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

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Fundamentals

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

Layered Risk Reduction Strategy
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
Mean = 75,400  SD = 97,300 / cough

Range:  900 – 302,000 / cough


• 0.35-10 μm
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
Exposure Pathways & General Fate

1. Direct contact
2. Fomites
3. Close contact: Near-field aerosols + droplets
4. Far-field aerosols
Inactivation Rates of SARS-CoV-2

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

- $t_{1/2} = 1.1 \text{ hr}$ → decay rate = 0.63/hr
- “ballpark” of ACH for residential buildings
- lower than many non-residential buildings
Deposited Inhalation Dose

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

- \( C_i \) = 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
- \( f_{\text{dep},i} \) = Deposition of particles of size \( i \) in resp
  - particle size; breathing mode; activity
Deposition In Respiratory System

![Diagram of the respiratory system]

![Graph showing predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.]

**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
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%

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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?
At air speed of 5 cm/s in free stream

<table>
<thead>
<tr>
<th>$d_a$ (μm)</th>
<th>$V_{TS}$ (m/s)</th>
<th>$k_d$ (1/hr)</th>
<th>$X_{1.5m}$ (m) - GS</th>
<th>$X_{50%}$ (m) - PF</th>
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<td>50</td>
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</tbody>
</table>

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

Even 50 to 100 μm particles can travel > 6 ft (warm jet)
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 = $\eta \times Q$
  - $\eta$ = single pass removal fraction (-)
  - Q = volumetric flowrate (ft$^3$/min)
- Example: $\eta = 0.5$; Q = 500 ft$^3$/min; CADR = 250 ft$^3$/min
Portable Air Cleaners

- Equivalent air changes per hour = EqACH = \( \frac{CADR}{V} \) (V = volume of indoor space)
- Example: \( V = 600 \text{ ft}^2 \times 8 \text{ ft} = 4,800 \text{ ft}^3 \)
- CADR = 300 ft\(^3\)/min
- EqACH = \( 300 \text{ ft}^3/\text{min} / 4,800 \text{ ft}^3 = 0.0625/\text{min} \) (or \( \times 60 = 3.8/\text{hr} \))

If \( \lambda = 0.5/\text{hr} \) \( \frac{3.8}{0.5} = 7.6 \)

\( 1 + 7.6 = 8.6 \)

89% reduction
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
Example: Portable Air Cleaners

Example of filter/fan performance
Black carbon during wildfire smoke event, house #4, windows and doors closed

@MPHPJect

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Summary

- 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

- Reduce source
- Require masks indoors
- Distance from source
- Reduce time indoors
- Ventilate
- Filter / Inactivate
- Clean
- Educate
Extra Slides for Discussion
Resuspension of Particles?

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

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**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?

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**Masks reduce airborne transmission**

Infectious aerosol particles can be released during breathing and speaking by asymptomatic infected individuals. No masking maximizes exposure, whereas universal masking results in the least exposure.

- **Particle size (µm)**
  - 100
  - 10
  - 1
  - 0.1

**Infected, asymptomatic**

**Healthy**

GRAPHIC: V. ALTOUNIAN/SCIENCE
Particle deposition in resp system

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

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 Mechanisms

Gravitational settling important
Other deposition mechanisms

- Humans
- Furnishings
- Fan blades
- Fiber in a filter

More “clutter” = more op for removal
More mixing = more op for removal

Electrostatic & thermophoretic effects

\[ \beta_i = \lambda + k_{dep,i} + \sum \frac{C_i Q_i c_i}{v} + f_{air,i} \frac{Q_b}{v} + \cdots \]


- \( k_{dep} \) for 0.5 to 10 \( \mu \)m particles \( \approx \) 0.1 to 7 h\(^{-1}\)
- Context: \( \lambda \approx (0.3 \text{ to } 4 \text{ h}^{-1})^* \) – \( fn(\text{type of building}) \)
EID Applied to Restaurant X

- 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
- 89 patrons / 1 infector / 10 infected
- Significant metadata
- 138 m² / 431 m³  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/10.1101/2020.04.16.20067728 doi medRxiv preprint
Comparative Analysis – Restaurant X

- EID: Deposited inhaled volume in ABC patrons
- $1 – 10 \text{ pL (}10^{-12} \text{ L)} / \text{patron for 75 min event}$
- 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 $\Omega$

$$\Omega = \frac{\text{Volume}_{\text{dep}}}{\text{Volume}_{\text{dep, Restaurant X}}}$$

* In lieu of having a dose-response relationship
Busy Restaurant

100 m² 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 m² 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

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

Additional considerations: close contact & fomites

- Concern across board
- Outdoors w/ distancing
- Remote?
Gym w/ Aerobic Activity

- 40 patrons; Staff member = Index X; Heavy breathing receptor (aerobics)
- 100 m² 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 $\Omega \approx 0.1$

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

< 1/1,000\(^{th}\) Restaurant X

100 x lower than previous low
• 700 ft²; 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 $\Omega$

Additional considerations: close contact & fomites
General Fate & Pathways

\[
\frac{dC_i}{dt} = \frac{E_i}{V} - \beta_i C_i \\
\beta_i = \lambda + R_{dep} + \sum \frac{z_i q_i}{V} + \sum f_{ani} \frac{Q_b}{V}
\]
Particle Deposition by Settling

Gravitational settling

\[ V_{TS} = \frac{\rho_p d_e^2 gC_c}{18 \eta X} = \frac{\rho_o d_a^2 gC_c}{18 \eta} \]

<table>
<thead>
<tr>
<th>( d_p (\mu m) )</th>
<th>( t (1.5 \text{ m}) )</th>
<th>( x (\text{ m}) )</th>
</tr>
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<tbody>
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<td>2 min</td>
<td>6</td>
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<tr>
<td>50</td>
<td>20 sec</td>
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</tbody>
</table>

Based on 5 cm/s air speed in free stream

Particles \( \geq 50 \mu m \) can travel further than 1 m

Other mechs important as \( d_p \) becomes small