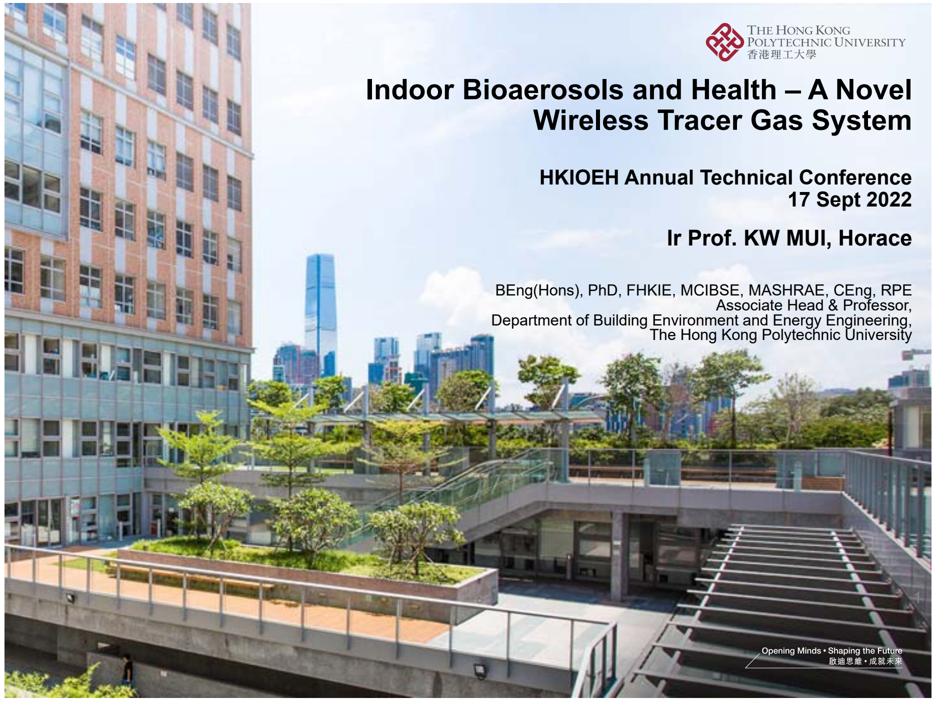

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# Indoor Bioaerosols and Health – A Novel Wireless Tracer Gas System

**HKIOEH Annual Technical Conference**
**17 Sept 2022**

**Ir Prof. KW MUI, Horace**

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Associate Head & Professor,
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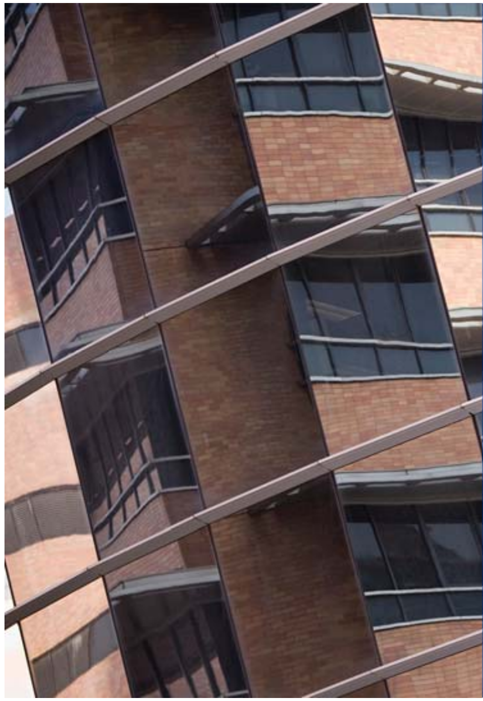
The Hong Kong Polytechnic University

Opening Minds • Shaping the Future 啟迪思維 • 成就未來



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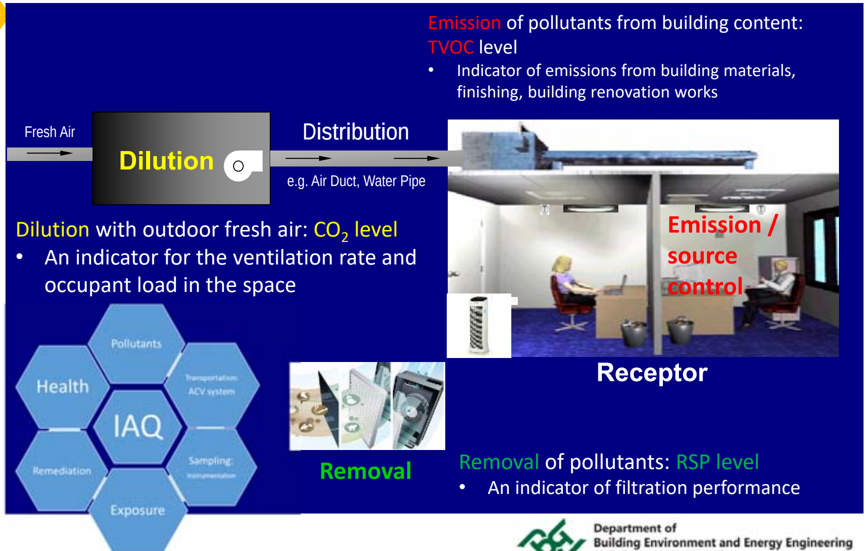
# General Principles….


Opening Minds • Shaping the Future 啟迪思維 • 成就未來

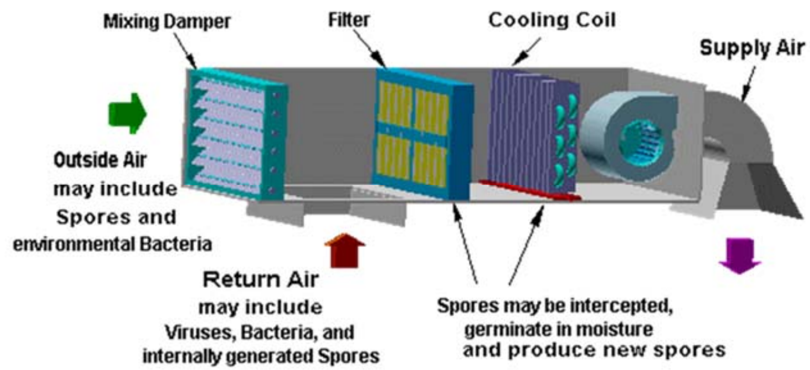
## Generalization Principle

### 3 common IAQ control strategies






## Airborne Pathogens in relation to a Typical Air Handling Unit (MVAC)



## Background

- More intensive surveys of microbes carried out in the 80s
- Microbes include fungi and bacteria
- In Europe and North America
  - Finland, Holland and England
  - *Canada and USA

(**relate data to health symptoms*)

Causes:

- Faulty ventilation
  - Insufficient provision of **outdoor air**
  - Altered pattern of **air distribution** due to alteration of partitioning
- Lack of maintenance - accumulation of dirt / dust, **biological agents** in carpets, ceiling tiles, ventilation ducts, air filters

## Why study Bioaerosols?

- Transmit Disease to Humans, animals
  - Costs measured in billions.
- Bioterrorism threats
  - Regional bacterials census to differentiate normal versus suspicious fluctuations in airborne pathogens.
- Influence on the environment
  - Spread of organisms.
- Monitoring production process
  - Food and beverage, pharmaceutical, hospitals.

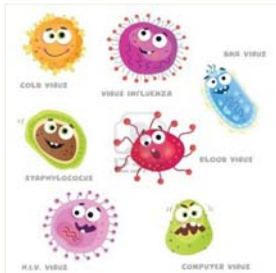
## Bioaerosols

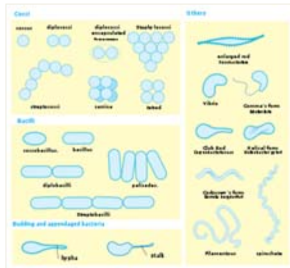
- Defined as organic aerosols that are alive, carry living organisms, or are released from living organisms
  - ***Bacteria, fungi and viruses**
- Natural or manmade
- Range from 0.010 (small virus) to 100 microns (pollen grains)
- Animal dander (dogs and cats)
  - Minute scales from hair, feathers or skin
- Plant pollen
- * Dust mites
  - ****Found in every home/office environment and impossible to get rid of them all***

## Bioaerosols - microbes

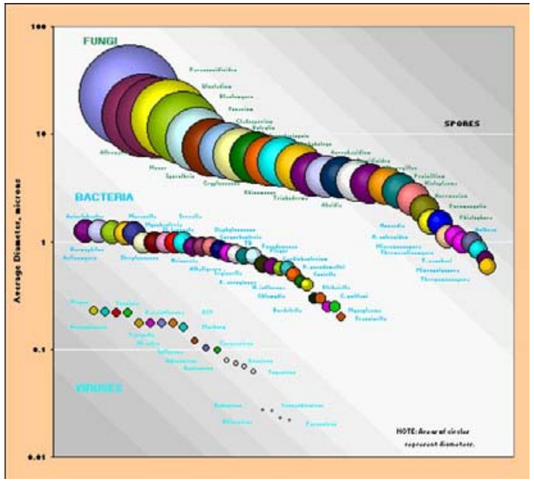
Main groups of concern

- Fungi
- Bacteria
- Virus





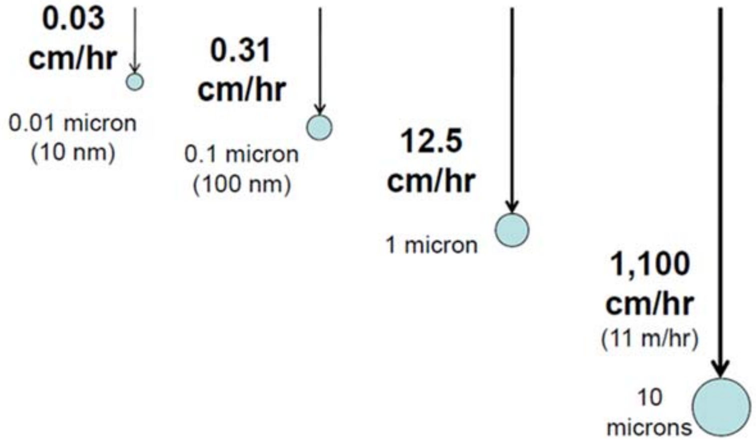
## Bioaerosols




Relative size of air-borne micro-organisms

*Extracted from Kolwaski (1998)*

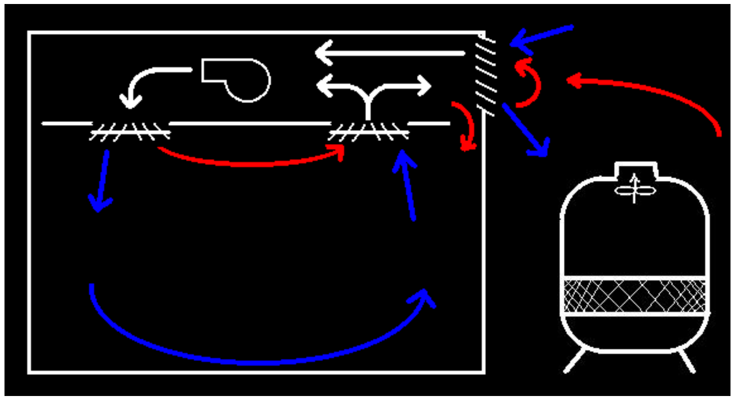
## Settling velocity




Aerosol measurement: Principle, techniques and Applications by Paul Baron & Klaus Willeke

## Preventing by BS system

- Clean Air



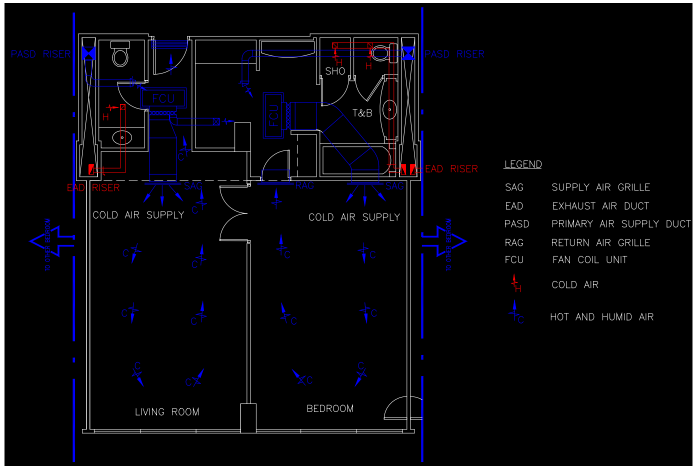
## Preventing by BS system (I)

- Ventilation

| Litre/s /person | Significance | Year of concern | Expected $CO_2$ (ppm) | Fanger's PPD(%) |
|---|---|---|---|---|
| 28 | reduced risk of spread of viable disease, e.g. Tuberculosis | 1893 | 500 | 6 |
| 17 | reduce microbial pollution | 1896 | 600 | 10 |
| 14 | use before recirculation was allowed | before 1973 | 650 | 11 |
| 10 | allows for low smoking rate | since 1989 | 800 | 15 |
| 7.5 | minimum for adapted person+odour contribution from ventilation system and furnishing | 1996 | 1000 | 20 |
| 2.5 - 3 | adapted person | 1973 | 2200 | 40 |
| 1 | level of concern | - | 5000 | 63 |

## Preventing by BS system (II)

- Ventilation (effective air distribution)



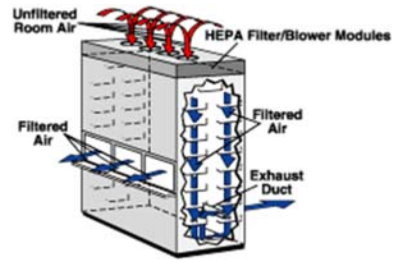

## Different types of air purification system

- High efficiency particulate air filter (HEPA)
- Ultraviolet germicidal irradiance (UVGI)
- Carbon filters
- Photocatalytic oxidation (PCO)
- Ozone oxidation
- Ionization

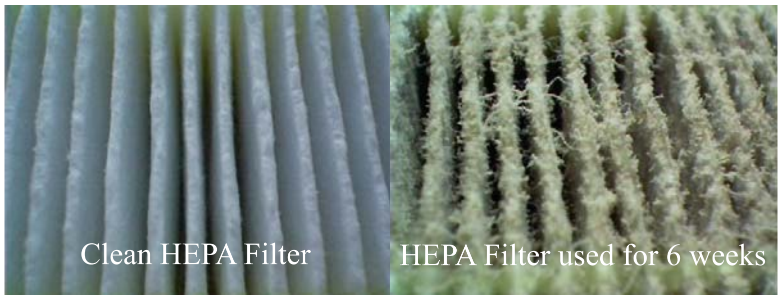


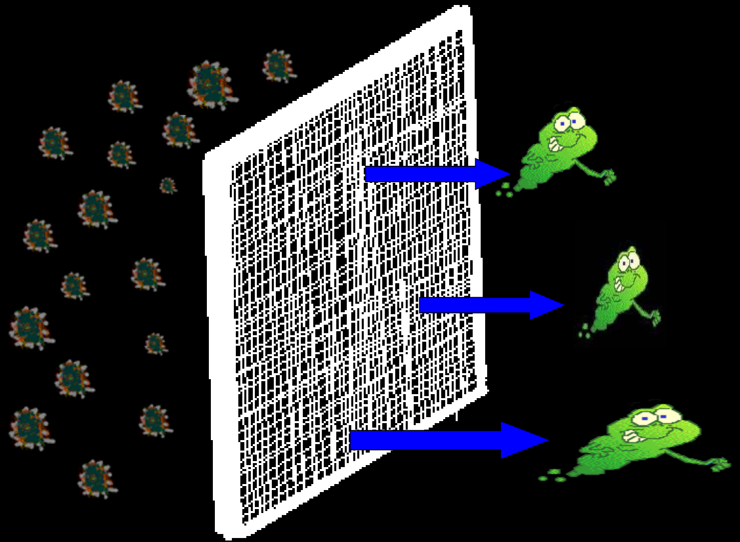
## Preventing by BS system

- Filtering (HEPA)




•99.999% efficient @ 0.12μm particles

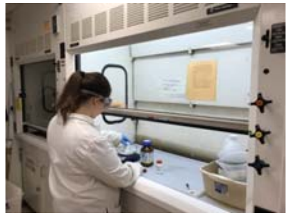




The dust is trapped by the filter. However, the bacteria and virus are difficult to be trapped since they are very small in size.

## IAQ improvement methods

- Local exhaust ventilation
  - Chemical fume hoods to control critical emission sources of chemical vapours
  - Ensure adequate removal of the pollutant
  - Air cleaner with HEPA filter
- Ultraviolet light Irradiation
  - Upper-room irradiation
  - Duct irradiation
  - Mobil





## Adsorption Mechanism

- Pollutants Treated by Adsorption
  - Gases
  - Odors
  - Fumes
- Common adsorbent
  - Active carbon
  - Silica gel
  - Activated aluminum oxide
  - Zeolite



## Adsorption Advantages & Limitations

- Advantages:
- High adsorption capacity & high removal efficiency for specific compounds
- Operation at room environment
- No harmful by-products.
- Good performance for gas-phase pollutants
  - e.g. activated carbon is effective in removing ozone

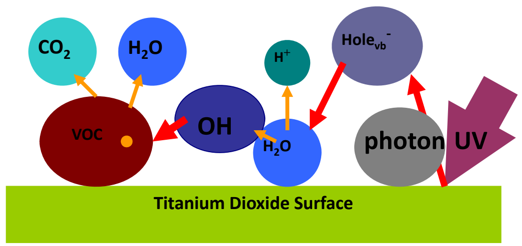
Disadvantages:

- Lose activity with time
- Post-treatment of adsorbent is required

## What is TiO2 and PCO?

### $TiO_2$ Chemical Reaction

- Photocatalytic Oxidation occurs only if photons water molecules and the organic pollutants are all on the catalyst surface:





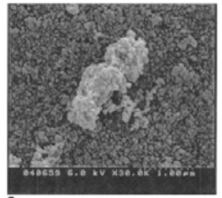

## What is TiO2 and PCO?

### SEM scanning of micro-organisms on $TiO_2$ disk…

*B. subtilis* without PCO exposure

*S. marcescens* without PCO exposure

*B. subtilis* exposed to PCO for 36 hours



*S. marcescens* exposed to PCO (11.75 hrs)

- The spore cells were broken…
- The bioaerosol was mineralized. [Goswami, 2003]



## Ozonation Mechanism

- Ozone can be generated by UV or NTP discharge
- Ozone is a strong oxidant
- To take reactions with pollutants and oxidizes them
- To oxidizes and decomposes the enzyme required by glucose to make the bacteria died
- To destroy the DNA structure and cellular of bacteria, virus and microorganisms



## Ozonation Advantages & Limitations

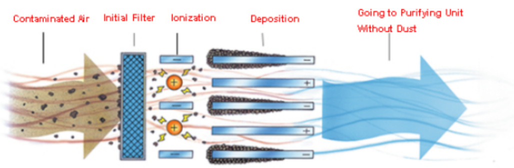
- Advantages:
- Ozone can produce hydroxyl radicals
  - Highly reactive to the pollutants
- Ideal aerial disinfectant
  - Penetrate to everywhere of the room, include a small corner

**Disadvantages:**

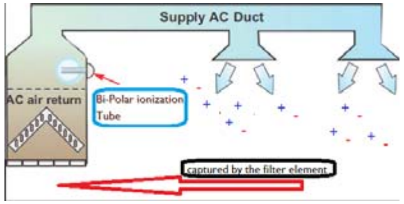
- Ozone output concentration needs to be strictly controlled
  - Health hazard
  - Slight: coughing, wheezing, headaches
  - Serious: lung diseases
- Damage some material
  - e.g. plastic

## Bi-polar Ionization- Principles

- Bi-polar ionization:
- Positive (+) and negative (-) ions
- generation by
- Bi-Polar Generator &
- Pulsed AC System








- Airborne particles then falls to the floor.
- These larger particles are also returned through the air conditioning system and captured by the filter element.

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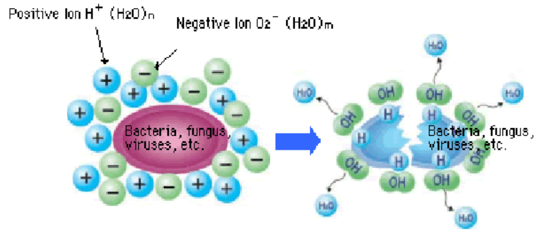
## Bi-polar Ionization- Principles

- Though positive and negative ions
- The organism was destroyed and deactivated

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## High Risk Premises

Mask Off
Close Proximity
Long Term Exposure
Enjoyable Loud Talking

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## Vulnerable Groups

Schools and Elderly Homes: Physically vulnerable segment with long term close interaction

Possible Out break if Teachers are infected and their offices become a hub

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# Any solutions?

## Problems today

- COVID-19 Virus is more viable than SARS in normal thermal condition
- Transmission of the virus through carrier in air seems to be effective
- The most effective way of precaution is to cut off all possible connections between people (not desirable)
- All interpersonal activities are halt and caused damage to most schooling (classroom, teacher's office)
- Difficult to perform effective risk assessment (Hidden paths of transmission are very hard to determine)
- Situations change so rapidly. When emergency out break takes place, how to respond?
- Actual Virus test in real environmental is not desirable

## What is needed?

- Simple assessment method
- Minimal disturbance to tenants and occupants
- Rapid response and deployment
- Provide all possible ways of dispersion profile
- Provide an easy-to-understand presentation of the current situation to the occupants
- Provide suggestions of remedy for effective precaution (i.e. seating plans modification, occupant allocation, operation scheduling, air purifications, system modifications)


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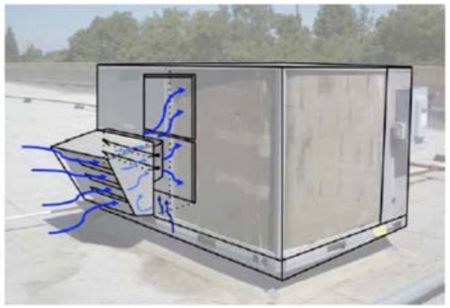
# Ventilation & Transmission

## Any Technologies?



# Ventilation Principles

- Ventilation is the supply of outdoor air to a building



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# Ventilation Principles

## Why is building ventilation needed?

- Ensure comfort and satisfaction
  - Remove odor
  - Avoid stuffiness
- Maintain overall indoor air quality
  - Remove indoor air pollutants (e.g., formaldehyde emitted from building materials, furnishings)
- Support health and productivity of occupants

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## Ventilation … any indicator?

### Carbon Dioxide ($CO_2$) as Proxy for Ventilation Rates

- $CO_2$ concentrations are often used as an easily measured proxy for ventilation rates
  - When unoccupied, indoor $CO_2$ approaches outdoor background level (0.04%, or 400 parts per million (ppm))
  - When people enter the space, $CO_2$ increase over time because we exhale $CO_2$ (4%)
  - Peak indoor $CO_2$ concentration above **1,000 ppm** indicates ventilation rates less than 7 L/s (15 cfm) per person (building ventilation requirement)
- Research suggests exposure to elevated level of $CO_2$ can also impact cognitive performance

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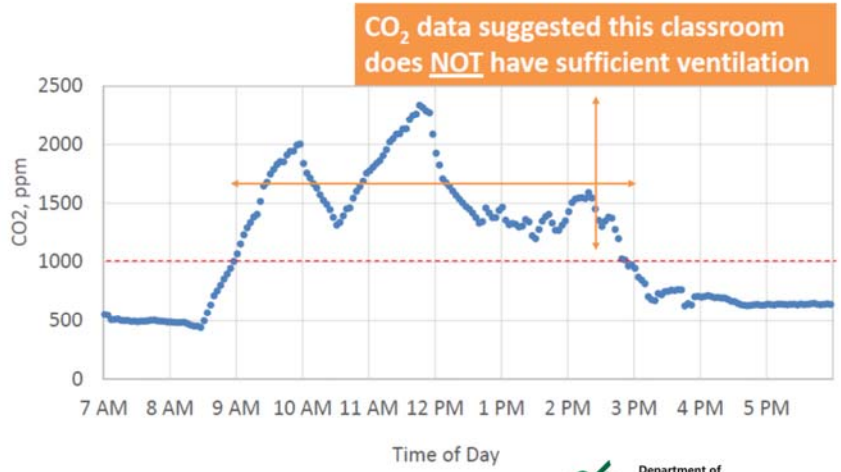
## Ventilation … any indicator?

### $CO_2$ Concentrations Measured in a Classroom

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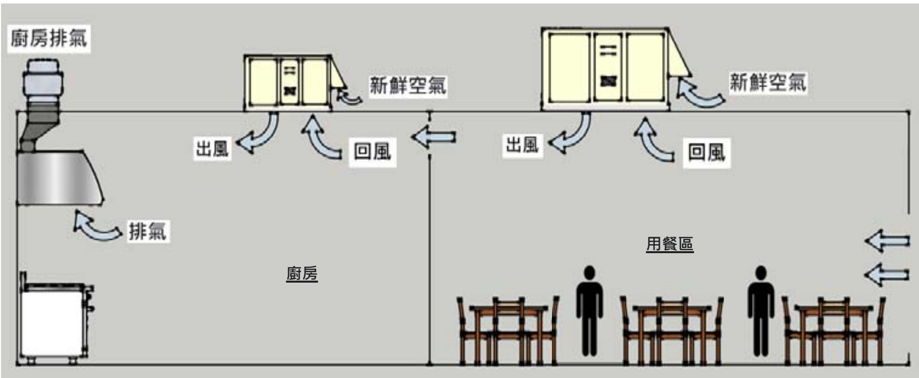
## Restaurant Ventilation




換氣率 (Air Change Rate) = 每小時每人立方米新鮮空氣 ($m^3$/hour/person fresh air) x 人數 (person) / 餐廳的體積 ($m^3$)

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## Restaurant Ventilation

A Guide to Application for Restaurant Licences (fehd.gov.hk)

**HEALTH REQUIREMENTS FOR THE ISSUE OF PROVISIONAL GENERAL/LIGHT REFRESHEMENT RESTAURANT LICENCE**

**STANDARD REQUIREMENTS**

1. **Ventilation** : When natural ventilation is insufficient (i.e., where openings and windows to the open air are less than 1/10th of the floor area), a ventilating system shall be provided to give not less than 17 cubic metres of outside air per hour for each person that the premises are designed to accommodate. A ventilating system, which shall be independent of any ventilating system provided for the seating accommodation, shall be provided for the kitchens and toilet rooms of the premises.

2. **Toilets** : At least one toilet compartment, one urinal and one wash-hand basin shall be provided on the premises for the use of customers and staff. If the premises are designed to accommodate more than 25 customers, at least 50% of the provision required for the issue of a full licence have been provided.

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## Restaurant Ventilation

How to calculate the Air Change Per Hour (ACH)

| Use | Factor used in determining the population |
|---|---|
| Seating Area | 1 $m^2$/person |
| Food Room Area | 4.5 $m^2$/person |
| Dancing Area | 0.75 $m^2$/person |

**ACH**

$$ACH = \frac{\text{Number of occupants (person)} \times \text{fresh air quantity } (m^3/h/\text{person})}{\text{Volume of the space } (m^3)}$$

換氣率 (Air Change Rate) = 每小時每人立方米新鮮空氣 ($m^3$/hour/person fresh air) x 人數 (person) / 餐廳的體積 ($m^3$)

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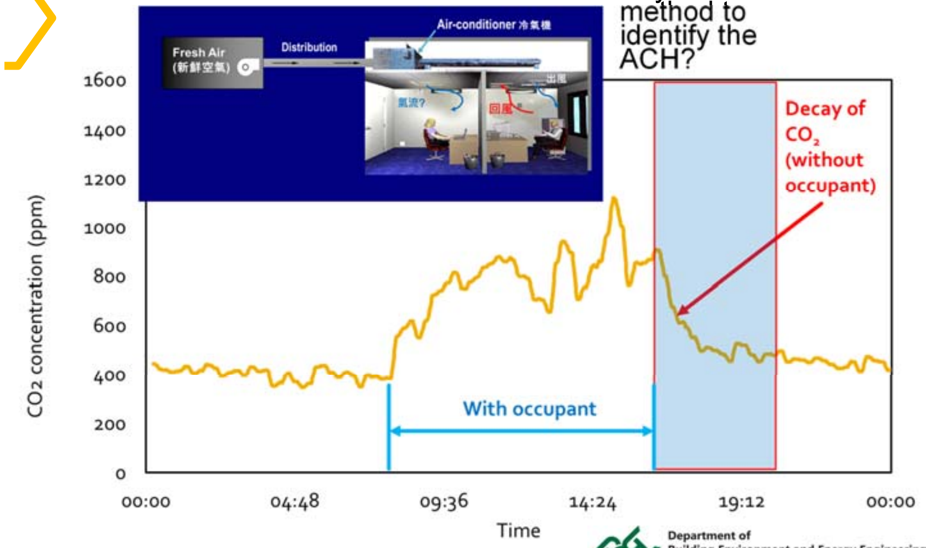
## How to calculate ventilation rate? What is decay test??

Any method to identify the ACH?

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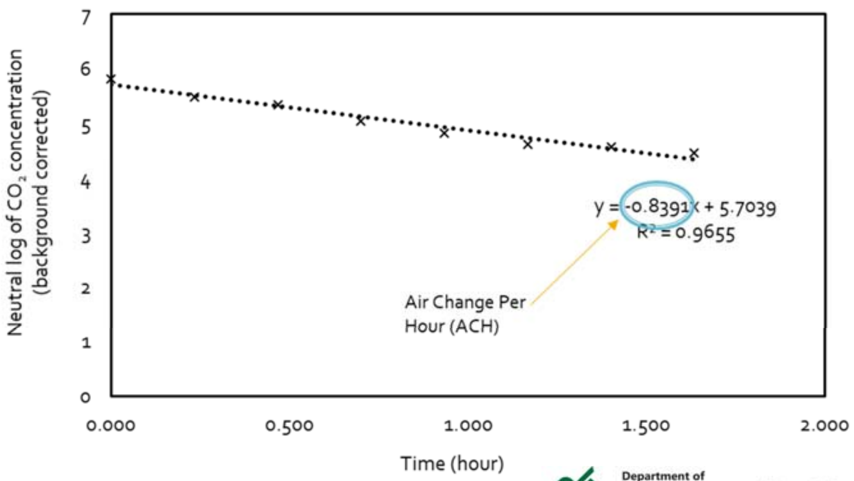
## Ventilation (ACH) calculation

Any method to identify the ACH?

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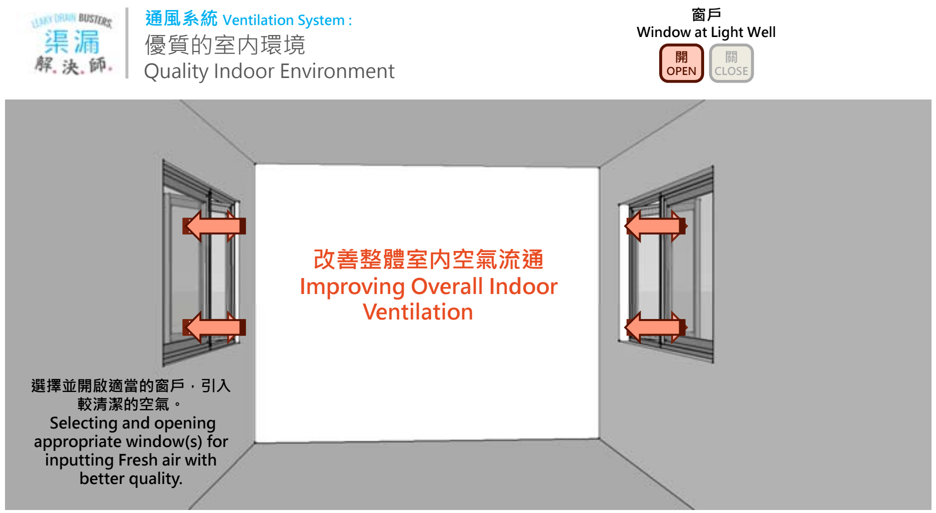
## Identification of air path

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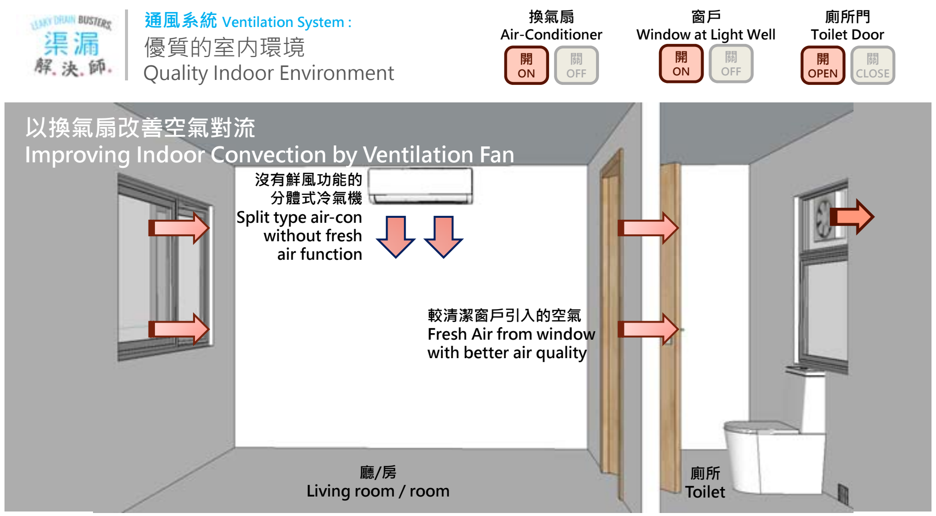
## Identification of air path

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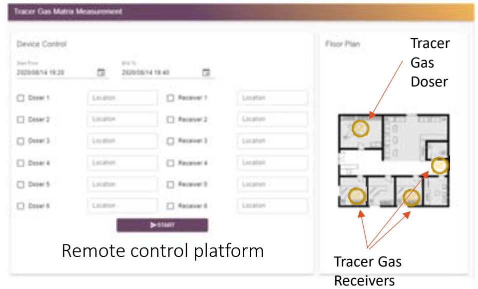
## Ventilation and identification of pathogen transmission path – Example I

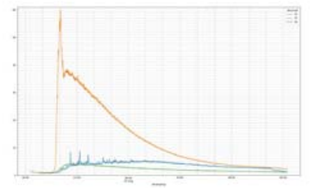



### Tracer Gas Matrix Surveying System

- Rapid deployment for Instant response
- Minimal training required for deployment
- Remote real time analysis possible
- Environmentally friendly R134A applied as easily available tracer gas

- ACH analysis by Decay Mode
- Cross Flow/Contamination analysis by Matrix Mode (Multi-Dosers/Receivers Sycnchronized Dosing Matrix)

Real Time Tracer Gas Profile at 3 defined locations



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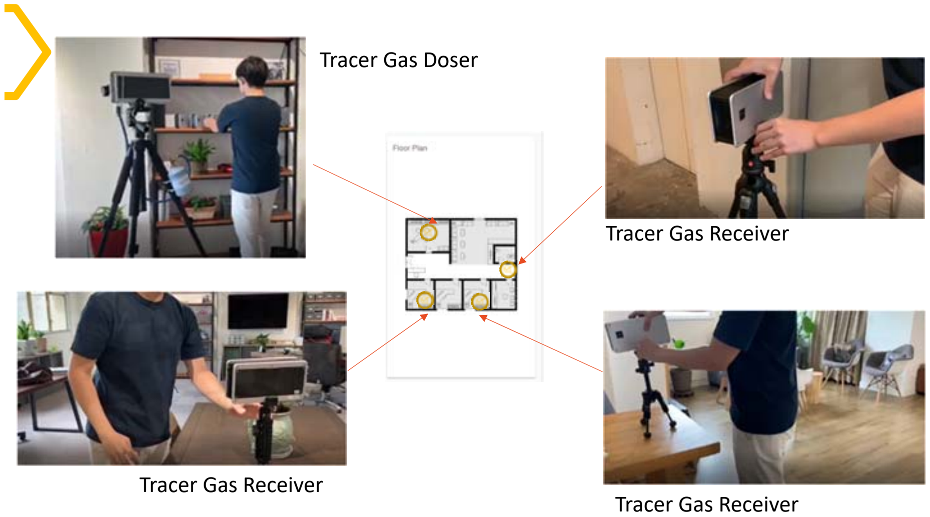
## Ventilation and identification of pathogen transmission path – Example I

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## Ventilation and identification of pathogen transmission path – Example I

## Ventilation and identification of pathogen transmission path – Video

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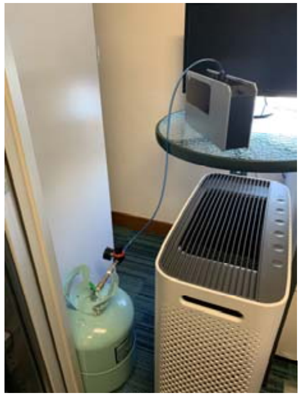
## Ventilation and identification of pathogen transmission path – Example II

Tracer Gas Matrix Measurement

Pathogen Source Dispersion Analysis
Contaminants Apportionment Analysis



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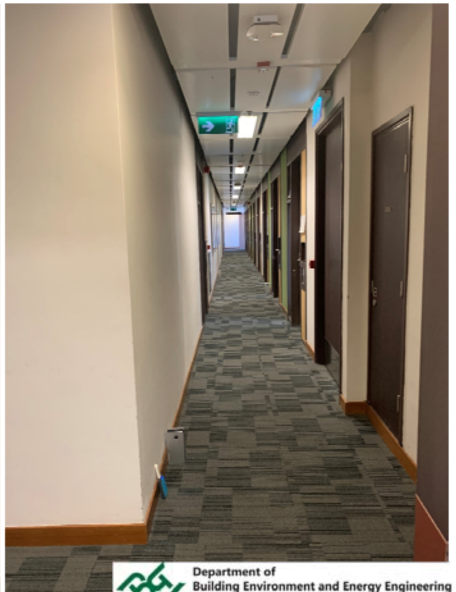
## Ventilation and identification of pathogen transmission path – Example II



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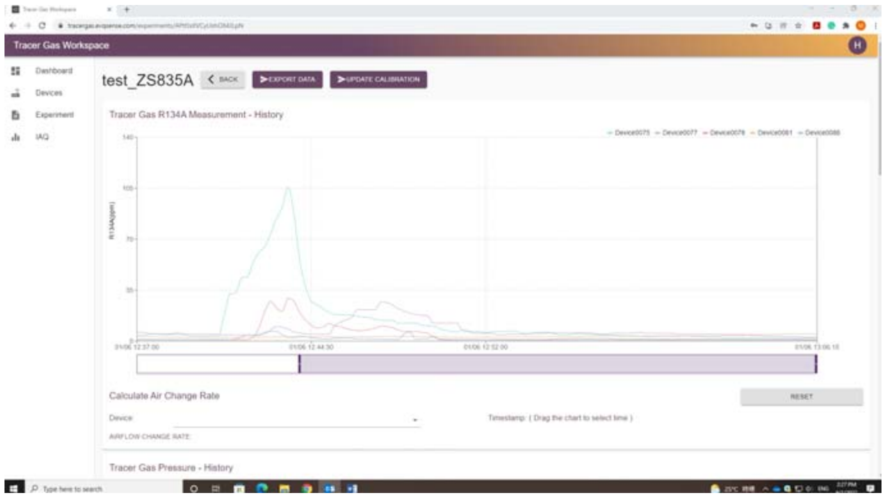
## Ventilation and identification of pathogen transmission path – Example II

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## Ventilation and identification of pathogen transmission path – video (8:13-10:00)




## Any more examples?

On Stage Tracer Gas Air Flow Analysis
for
Risk Assessment of Potential Pathogen Dispersion Profile

In Association with
Hong Kong Philharmonic Orchestra


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## Objective for HK Phil On Stage Air Flow Analysis – Example III

- Determine the spreading path of potential pathogen from any player on stage
- Determine the potential risk level for other occupants on stage
- Determine the ventilation rate of the current system settings
- Help defining an optimized seating plan to minimize risk level
- Determine the best way of deployment of air purifiers if necessary
- Determine the best arrangement of barrier settings
- Evaluate the risk level at the common areas where the players may gather
- Define all possible measures that could provide a safe environment for the next performance

- https://pc.watch.impress.co.jp/docs/news/1282701.html


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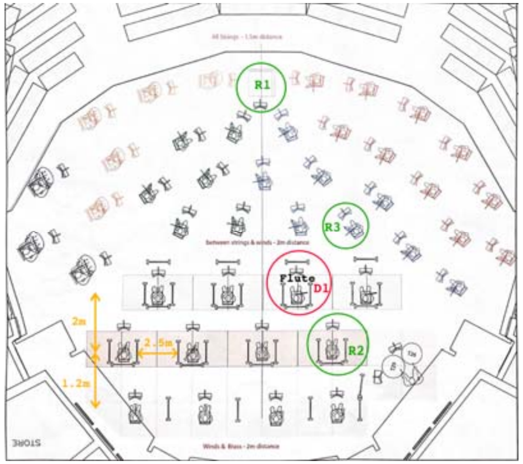
## Tracer gas profile against Individual Barrier

### Test Upon Individual Barrier Setting

Experimental condition

- Doser: Flute player
- Receiver
  - R1 – 54: conductor
  - R2 – 55: back-right
  - R3 – 56: front-left
- Tracer gas operation
  - Release at: 10:56:10
  - Stop at: 11:07:01





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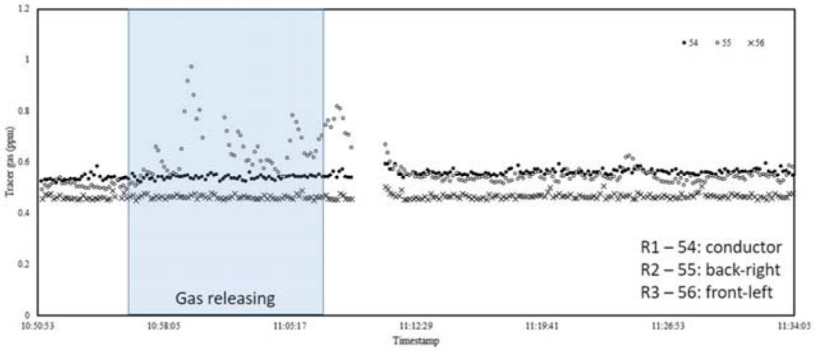
## Tracer gas profile against Individual Barrier

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## Tracer gas profile against Optimised Seatings with Inline Barriers

### Test upon Optimized Seatings with Inline Barriers

Experimental condition

- Doser: Flute player
- Receiver
  - R1 – 54: front-right
  - R2 – 55: back-right
  - R3 – 56: further back-right
- Tracer gas operation
  - Release at: 14:53:00
  - Stop at: 15:03:36


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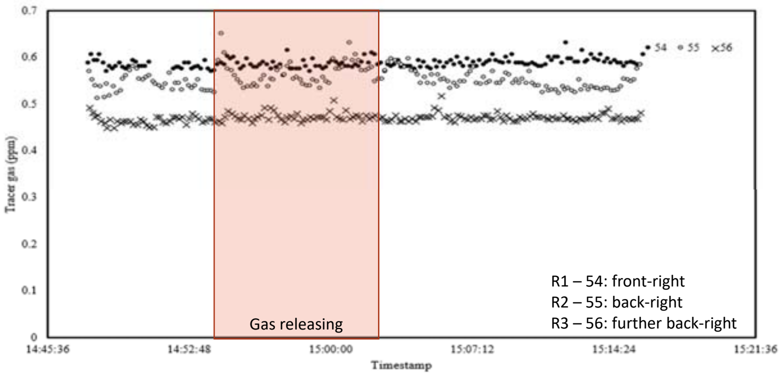
## Tracer gas profile against Optimised Seatings with Inline Barriers

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## Identify the dispersion of COVID-19

- Applicable to special situation, for instant during a pandemic, to conduct monitoring in wet market and restaurants where transmissions are observed, even clean-up has been done
- Once the equipment is set-up, the system will release and track the tracer gas **remotely** without the presence of technician. Much less manpower and time are needed
- **No personnel is required** to be on-site. Data will be automatically transmitted to server for analysis
- Compare to traditional method which takes about half a day to collect and analysis the data, this **new approach takes only 2 hours** to report the pathogenic bioaerosol dispersion pathway

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## The Tracer Gas Measurement Exercise helps to

- Define better seating arrangement at with respect to the existing ventilation profile
- Determine the potential pathogen dispersion coverage
- Determine the existing risk level deduced by the ACH evaluating
- Determine the optimized occupation number
- Conduct cross platform analysis with long term IAQ monitoring data
- Define emergency control plan
- Define ventilation system modification plan

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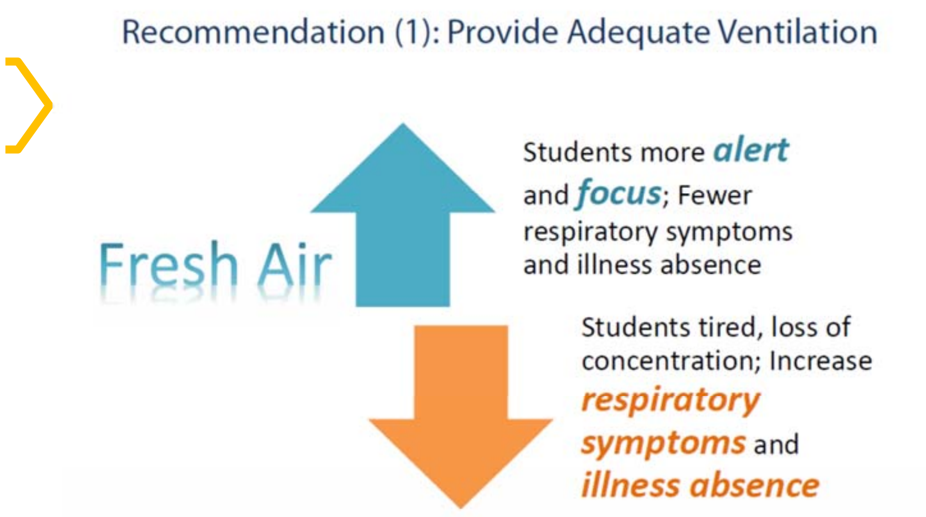
## So…?

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THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

## Any other high-risk area?

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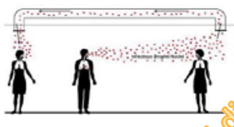
## Hong Kong's classic example - SARS

In 2003, SARS outbroke in General Inpatient Ward caused by a SARS patient be given with nebulized treatment

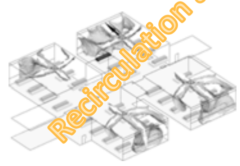
- Aerosolized coronavirus particles re-circulated in the whole ward, infecting 277 staff and patients, leading to the community outbreak in HK

In 2004, HK Government approved the construction of the 1st Infection Disease Control centre in HK

- 17-storeys with 108 negative pressure isolation beds
- Started operation in 2007



Infections droplet nuclei travel within environment




Transmission paths for the pathogenic between general inpatient ward cubicle

1st Infection disease centre in HK

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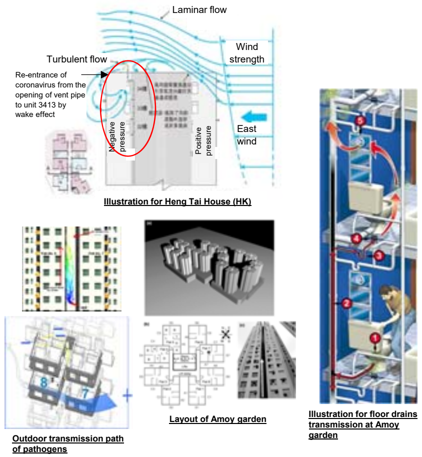
## Introduction: Hong Kong is a classic example (Drainage design)

Heng Tai House, Tai Po (COVID-19)

- When flushing, an amount of air that contained the virus went to the top floor through the **drainage ventilating pipe** discharge, and re-entered the top floor by wake effect

Amoy Garden (321 SARS cases out of 1755)

- The bathroom floor drains with **dried-up U-traps** provided a pathway through which residents came into contact with small droplets containing viruses from the contaminated sewage
- **Crack in vent pipe** emitted contaminated air droplets into light well

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## (Some of the) Existing solutions

Temporary segregation on A&E area

HEPA unit is placed at A&E area

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

- 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


Design references?

Technical gap !!

Problem solved?

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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) (~~infection disease ward, laboratory & operating theatre etc~~)

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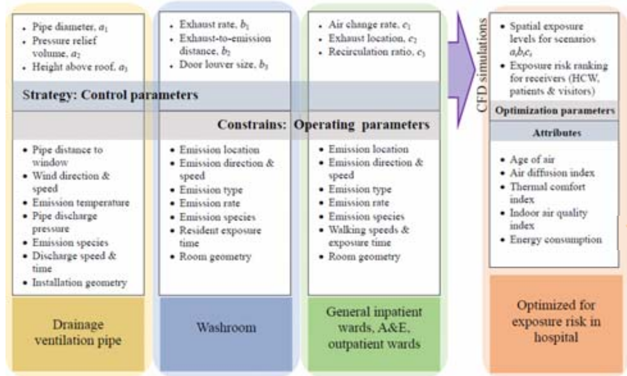
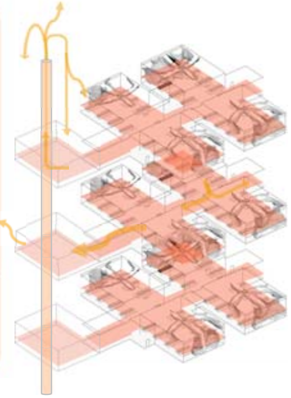
## What we need to take care of?




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



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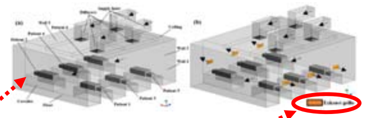
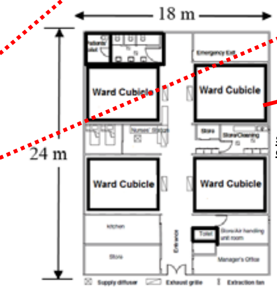
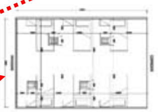
## Task 1: Hospitals layout and ventilation strategies data collection

- Arrangement drawings and technical details of GHOAs in hospitals (e.g. dimensions, ventilation rates and outlet locations)
- 27 ventilation scenarios for general inpatient ward (the most complicated one) will be simulated using
  - (a) **ach** (3, 9 and 13$h^{-1}$)
  - (b) **exhaust locations**
    - EXISTING: no exhaust
    - low level exhaust near the beds
    - low level exhaust on the window side; and
  - (c) **recirculation ratios** (10, 30 and 50%)






Layout of general inpatient ward



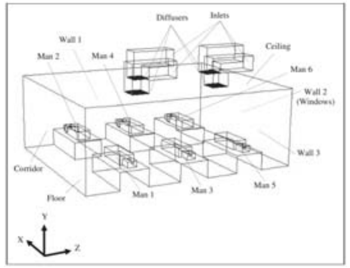
Single general inpatient ward cubicle

Consider the air flow between **clean** and **dirty** zone

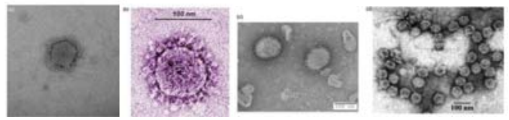


## Research into the ventilation of general hospital wards for mitigating infection risks

- A typical semi-enclosed six-bed general ward -7.5 m (L) x 6m (W) x 2.7 m (H)
- 3 respiratory viruses (MERS-CoV, SARS-CoV and H1N1 influenza virus)
- Computational fluid dynamics (CFD) simulation of airflow field and virus dispersion inside the ward with various ACH




CFD configurations of a six-bed general ward cubicle



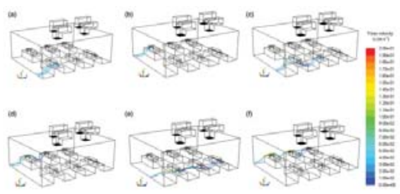
Electron micrograph of reference viruses. (a) MERS-CoV19 (b) SARS-CoV20 (c) H1N1 influenza virus21 and (d) Bacteriophage Phi X174

Reference: Yu, H.C., Mui, K.W., Wong, L.T. and Chu, H.S., 2017. Ventilation of general hospital wards for mitigating infection risks of three kinds of viruses including Middle East respiratory syndrome coronavirus. *Indoor and Built Environment*, 26(4), pp.514-527.



## Potential risks of cross infection with through air pathways

- Patients staying on the same side of an infected patient, especially the one located next to the corridor (i.e. Man 1 or Man 2), would have a higher chance of cross infection
- Two different virus pathway flows in the simulation due to the asymmetric diffuser locations
- The virus moved along floor surface of the ward but in cases shown in Figure d and f, virus would pass over nearby patients' heads, then flew to the corridor [Figure c and e]

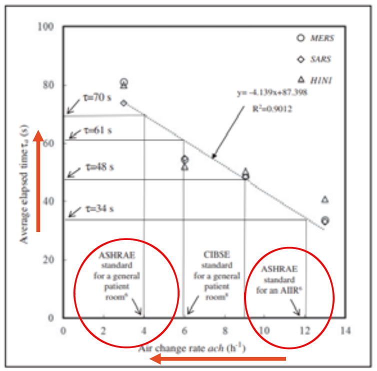


MERS-CoV pathways for six source locations with ach=6 $h^{-1}$ (a) Man 1, (b) Man 2, (c) Man 3, (d) Man 4, (e) Man 5 and (f) Man 6



## Optimal ACH for hospital

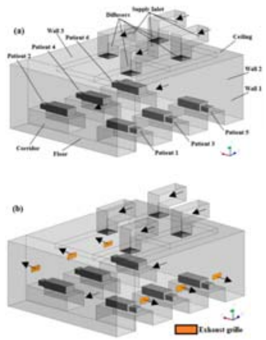
- The average elapsed time against ACH could be significantly shortened by increasing the air change rate in the ward
- The elapsed time doubled when ACH dropped from 12 to 4 $h^{-1}$, and thus doubling the potential inhalation risk
- Based on the median value in accordance with both ASHRAE and CIBSE standards, the maximum ACH in a general hospital ward should be *9 $h^{-1}$ (elapsed time=48 s)* for the needs of maximizing energy efficiency and minimizing infection risk




Average elapsed time with various design standards. AIIR: airborne infection isolation room.

## Research into ventilation strategies and the use of local exhaust grilles for infection risk mitigation

- To evaluate the combined impacts of air change rate and exhaust airflow rate on the airflow and infection risk distributions of droplet nuclei of size 0.167 μm (i.e. MERS-CoV) within an air-conditioned general inpatient ward cubicle using CFD
- To develop a simple yet cost-effective ventilation system design that can minimize the risk of infection in an existing hospital ward



Inpatient ward cubicle with patients: (a) without exhaust grilles; (b) with local exhaust grilles

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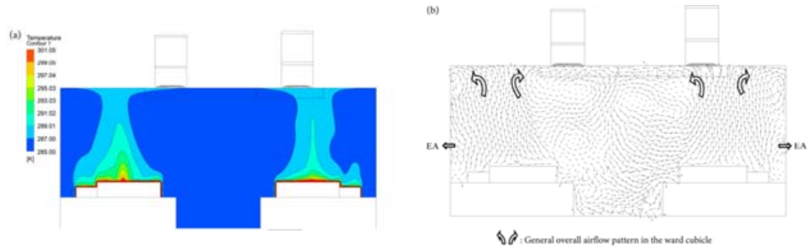
Reference: Satheesan, M.K., Mui, K.W., and Wong, L.T., 2020. A numerical study of ventilation strategies for infection risk mitigation in general inpatient wards. *Building Simulation*, 13, pp. 887-896.



## Use of local exhaust grilles

- The local exhaust grilles not only facilitated the removal of a portion of exhaled virus particles but also tended to increase the particle deposition in the source patient's body and thereby reduced the residual viral load present in the air



Simulation results of ward cubicle with exhaust grilles at 6ACH and exhaust air (EA)=50%: (a) temperature distribution; (b) velocity vector plot

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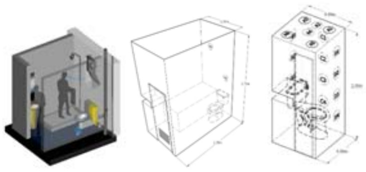
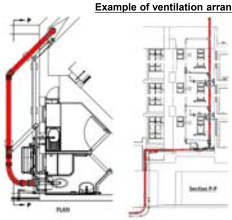
## Task 2: CFD simulation for dynamic water and airflow in drainage system in relation with washroom

- **Potential infection risk** associated with toilet flushing and the influence of pathogen in common areas such as corridor or ward cubicle have not been sufficiently addressed in the design of residential washroom exhaust system
- A two-phase flow CFD model for **air and water flows inside the drainage system** will be developed
- Verification and application of CFD simulation using drainage test rig



Example of ventilation arrangement for Washrooms



Layout of drainage pipe

Drainage test rig at PolyU

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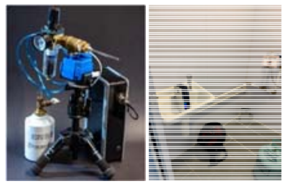
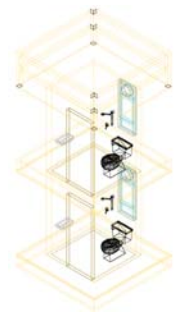
## Collaboration with IC

**The Research Platform of Sanitation Hygiene and Environment (RPSHE)**



Pathogenic bioaerosols tracking system

Tracer gas and aerosol experiments can be conducted to identify the pathway of re-entrance of airborne pathogens under the influence of outdoor conditions and various combinations of toilet ventilation.



3D drawing of RPSHE

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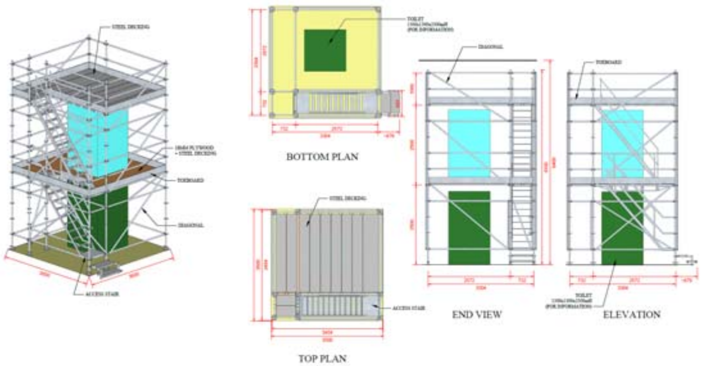
## Design drawing of the proposed two-storey test rig of building drainage

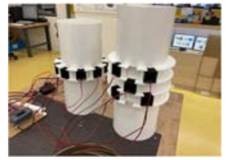
### The Research Platform of Sanitation Hygiene and Environment (RPSHE)



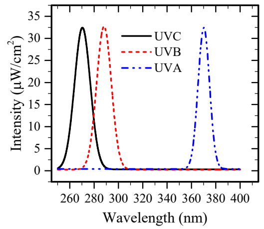



## Collaboration with IC

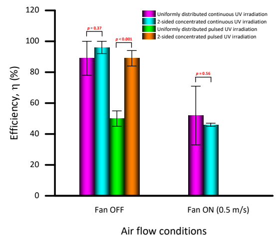
(Left) Sampling bioaerosol generated during flushing (Right) Ring-shape UV LED disinfection module for the drainage-ventilation pipe



Different UV-LED configurations (ring &square)




Spectral distribution of UV wavebands

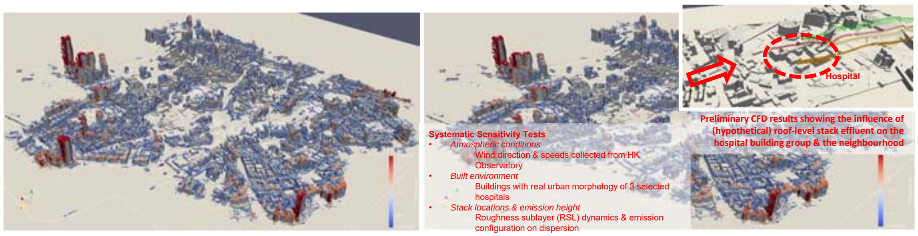



Disinfection efficiency of UV-LED



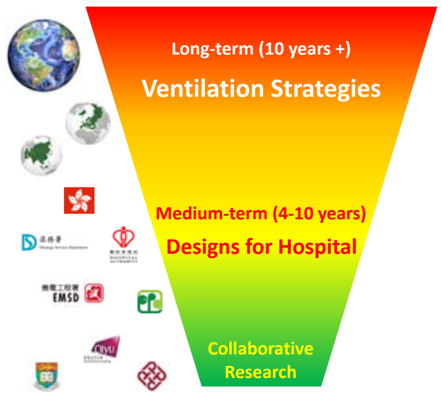
## Task 3: CFD simulation for spatial exposure levels at drainage ventilation pipe discharge

- Dynamic of airflow fields and spatial distribution of aerosols from the **toilet exhaust** and **ventilation pipe discharge at hospital roof** will be simulated
- Roof configuration, surrounding built environment, atmospheric conditions, stack location and emission height causing **the risk of short circuit** of contaminants from discharge to **fresh air intake** will be identified






## 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**

## In conclude …

**Embrace more health-conscious design, and work cooperatively as an international community to solve problems, pave the way for a healthier future**

**Question & answer?**

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