Fundamentals of COVID-19 Risk Management

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SARS-CoV-2, The virus that causes Covid-19

- Coronavirus – related to strains that cause SARS and MERS
- RNA virus with lipid envelope
- Diameter $\approx 120$ nm (0.12 $\mu$m)
- Survives for hours in air, days on surfaces
  Duration affected by T and RH
- Not accurately determined yet orders of magnitude range:
  - Shedding rate
  - Infectious dose
Infectious Disease Transmission Modes

- Airborne
  - Droplet spray
  - Aerosol
- Fomite – intermediate surface
- Physical contact
- Water/food
- Insect/animal vector

...HVAC mainly impacts aerosol and fomite transmission
Sources of Infectious Aerosols

- Humans – breathing, talking, singing, coughing, sneezing
- Plumbing – toilet flushing, splashing in sinks
- Medical procedures – dentistry, endotracheal intubation, and others
Respiratory Droplet Size and Concentration

Small droplets become particles that remain in air

- Droplets contain water, proteins, salts...
- Dry to 20 – 40% of initial size
- Viruses non-uniformly distributed by size
- Studies of influenza have found ~90% of viral load in particles < ~5 µm (Milton, et al. PLoS Pathog 9(3): e1003205. doi:10.1371/journal.ppat.1003205)

Particle Settling in Still Air

Time to settle 5 feet by unit density spheres

- 0.5 µm 1 µm 3 µm 10 µm 100 µm
- 41 hours 12 hours 1.5 hours 8.2 minutes 5.8 seconds

Aerodynamic diameter definition: diameter of a unit density sphere that settles at the same velocity as the particle in question

5 ft = 1.52 m
Evaporation of respiratory droplets with variable humidity

http://dx.doi.org/10.1098/rsif.2017.0939
SARS-CoV-2 RNA has been found in aerosols

SARS-CoV-2 RNA has been recovered from HVAC systems

Found on pre-filters, final filters, and supply air dampers

Active SARS-CoV-2 has been found in aerosols

Community Spread Incidents Suggest In-Space Airborne Spread

- Guangzhou restaurant
  - Split system air-conditioning – strong in-space recirculation
  - No ventilation air supply
  - Four exhaust fans, none running
  - No close contact observed on video
  - Measured ventilation rate ~0.75 – 1 L/s per patron
- Conclusions: “aerosol transmission of SARS-CoV-2 due to poor ventilation may explain the community spread of COVID-19.”
The streamlines showed how the ABC recirculation bubble was possibly established.
Summary – HVAC-related transmission

• Active SARS-CoV-2 has been found in indoor air
• There is evidence that viral aerosols are captured by return air and can pass through air handling units
• There is evidence of airborne infection in poorly ventilated spaces where infectors and susceptibles are present for a significant period of time
• There is no clear evidence of transmission of COVID-19 from one space to another
Fecal aerosol transmission is suspected in some cases, similar to SARS Amoy Garden outbreak

- SARS-CoV-2 has been cultured from feces
- 9 infections in three families
- Apartments vertically aligned and connected to same plumbing stack
- No evidence (sampling) of transmission via elevator or other routes

ASHRAE position since April 2020

- Transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating, ventilating, and air-conditioning systems, can reduce airborne exposures.

Park, et al. (2020) Emerging Infectious Diseases 26(8), August.
The Precautionary Principle

“One should take reasonable measures to avoid threats that are serious and plausible.”

Recent CDC statements on COVID-19 transmission (10/5/2020)

- **COVID-19 most commonly spreads during close contact**

- **COVID-19 spreads less commonly through contact with contaminated surfaces**

- **Airborne transmission of SARS-CoV-2 can occur under special circumstances**
  - Enclosed spaces
  - Prolonged exposure to respiratory particles
  - Inadequate ventilation and air-handling
Risk Management – HVAC is one layer of an effective mitigation strategy

- Source elimination
  - Testing, contact tracing
- Substitution – NA
- Engineering controls
  - HVAC interventions to control aerosols
- Administrative controls
  - Rules and procedures
- Personal protective equipment
  - N95 mask – mainly protects wearer
  - Surgical/cloth masks mainly protect others
Quantifying airborne risk – the Wells-Riley model

\[ P = \frac{C}{S} = 1 - \exp \left( - \frac{Iqpt}{Q} \right) \]

- **P** = probability of new infections
- **C** = new infections
- **S** = number of susceptibles
- **I** = number of infectors
- **q** = quanta generation rate (1/hr)
- **p** = pulmonary ventilation rate per susceptible (m3/h)
- **t** = exposure time (hr)
- **Q** = flow rate of uncontaminated air (1/hr)

- Steady-state conditions
- Time-dependent risk
- Quanta determined from data
Equivalent clean (outdoor) air flow for other removal factors can be included in Wells-Riley

\[ P = 1 - \exp \left( -\frac{ipt}{Q} \right) = 1 - \exp \left( -\frac{ipt}{V} / \alpha_{OA} \right) \]

Substitute outdoor air changes, \( \alpha_v \)
for \( Q \)

For an air cleaner with CADR = \( Q_{AC} \),

\[ \alpha_{AC} = \frac{Q_{AC}}{V} \]

Equivalent ACH = \( \alpha_{OA} + \alpha_{AC} \), so

\[ P = 1 - \exp \left[ -\frac{ipt}{V} / (\alpha_v + \alpha_{AC}) \right] \]

• Can include outdoor air, mechanical filtration, air cleaners, deposition, natural decay if quantifiable
• Applies contaminant by contaminant
• Placement of filter or air cleaner in system matters
Exposure time and air flow are the main independent parameters

• Stephens (2012) HVAC filtration and the Wells-Riley approach to assessing risks of infectious airborne diseases. Final report to NAFA.

• Risk of infection for an average adult susceptible ($p = 0.48 \text{ m}^3/\text{h}$) in a 500 m$^2$ office for 8 hours with one infected person
Quanta emission rates have been estimated for SARS-CoV-2…but not very accurately

<table>
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<th>ERₙ</th>
<th>5th percentile</th>
<th>25th percentile</th>
<th>50th percentile</th>
<th>75th percentile</th>
<th>90th percentile</th>
<th>95th percentile</th>
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Quantiative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications

G. Buonanno, L. Morawski, L. Stahle

ABSTRACT
Airborne transmission is a recognized pathway of contagion; however, it is rarely quantitatively evaluated. The numerous outbreaks that have occurred during the SARS-CoV-2 pandemic are putting a demand on researchers to develop approaches capable of both predicting contagions in closed environments (prospective assessment) and analyzing previous infections (retrospective assessment).

This study presents a novel approach for quantitative assessment of the individual infection risk of susceptible occupants exposed to airborne aerosols in the context of an asymptomatic infected SARS-CoV-2 subject. The application of a Monte Carlo method allowed the risk for an exposed healthy subject to be evaluated, starting from an acceptable risk, the maximum exposure time. We applied the proposed approach to four distinct scenarios for a prospective assessment, highlighting that, in order to guarantee an acceptable risk of 10⁻³ for exposed subjects in naturally-ventilated indoor environments, the exposure time could be well below one hour. Such maximum exposure time clearly depends on the viral load emission of the infected subject and on the exposure conditions; thus, longer exposure times were estimated for mechanically ventilated indoor environments and lower viral load emissions. The proposed approach was used for retrospective assessment of documented outbreaks in a restaurant in Guangzhou (China) and at a choir rehearsal in Mount Vernon (USA), showing that, in both cases, the high attack rate values can be justified only assuming the airborne transmission as the main route of contagion. Moreover, we show that such outbreaks are not caused by the fart production of a superspreader, but can be likely explained by the co-existence of conditions, including emissions and exposure parameters, leading to a high probabil of attack, which can be defined as a “superspreading event.”
Engineering Controls

- Ventilation
- Air distribution
- Filtration
- Disinfection
- Temperature and humidity control
Ventilation with Outdoor Air

- Dilutes contaminants, increases exposure time required for exposure to an infectious dose
- Effective, but energy intensive, even with energy recovery
- Minimum required (e.g., ASHRAE 62.1) is a good baseline
- 7-10 L/s-pers ≈ 15-20 cfm/pers

Sun, et al. (2011)
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3217956/
How much ventilation is enough?

- Difficult to say for Covid-19 due to limited knowledge of shedding rate and infectious dose
- Superspreading incidents seem to be associated with lower than minimum standard ventilation rates
- At least up to minimum standard seems like a good starting place
- ~7L/s-pers, 15 cfm/pers
Many studies point to health and productivity benefits at 2 – 3X current minimums.
Air Distribution

- Strong drafts may extend distance travelled by large droplets
- Lower velocity mixing may be preferable to displacement
- Personalized ventilation/exhaust may apply in some cases
Filtration

- High efficiency filters can remove respiratory aerosols efficiently
- For indoor sources, must have recirculation in space or through central system
- Effective if clean air delivery rate (efficiency × flow rate) is high enough

Representative MERV rated filter performance (Kowalski and Bahnfleth 2002)
Respiratory droplets that carry infectious disease pathogens are not captured by minimum standard (MERV 6, 8) filters – use MERV 13

<table>
<thead>
<tr>
<th>Diameter Range</th>
<th>MERV 6</th>
<th>MERV 8</th>
<th>MERV 13</th>
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<tbody>
<tr>
<td>1 (0.3-1µm)</td>
<td>N/A</td>
<td>N/A</td>
<td>≥ 50%</td>
</tr>
<tr>
<td>2 (1-3 µm)</td>
<td>N/A</td>
<td>≥ 20%</td>
<td>≥ 85%</td>
</tr>
<tr>
<td>3 (3-10 µm)</td>
<td>≥ 35%</td>
<td>≥ 70%</td>
<td>≥ 90%</td>
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</table>

Filtration can be a lower energy way to reduce aerosol/airborne infection risk

Relative influenza risk reduction, filters vs. ventilation cost, 500 m² office building
Particles that can penetrate the alveolar region of the lungs are not captured by minimum standard filters.

FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.
Filtration has benefits other than infection control

Air disinfection – germicidal UV light

- Ultraviolet light in UVC band
- 265 nm ideal, 254 nm produced by low pressure Hg vapor lamps is standard
- Disrupts microbial DNA/RNA, prevents reproduction
- Exponential dose response
- Coronavirus susceptibility is good
- Long record of application, CDC approved for tuberculosis control as adjunct to filtration
- Emerging technology – LEDs, far UV (222 nm) from Kr-Cl excimer lamps
Germicidal UV applications

Upper Air UVGI

In-Duct/Coil UVGI

Portable Surface Treatment UVGI
Other air cleaners – many types with different evidence of effectiveness and safety

- Electrostatic precipitators
- Thermal filters
- Reactive oxygen species - based
  - Ionization
  - Dry hydrogen peroxide
  - Photocatalytic oxidation

Key questions
- What is evidence for effectiveness as applied?
- Is it safe in application?
  - Direct exposure
  - Byproducts
- Is it really better than increased filtration efficiency or outdoor air?
System Effects – Combining Ventilation, Filtration, and Air Cleaning

- Combinations of controls can be synergistic
  - MERV rated filter + UV can approach HEPA performance
- Some combinations of controls are mutually exclusive
  - DOAS + central filtration for indoor contaminants
- Some are additive but trade off
  - Ventilation + air cleaning

- Air cleaner effectiveness – describes incremental effect of a control

\[ \varepsilon = \frac{C_{\text{uncontrolled}} - C_{\text{controlled}}}{C_{\text{uncontrolled}}} \]

Ventilation/Filtration Trade Off

• Simple example: Ventilation + Filtration
  • Well-mixed, steady state
  • $Q_s = 100$
  • $S = 1$
  • $C_O = 0$

• Scenario 1
  • $\eta_F$ = variable
  • 20% OA

• Scenario 2
  • $\eta_F$ = 60%
  • $f$ = variable
Ventilation/Filtration Trade-Off

20% OA, variable filter efficiency

60% filter efficiency, variable OA OA

Normalized space concentration is relative to value at 20% OA with no filter
Temperature and Humidity Control

• Faster inactivation of SARS-CoV-2 at higher T and RH
• Limited ability to vary T in comfort zone
• 40-60% RH → lower infection rates in some studies
• Good to do if feasible
• Difficult to humidify many existing buildings safely
• Significance for COVID-19 needs further investigation
Humidity has a large impact on rate of inactivation
Settling is affected by humidity, but not much
If ventilation and filtration are at recommended levels, impact of RH on exposure is secondary
Not clear – effect of RH on susceptibility
Without masks, 6 ft/2m distancing isn’t enough, and aerosol emissions may be more than 2X


Credit: M. Staymates/N. Hanacek/NIST
doi:10.20944/preprints202004.0203.v2
ASHRAE Epidemic Task Force

- Formed in March 2020 by direction of ASHRAE BOD to Environmental Health Committee
- Scope
  - Short term guidance
  - Re-opening/2nd wave guidance
  - Future directions
    - Research
    - Standards
    - Education
- 26 members
  - 22 volunteers
  - 4 ASHRAE staff
- Functions as a steering committee
- 15 teams with over 150 members
- Activities
  - Guidance
  - Q&A
  - Meetings and presentations
  - Educational programs
Core Principles of Airborne Engineering Control

- Follow public health guidance: masks, distancing, hygiene, etc.
- Ventilation, Air Cleaning, Air Distribution
  - Fundamental
    - Required minimum outdoor air (e.g., ASHRAE 62.1)
    - Filtration – MERV 13 or equivalent for recirculated air
  - Supplemental
    - Standalone filters
    - Air cleaners -technologies demonstrated to be effective/safe
    - Increased outdoor air
  - Where directional airflow is not specifically required, promote mixing without causing strong air currents that increase direct transmission from person-to-person.
  - Use equivalent outdoor air approach to exceed baseline outdoor air and filtration requirements (e.g., air change targets)
Core Principles (continued)

- Operations
  - Maintain T and RH set points…not a first order control
  - Maintain outdoor and cleaned airflows required for design occupancy whenever anyone is in the building
  - When necessary to clear spaces between occupied periods, flush with 3 equivalent air changes pre-occupancy
  - Limit re-entry to acceptable levels – exhaust, energy wheels, etc.

- HVAC commissioning
  - Verify that HVAC systems are functioning as designed
  - GAO report indicates that in more than in ~41% of US school districts, more than 50% of HVAC systems require major repairs or replacement

Summary

• HVAC systems reduce risk of aerosol/airborne transmission by reducing airborne concentration – one part of a layered risk management program

• Risk can be reduced, not eliminated

• Multiple engineering controls are available – equivalent air exchange rate approach provides a path to optimization

• ASHRAE Epidemic Task Force has produced a large body of detailed guidance – but the underlying principles are straightforward
Thank You!

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ashrae.org/covid19