Joint Symposium 2023 22 November 2023

SHAPING the FUTURE:

Trends and Insights for Tomorrow Technologies Development in Greater Bay Area

Optimal Ventilation Strategy for Hospital Inpatient Wards

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Introduction

- In the recent two decades, three global viral infectious diseases, severe acute respiratory syndrome (**SARS**), middle east respiratory syndrome (**MERS**), and coronavirus disease (**COVID-19**), have occurred worldwide
- **Airborne transmission** has been shown with other viral respiratory diseases, during aerosol-generating procedures (e.g., tracheal intubation, bronchoscopy), thus WHO recommends airborne precautions for these procedures
- Healthcare-associated infections (HAIs) still threaten the public health during the time of epidemic and pandemic
- **Did very well for infection disease wards**, however, the risk of in-hospital outbreak by pathogenic bioserosols in **general wards and common areas** (such as **A&E, general inpatient and outpatient wards**) is often ignored

Urgent needs!!

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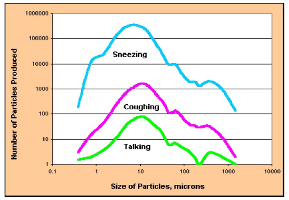
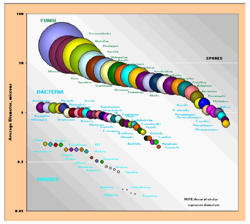
Indoor Air Quality (IAQ) and airborne pathogen

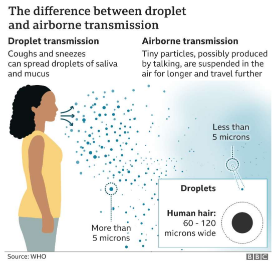
- Airborne particles - Dust, smoke, pollen, fibres
- Odor and gases - Chemicals, smells
- Volatile organic compounds (VOCs) - Paints, disinfectants
- Micro-organisms - Bacteria, pathogen, virus

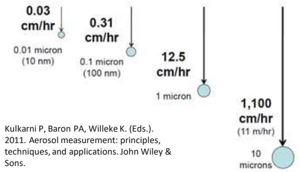


Profile of particle sizes produced by an infectious person



Relative size of airborne micro-organisms





Kulkarni P, Baron PA, Willeke K. (Eds.). 2011. Aerosol measurement: principles, techniques, and applications. John Wiley & Sons.

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Introduction: International example

- **MERS-CoV** in hospitals in Jeddah, Abu Dhabi and South Korea (~18% in hospital)
- **SARS-CoV-2** in UK, Australia (~21% in hospital)
- **COVID-19** ~ 20%

Country	Number of total cases	Number of HCW affected	Percent
Saudi Arabia	2121	405	[illegible]
South Korea	186	25	[illegible]
Global Total	2519	450[a]	17.86%[a]

[a] Speculative data.

Country	Number of total cases	Number of HCW affected	Percent
China	7429	1456	19.60
Canada	251	109	43.43
France	7	2	28.57
Germany	9	1	11.11
Philippines	14	4	28.57
Singapore	238	97	40.76
Thailand	9	1	11.11
Vietnam	63	36	57.14
Total	8020	1706	21.27

Journal of Infection and Public Health, 13, 843-848 (2020)

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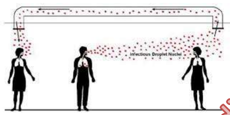
Introduction: Hong Kong is a classic example (Hospital)

In 2003, **SARS** outbreak in **General Inpatient Ward**, caused by a SARS patient given nebulized treatment.

- The aerosolized coronavirus particles re-circulated in the whole ward, infected 277 staff and patients
- This had directly caused community outbreak in HK

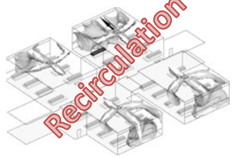
In 2004, HK Government approved building the 1st Infection Disease centre in HK

- 17-storeys with 108 –ve pressure isolation beds
- Started operation at 2007

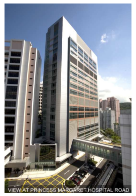


Infections droplet nuclei travel within environment

Recirculation and dispersion



Transmission paths for the pathogenic between general inpatient ward cubicle



1st Infection desease centre in HK

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(Some of the) Existing solutions

Temporary segregation on A&E area

HEPA unit is placed at A&E area

- Existing design standard?
- A minimum of total **6 ACH** for existing settings (% for fresh air or recirculation?)
- Deploy ward with air handling unit **exhaust out to ambient having 3-meter away from fresh air intake**
- **Enhanced ventilation** at A&E, General Out-Patient Clinic (GOPC) & SOPC waiting areas
  - Widest opening of the fresh air dampers

Technical gap !!

Problem solved?

Design references?

Reference: Hospital Authority communication kit – COVID-19 version 6.3 (27 Oct 2020)

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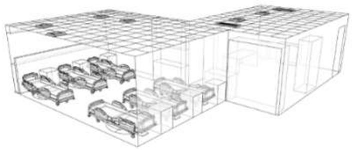
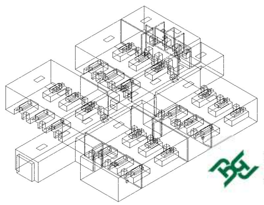
Project aims

- Understand the spatial distribution of pathogenic bioaerosols in **General Human Occupied Areas (GHOAs)**
- Identify the temporal influence of possible combinations of **control** and **operational** parameters on the **estimation of infection risk** within the mechanically ventilated enclosure in hospital
- Evaluate and update current **air change requirements (ACH)** in hospital
- Provide **proper ventilation strategies** which mitigate the risk of airborne infection transmission (for GHOAs) (Not include → infection disease ward, laboratory & operating theatre etc)





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What we need to take care?

Air flow should never go from **dirty** to clean

Discuss this today ...

[redacted]

- Air change rate, c_1
- Exhaust location, c_2
- Recirculation ratio, c_3

[redacted]

Operating parameters

- Emission location
- Emission direction & speed
- Emission type
- Emission rate
- Emission species
- Walking speeds & exposure time
- Room geometry

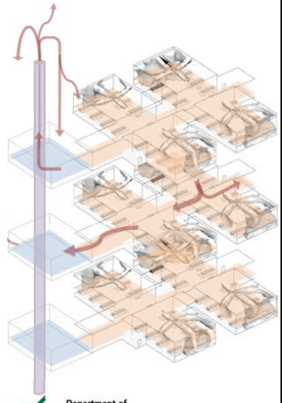
[redacted]

Drainage ventilation pipe

Washroom

General inpatient wards, A&E, outpatient wards

Optimized for exposure risk in hospital



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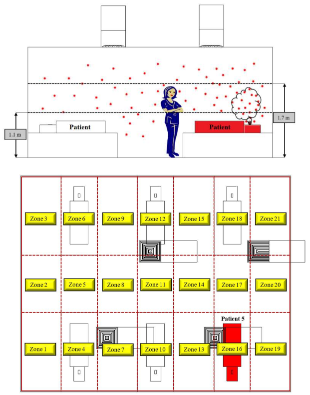
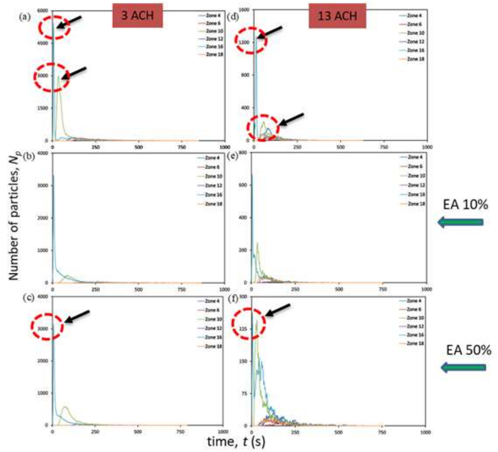
Airborne pathogens suspended in the air

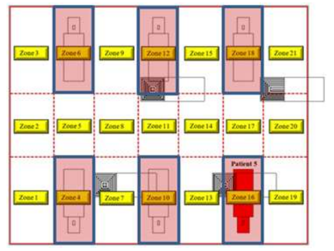
- An infected patient (patient 5) sneezes one time to expel 10,000 particles from the mouth by sneezing
- The spatial and temporal distribution of particles is evaluated at ward users breathing height
- The amount of time each particle spends in different breathing zones is determined from the moment it is expelled from the source location
- Four different ACH ($3h^{-1}$, $6h^{-1}$, $9h^{-1}$, $13h^{-1}$) and two exhaust flow rates (10%, 50% of supply air) are considered
- 100% virus-free air is considered with / without recirculation



Preliminary results: Effect of ACH

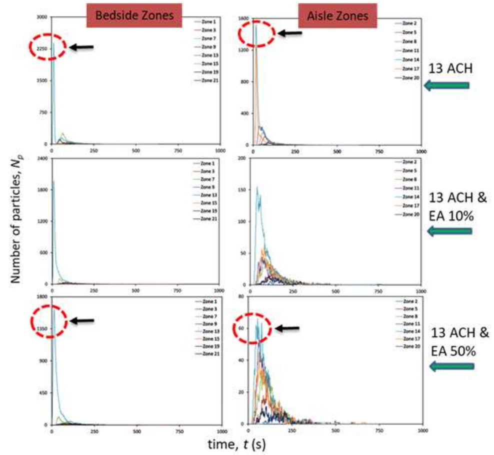


Patient Zones (4,6,10,12,16,18)



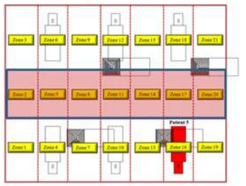
- Maximum number of pathogen presence is in the zone directly above the source patient
- The dispersion of pathogens towards other patient zones over time is also apparent
- At 13 h^{-1}, there is a greater reduction in the number of pathogens compared to 3 h^{-1}
- Significant reduction is noted at an air change rate of 13 h^{-1} and an exhaust flow rate of 50%

Preliminary results: Exposure in different zones



Bedside Zones (1,3,7,9,13,15,19,21)

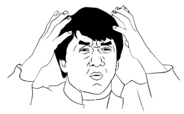
Aisle zones (2,5,8,11,14,17,20)



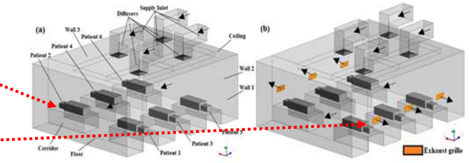
Obstacles

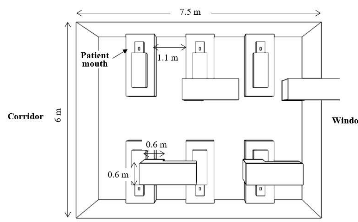
- Infected **patients** [1-6]
- Air change per hour, **ACH** (h^{-1}) [3,6,9,13]
- Number of **supply diffusers** [3,4,6]
- **Size** of supply diffusers (m^2) [0.09, 0.36]
- Number of **exhaust grilles** [0,4,6]
- **Size** of exhaust grilles (m^2) [0.0225, 0.04, 0.1]
- Exhaust **flow rate** (% of supply air) [0, 10, 30, 50]
- Exhaust **height** from floor (m) [0.8, 1.1, 1.4, 1.7]

Over 20,000 combinations…



How to do?

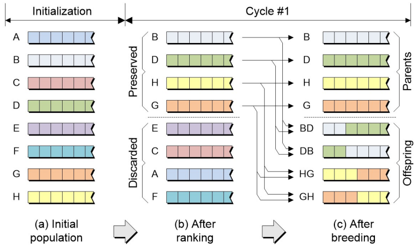




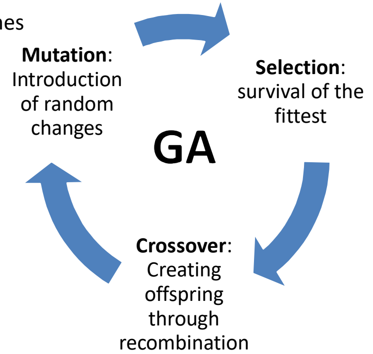
- A standard inpatient ward cubicle with dimensions of 7.5 m (L) x 6 m (W) x 2.7 m (H)
- Four supply diffusers positioned on the ceiling, each measured 0.6 m x 0.6 m
- Six beds situated at a height of 0.6 m, with a separation distance of 1.1 m between each bed

What is Genetic Algorithm? How they work?

- Adopted from the **concept of evolution**
- Representation of solutions using chromosomes
- Initialization of a population
- Evaluation and fitness function

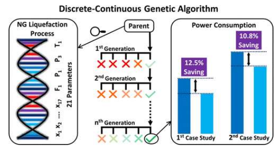


Genetic algorithm process (Image source: Max Maxfield)



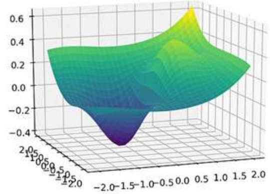
Advantage and real-world application

Advantages
- **Effective optimization** and search capabilities
- Ability to handle **complex, non-linear problems**
- No requirement for derivative information
- Parallel processing potential
- Robustness and adaptability



Application of GA in designing a mixed refrigerant cryogenic process (Ebrahimi *et al.* 2021)

Applications across different fields
- Genetic algorithms in engineering and design optimization
- Financial modeling and portfolio optimization
- Computer science and artificial intelligence
- Bioinformatics and DNA sequence analysis


An optimization problem (Image source: Franky Liang)

Our study

- **Parametric assessments** using computational simulations to evaluate and optimize ventilation strategies in ward environments
- Iteratively evaluated diverse design solutions with **fewer CFD simulations** compared to traditional approaches
- Develop a CFD model coupled with a genetic algorithm (GA) to **minimize the exposure risk of infectious pathogen deposition** in a general inpatient ward cubicle
  - **Four supply diffusers** positioned on the ceiling, each measured **0.6 m x 0.6 m**
  - **Six beds** situated at a height of 0.6 m, with a separation distance of 1.1 m between each bed
  - An initial population of 133 random input parameter combinations (chromosomes)
  - A crossover rate of 0.5 and a mutation rate of 0.1

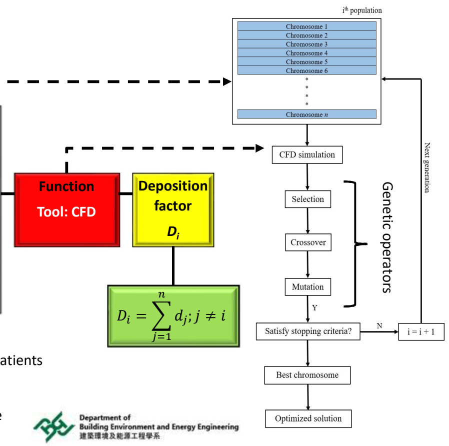
CFD simulation parameters

Computational domain	7.5m(L) × 6m(W) × 2.7m(H), RNG k-ε turbulence model with enhanced wall treatment
Total supply airflow rate	0.124kg·s^{-1} (ACH=3), 0.248kg·s^{-1} (ACH=6), 0.372kg·s^{-1} (ACH=9), 0.537kg·s^{-1} (ACH=13), 285K (air temperature)
Each diffuser	4-way spread pattern, air supplied at an angle of 15° from the ceiling, adiabatic
Corridor	Outflow with flow rate weighting, 295K (backflow temperature), adiabatic, escape boundary type
Exhaust grille	Outflow with flow rate weighting, 295K (backflow temperature), adiabatic, escape boundary type, Exhaust air 0%, 10%, 30%, 50% of total supply air
Walls, ceiling, floor, beds	No-slip wall boundary, adiabatic, trap boundary type
Patients	Six patients, No-slip wall boundary, 23.3Wm^{-2} for each patient, trap boundary
Mouth of patient (0.05m×0.05m)	Single shot release with an exhalation upward velocity of v_b=50ms^{-1},[50] n_s=10,000 virus particles, density of bioaerosol particles ρ_b=1,100kgm^{-3}
Species and aerodynamic diameters	MERS-CoV (0.167±0.012μm)

Optimization parameters and criteria

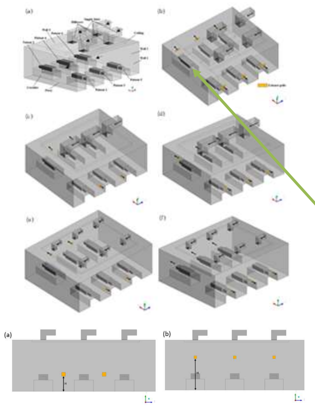
Parameters (Genes)

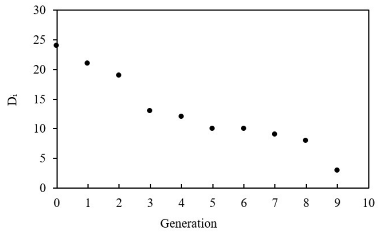
i. Infected **patients** [1-6]
ii. Air change per hour, **ACH** (h^{-1}) [3,6,9,13]
iii. Number of **supply diffusers** [3,4,6]
iv. **Size** of supply diffusers (m^2) [0.09, 0.36]
v. Number of **exhaust grilles** [0,4,6]
vi. **Size** of exhaust grilles (m^2) [0.0225, 0.04, 0.1]
vii. Exhaust **flow rate** (% of supply air) [0, 10, 30, 50]
viii. Exhaust **height** from floor (m) [0.8, 1.1, 1.4, 1.7]



where
- D_i accounts for the pathogens deposited on other patients due to the exhalation activity of infected patient i,
- d_j is the particle deposited on patient j
- n is the total number of patients in the ward cubicle

Best case with respect to patient location





Parameter (gene)		Deposition factor (D_i)
Infected patient	2	3
Air change rate (ACH) (h^{-1})	6	
No. of supply diffusers	3	
Size of supply diffusers (m^2)	0.36	
No. of exhaust grills	4	
Size of exhaust grills (m^2)	0.04	
Exhaust flow rate (% of supply air)	30	
Exhaust height from floor (m)	0.8	

Optimal ventilation design in general

- Seven most favorable scenarios regarding pathogen deposition (total D_i) in other patients due to the exhalation activity of all infected patients
- Maintaining an ACH of 6 or 9 h^{-1}, along with the appropriate ventilation measures such as localized exhaust grills, can achieve effective infection control in a general inpatient ward cubicle

Rank	ACH	No. of supply diffusers	Size of supply diffusers (m^2)	No. of exhaust grills	Size of exhaust grills (m^2)	Exhaust flow rate (% of supply air)	Exhaust height from floor (m)	Total D_i
1	**9**	**3**	**0.36**	**6**	**0.04**	**30**	**0.8**	**504**
2	6	4	0.36	6	0.1	50	1.1	568
3	9	3	0.36	4	0.04	30	0.8	602
4	9	3	0.36	4	0.04	30	1.4	630
5	9	4	0.36	6	0.1	50	1.1	631
6	6	6	0.09	6	0.0225	30	1.4	728
7	6	4	0.36	6	0.1	10	1.1	757

Input parameter combinations with the top seven lowest overall deposition factor

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Suggested management practice

- Initially place patients with unknown or novel diseases **near the corridor** during their stay
  - This strategic positioning, combined with an optimized ventilation system, helps minimize the spread of infectious bioaerosols
- When designing **new or renovated hospitals**, it is worth considering improvements to ventilation strategies

ACH	No. of supply diffusers	Size of supply diffusers (m^2)	No. of exhaust grills	Size of exhaust grills (m^2)	Exhaust flow rate (% of supply air)	Exhaust height from floor (m)
9	3	0.36	6	0.04	30	0.8

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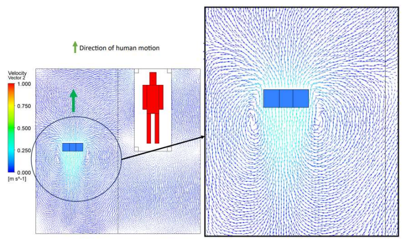
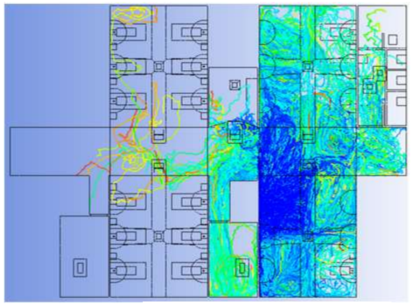
Our next step in the hospital

Effect of human movement on airflow and pathogen deposition



Airborne transmission of pathogens in a general inpatient ward



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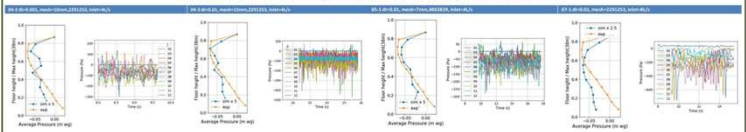
Our next step in the hospital: Drainage system

CFD simulation for dynamic water and airflow in drainage system

Evaluation of cross-vent design on air pressure variation in the drainage stack

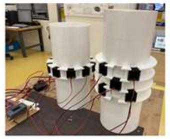


- The discharge from the highest level causes the largest air pressure variation along the length of the vertical drainage stack
- Increase in the size of the drainage stack can provide similar effect as the cross-vents provided at each or alternative floors

Experimental validation of CFD and experiment work

Validation by field data

Inactivation of entrained microorganism in drainage stack discharge

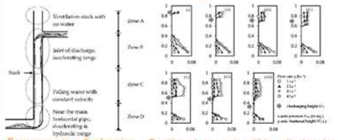


- The antimicrobial efficiency of the novel disinfection system is >95%

Vertical transmission of bioaerosols in the drainage system

- Flushing significantly increase the exposure of airborne pathogen inside the washroom

Understanding the effects of positive air pressure on trap seals connected to a drainage stack



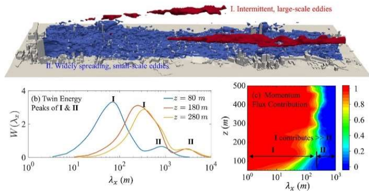
Four zones in a discharging drainage stack

Positive air pressure within a discharging drainage stack

- Increase in the frequency of discharge flow rate, increase the number of floors identified at risk in high-rise storey residential buildings

Our next step in the hospital: Bioaerosol transmission in ambient environment

- Spatial exposure levels from drainage ventilation pipe discharge by CFD, validated by field data and tracer gas experiments
- Spatial exposure levels from drainage ventilation pipe discharge



Liu *et al.* (2023)

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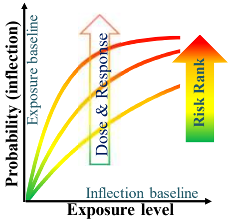
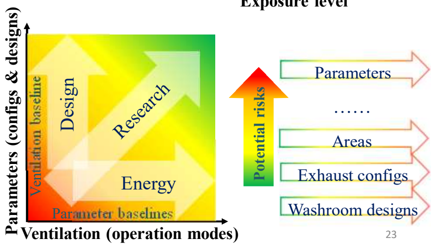
Our next step in the hospital: Occupancy Patterns, Exposure Risk Ranking & Optimization

- **Risk assessment model**
  - Inhalation dose-response exposure of receivers (HCWs, patients and visitors)
  - Inflection probability & consequence
- **Exposure risk ranking**
  - Links to impacts of finance & facilities
  - Links to ventilation strategies

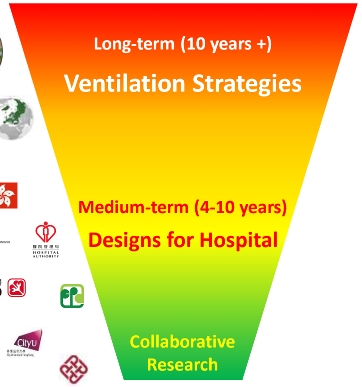


- **Optimization for exposure risk level**
  - Parameters for airflow field phenomena
  - Exhaust configuration (airborne pathogens)
  - Washroom layout & geometry,
  - drainage stack & drainage vent pipe arrangements
  - Impacts to designs & energy consumption
  - Risk of cross-inflection: among patients, deposited & exhausted bioaerosols on surfaces, and those from inhalation

Control / Constrain



Pathway to impact



- Inter-institutional **collaboration locally and internationally**
- **Policy** and **regulations**
- **Improve** international ventilation standards, codes of practice
- **Ventilation strategies**
- **Reference** and **guideline**
- **Better** for Hospital design

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Thank you!

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References

- Zhou, Q., Gao, Y., Wang, X., Liu, R., Du, P., Wang, X., ... & Yang, K. (2020). Nosocomial infections among patients with COVID-19, SARS and MERS: a rapid review and meta-analysis. Annals of Translational Medicine, 8(10).
- Park, J. W., Lee, K. J., Lee, K. H., Lee, S. H., Cho, J. R., Mo, J. W., ... & Nam, H. S. (2017). Hospital outbreaks of middle east respiratory syndrome, Daejeon, South Korea, 2015. Emerging infectious diseases, 23(6), 898.
- Assiri, A., McGeer, A., Perl, T. M., Price, C. S., Al Rabeeah, A. A., Cummings, D. A., ... & Memish, Z. A. (2013). Hospital outbreak of Middle East respiratory syndrome coronavirus. New England Journal of Medicine, 369(5), 407-416.
- BBC News. 2020. Coronavirus: WHO rethinking how Covid-19 spreads in air.
- Kowalski W, Bahnfleth WP. 1998. Airborne respiratory diseases and mechanical systems for control of microbes. Heating, piping, and air conditioning, 70, 34-48.
- Max Maxfield. Online image. https://www.eejournal.com/article/when-genetic-algorithms-meet-artificial-intelligence/
- Franky Liang. Online image. https://towardsdatascience.com/optimizing-machine-learning-models-with-genetic-algorithms-2a38682a0610
- Ebrahimi, A., Tamnanloo, J., Mousavi, S. H., Soroodan Miandoab, E., Hosseini, E., Ghasemi, H., & Mozaffari, S. (2021). Discrete-continuous genetic algorithm for designing a mixed refrigerant cryogenic process. Industrial & Engineering Chemistry Research, 60(20), 7700-7713.
- Liu, Y., Liu, C. H., Brasseur, G. P., & Chao, C. Y. (2023). Wavelet analysis of the atmospheric flows over real urban morphology. Science of The Total Environment, 859, 160209.