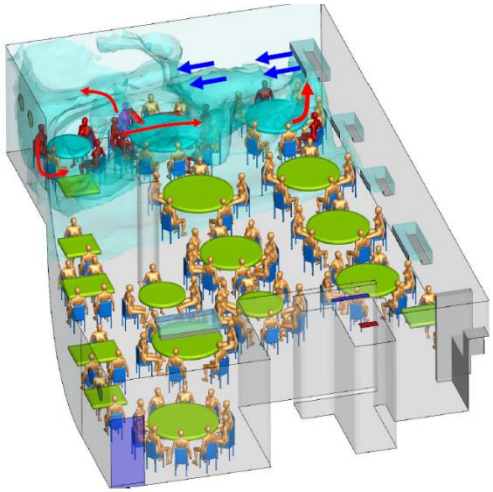


- 89 patrons / 1 infector / 10 infected
- Significant metadata
- 138 m^2 / 431 m^3 ACH = 0.6-0.8 h^{-1} (0.75-1.04 L/s-p)
- Video; tracers (researchers/manikins); CFD

Li, Y. *et al.*, doi.org/10.1101/2020.04.16.20067728doi medRxiv preprint

- Use metadata from restaurant + tracer studies
- Index case: Assumptions related to emissions (cough, speak, breathe)
- Particle size distributions (0.5 to 4 μm) – can do more

Comparative Analysis – Restaurant X



- EID: Deposited inhaled volume in ABC patrons
- 1 – 10 pL (10^{-12} L) / patron for 75 min event
- Range depends on assumed emissions / mixing

Screening Approach (scenario comparisons)*

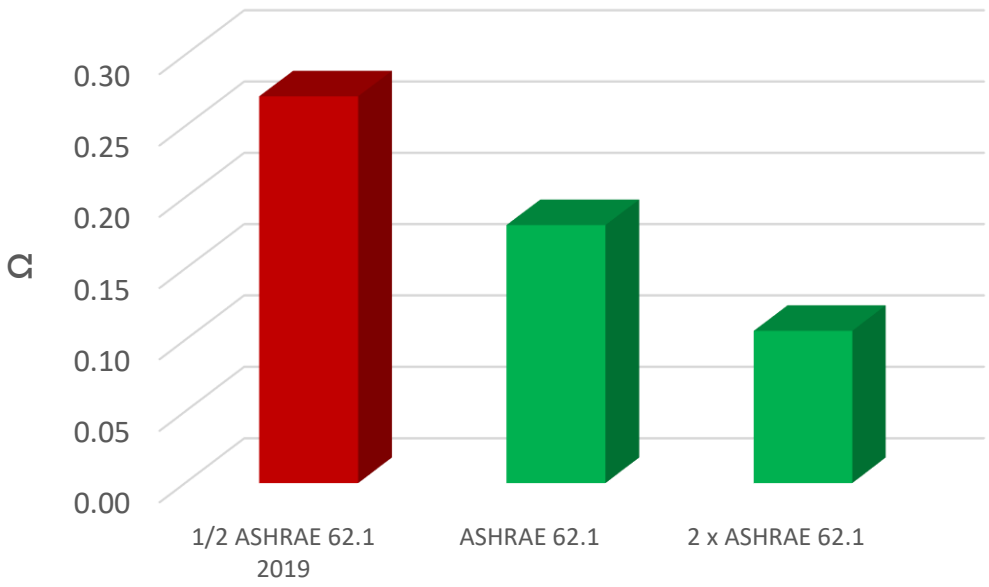
- Take index case (Index X) for Restaurant X (similar emissions)
- Place in different environments & determine Ω

$$\Omega = (\text{Volume}_{dep}) / (\text{Volume}_{dep,\text{Restaurant X}})$$

* In lieu of having a dose-response relationship

Busy Restaurant

100 m^2 x 3.14 m; 69 patrons + Index X; 75 minute event
ASHRAE 62.1 yields 4.1 h^{-1}

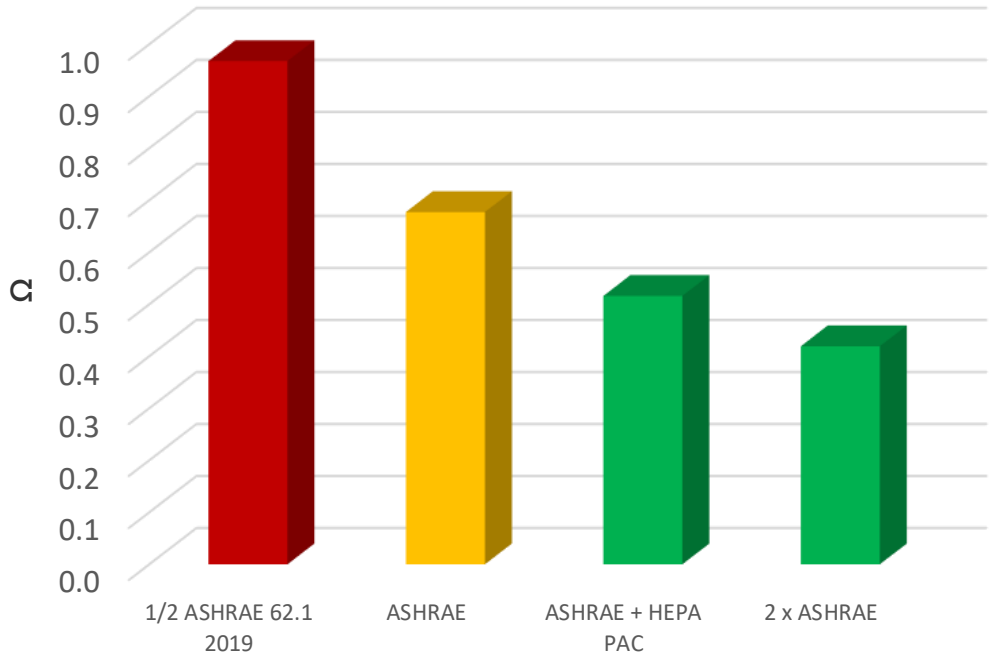


- Masks
- Distancing
- Very well ventilated
- Outdoors
- Reduced time
- Take out
- Delivery

Additional considerations: close contact & fomites

Choir Practice

- 50 participants (+ Index X) in 100 m^2 x 2.8 m for 75 min
- 50% time singing (elevated speaking); Heavier breathing (emit & inhale)*
- ASHRAE 62.1 2019 yields 3.6 h^{-1}



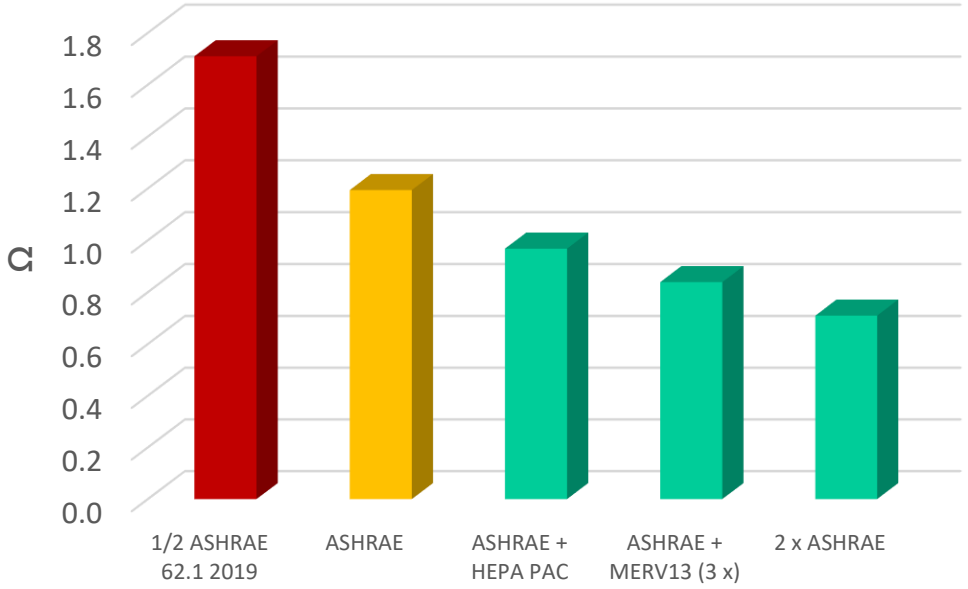
- Concern across board
- Outdoors w/ distancing
- Remote?

Additional considerations: close contact & fomites

* Based on literature, e.g., Salomoni et al., *PloS One*, 2016; 11(5): e0155084

Gym w/ Aerobic Activity

- 40 patrons; Staff member = Index X; Heavy breathing receptor (aerobics)
- 100 m^2 x 4 m; ASHRAE 62.1 2019: yields 3.9 h^{-1}



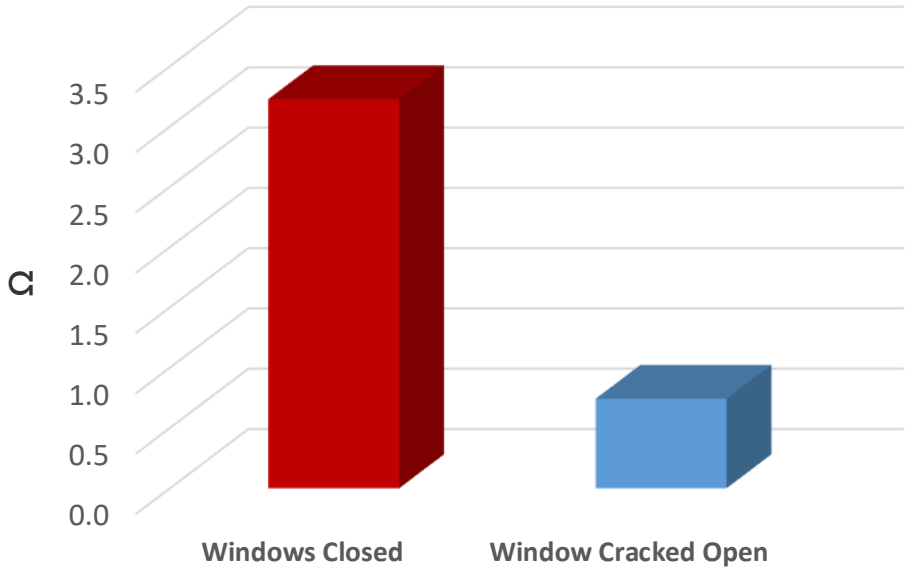
- Avoid indoor gyms (perhaps signif' cross-flow)
- Outdoor workout
- Masks
- Physical distancing

Additional considerations: close contact & fomites

Ride Share

1 Patron + Index X as driver; 3 m^3 cab; 20 mph; 20 minutes across town

Air exchange rates reasonable based on a number of peer-reviewed papers

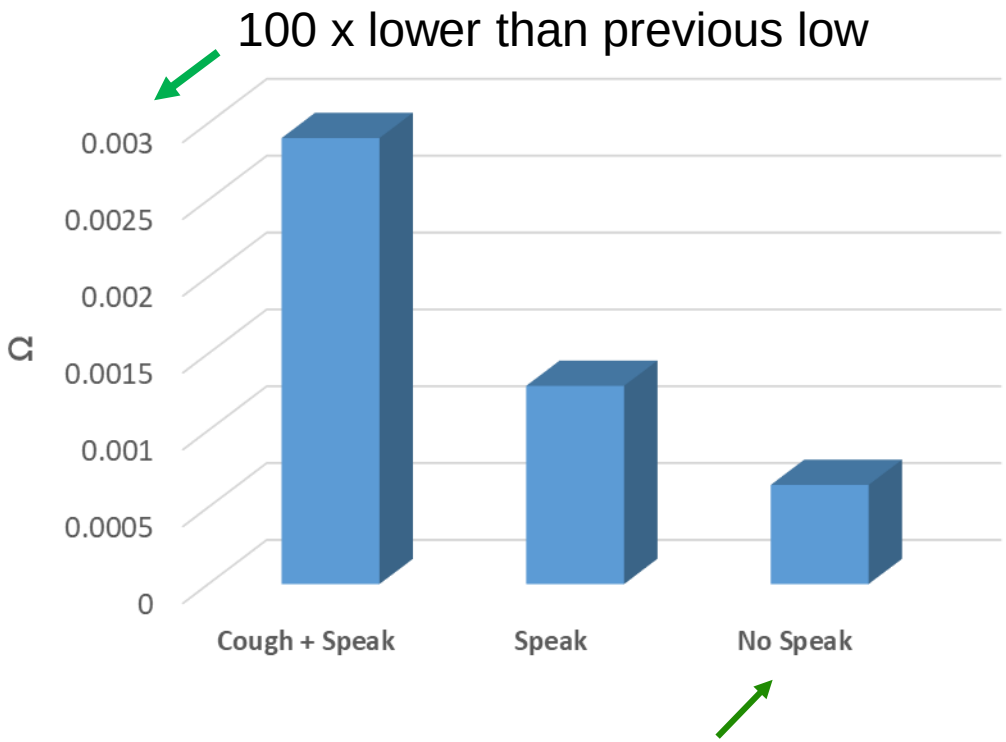


- Wear mask
- Insist driver wears mask
- Crack open windows
- Avoid long trips / busy commutes
- Can get Ω ≈ 0.1

Additional considerations: close contact & fomites

Elevator

Index X + 1; 1 min travel w/o door opening; Air changes = 60 h^{-1} (1 min^{-1})



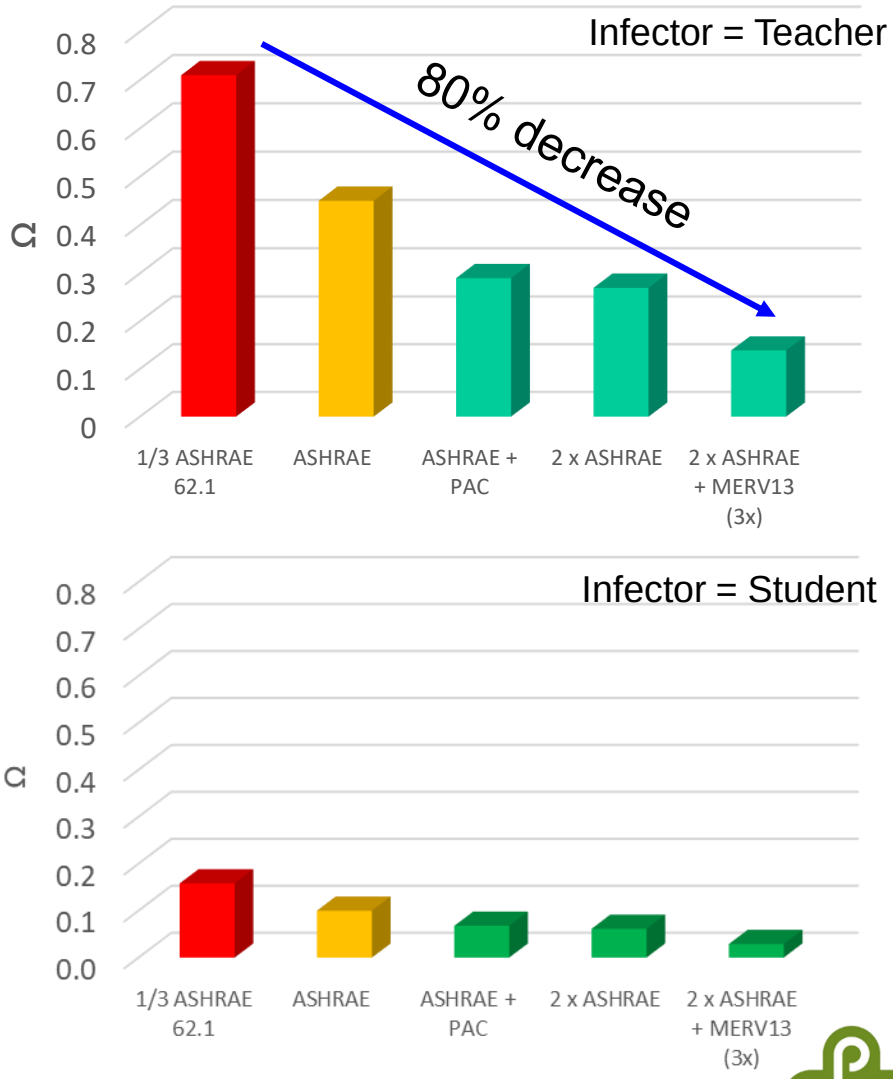
- Elevator airborne negligible
- Short trip / well-ventilated

- Focus on close contact (but note short time)
- Masks
- No speaking etiquette
- Reduce density
- Distance & face away

Additional considerations: close contact & fomites

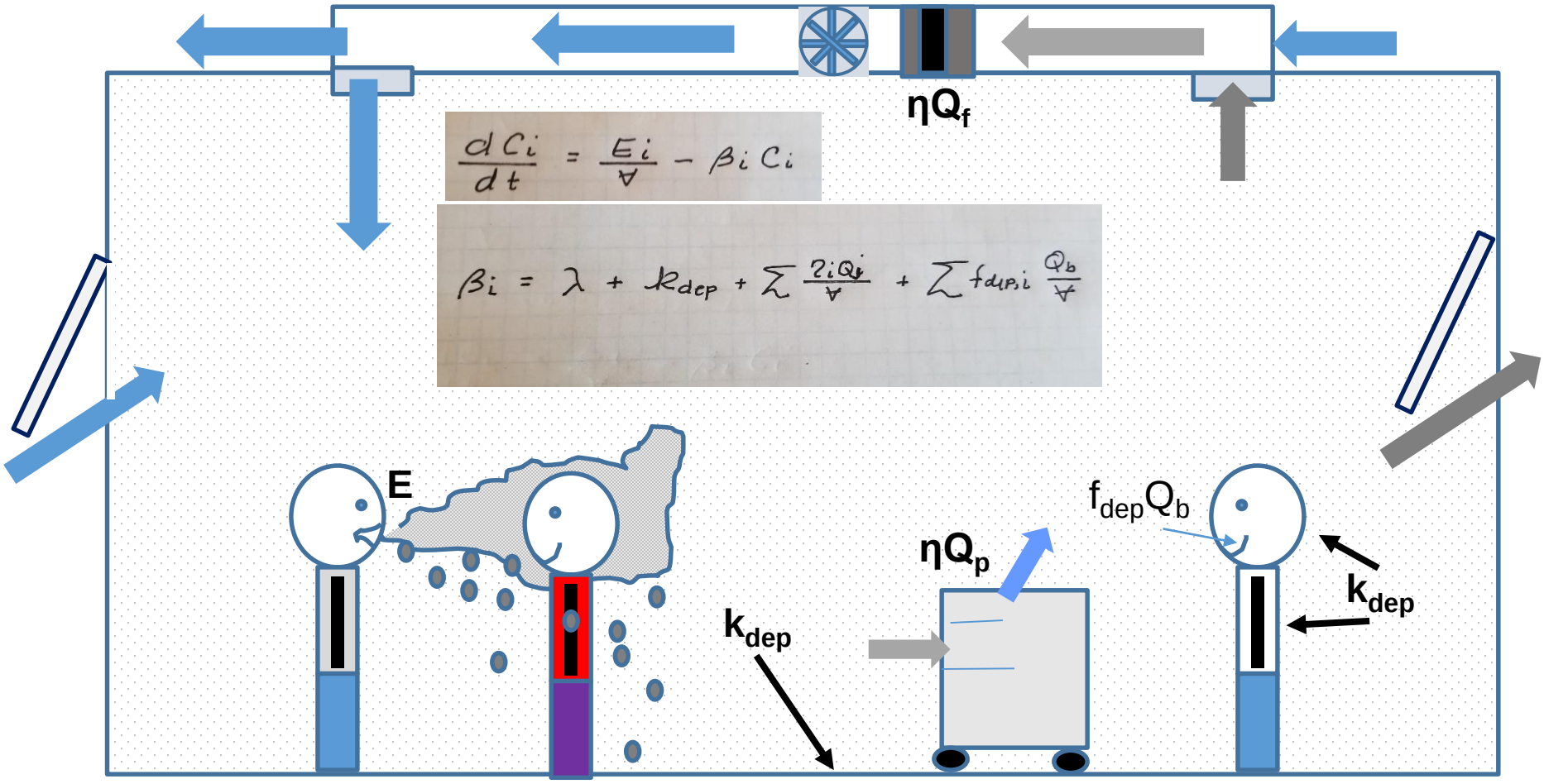
School Classroom

- 700 ft^2; 25 students for 75 min
- **Infector = teacher**
  - Occasional cough (Index X)
  - Speaks 50% of time
  - Lower amp than Index X
- **Infector = student**
  - No cough (10% speak)
- Masks decrease **Ω**



Additional considerations: close contact & fomites

General Fate & Pathways

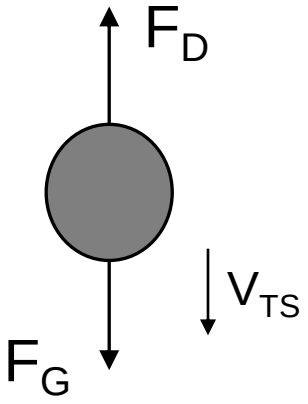


$$\frac{dC_i}{dt} = \frac{E_i}{\forall} - \beta_i C_i$$

$$\beta_i = \lambda + k_{dep} + \sum \frac{\gamma_i Q_i}{\forall} + \sum f_{dep,i} \frac{Q_b}{\forall}$$

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

Particle Deposition by Settling



Gravitational settling

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

$$V_{TS} = \frac{\rho_p d_e^2 g C_c}{18\eta X} = \frac{\rho_o d_a^2 g C_c}{18\eta}$$

Based on 5 cm/s air speed in free stream

Particles ≥ 50 µm can travel further than 1 m

Other mechs important as d_p becomes small

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