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Effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2

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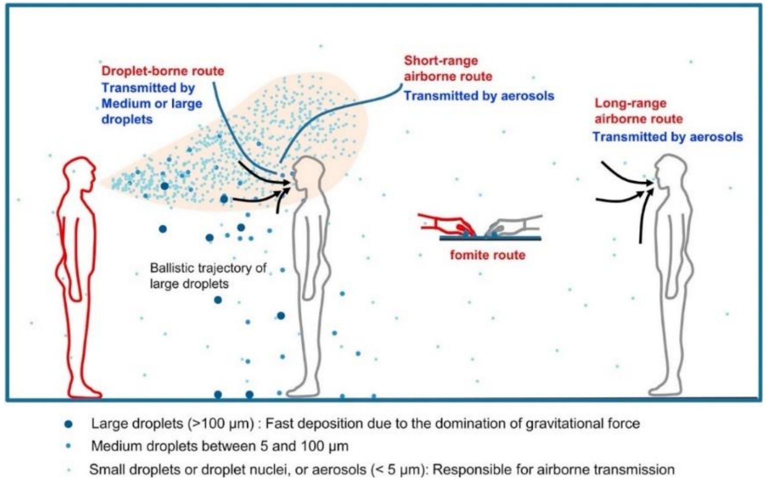
Background

Airborne transmission of SARS-CoV-2

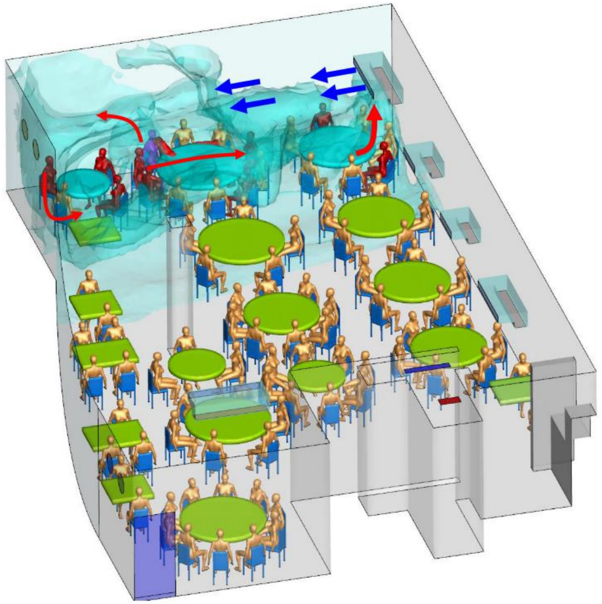
Infection transmission usually includes 3 routes:

1. Fomite route (building surface, skin...)
2. Droplet-borne route (medium or large droplets)
3. Short-range/long-range **airborne route** (by aerosol)



Airborne transmission of SARS-CoV-2 is supported by

1. Onsite virus measurements in the air or aerosols (infectious aerosols detected in hospitals)
2. Laboratory experiments
3. Animal experiments
4. Retrospective analysis on real outbreak events (e.g. Guangzhou restaurant, Skagit Valley Chorale, German meat processing plant, apartments in Seoul and Guangzhou, buses and coaches)



Guangzhou restaurant case (Jan 2020)

Wei, J.; Li, Y. 2016. https://doi.org/10.1016/j.ajic.2016.06.003.
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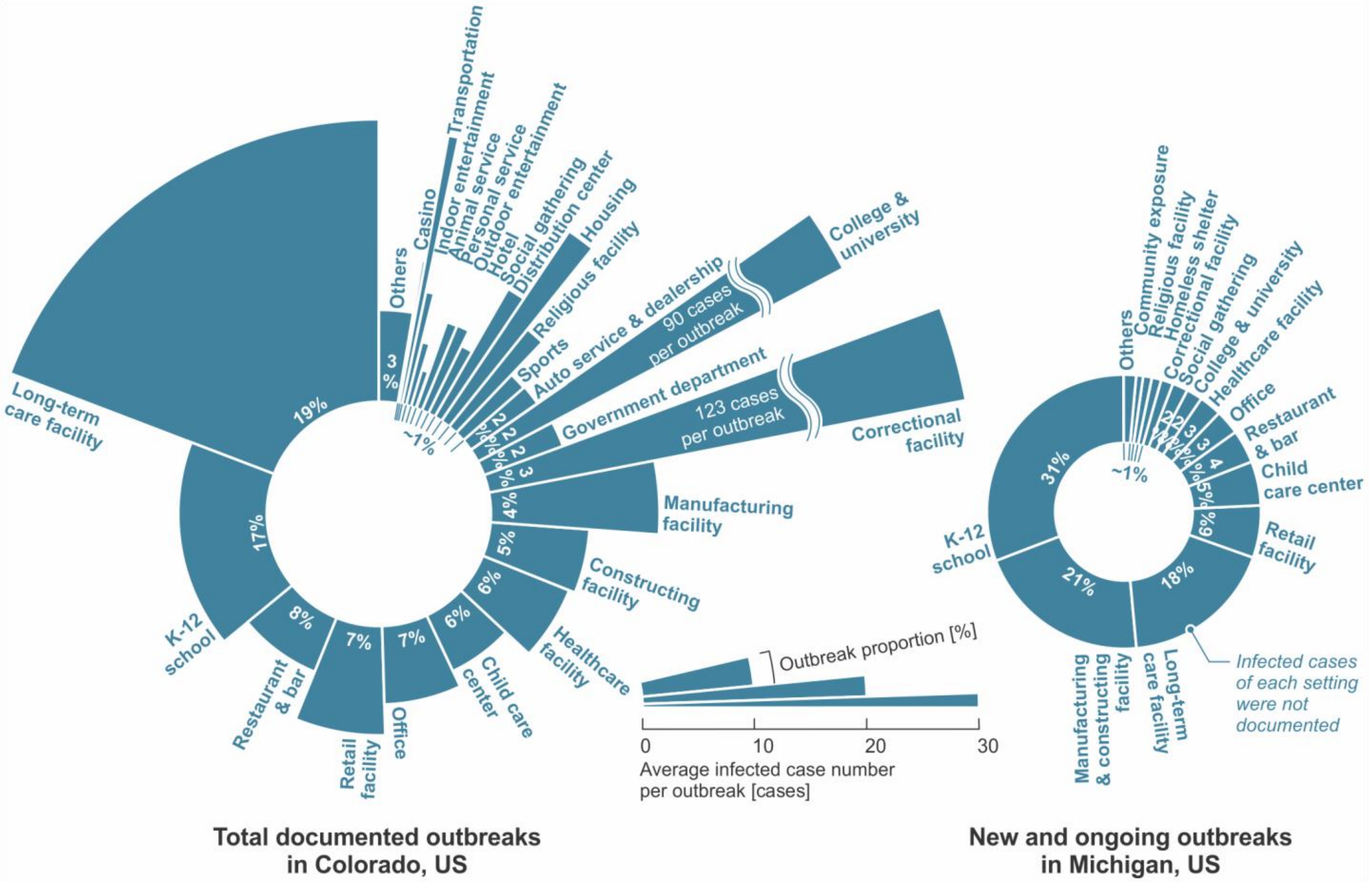
Background

SARS-CoV-2 outbreaks in indoor environments

Indoor COVID-19 outbreaks
- Home-based outbreaks: 79.9%
- Transportation-based outbreaks: 34.0%

→ **Poor ventilation** indoors increase the infection risk through airborne transmission

Hotspots of indoor outbreaks
- Long-term care facilities
- K-12 schools
- Restaurants
- Retail facilities
- Offices
- …



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Background

Control strategies for mitigating airborne risk of SARS-CoV-2

Control strategies for mitigating COVID-19 risks

Category	Strategy
PPE	Cloth mask
	Surgical mask
	N95 mask
	Face shield
	Mask fitter/sealer/brace
Ventilation	Upgrading filters of building ventilation systems (e.g. HEPA)
	Increasing outdoor air supply of ventilation systems
	Personal ventilation (for fresh air supply)
	Local air exhaust
	Displacement ventilation
	Natural ventilation
	Closing doors between rooms (blocking air flow across rooms)
Partition	Partition screens
	Cubicle workstation
	Enclosed/semi-enclosed modular office walls
Air cleaning and disinfection	Upper-room UVGI system
	Portable air cleaners
	Sunlight
Occupancy control	Occupancy density restriction
	Intermittent occupancy or staggered scheduling

IAQ control strategies

- Source control
- Ventilation
- Air cleaning

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- Building scale
- Room scale
- Personal microenvironment
- Breathing zone

Effectiveness

Benefits

- IAQ improvement
- Infection risk mitigation

Costs

- Capital cost
- Energy consumption

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Methodology

Theoretical model

Wells-Riley model (steady-state well-mixed air)

Infection probability:

$$P = \frac{new\ cases}{susceptible} = 1 - e^{-R_S R_I \frac{Iqpt}{V\lambda}} = 1 - e^{-\frac{(IqR_I)}{(V\lambda)}(R_S pt)}$$

Source emission

Inhalation

Dilution (ventilation or disinfection)

$$\lambda = \underbrace{\lambda_{HVAC}\varepsilon_{vent}}_{\text{equivalent fresh air supply}} + \underbrace{k_{UV}}_{\text{disinfection}} + \underbrace{k_{deposition}}_{\text{particle deposition}} + \underbrace{k_{AirCleaner}}_{\text{removal by air cleaner}} + \underbrace{k_{inactivation}}_{\text{natural inactivation rate}}$$

$$\lambda_{HVAC} = \underbrace{\lambda_{outdoor}}_{\text{outdoor air}} + \underbrace{\lambda_{recirculated}\eta_{filter}}_{\text{filtered recirculated air}}$$

Viral quanta generation rate model:

$$q = c_v \cdot c_i \cdot p \cdot \int_0^{10\mu m} N_d(D) \cdot dV_d(D)$$

Depends on

- viral load of sputum (10^9 RNA copies/mL, $c_i = 0.02$),
- pulmonary rate, and
- particle number concentration and size distribution.

Stephens, B. 2013.

P: infection probability.

R: fraction of infectious particles penetrating through the mask of the susceptible (R_S) and infected (R_I).

I: initial infected patient number.

q: infectious quanta generation rate (1/h).

p: pulmonary ventilation rate of a person (m^3/h).

t: exposure time (h).

V: room volume (m^3).

λ: total effective air change rate for dilution in the space.

Calculated viral quanta generation rate:

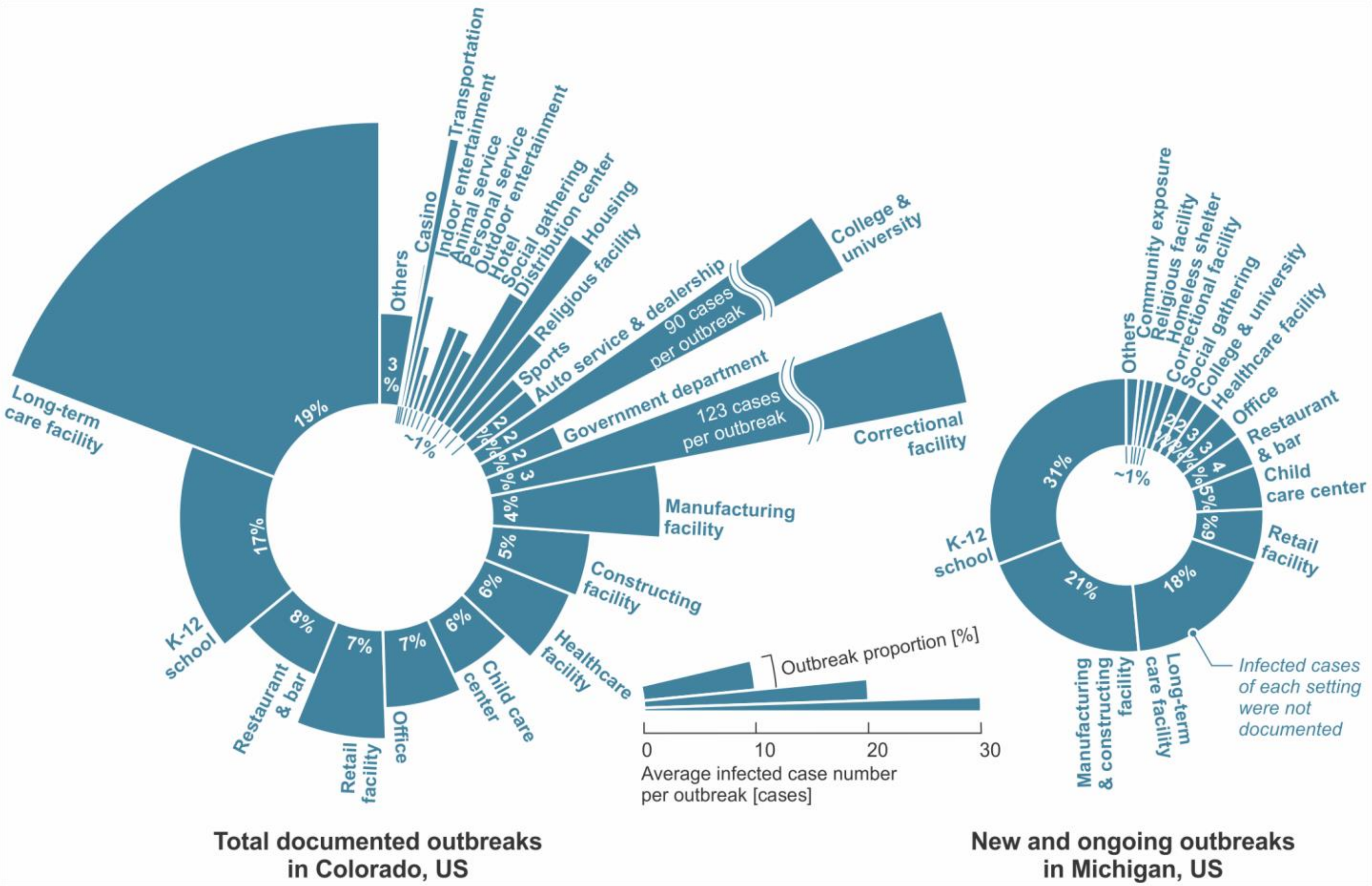
Group	Age [years]	Infectious quantum generation rate (Mean±SD) [h^{-1}]		
		Sedentary or light activities	Moderate-intensity activities	High-intensity activities
Children	<16	58±31	251±134	492±270
Adults	16-61	58±31	318±177	610±347
Elders	>61	58±31	305±158	555±307

Methodology

Theoretical model

Baseline indoor environments:

- Long-term care facility
- Educational
  - K-12
  - Colledge
- Mean processing plant
- Retail
  - Standalone
  - Strip mall
- Hopital
- Office (medium)
- Prison
- Hotel
- Restraunt
- Religious building
- Casino
- Transportation
  - Airplane
  - Cruiseship
  - Subway
  - Bus
  - Taxi



Baselines are created based on:

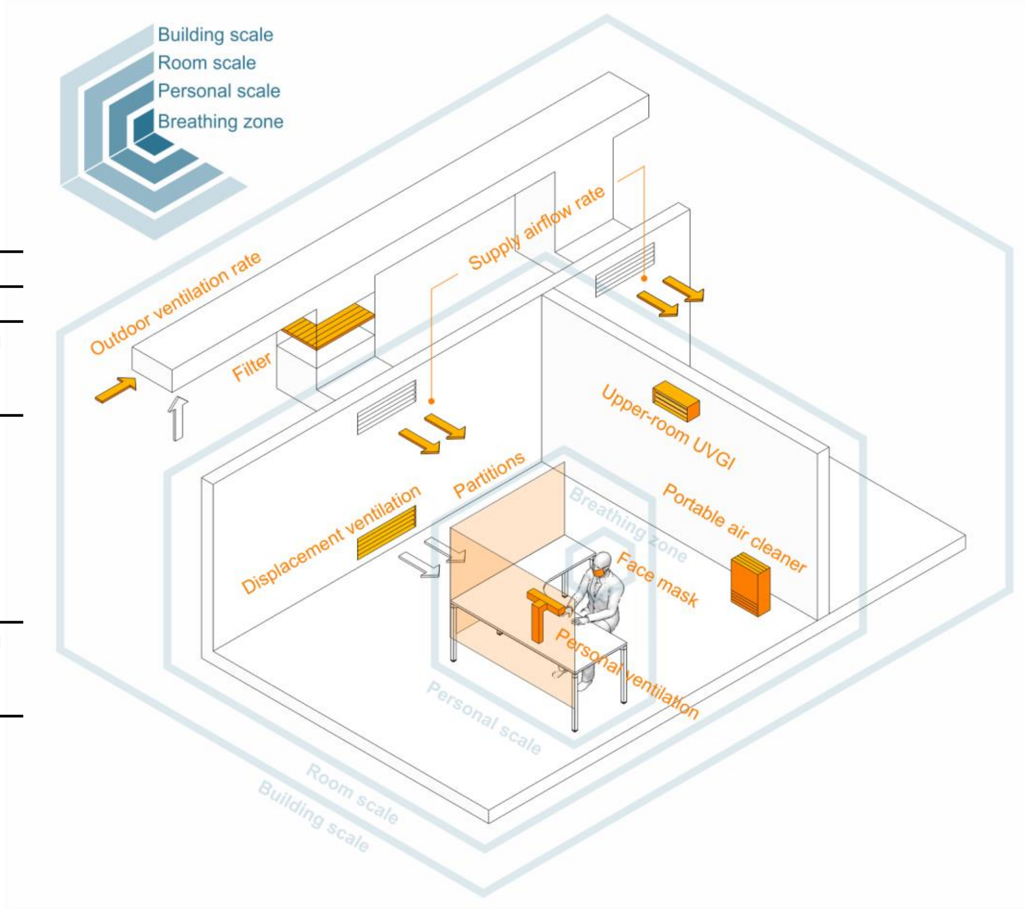
- U.S. DOE and PNNL prototypes (ASHRAE 90.1 and IECC standards)
- Design guidelines or real practices
- Ventilation rate based on ASHRAE 62.1 or data from literature or typical practices

Methodology

Theoretical model

Possible IAQ control strategies in different scales:

Strategies	Scales			
	Building	Room	Personal	Breathing zone
Source control	• Reducing occupants	• Reducing occupants • Intermittent occupancy	• Local air exhaust	• Face masking
Ventilation	• Increased ventilation supply airflow • Elevated outdoor air fraction for ventilation system	• Semi-open partition • Displacement ventilation	• Personal ventilation	
Air cleaning	• High-efficiency filters for ventilation system	• Portable air cleaners • Upper-room UVGI		• Face masking



Methodology

Theoretical model

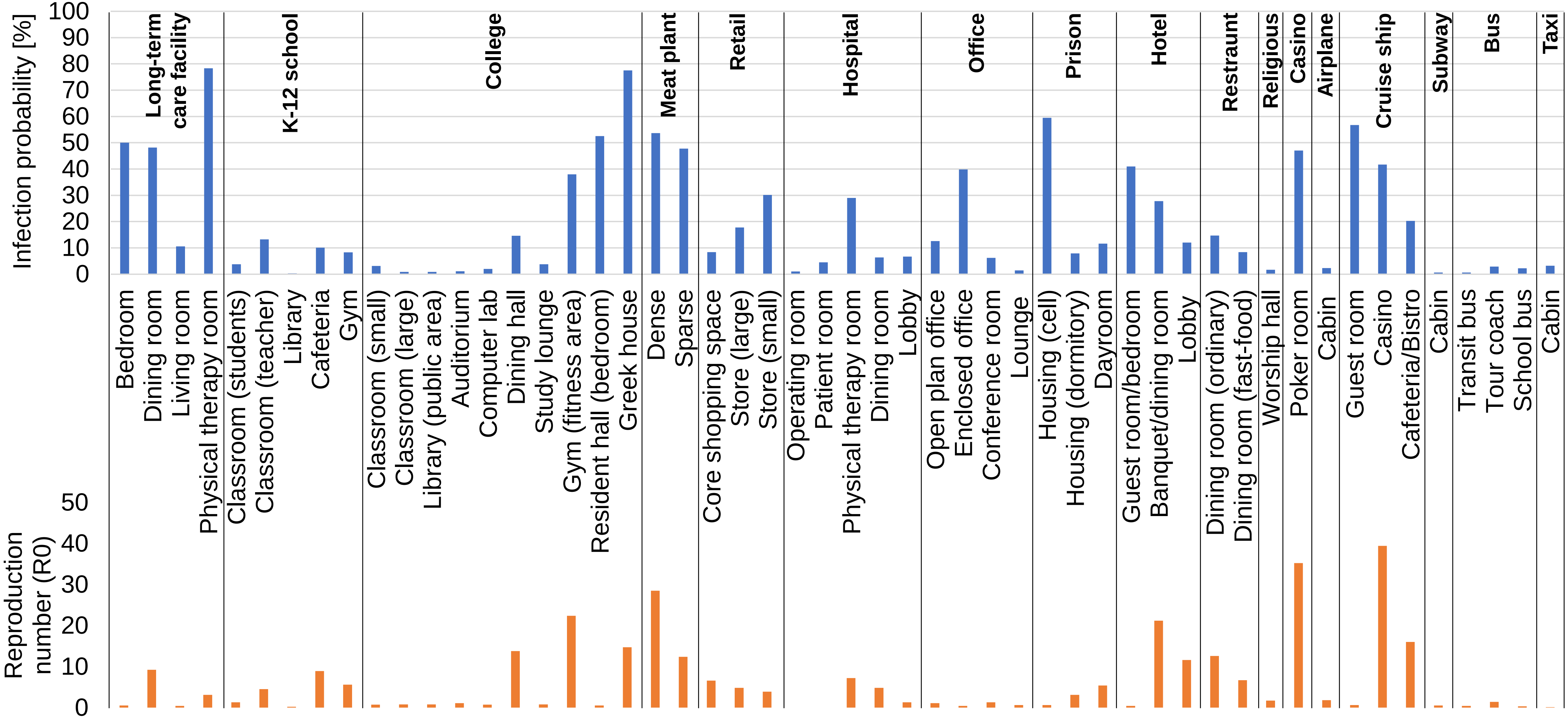
Configurations of baseline and proposed cases

Strategies		Baseline	Proposed
Ventilation system	Ventilation rate (outdoor air)	• Reference values (25% outdoor air)	• Baseline supply air, 50% outdoor air • Baseline supply air, 75% outdoor air • Baseline supply air, 100% outdoor air
	Total supply airflow rate	• Estimated based on ventilation rate and reference outdoor air fraction (25%)	• 50% more supply air, 25% outdoor air • Double supply air, 25% outdoor air
	Air distribution[a]	• Mixing (ε_{vent} = 1)	• Displacement ventilation (ε_{vent} = 1.2 to 2) • Partitions (semi-open space) (ε_{vent} = 2 to 3) • Displacement ventilation + Partitions (ε_{vent} = 14 to 100) • Personal ventilation (ε_{vent} = 1.4 to 10)
	Filter	• MERV 8[b]	• MERV 13 • HEPA
Standalone devices	Portable air cleaners	• None	• CADR = 12m^3/(h·m^2) × room area
	Upper-room UVGI system	• None	• Equivalent ACH[c] = 12h^{-1} (MV) or 9.6h^{-1} (DV)
PPE	Mask	• None	• Cloth mask • Surgical mask • N95 mask

[a] Mixing ventilation: ε_{vent} = 1; Displacement ventilation: ε_{vent} = 1.2 to 2; Semi-open space with partitions installed: ε_{vent} = 2 to 3; Displacement ventilation with partitions installed: ε_{vent} = 14 to 100; Personal ventilation: ε_{vent} = 1.4 to 10; all assuming uniform distribution.
[b] HEPA filter is used in the baseline cases of hospital operating room and airplane cabin. All other spaces use MERV 8 filter as the baseline setup.
[c] Equivalent ACH = 12h^{-1} for mixing ventilation and equivalent ACH = 9.6h^{-1} for displacement ventilation.

Results and discussions

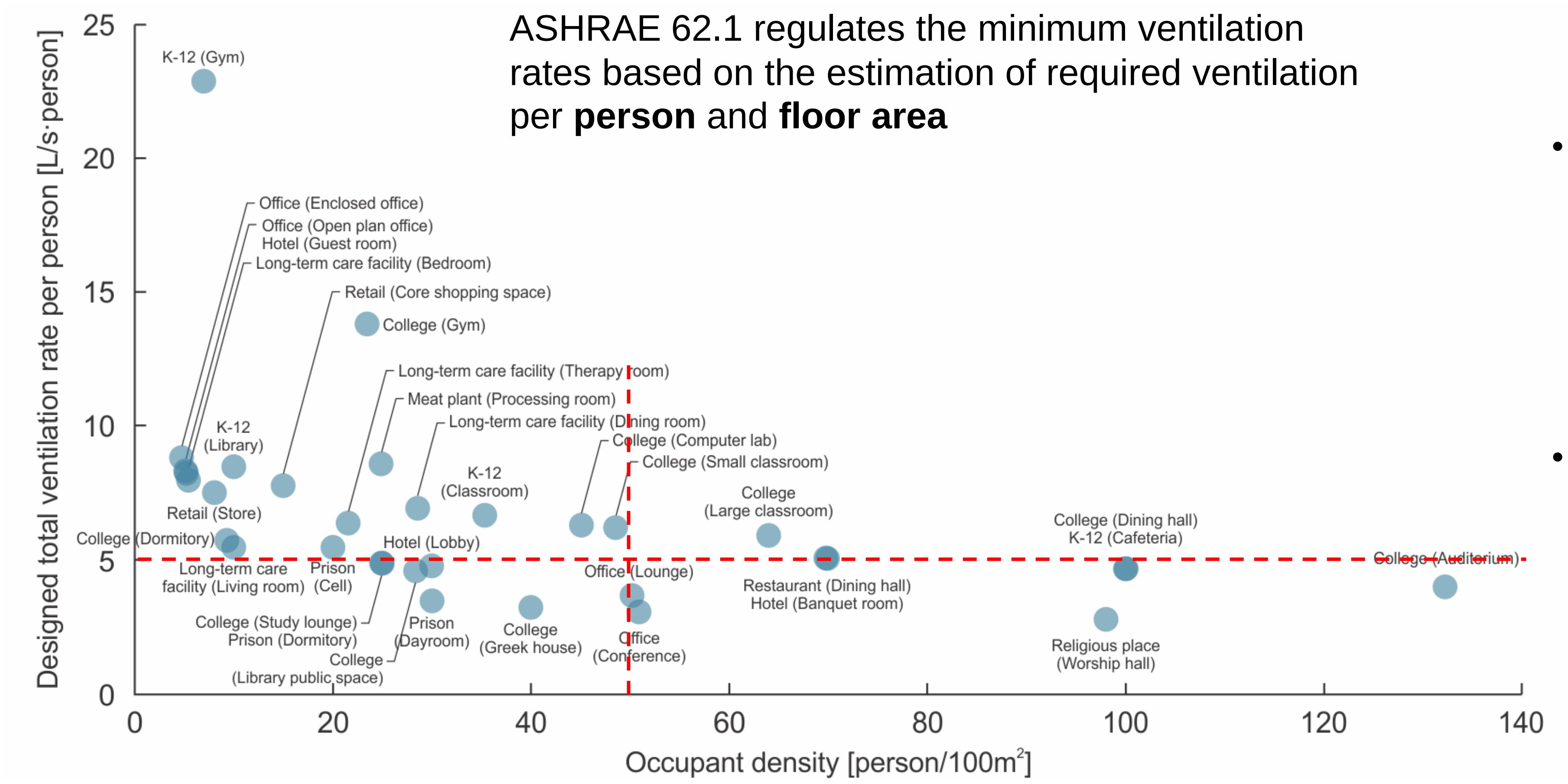
Baseline infection risk in different spaces



Results and discussions

Baseline infection risk in different spaces

ASHRAE 62.1 regulates the minimum ventilation rates based on the estimation of required ventilation per **person** and **floor area**



Relationship between occupant density and designed total ventilation rate per person in different scenarios based on ASHRAE 62.1

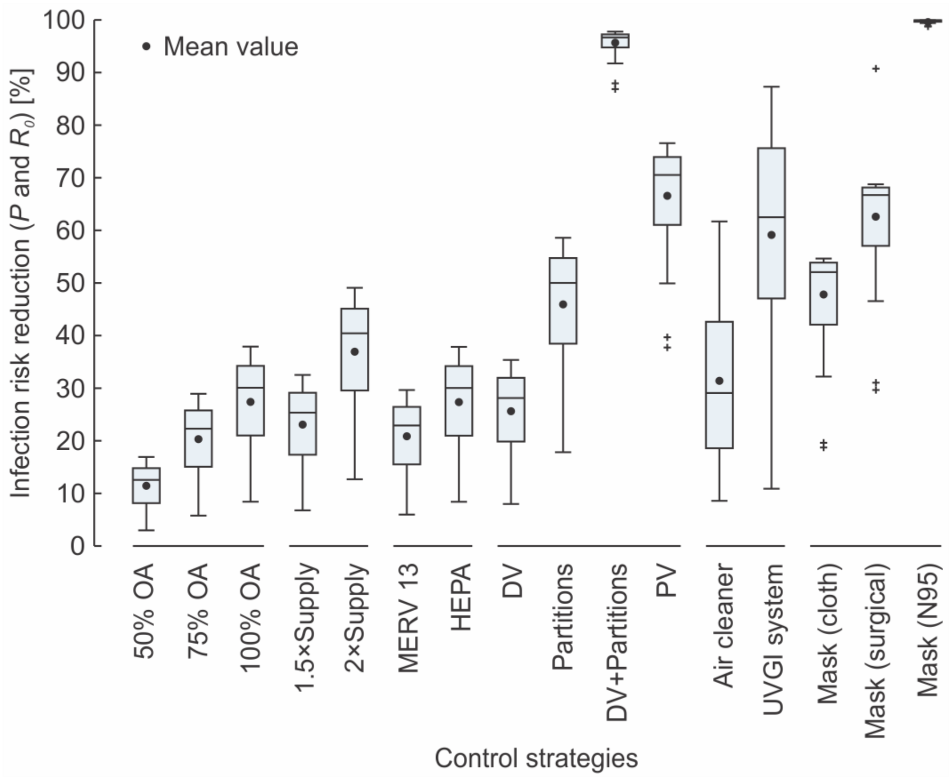
- Ventilation designed based on ASHRAE 62.1 may not always be sufficient for occupants, particularly considering the requirements for mitigating infection risks.
- A pathogen-source-based or health-based design criteria for indoor ventilation is probably more applicable for infection prevention.

Results and discussions

Effectiveness of IAQ control strategies

Effectiveness = Infection risk reduction percentage (compared to the baseline case)

- Advanced air distributions (e.g. displacement ventilation + partitions) can have significant effectiveness on mitigating infection risks, but also need professional design and implementation to maximize their performance.
- Using HEPA filter has an equivalent effectiveness with using 100% outdoor air in HVAC system.
- Standalone AC and UVGI systems can be an effective solution for infection risk mitigation.
- Wearing masks is very useful for reducing infection risks.



Risk reduction distribution of the mean infection probabilities in different spaces

Results and discussions

Effectiveness, effective scales, and costs of IAQ control strategies

Effectiveness (infection risk reduction)

Effective scales (building scales, affecting the benefitted occupant number/scale)

Costs (capital costs, including first investment and maintenance & operation costs)

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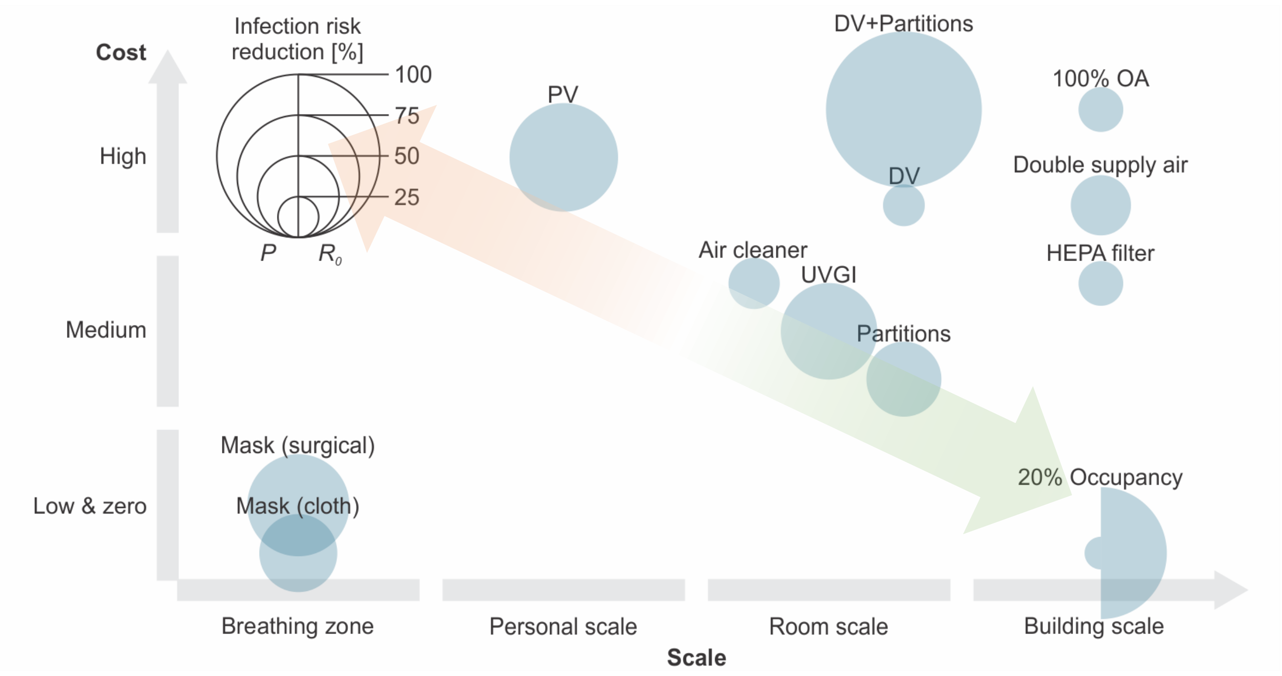
An ideal strategy:
- High effectiveness
- Larger effective scale
- Low/affordable cost



Infection risk reduction potentials and costs of control strategies in different scales

Effectiveness, effective scales, and costs of IAQ control strategies

Effectiveness of vaccination on risk mitigation (Example: K-12 Classroom and open plan office)

Room and occupant configurations

Scenario	Room configurations			Occupancy conditions		
	Area [m^2]	Height [m]	Number [#]	Activity	Group	Exposure time [h]
Classroom	125	4	70	Sitting	Children	8
Open plan office	350	3	18	Sitting	Adults	8

Vaccination facts

- 62.6% of people in the U.S. have been fully vaccinated (U.S. CDC)
  - 73.3% adults
  - 25.3% of people <18
- Effectiveness of vaccine (Pfizer):
  - 93.7% for other strains
  - 88.0% for Delta (no sufficient data for Omicron, likely less effective)

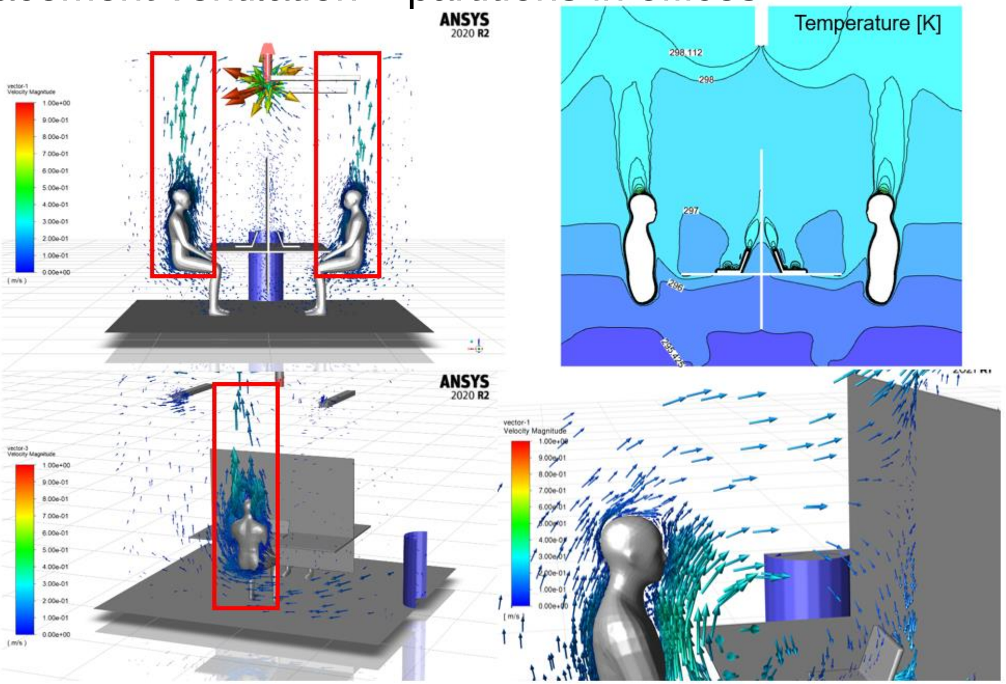
Effectiveness on reducing new infection cases

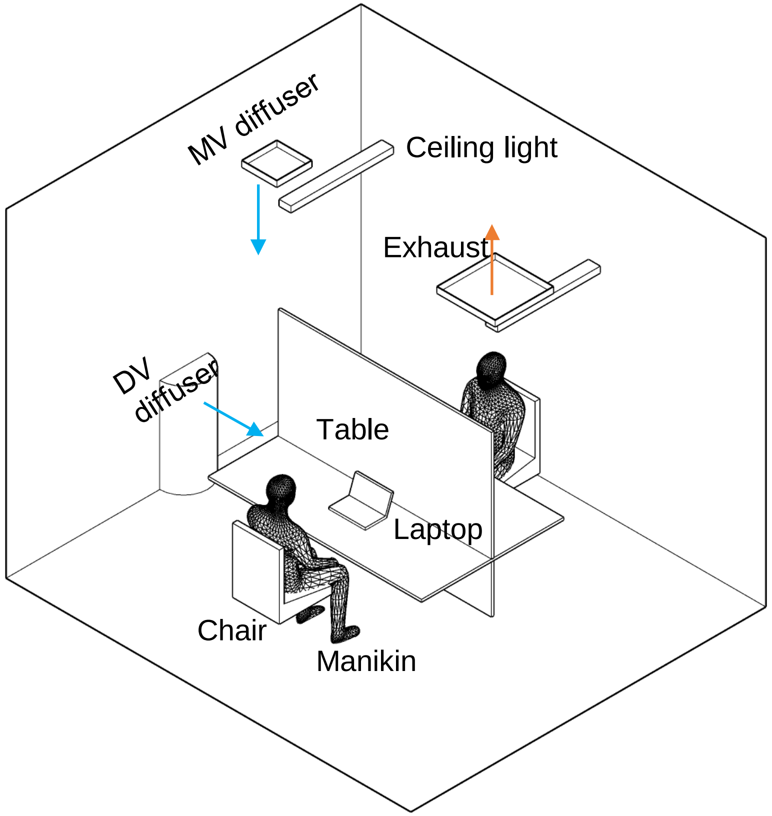
Scenario		Classroom (children)		Open plan office (adults)	
Virus variant		Original	Delta/Omicron	Original	Delta/Omicron
Susceptible number [#]	Vaccinated	17 (25.3%) **70%**	17 (25.3%) **70%**	13 (73.3%) **90%**	13 (73.3%) **90%**
	Unvaccinated	52	52	4	4
	Total	69	69	17	17
Infection probability [%]	Vaccinated	0.8±0.3	2.7±0.9	0.6±0.2	2.3±0.8
	Unvaccinated	12.3±4.2	22.8±7.2	10.0±3.8	18.9±6.6
	Overall	9.4	17.9	2.9	6.2
New infection case [#]	Total	**6.5** **2.8**	**12.3** **5.9**	**0.5** **0.2**	**1.1** **0.6**
	No vaccination	**8.4**	**15.7**	**1.7**	**3.2**

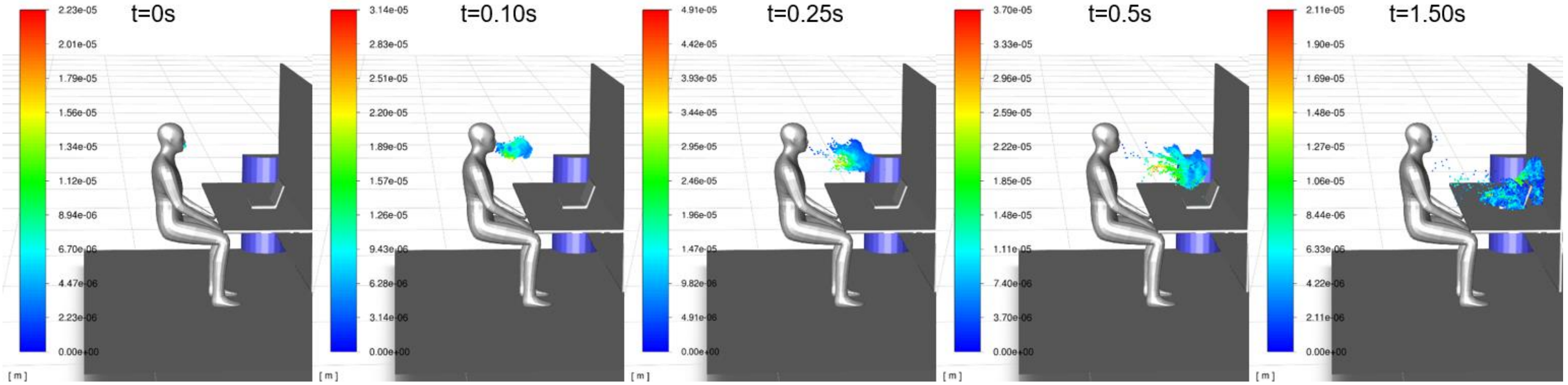
Results and discussions

CFD simulations and chamber & field tests for selected strategies

Displacement ventilation + partitions in offices







Results and discussions

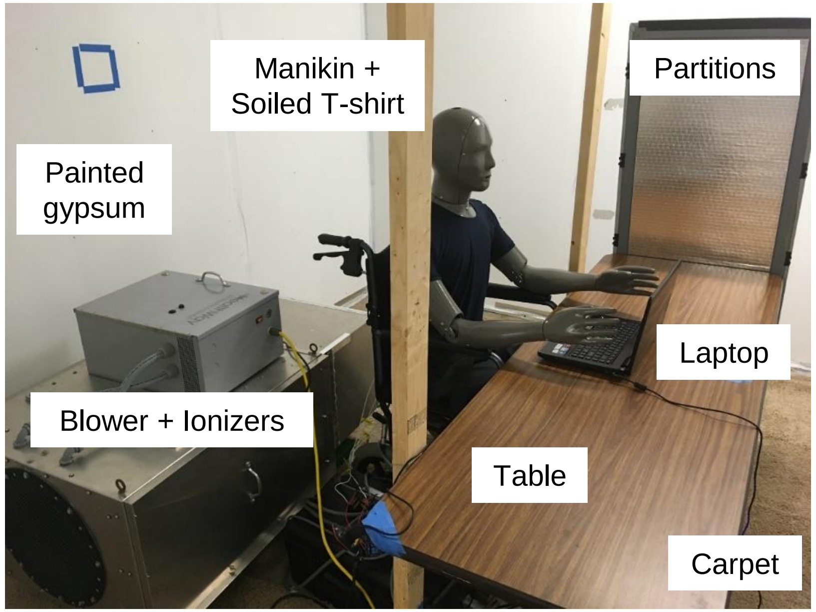
CFD simulations and chamber & field tests for selected strategies

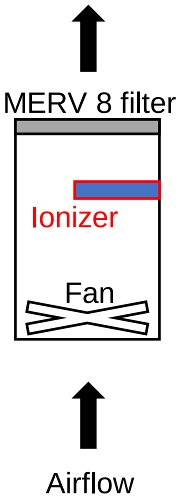
In-duct bipolar ionization technology

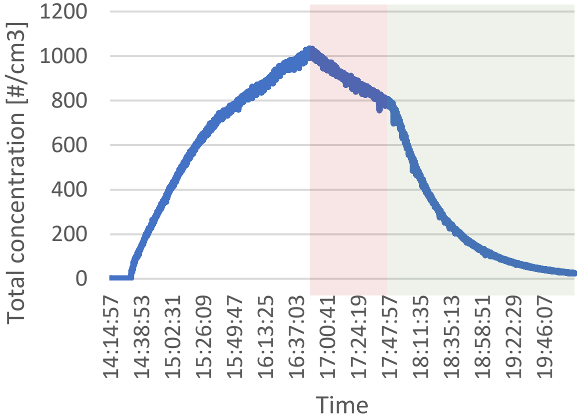
Chamber tests
- Pull-down test (for particle removal)
- Continuous injection test (for particle & VOC removal or byproducts)

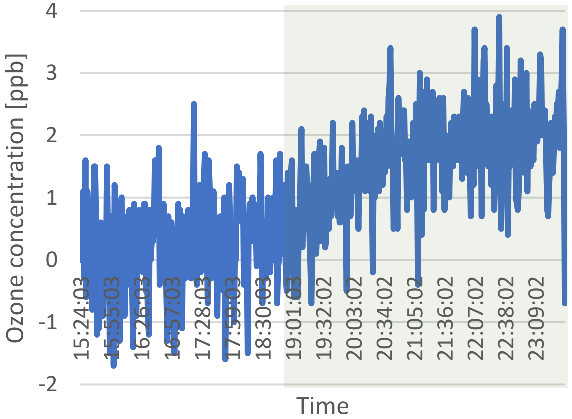
Ozone (2B Model 202), particle (APS), VOCs (GCMS, HPLC), ion

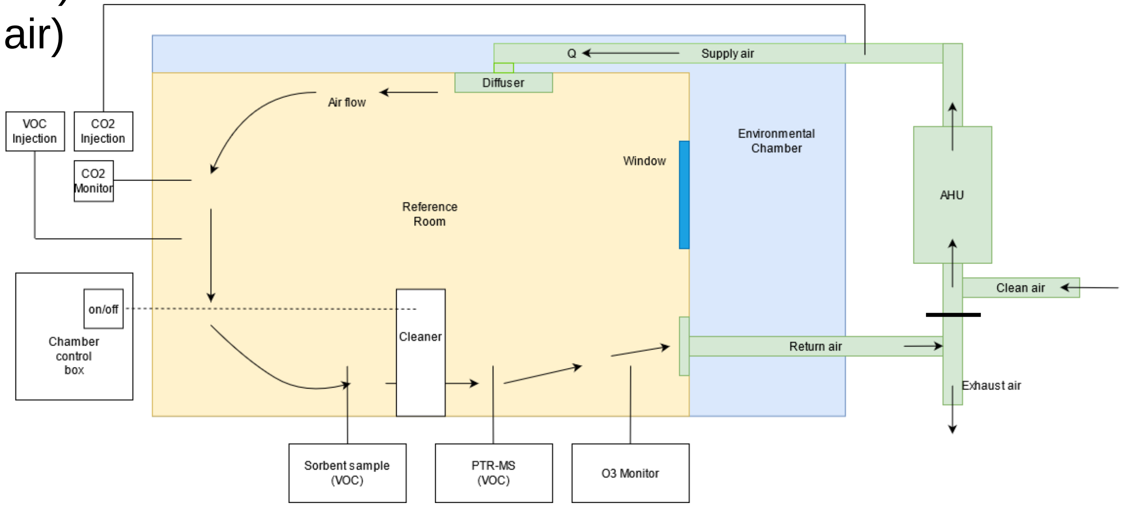
In-duct bipolar ionizers:
- Particle removal:
  - 16.6 to 21.7 CFM CADR (vs 5.6 CFM of a MERV 8 filter)
- Negligible ozone generation
- No significant VOC removal or byproducts (within detection error)
- Filter removed most ions (no significant ion leakage to indoor air)











Conclusions

- Spaces in long-term care facilities, colleges, meat plants, hotels, restaurants, casinos and cruise ships are facing considerably higher infection probabilities (over 30%) and have a higher potential to result in a serious outbreak event ($R0 > 10$).
- Common areas with higher occupant density (e.g. dining room) face higher potentials of viral spreading.
- Ventilation designed based on ASHRAE 62.1 may not always be sufficient for occupants considering the requirements for mitigating infection risks, particularly in the spaces with higher occupant densities.
- Advanced air distributions can have significant effectiveness on mitigating infection risks, but also need professional design and implementation to maximize their performance.
- Using HEPA filter has an equivalent effectiveness with using 100% outdoor air in HVAC system, while it has a less cost on additional energy consumption.
- Wearing masks is very useful for reducing infection risks (particularly high-efficiency masks).
- An ideal infection risk mitigation strategy should have high effectiveness, larger effective scale, but affordable cost.
- Vaccination can provide significant protection against COVID-19 transmission
- Displacement ventilation + partitions have high potential for infection mitigation
- In-duct bipolar ionizers can provide 16.6 to 21.7 CFM CADR while no significant byproducts generated.

References & Acknowledgements

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Acknowledgements

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Q & A

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