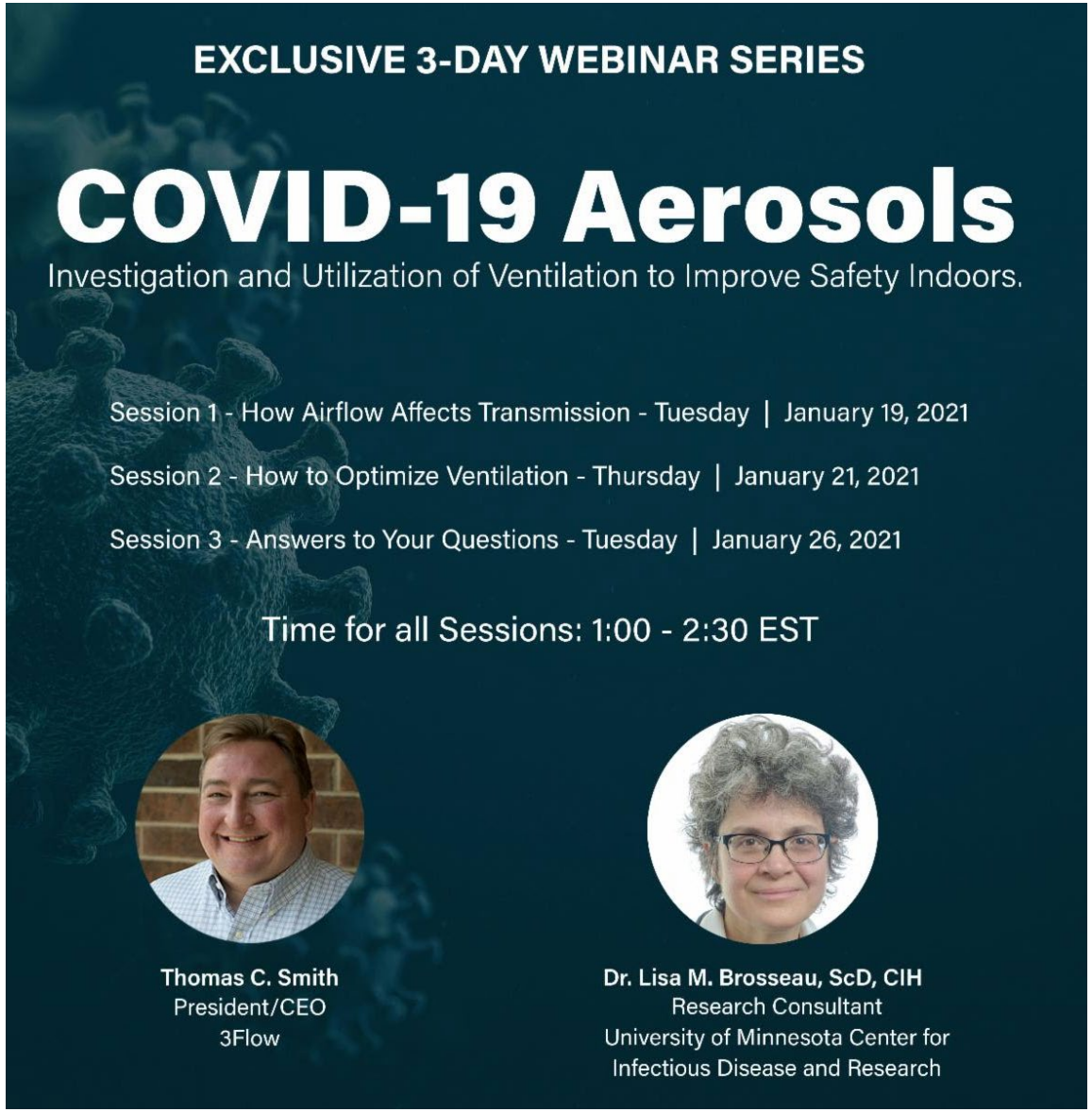
Session 1
How Airflow Affects Transmission



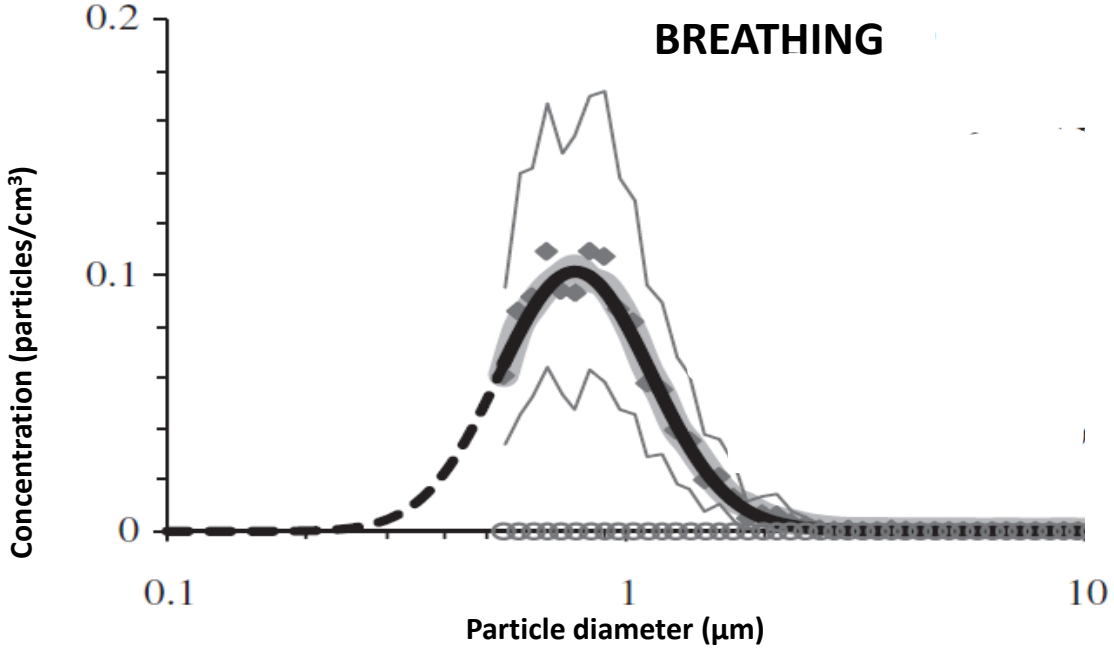
Objectives

- Human-generated aerosols and their transmission indoors
- Linking exposure, dose, infection, and disease
- Risk factors for indoor infectious aerosol transmission
- How ventilations systems impact exposure

Human Generated Aerosols and Transmission Indoors

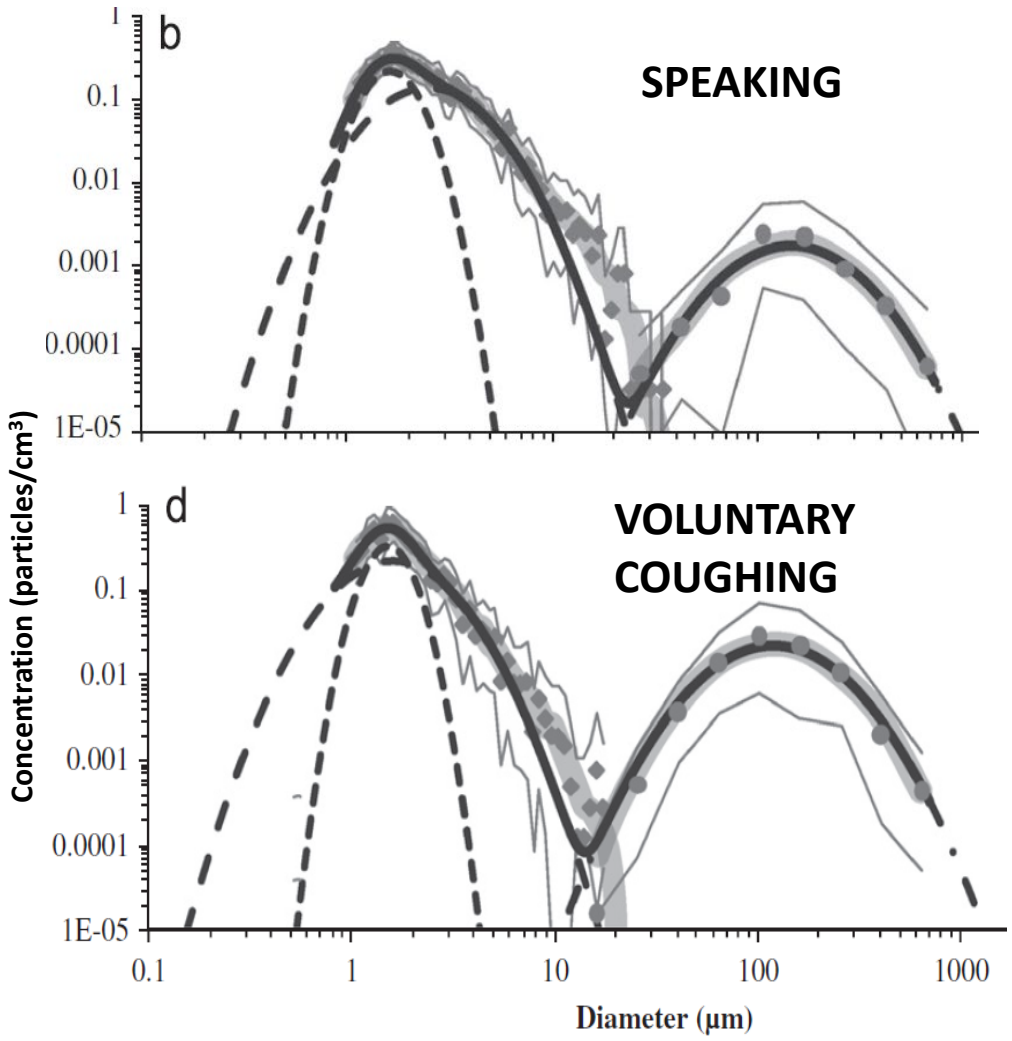
Human-Generated Aerosols

Breathing: 0.1 – 10 µm; most around 1 µm



Sneeze aerosols are similar to coughing & speaking with 2 peaks at about 40 and 140 µm*

Speaking & Coughing:
0.1 - > 1000 µm
2 peaks: 1-2 µm & 100-200 µm



Figures from Johnson, G. R., et al. "Modality of human expired aerosol size distributions." Journal of Aerosol Science 42.12 (2011): 839-851.

*Han, Z. Y., W. G. Weng, and Q. Y. Huang. "Characterizations of particle size distribution of the droplets exhaled by sneeze." *Journal of the Royal Society Interface* 10.88 (2013): 20130560.

Close-Range Aerosol Inhalation Route Dominates Near the Source

Exposure to Exhaled Particles at Close Range (< 6 feet)
During Talking & Coughing

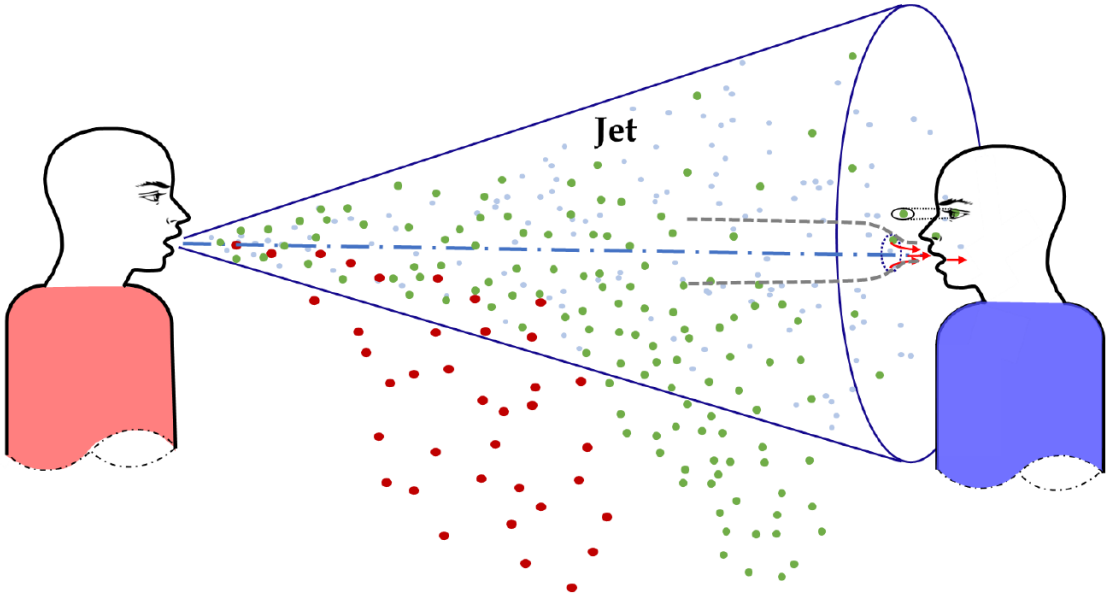
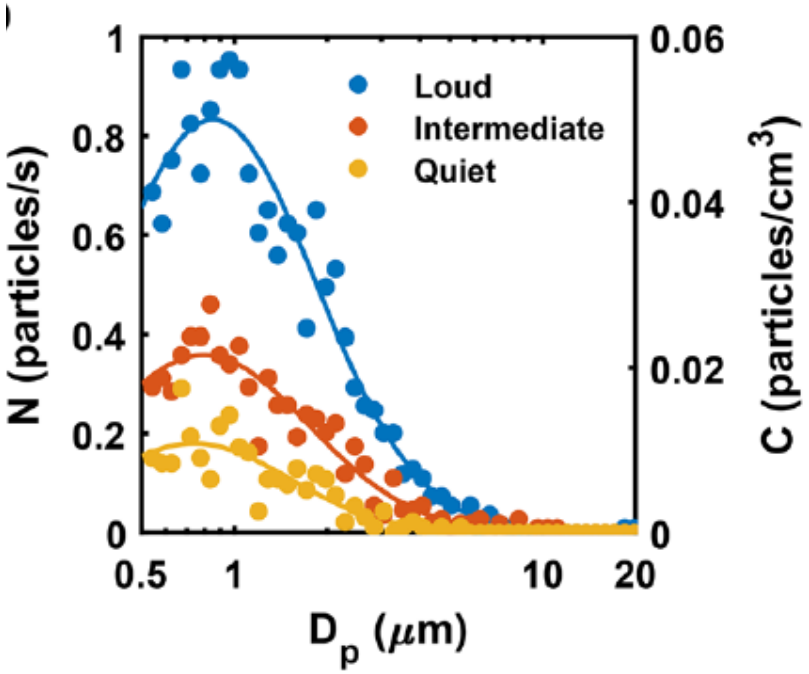


Figure 1. Schematic diagram of close contact scenario with exhalation from the infected (left) and inhalation through the mouth of the susceptible person (right).

- **Aerosol inhalation dominates at most distances during talking and coughing**
- **Large droplet propulsion is important only for large particles (> 100 µm)**
  - **0.5 ft (talking)**
  - **1.5 ft (coughing)**

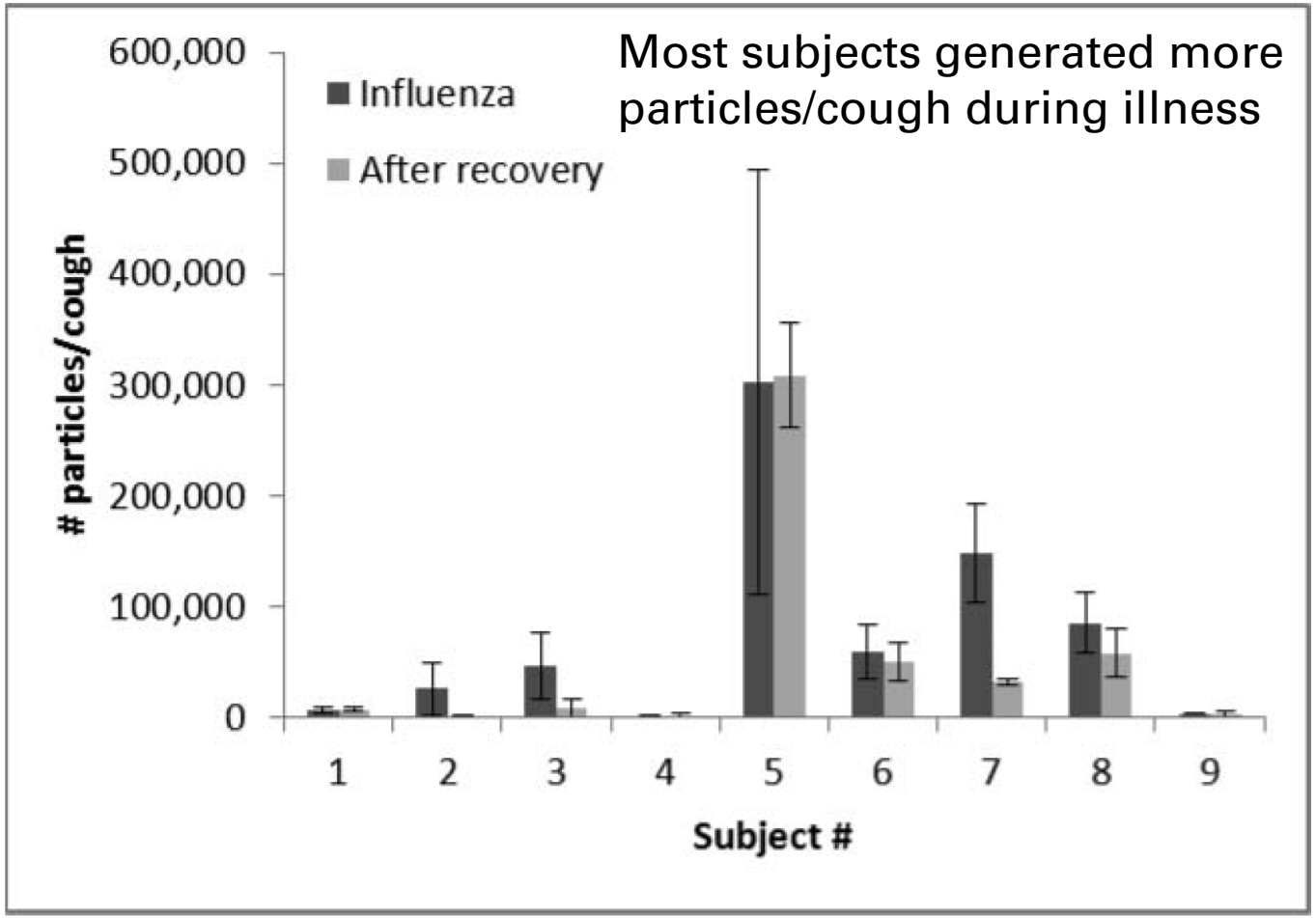
Chen, Wenzhao, et al. "Short-range airborne route dominates exposure of respiratory infection during close contact." *Building and Environment* (2020): 106859.

Louder speech generates more particles

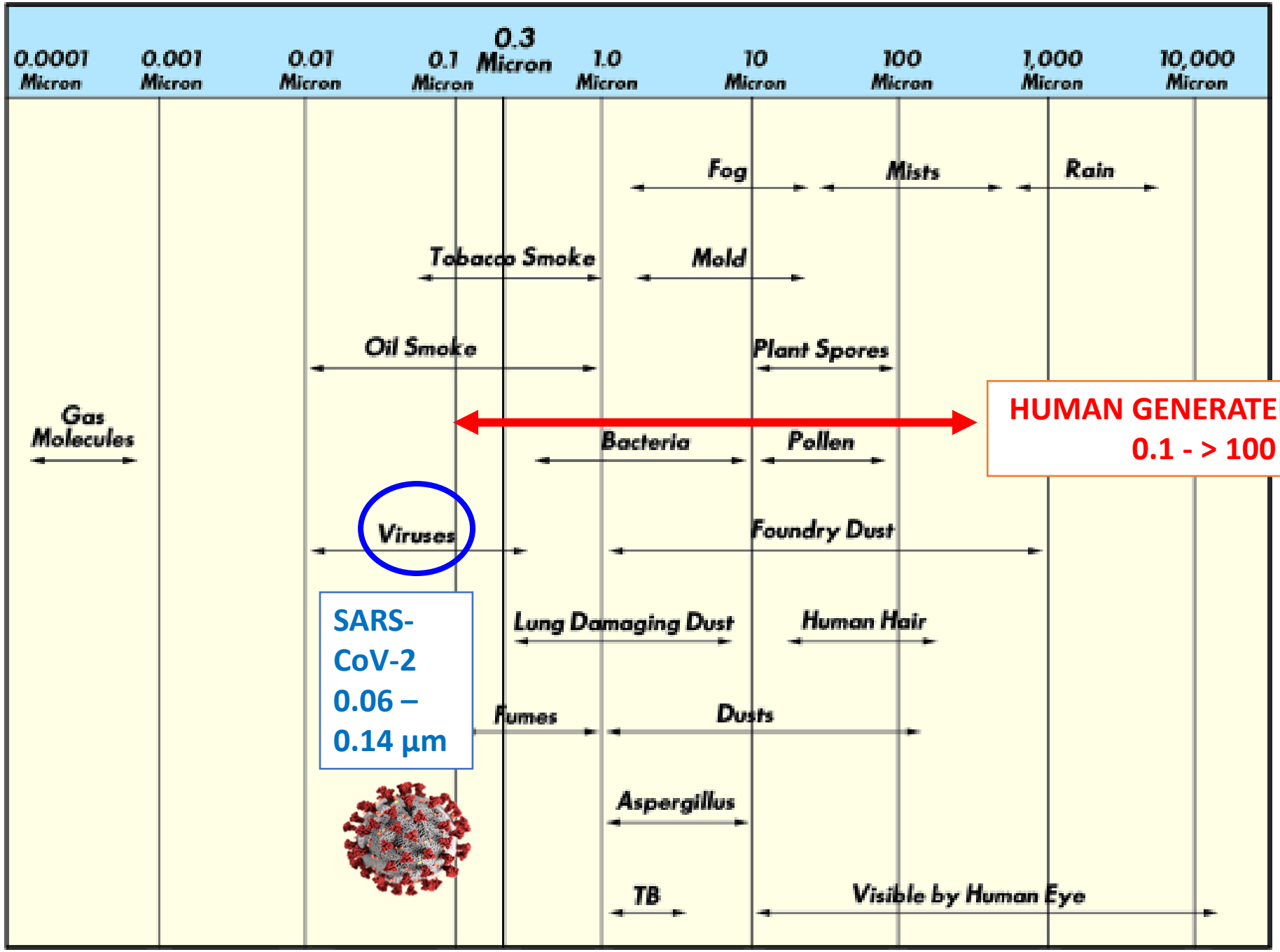


Asadi, Sima, et al. "Aerosol emission and superemission during human speech increase with voice loudness." *Scientific reports* 9.1 (2019): 1-10.

People are highly variable in number of particles they generate



Lindsley, William G., et al. "Quantity and size distribution of cough-generated aerosol particles produced by influenza patients during and after illness." Journal of occupational and environmental hygiene 9.7 (2012): 443-449.



http://www.abatement.com/residential/air_quality.htm

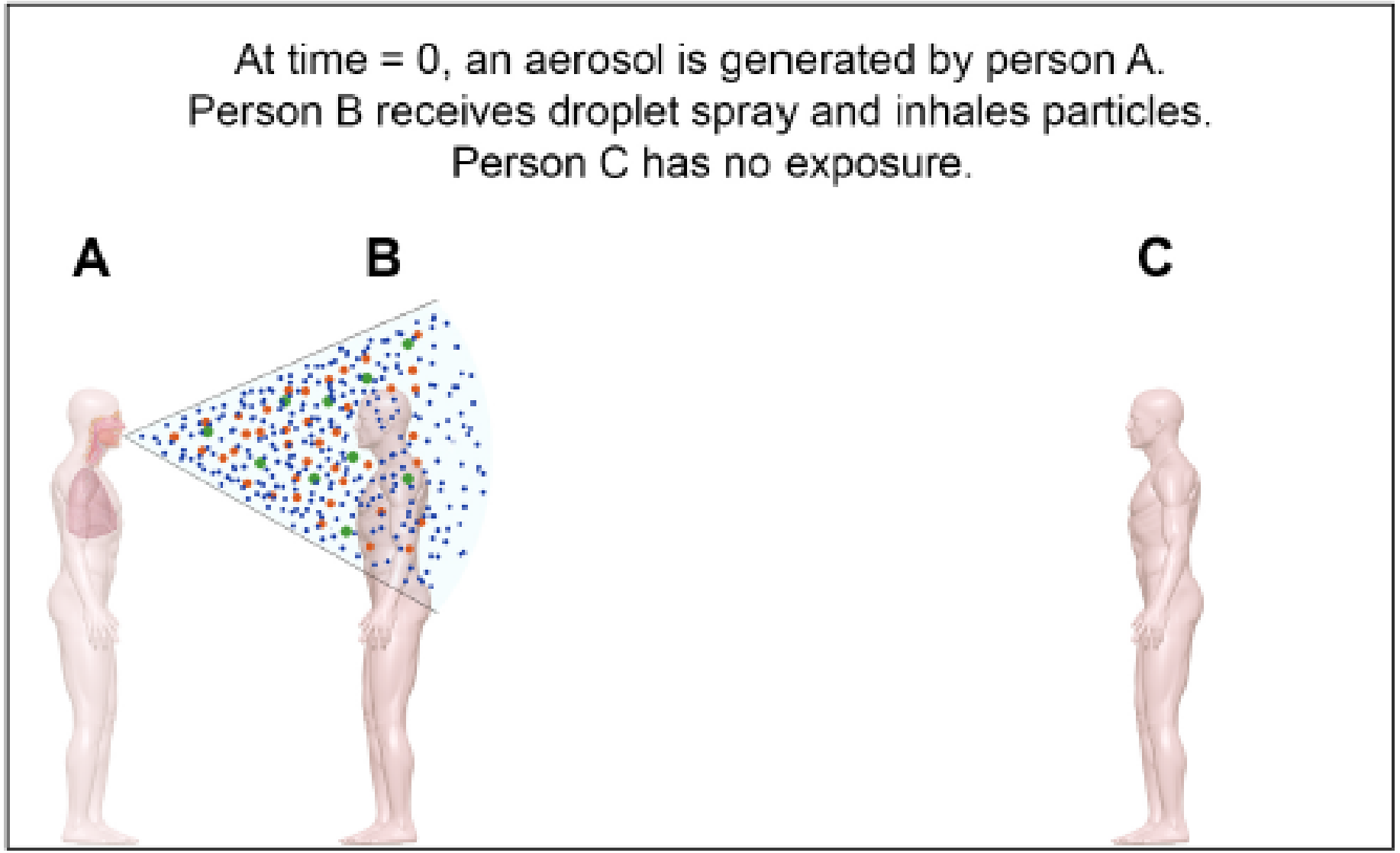
AEROSOL GENERATION

Droplet propulsion & aerosol inhalation at time and point of generation

People generate a wide range of particle sizes during breathing, talking, coughing, sneezing.

Large droplets can be propelled into the nose, mouth & eyes of someone nearby.

Large and small particles can also be inhaled by someone standing nearby.



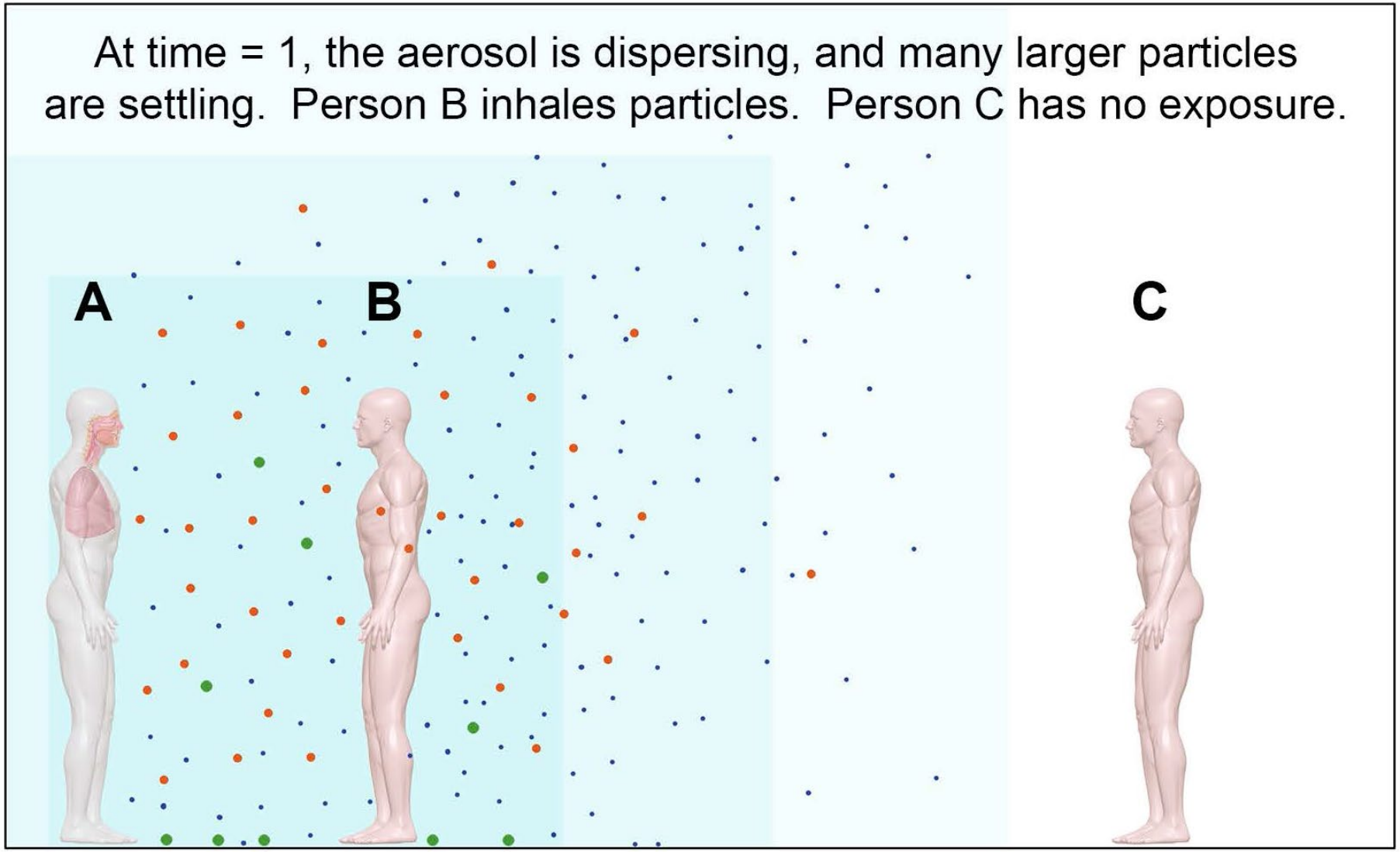
AEROSOL SETTLING AND DIFFUSION

Inhalation near and further from the point of generation

Inhalation continues to be possible near the source as settling and diffusion take place.

Aerosol inhalation is possible further from the source over time.

Infection depends on organism viability and dose (concentration of organisms in aerosol).

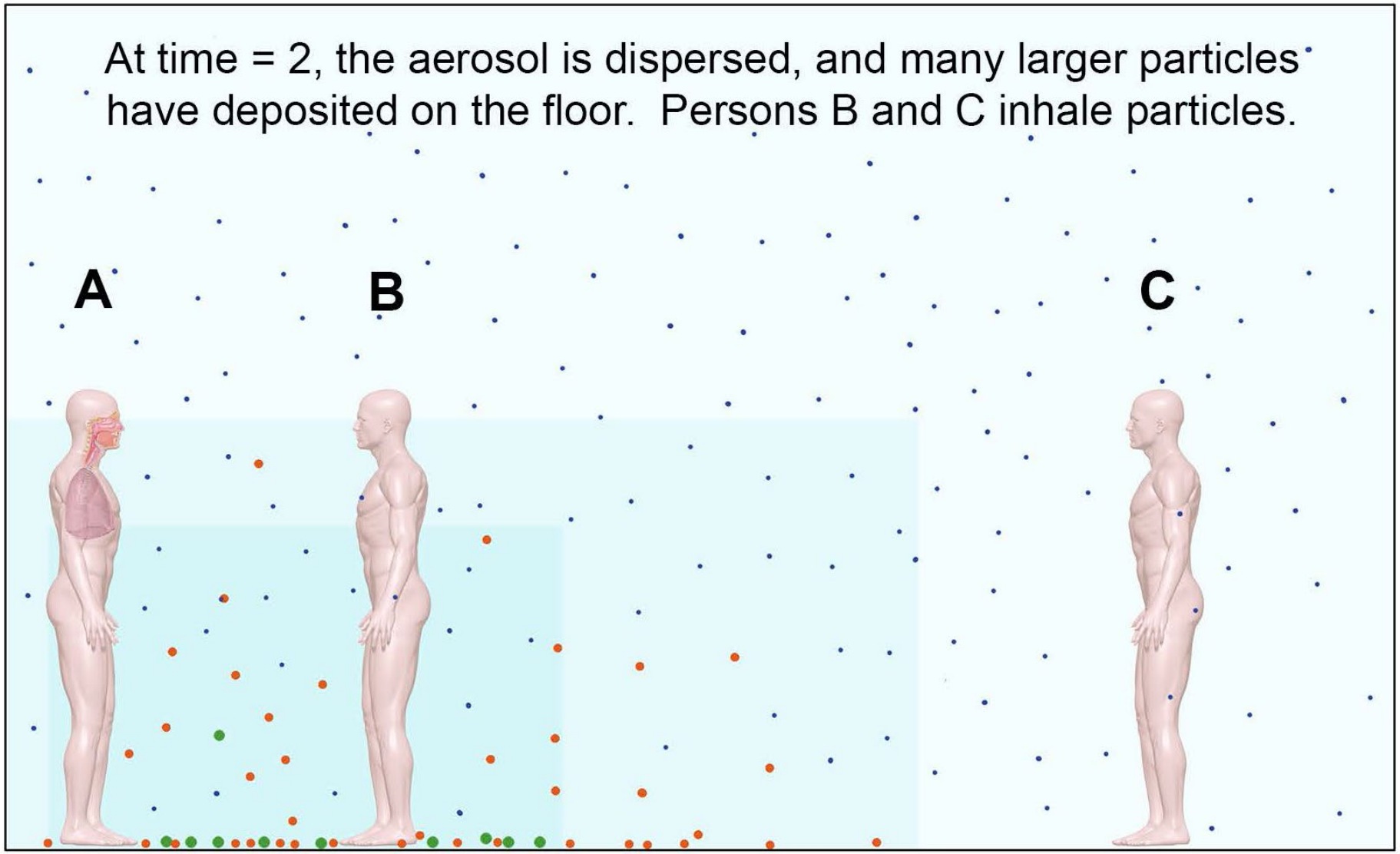


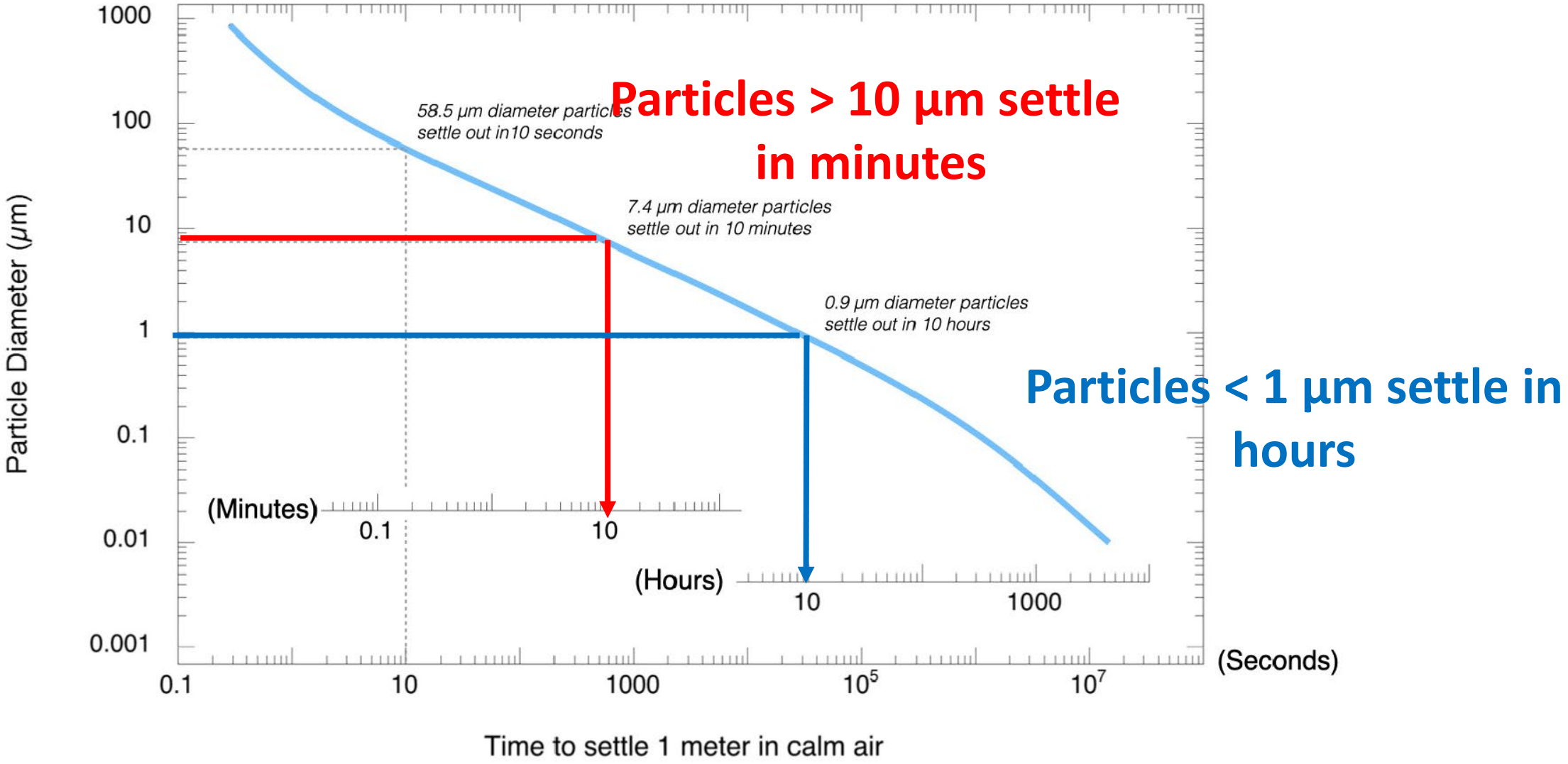
AEROSOL SETTLING AND DIFFUSION

Aerosol inhalation possible throughout the space

Larger particles will settle out, but smaller ones will remain suspended in air and be distributed throughout the space.

People near and far can inhale small suspended particles.



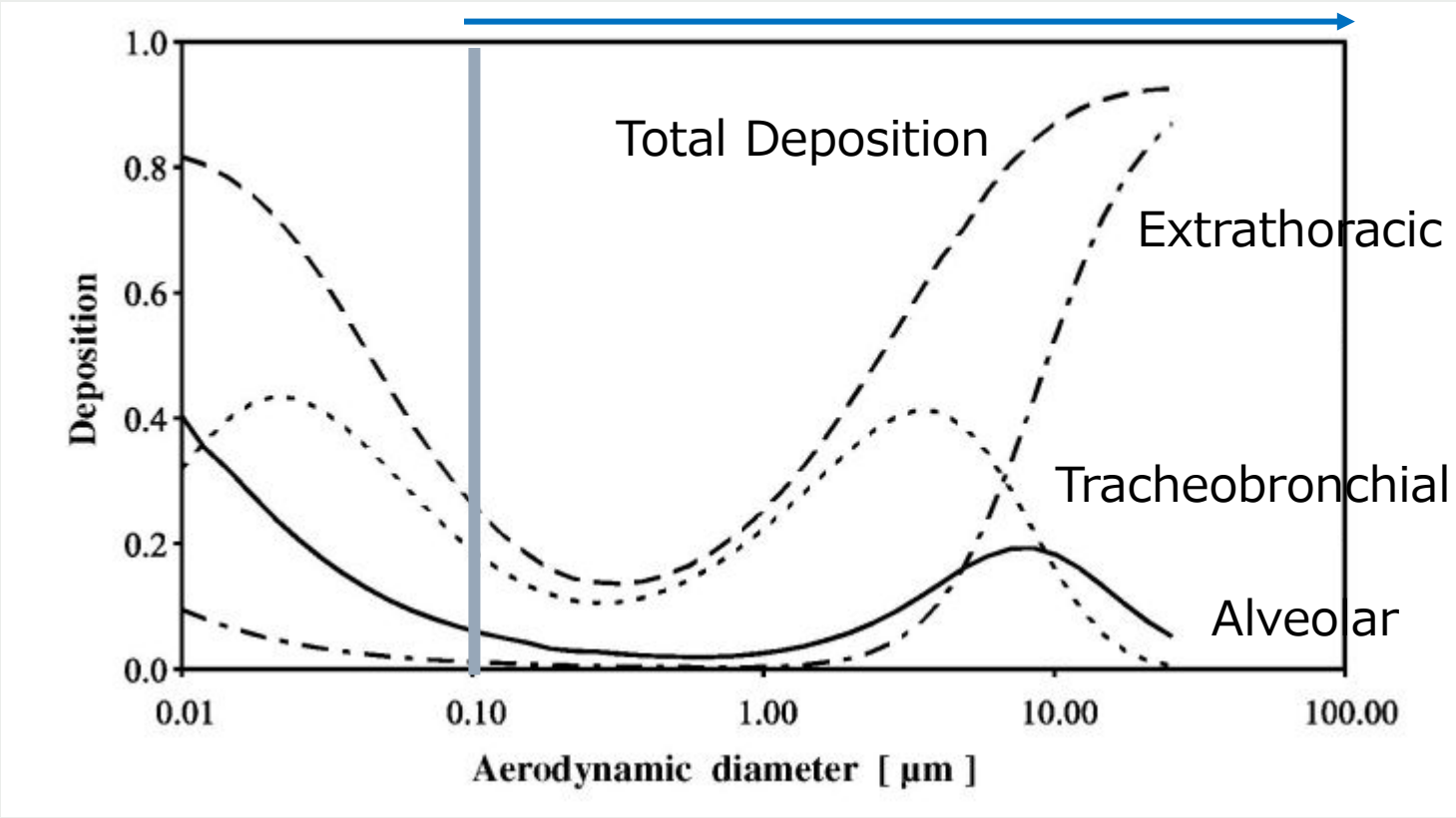


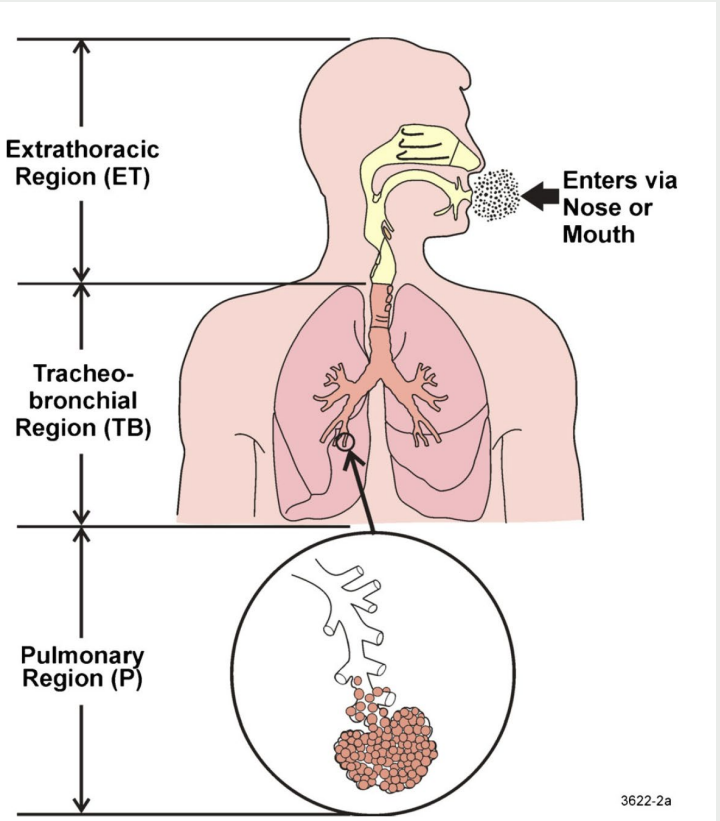
Particles > 10 µm settle in minutes

Particles < 1 µm settle in hours

https://therealandrewmaynard.com/category/health/

Human-generated aerosols are mostly greater than 0.1 µm





5-100+ µm deposit in nose, larynx, pharynx (40-90%)
0.1-30 µm deposit in the lungs (20-40%)
3-30 µm deposit in alveoli (gas exchange region) (10-20%)

Major Reference Works, Pages: 272-292, First published: 31 January 2012, DOI: (10.1002/3527600418.mb0aeroaere0012)

Cheng YS. Mechanisms of pharmaceutical aerosol deposition in the respiratory tract. AAPS PharmSciTech. 2014 Jun;15(3) 630-640. doi:10.1208/s12249-014-0092-0. PMID: 24563174; PMCID: PMC4037474.

Air Mixing

Air isn’t “still” but moves throughout a space:

Ventilation

People movements

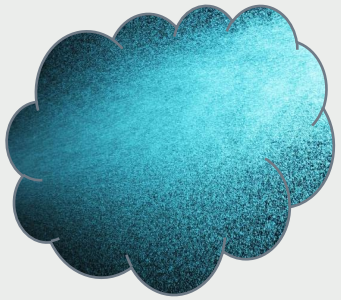
Temperature gradients

Particles move with air, which increases their settling time

New Infection Control Paradigm

Includes Close-Range Aerosol Inhalation

Human-Generated Aerosols Contain Particles in Wide Range of Sizes



Sources:
Breathing
Talking
Singing
Coughing
Sneezing

AEROSOL Transmission

INHALATION OF SMALL PARTICLES AT CLOSE RANGE

AIRBORNE Transmission

INHALATION OF SMALL PARTICLES AT FAR RANGE

PROPULSION OF LARGE PARTICLES AT CLOSE RANGE

DROPLET Transmission

AN ORGANISM CAPABLE OF AIRBORNE TRANSMISSION IS ALSO AEROSOL TRANSMISSIBLE

Person-to-Person Transmission

Lots of transmission in clusters

- Families (households)
- Indoors (restaurants, bars)
- Workplaces

Lots of transmission from people who don’t have symptoms (not coughing or sneezing)

Lots of transmission when people are talking, singing

- Choirs
- Churches

Risk Factors for Person-to-Person Transmission

- Indoors & enclosed spaces
- Low ventilation
- Lots of people
- Long periods of time

ACH < 1; room exhaust fans turned off & sealed

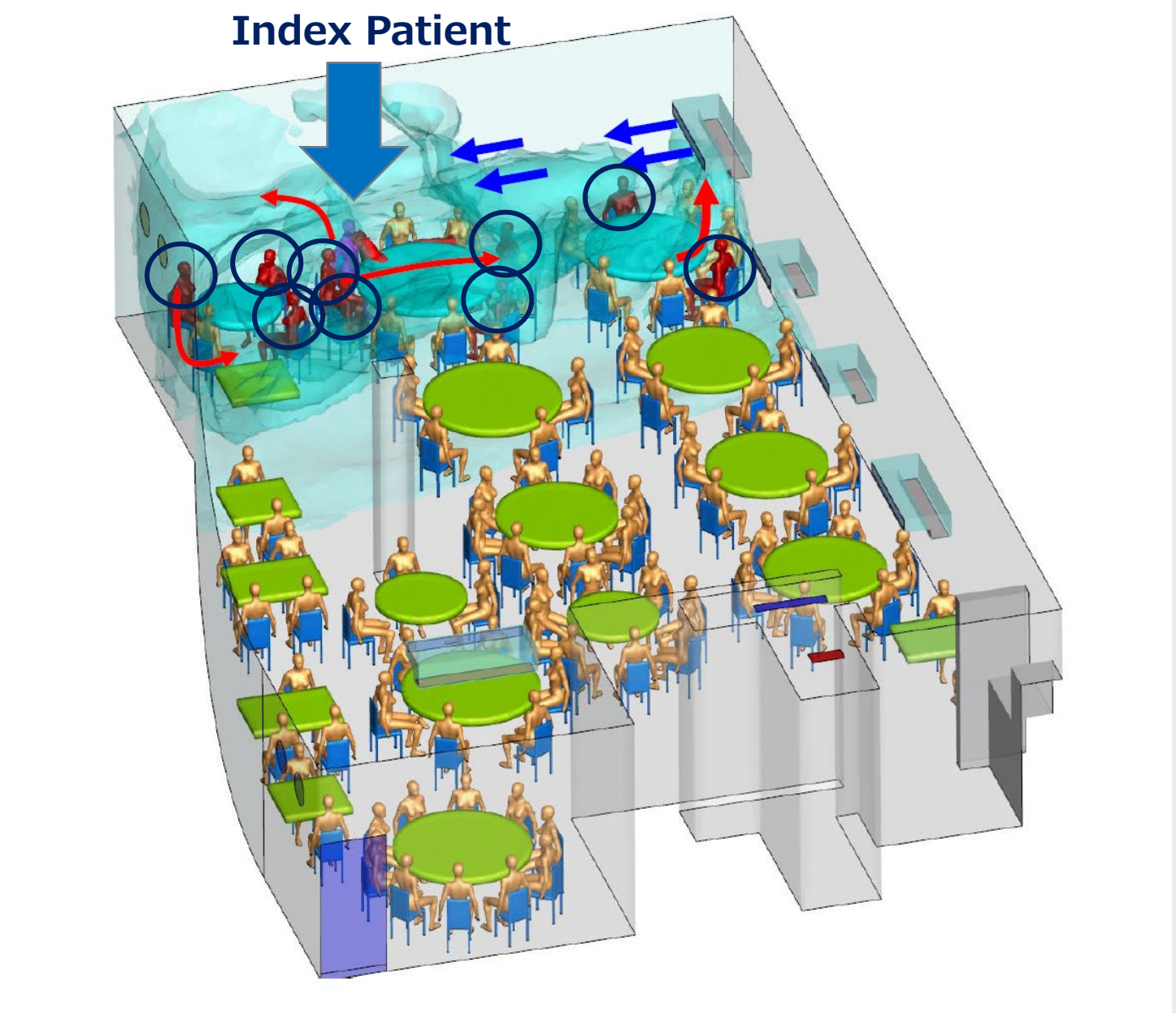
Air conditioning unit created a recirculation zone

Droplet transmission unlikely: distances between index patient and patrons at other tables > 1 m

No evidence for contact or fomite transmission

Three families overlapped for 53-75 min.

Index family = 4 infected
Other families = 2 & 3 infected



Li, Yuguo, et al. "Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant." medRxiv (2020).

What’s the exposure?

Many mobile point sources (people)

Lots of pre- and asymptomatic transmission (minimal coughing and sneezing)

People exhale many large and small particles during breathing and talking

Concentrations are highest in the immediate vicinity of the source, but particles disperse throughout a space

Exposure = Concentration x Time

Source-Pathway-Receptor

SOURCE

PATHWAY

RECEPTOR

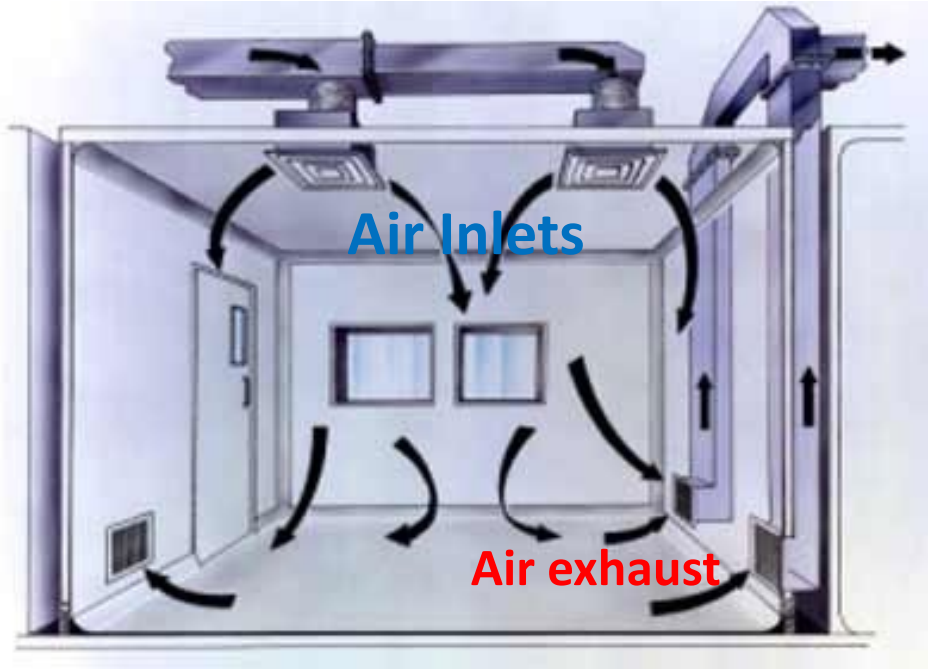
Examples of Source Controls

- Remove workers from workplace – remote work
- Screening & testing to identify infected individuals
  - Not guaranteed to work if there are people without symptoms
- Adjust work schedules to limit the number of people in a space

Pathway Controls

Interrupt the pathway from the source to the receptor

Enclose the source
(requires ventilation in each enclosure)



Use ventilation to dilute and
remove air contaminants

Examples of Pathway Controls

- Barriers that interrupt flow of infectious aerosols from source to receptor
  - Need to be careful about changing airflow from HVAC system
- Increase the amount of dilution air (air changes per hour)
- Separate “clean” and “dirty” sides
- Use distancing
  - But coughs and sneezes can easily travel beyond 6 feet
  - Small particles can be easily distributed throughout a space
- Use local exhaust ventilation to capture infectious aerosols at the source
- Use high efficiency portable air cleaners to remove particles near the source and improve air mixing and cleaning throughout the space

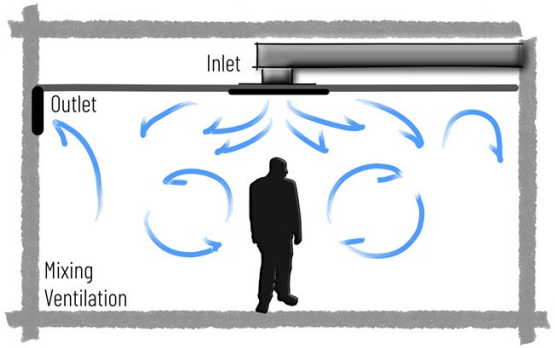
MAY NEED A COMBINATION & MANY REQUIRE EXPERTISE TO SELECT AND MEASURE EFFECTIVENESS

Examples of Receptor Controls

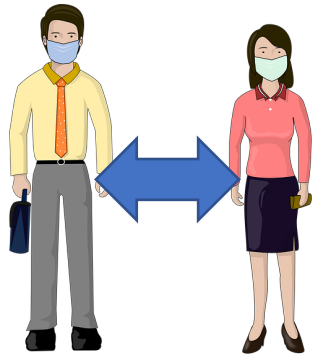
- Control booths
  - Often used in hazardous processing plants
  - May be a problem if occupied by more than one person
- Personal protective equipment
  - Respirators (not face coverings or surgical masks)
- Enclosed separately ventilated spaces (cabs, offices, etc.)

What Determines Aerosol Exposure Indoors?

- Ventilation mode – how air is added and removed from a space
  - Mixing (most common) vs. other (displacement, under-floor, etc.)
- Ventilation rate – amount of air moving through a space in a certain time period (air changes per hour or similar)
- Person-to-person distance



Area	ASHRAE Handbook (1999) Min. Total Air Changes per Hour
Operating Rooms (recirculating air system)	25
Delivery Rooms (recirculating air system)	25
Recovery Rooms	6
Nursery Suite	12
ICU	6
Patient Rooms	4
Medical Procedure/Treatment Rooms	6
Autopsy Rooms	12
Physical Therapy	6
Positive Isolation Rooms	15
Negative Isolation Rooms	6



Immediate vs. Delayed Exposure

- Person-to-person distance is most important for immediate, direct exposure to exhalation from an infected person
  - Closer the distance the more likely and higher the exposure
- Ventilation mode and rate determine what happens to particles over time in a space
  - In well-mixed rooms, distance from the source matters less over time as particles are dispersed throughout the space
  - Higher ventilation rates lower the exposure because air and particles are removed more quickly

Stay far away from people and spend as little time in poorly-ventilated spaces as possible

Similar hazardous aerosol problems?

- Pharmaceuticals
  - No exposure limits
  - Bioactive and highly hazardous
  - Some animal toxicity
- Nanoparticles
  - No exposure limits
  - Highly hazardous materials
  - Limited animal toxicity at the beginning

Control Banding!

Exposure = Likelihood * Duration

Likelihood	Daily Duration		
	D1 (0-3 hours)	D2 (3-6 hours)	D3 (>6 hours)
L1 (Unlikely Exposure)	E1	E1	E1
L2 (Possible Exposure)	E2	E2	E3
L3 (Likely Exposure)	E2	E3	E3

Sietsema, Margaret, et al. "A control banding framework for protecting the US workforce from aerosol transmissible infectious disease outbreaks with high public health consequences." *Health security* 17.2 (2019): 124-132.

Control Band

	Risk Rank			
Exposure Rank	**R1**	**R2**	**R3**	**R4**
E1	A	A	A	B
E2	A	B	B	C
E3	A	B	C	C

Risk Group 3 = Agents associated with serious or lethal human disease for which preventive or therapeutic interventions may be available

Accounts for both the degree of harm and the availability of prophylaxis: https://my.absa.org/Riskgroups

Control Methods Should Follow a Hierarchy

BEST

WORST

FIRST - Source Controls

- isolation, social distancing

NEXT - Pathway Controls

- local exhaust ventilation, barriers

LAST-Receptor Controls

- personal protective equipment

Aim to Lower Exposure Level

GOAL

Reduce exposure to E1 levels by selecting additional control strategies from the source and pathway categories and reducing reliance on PPE

Band	Control Options
A	Source – Do these first! Pathway – May be prudent Receptor – Not necessary
B	Source – Do these first! May require multiple options Pathway – Do these next & may require multiple options Receptor – Only if source and pathway controls are not effective
C	Source – Do these first! May require multiple options Pathway – Do these next & may require multiple options Receptor - May be prudent

Aerosol Transmission = Inhalation of Infectious Particles

- The probability of getting infected depends on inhaling an “infectious dose” = the number of virions needed to make infection likely
  - Function of where particles land in the lung
  - Likelihood of deposition
- Infectious dose does not necessarily imply illness (symptoms and disease)
- Don’t know infectious dose for COVID-19, but might estimate 1000 virions by analogy to influenza and other coronaviruses

Matthew Evans. Avoiding COVID-19: Aerosol Guidelines. Preprint 2020 https://www.medrxiv.org/content/10.1101/2020.05.21.20108894v2

Infectious Dose

- Viral load (RNA copies per mL) in sputum = viral load in particles emitted during breathing, talking, coughing, sneezing, etc.
- Viral emission rate is a function of:
  - Viral load in sputum
  - Volume of air exhaled per breath
  - Breathing rate
  - Number of particles emitted per breath
  - Volume of a particle (function of particle diameter)

Buonanno, Giorgio, Luca Stabile, and Lidia Morawska. "Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment." *Environment International* (2020): 105794.

Steady State Concentration

Steady state concentration of infectious virus in the air (C, virions/m^3) is a function of*

- Generation rate of virions by infectious person (G, virions/min)
- Ventilation rate (Q, m^3/min)

$$C = G/Q$$

Person infected with SARS-CoV-2 generates 1000 virions/nL saliva.**

Human Activity	**Volume of Saliva**	**virions/min (G)**
Sneeze	1 µL (1000 nL)	10^6 (1 sneeze/min = 1,001,000/min)
Cough	100 nL	10^5 (1 cough/min = 101,000/min)
Talking	10 nL/min	10^4
Breathing	1 nL/min	10^3

*Hewett, Paul, and Gary H. Ganser. "Models for nearly every occasion: Part I-One box models." Journal of occupational and environmental hygiene 14.1 (2017): 49-57.

** Evans, Matthew. "Avoiding COVID-19: Aerosol Guidelines." *arXiv preprint arXiv:2005.10988* (2020).

Steady State Concentration

Ventilation rate (Q, m^3/hr) is function of:*

- Number of Air Changes per Hour (ACH) (n)
- Volume of the room (V, m^3)

$$Q = nV$$

Example

Room volume (V) = 300 m^3 and ACH = 5

Q = 1500 m^3/hr or 26 m^3/min

*Hewett, Paul, and Gary H. Ganser. "Models for nearly every occasion: Part I-One box models." Journal of occupational and environmental hygiene 14.1 (2017): 49-57.

Example – Hotel Room

What's the concentration in a 300 m^3 hotel room with 5 ACH if an infectious guest stays overnight (12 hrs)?

Assume mostly breathing (90%), some talking (10%) & periodic coughing (1/hr).

Activity	**Calculation**	**G (virions/min)**
Breathing	0.9 x 10^3 virions/min	900
Talking	0.1 x 10^4 virions/min	1000
1 cough/hr	10^5/hr x (hr/60 min)	1667
Overall		3567

$C = G/Q$ = 3567 virions/min ÷ 26 m^3/min = 137 virions/m^3

What's the exposure?

- What if one person in the room is infectious and the other is not?
- Steady state concentration = 137 virions/m^3
- Dose (D) is a function of concentration (C), breathing rate (Q_{BR}) and time (t):

$$D = CQ_{BR}\mathrm{t}$$

Someone sharing the room with this person, for 12 hours, breathing at a rate of 10 L/min (0.01 m^3/min) will have a dose of 986 virions.

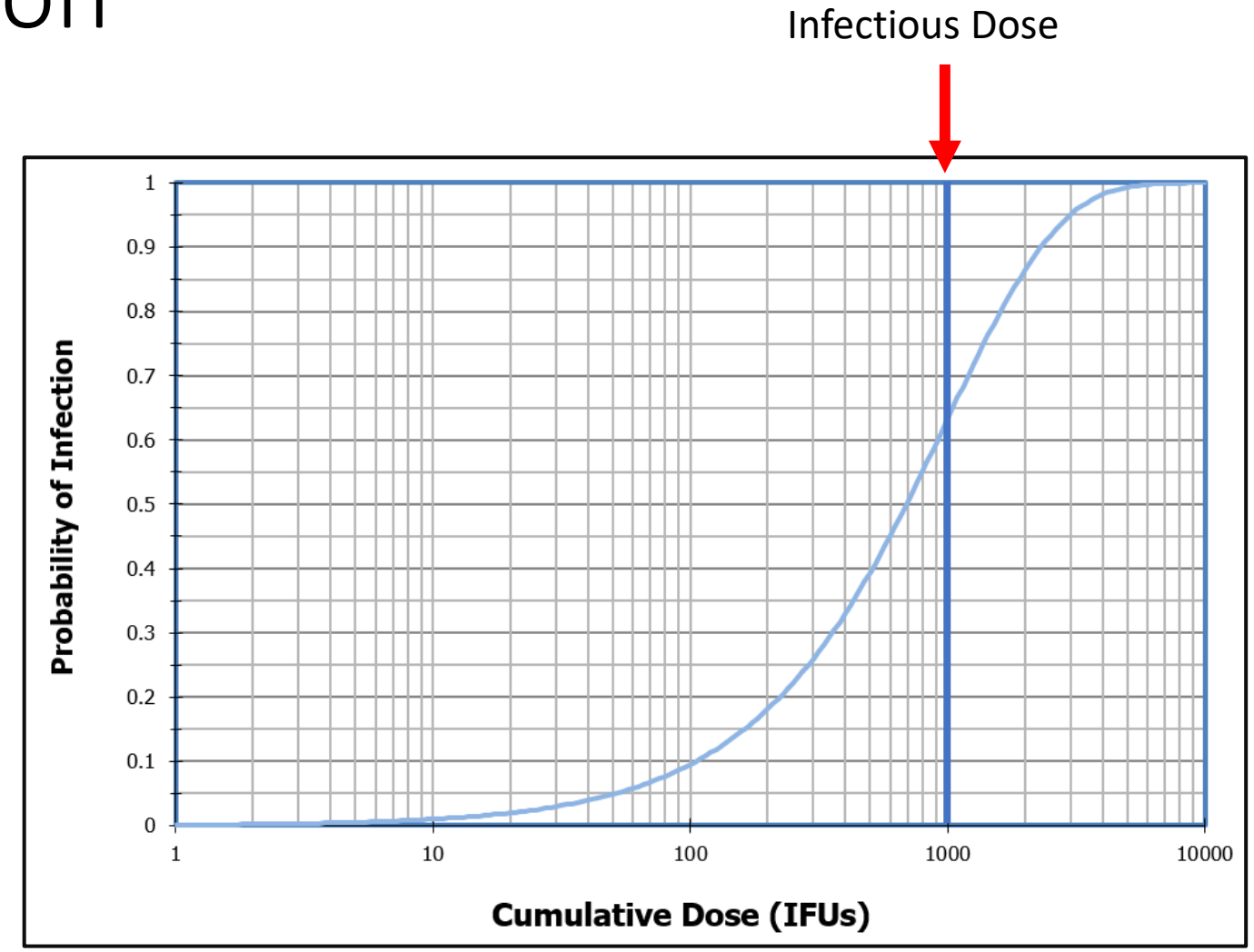
Probability of infection

- Estimate the probability of infection*

$$P(infection) = 1 - \exp(-\frac{D}{D_{infectious}})$$

$D_{infectious}$ = infectious dose = 1000 virions (estimated; not known for SARS-CoV-2)

A dose of 986 virions has a 62% chance of leading to an infection



* Evans, Matthew. "Avoiding COVID-19: Aerosol Guidelines." *arXiv preprint arXiv:2005.10988* (2020).

Using time to infectious dose to illustrate impact of interventions

- Assume a certain dose has a high probability of causing infection.
- Assume the time to an infectious dose (t_{ID}) is 15 min (CDC contact tracing guidelines)
  - Assume this occurs when exposed to a source in a poorly ventilated space (ACH = 1).
  - Note: Contact tracing guidelines also suggest an infectious dose is possible if the 15 min are spread out over a 24 period.
- If a source is wearing a facepiece, the particle generation rate is reduced to its outward leakage (L_O, %), which increases the time to receive an infectious dose to $t_{ID} / L_{O.}$
- If receptor is wearing a facepiece, their exposure concentration is reduced by its inward leakage (L_I, %), which increases the time to receive an infectious dose to $t_{ID} / L_{I.}$
- If both source and receptor are wearing a facepiece, the time to infectious dose is increased by $t_{ID} /(L_I L_O)$.

RECEPTOR'S TIME TO INFECTIOUS DOSE*

	Inward Leakage at the Receptor				
Outward Leakage From the Source	No Facepiece (100%)	Typical Face Covering (75%)	Better Face Covering (50%)	Respirator with Some Leakage (10%)	Well-Fitting Respirator (1%)
No Facepiece (100%)	15 min	20 min	30 min	2.5 hr	25 hr
Typical Face Covering (75%)	20 min	27 min	40 min	3.3 hr	33 hr
Better Face Covering (50%)	30 min	40 min	60 min	5 hr	50 hr
Respirator with Some Leakage (10%)	2.5 hr	3.3 hr	5 hr	25 hr	250 hr
Well-Fitting Respirator (1%)	25 hr	33 hr	50 hr	250 hr	2500 hr

*Assumes that, for a dose with a high probability of infection, the time to infectious dose = 15 min (CDC contact tracing time)

Face Coverings, Surgical Masks & Respirators

Face Coverings

- Filters are very inefficient
- Fit is almost impossible to achieve
- May be possible to get a fit factor of 2

PUBLIC SHOULD WEAR

Surgical Masks

- Filters may be a little more efficient than face coverings, but impossible to predict
- Fit is very poor
- May be possible to get a fit factor of 4-6 for masks with “good” filters

PATIENTS SHOULD WEAR

Respirators

- Filters are very efficient
- Fit must be evaluated for each person & respirator
- Must be able to achieve a fit factor of 100 for use in the workplace

WORKERS SHOULD WEAR

Using time to infectious dose to illustrate impact of increasing the air exchange rate

- Assume a certain dose has a high probability of causing infection.
- Assume the time to an infectious dose (t_{ID}) is 15 min (CDC contact tracing guidelines)
  - Assume this occurs when exposed to a source in a poorly ventilated space (ACH = 1).
  - Note: Contact tracing guidelines also suggest an infectious dose is possible if the 15 min are spread out over a 24 period.
- If increase ACH by 2, time to an infectious dose also increases by 2
- If increase ACH by 3, time to an infectious dose increases by 3
- etc….

RECEPTOR'S TIME TO INFECTIOUS DOSE*

	Inward Leakage at the Receptor				
Outward Leakage From the Source	1 ACH + No Facepiece	3 ACH + No Facepiece	6 ACH + No Facepiece	6 ACH + Better Face Covering (50%)	6 ACH + Respirator with Some Leakage (10%)
No Facepiece (100%)	15 min	45 min	1.5 hr	3 hr	15 hr
Typical Face Covering (75%)	20 min	1 hr	2 hr	4 hr	20 hr
Better Face Covering (50%)	30 min	1.5 hr	3 hr	6 hr	30 hr
Respirator with Some Leakage (10%)	2.5 hr	7.5 hr	15 hr	30 hr	150 hr

*Assumes that, for a dose with a high probability of infection, the time to infectious dose = 15 min (CDC contact tracing time)