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Hospital Design and Operation

Considerations for infections, energy, comfort.

HumanIC CBT1

26th Feb 2025

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HumanIC project has received funding from the European Union’s Horizon Europe research and innovation program under the Marie Sklodowska-Curie (HORIZON-MSCA-2022-DN-01, project no 101119726

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Session Objectives

- To understand how environmental design in hospitals can affect health, comfort, energy and delivery of services
- To explore the factors that affect these aspects in different functional areas of a hospital
- To understand the design, operation and challenges for three example areas: isolation rooms, naturally ventilated wards, application of air cleaning technologies
- To consider what may be important if collecting data for research studies in a hospital setting

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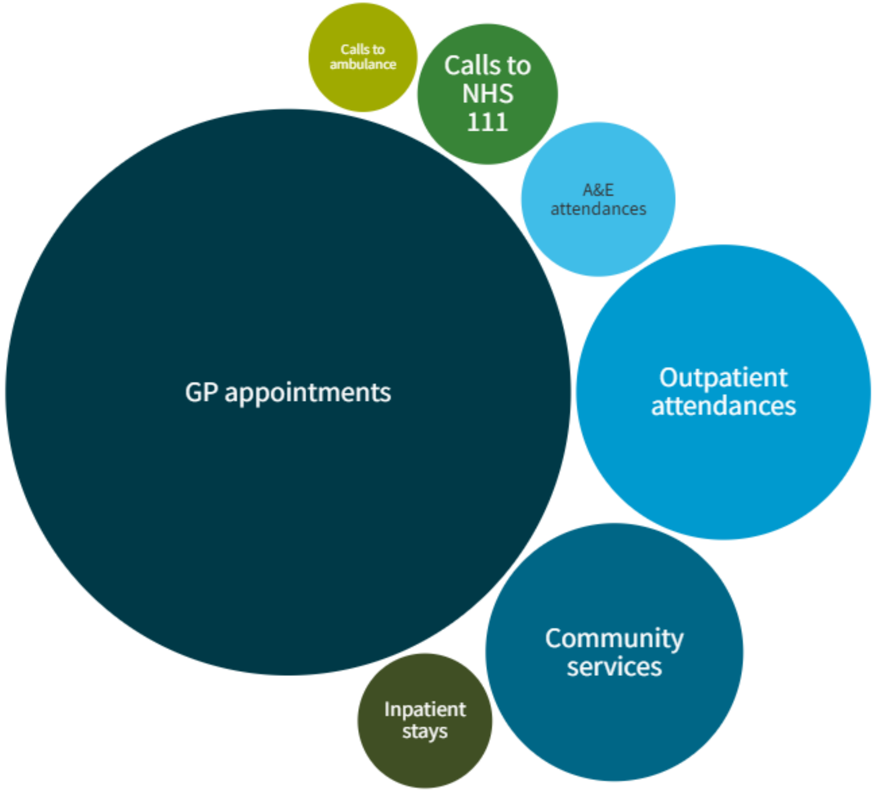
UK Healthcare provision

- National Health Service (NHS)
  - Began in 1948
  - Government funded – free at point of use
  - Includes preventative care, mental health, primary care and hospitals
  - Around 1.7 million interactions with patients every day
  - Employs 1.5M people in England, annual budget of £129.9 billion (2020-21)

- Private Healthcare Providers
  - Operate own hospitals and within NHS hospitals
  - Funded through private medical insurance – often through employer



Source: The King's Fund analysis of NHS England data., GP, A&E, ambulance and NHS 111 data is from 2023/24. Inpatient and outpatient data is from 2022/23. Community data is from 2021/22. Patient contacts are not weighted according to the level of resource they require but are the count of the start of an interaction with the health service. This means, for example, a call to NHS 111 counts as one contact, and a patient being admitted to hospital for three days for surgery counts as one contact.

TheKingsFund›

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Size and shape of the NHS estate

- 222 community hospitals (with beds)
- 228 general acute hospitals
- 564 mental health facilities
- Over 1800 other sites – not including primary care

- Total internal floor area 27.5 Mm^2
- Total running costs 2023-2024 £13.6 billion
- Total energy usage from all energy sources 11.1 billion kWh
- Total cleaning services £1.5 billion

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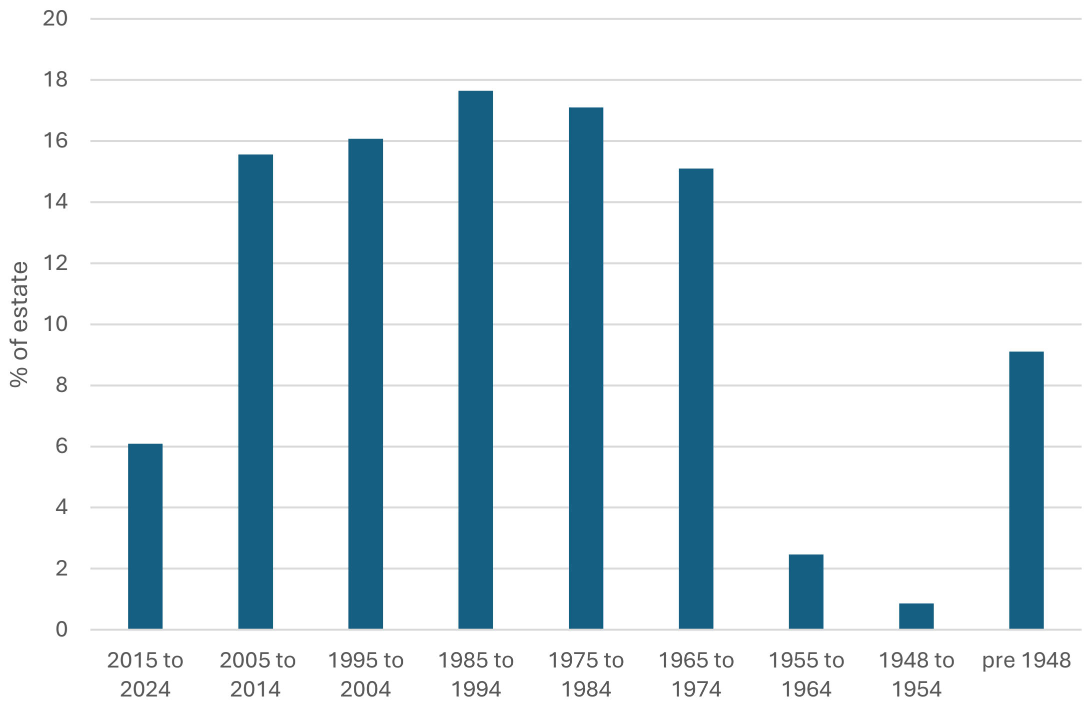
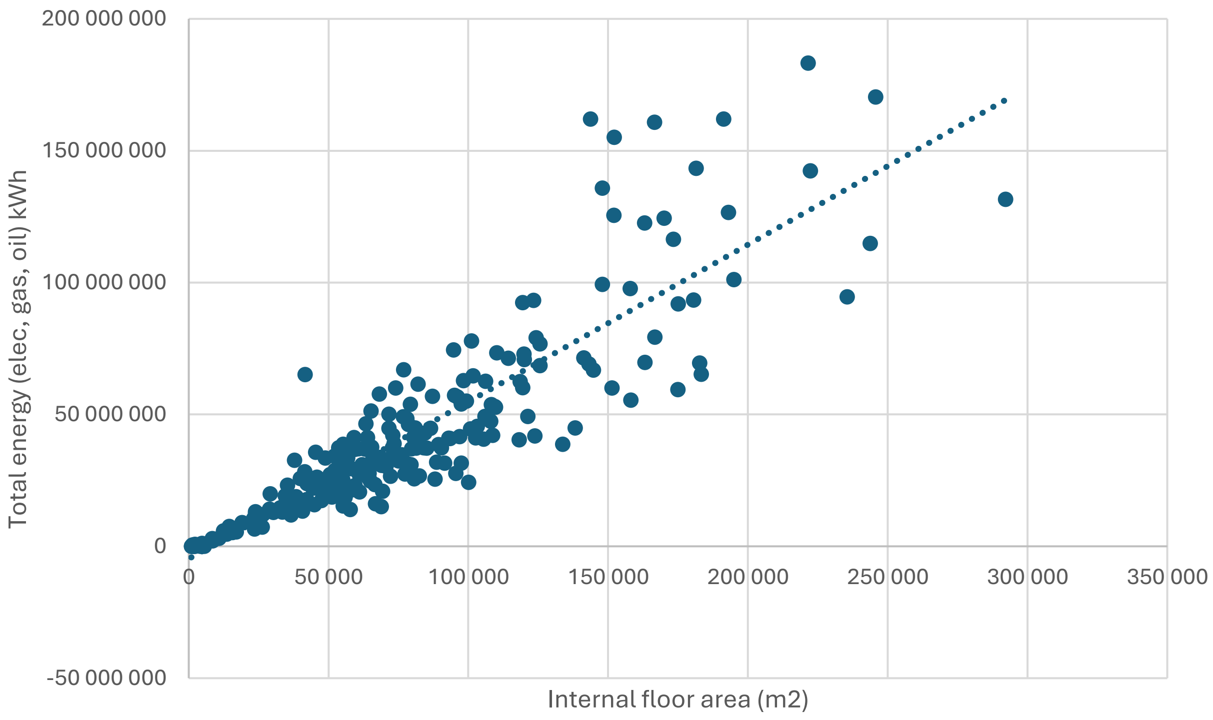
Size and shape of the NHS estate

Age profile of general acute hospitals in the NHS Estate



Total energy by floor area for general acute hospitals in the NHS Estate



https://digital.nhs.uk/data-and-information/publications/statistical/estates-returns-information-collection

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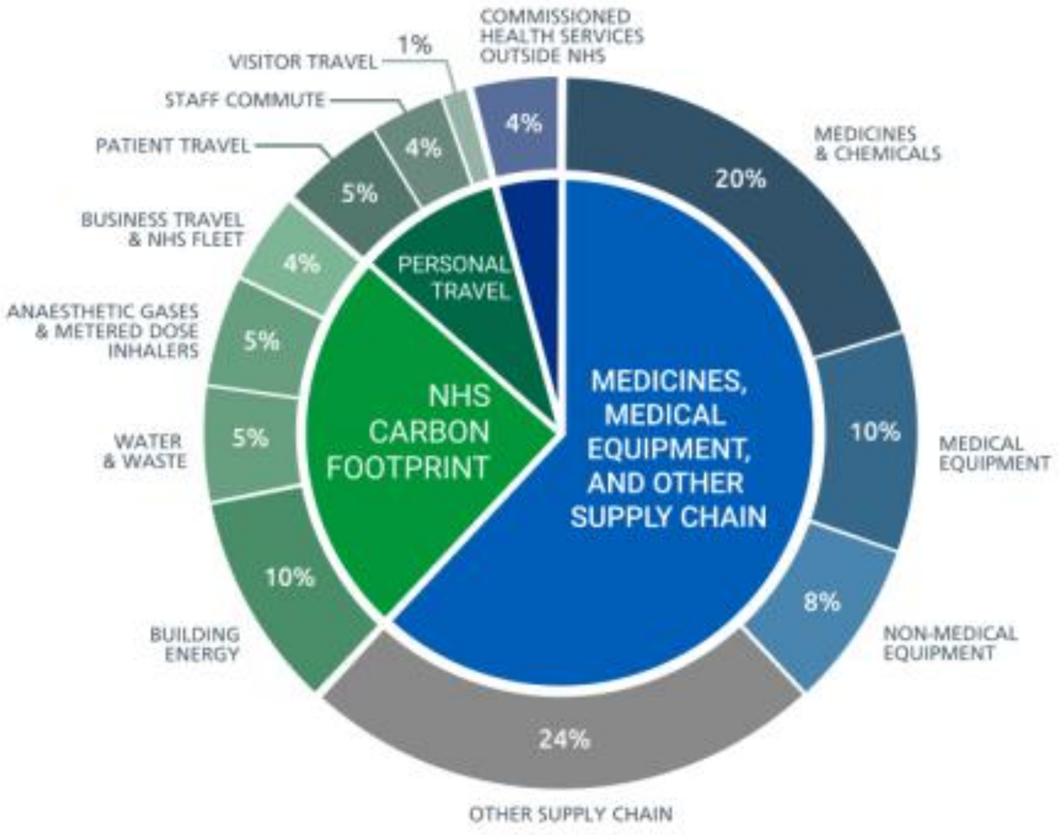
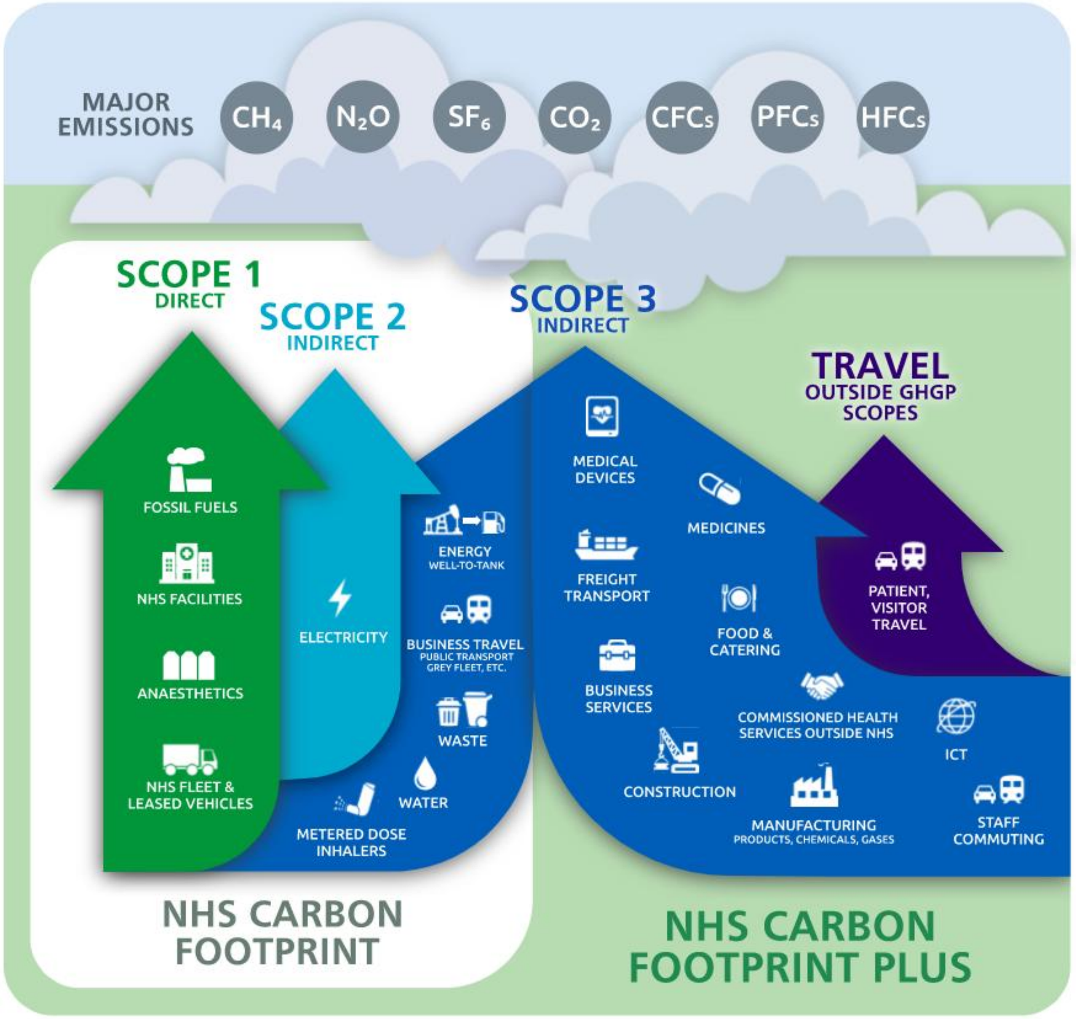
Net-zero and healthcare





Images from: NHS (2020) Delivering a 'Net Zero' National Health Service

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A brief reminder on comfort and ventilation

- **Comfort**
  - **Physical** - air temperature, radiant temperature, air velocity, humidity
  - **Personal** - clothing, age, health, activity
  - **Temperature** - typically 18-24C
  - **Humidity** – typically 40-60 %RH
- **Ventilation**
  - **Rate** – dilution and removal
  - **Pressure differences** – airflow between spaces
  - **Air distribution** – local flow patterns

- Mechanical Ventilation
- Natural Ventilation
- Extract Ventilation
- Ultra clean/laminar flow systems
- Hybrid Ventilation
- Air conditioners and fans
- Air Cleaning Technologies

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Air and Infection

- Airborne transmission of communicable diseases
  - Respiratory infections – TB, measles, influenza, Covid-19
- Airborne transmission of opportunistic pathogens
  - Vulnerable patients (e.g.CF) – pseudomonas, aspergillus, NTMs, pneumocystis
- Airborne dispersion of HAIs
  - MRSA, C Diff, norovirus, CPE

Patients

Staff and visitors

Resuspension

Water systems

Outdoor air

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Transmission through the air

Updated WHO terminology – April 2024

- Airborne transmission/inhalation – any distance, deposit anywhere on the respiratory tract
- Direct deposition – ballistic, short range, lands on mucosa
- Direct contact – physical transfer (hands), not through the air
- Infectious Respiratory Particles (IRPs) rather than aerosol or droplet
- Recognises the complexity of emissions and spectrum of sizes

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Air change rate

$$\text{Air change rate} = \frac{\text{flow rate } (m^3/hr)}{\text{room volume}}$$

For a 60 m3 patient room

- 1 ACH is 60 m3/hr
- 2 ACH is 120 m3/hr
- 6 ACH is 360 m3/hr

For a 120 m3 patient room

- 1 ACH is 120 m3/hr
- 2 ACH is 240 m3/hr
- 6 ACH is 720 m3/hr

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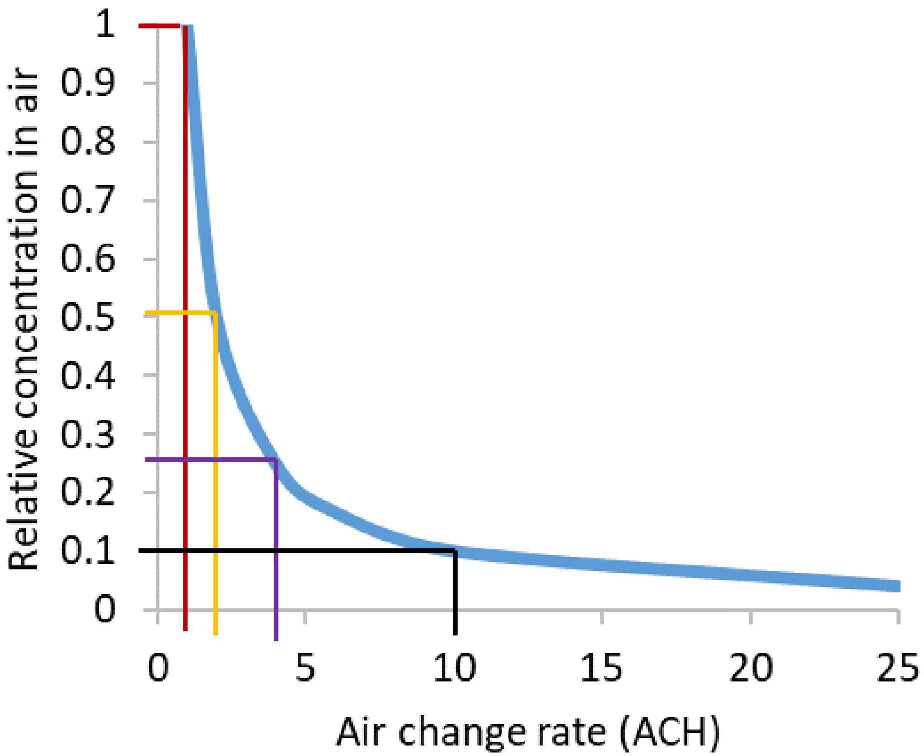
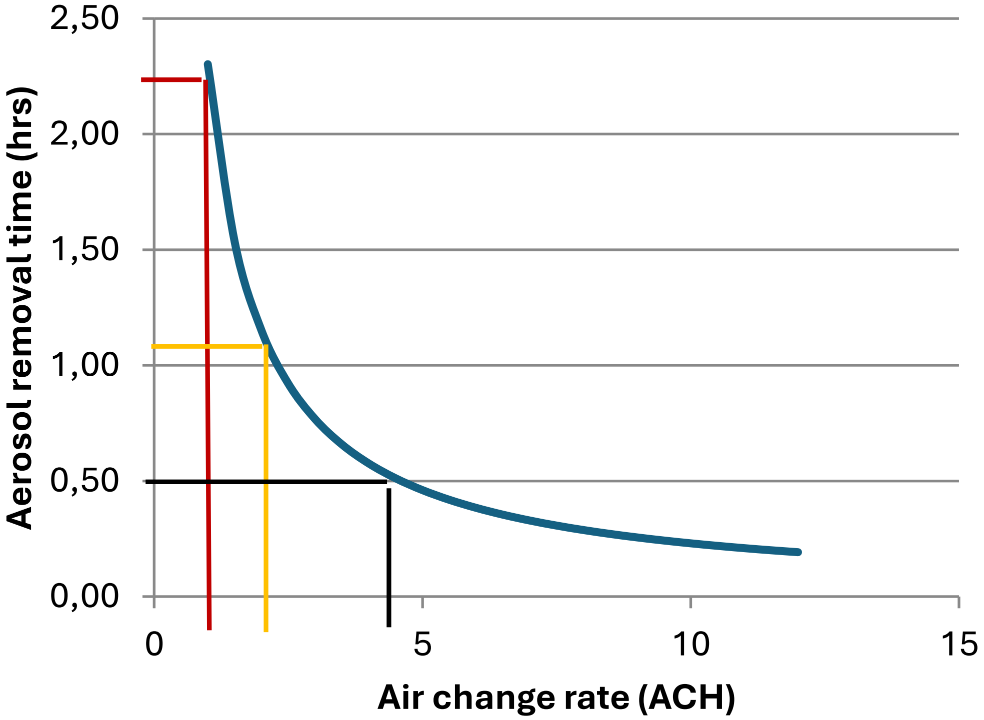
Dilution

Lower room concentration for constant occupancy



More rapid clearance rate for changing occupancy



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UK Ventilation requirements

Application	Ventilation	Air-change rate (ac/h)	Pressure (Pascal – Pa)	Supply filter grade (BS EN 16798)	Noise (dB(A))	Temp (°C)
General ward (level 0 and 1 care)	S/N	6	–	SUP2	35	18–28
Communal ward toilet	E	6	–ve	–	45	–
Single room	S/E/N	6	0 or –ve	SUP2	35	18–28
Single room WC	E	3	–ve	–	45	–
Clean utility	S	6	+ve	SUP3	45	18–22
Dirty utility	E	6	–ve	–	45	–
Ward isolation room (PPVL)	S	10	Lobby +10 Room 0	SUP2	35	–
Infectious diseases isolation room	E	10	–5	SUP2	35	–
Neutropaenic patient ward	S	10	+10	H12	35	–
Critical care areas (Level 2 and 3 care)	S	10	+10	SUP1	35	–
Birthing room	S & E	10	0	SUP2	45	*20–25*
NICU/SCBU	S & E	10	+ve	SUP1	35	*20–28*

- HTM03-01 A & B 2021 update
- Stronger requirements on inspection/audit
- Introduction of ventilation safety group
- Challenge with historical spaces and compliance
- ~50% don’t comply

Table from HTM03-01, 2021 https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/

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Infection, Water Systems and Air

- Toilets
  - Measured dispersion of microorganisms
  - Contamination of bathroom surfaces
  - Short duration event – challenge to measure
- Showers and taps
  - Biofilm in fittings and microorganisms in water
  - Studies show aerosolization
  - Association with disease – legionella, NTMs
- Sinks and drains
  - Association with HAIs and virus (SARS, COVID-19?)
  - Sink, trap, and drainage system all play a role
  - Splash contamination and aerosolisation

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Where does the balance lie?

Usability

Medical gases

Safety & security

Energy & carbon

Airborne diseases

Noise

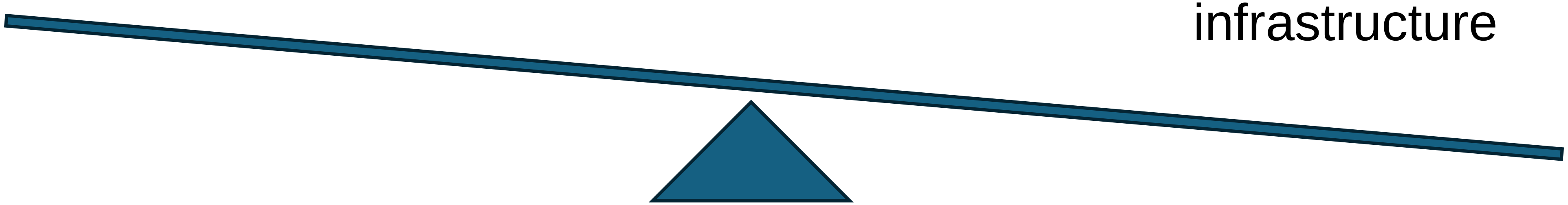
Maintenance

Space

Cost

Comfort

Legacy infrastructure



Depends on pathogen, clinical area, patient cohort, staff, existing infrastructure.....

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Exercise 1: Trade-offs

- What type of environment do we need in different parts of a hospital?
- In your group consider the factors that are important in these different spaces. What might this mean for design and where the trade-offs lie? What information might you need to support decisions?
    - Group 1: Infectious diseases isolation room
    - Group 2: Paediatric intensive care unit
    - Group 3: General surgical ward
    - Group 4: Emergency department waiting room
- 10 min discussion then feed back your thoughts to the rest of the group.

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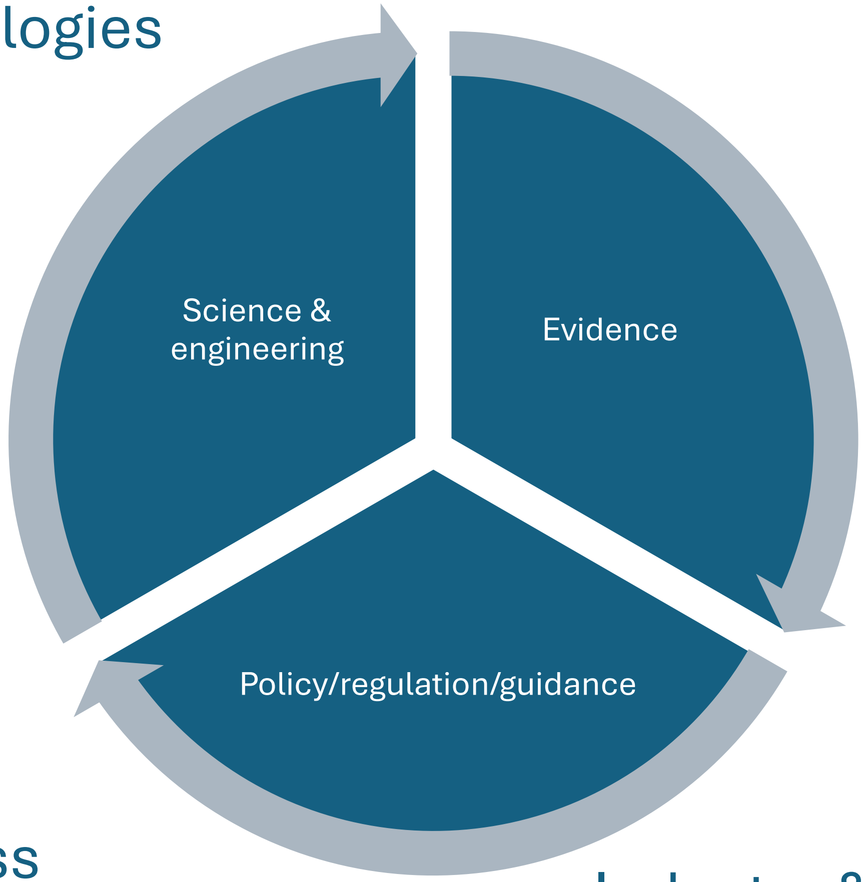
Evidence based design

Global challenges

New technologies

Emerging diseases

National policy



Political pressures

Public awareness

Industry & practice drivers

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Evidence for healthcare design

- How does it impact on infection transmission, comfort, energy?
- How reliable/robust is the solution?
- How practical and costly is it to implement?
- How easy is it to use?
- What is the long term maintenance/cost/usefulness?

Small scale lab studies

Modelling and simulation

Large scale chamber/mock up tests

Cost benefit and risk analysis

Real-world environment & behavioural data

Full scale trials for infection transmission?

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Case 1: Isolation Rooms

- Prevent an infectious patient infecting others or (and?) protecting a highly vulnerable patient
- Different levels of protection: closed door, nursing precautions, medication, ventilation
- Key principles
  - Must be reliable and easy to operate
  - Must be buildable and affordable
  - Must be designed for the right purposes
  - Must enable an appropriate care environment – comfort, dignity, clinical delivery

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Isolation Room Airflow requirements

- Between rooms: limit transmission between patient and those outside
  - Minimise the transfer of air between the room and other areas of the hospital
  - Airtight construction + well defined air supply and extract to create pressure differences
- Within room: limit transmission between staff and patient
  - Dilute and exhaust air in the room
  - High ventilation rate + good mixing
- Robust design that “fails safe”
  - Minimises the risk when doors are opened or the ventilation system fails
  - Minimises chances of user error

- **Positive pressure room** – transplant units, chemotherapy
- **Negative pressure room** – infectious diseases unit
- **Switchable room** (pos/neg) – wards/ICU
- **PPVL room** – universal?

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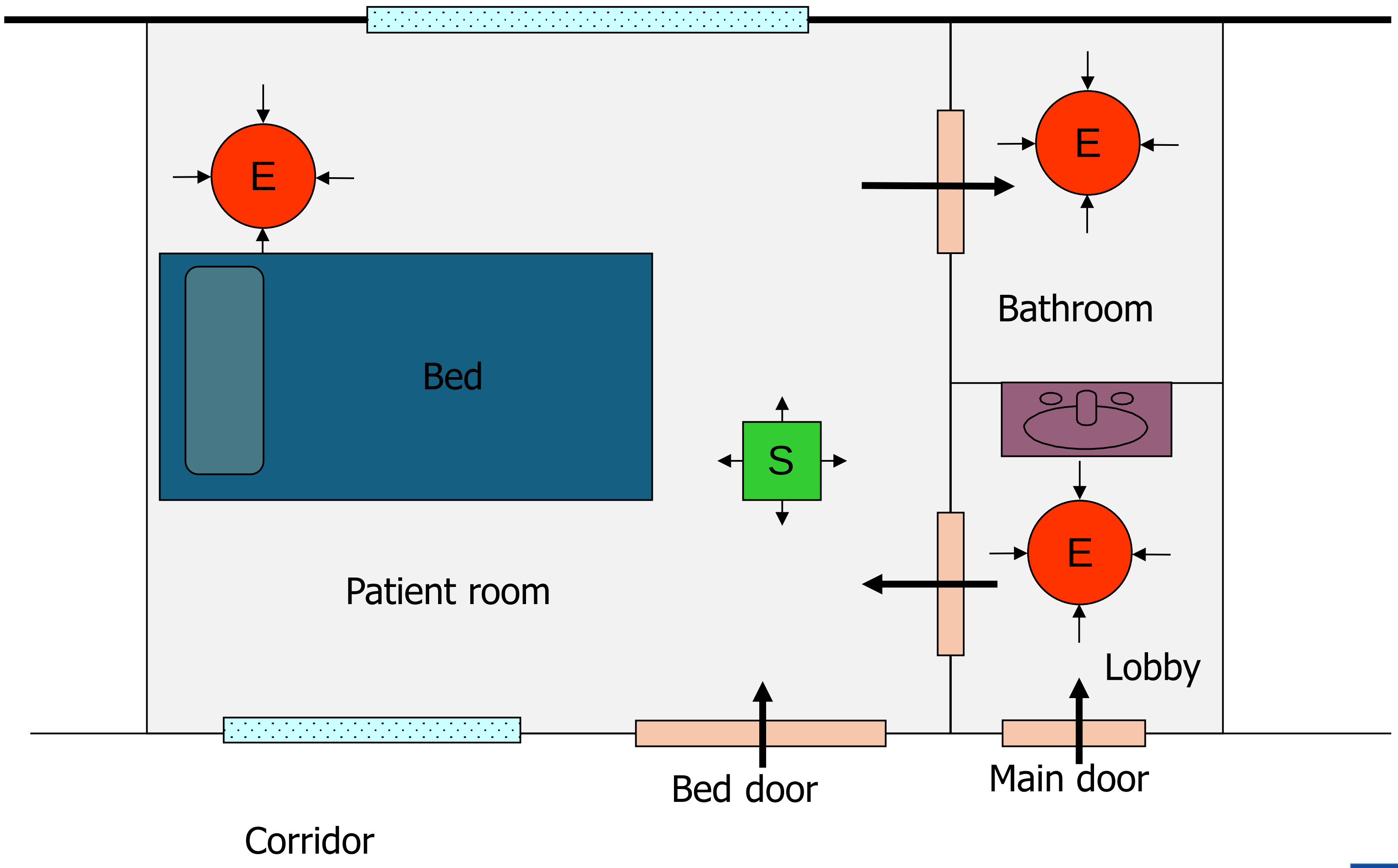
Negative Pressure Isolation Room

- Extract > Supply
- Lobby negative w.r.t. corridor
- Room and bathroom negative w.r.t. lobby and corridor



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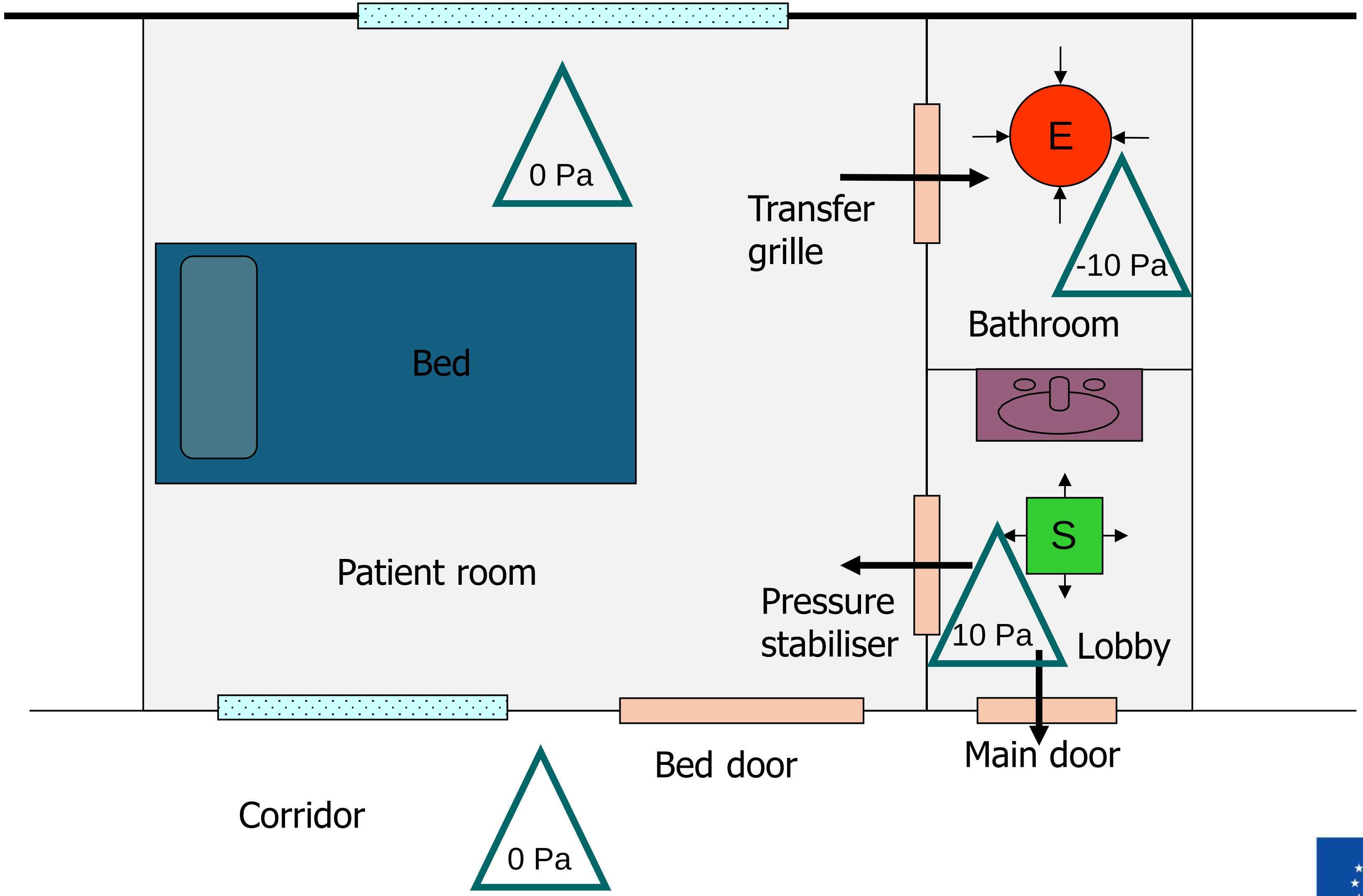
Positive Pressure Ventilated Lobby (PPVL) Room

- Patient room is neutral w.r.t corridor
- Lobby is positive w.r.t corridor and room
- Pressure stabiliser transfers air and acts as ventilation diffuser
- Extract through bathroom, negative w.r.t room



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How robust is the PPVL design?

- Airflow distribution and thermal comfort
- Risk to patient and staff
  - Ventilation failures
  - Flows when doors opened

- Programme of work to test concept
  - Mock room with full fixtures
  - Airtightness, ventilation flows, anemometry & temperatures, noise
  - Smoke visualisation
  - CFD modelling
  - Particle and gas tracer measurements

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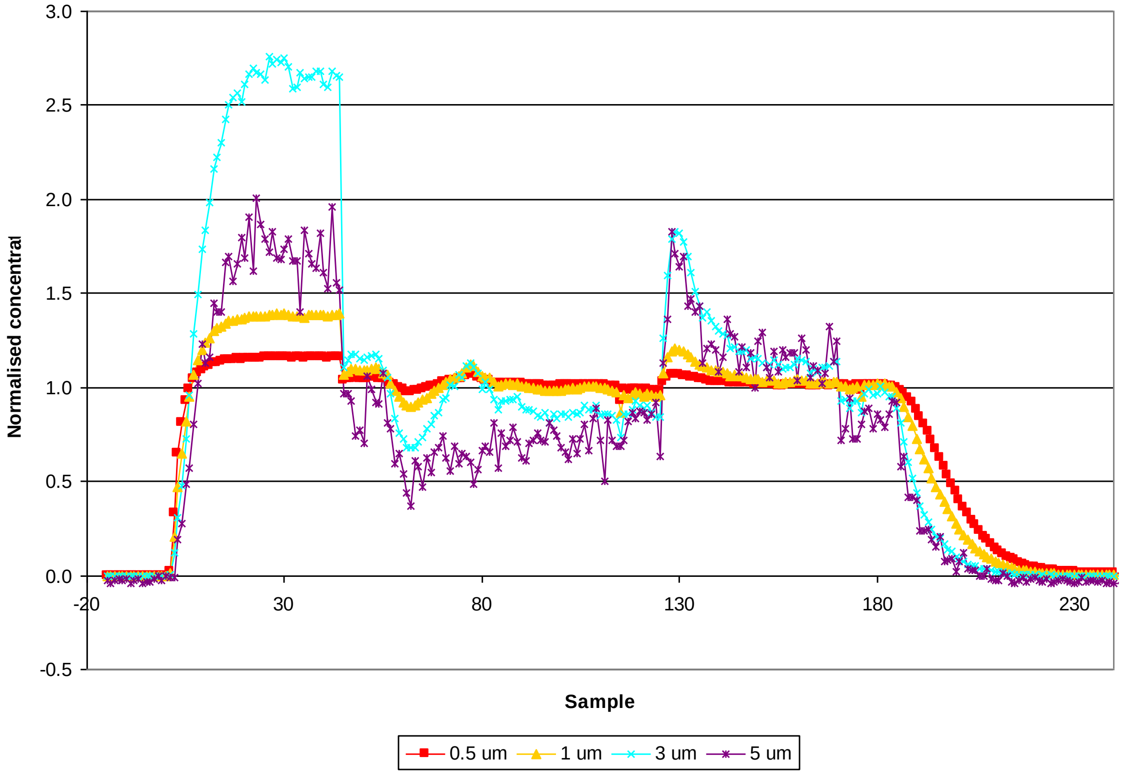
Test results

- Experimental programme very successful
  - Well mixed room with flows as designed
  - Comfort temperature and no cold drafts
  - No transfer of gas/particles when doors closed
  - Room fails safe and recovers after door opening
  - Can create a negative pressure version



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Real world

- Real world can pose challenges
  - Quality of build is crucial – airtight construction, properly set up gaps under doors, properly set up pressure stabiliser
  - Sensitive to external flow pressures, particularly in high rise
  - Negative pressure variant may be more robust

- New guidance in 2024
  - Different room configurations and ventilation strategies
  - Provision for isolation suites as well as single rooms
  - Considerations around fire, commissioning, annual validation

https://www.england.nhs.uk/wp-content/uploads/2009/12/Health-building-note-04-01-supplement-1-special-ventilated-isolation-facilities-for-patients-in-acute-settings.pdf

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Case 2: Naturally Ventilated Wards

- Natural or hybrid ventilation very common across the world
- Usually in single or multi-bed wards for a range of medical specialisms
- Rarely higher risk settings, but happens
- Pros
  - Low cost, low (?) energy solution
  - Good level of control by users
- Cons
  - Managing good ventilation year round
  - No control of heat loss or external pollution
- Evidence base on infections, energy, comfort limited

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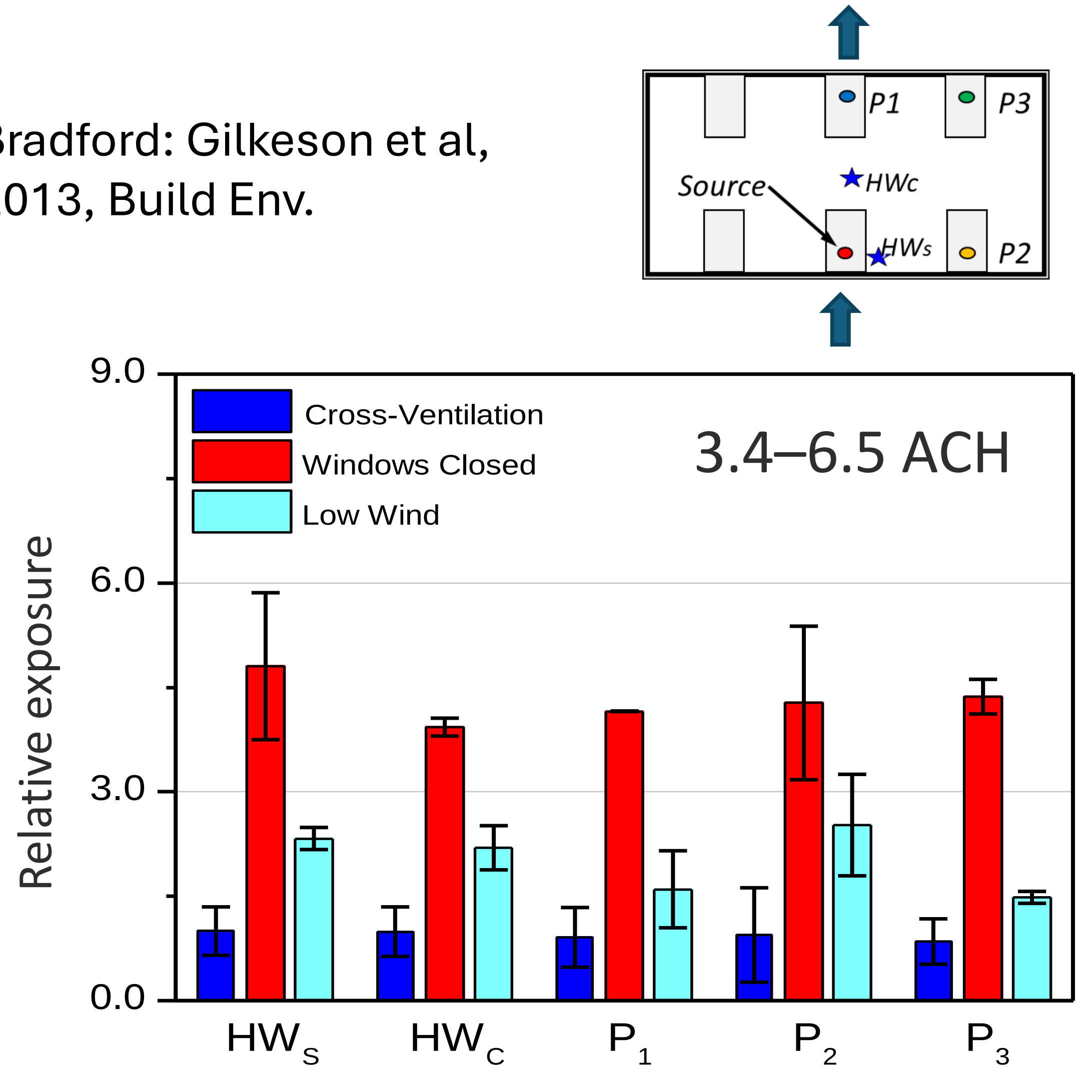
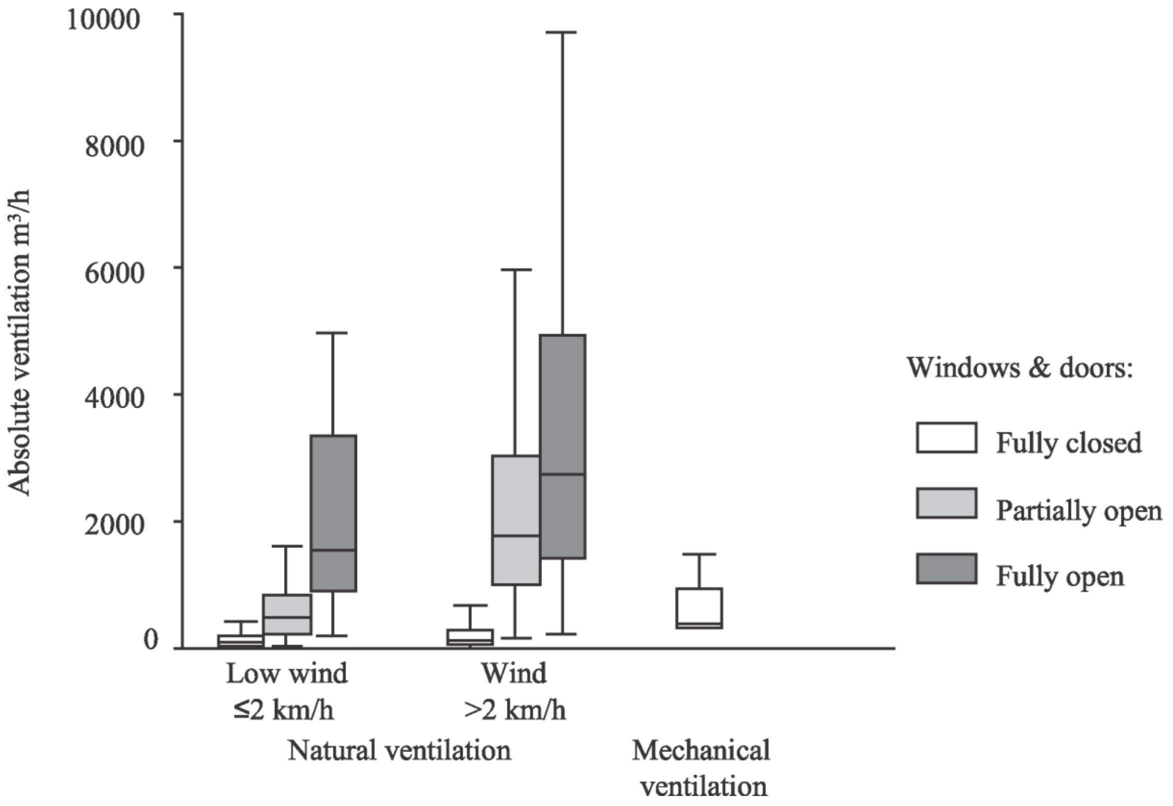
High ventilation rates are possible

Bradford: Gilkeson et al, 2013, Build Env.





Peru: Escombe et al, PLoS Med, 2007

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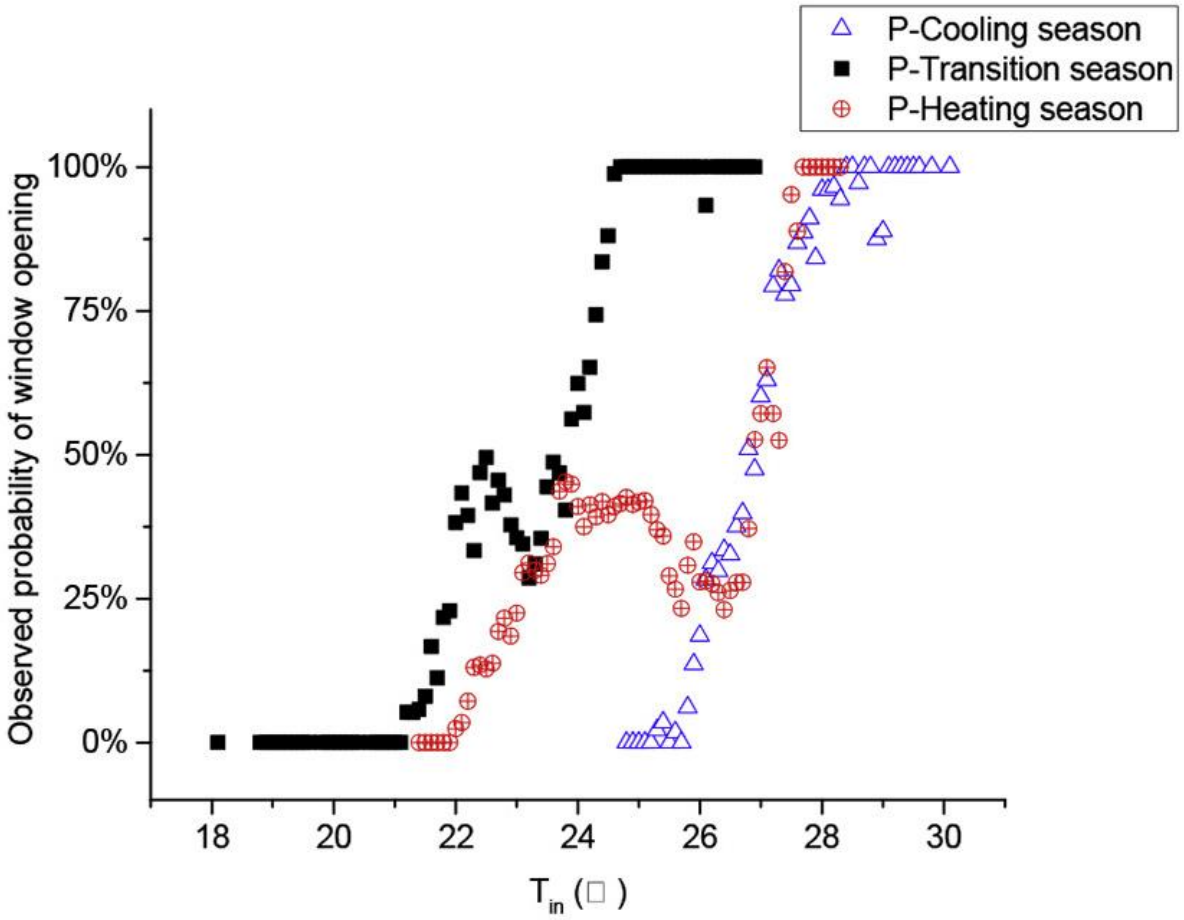
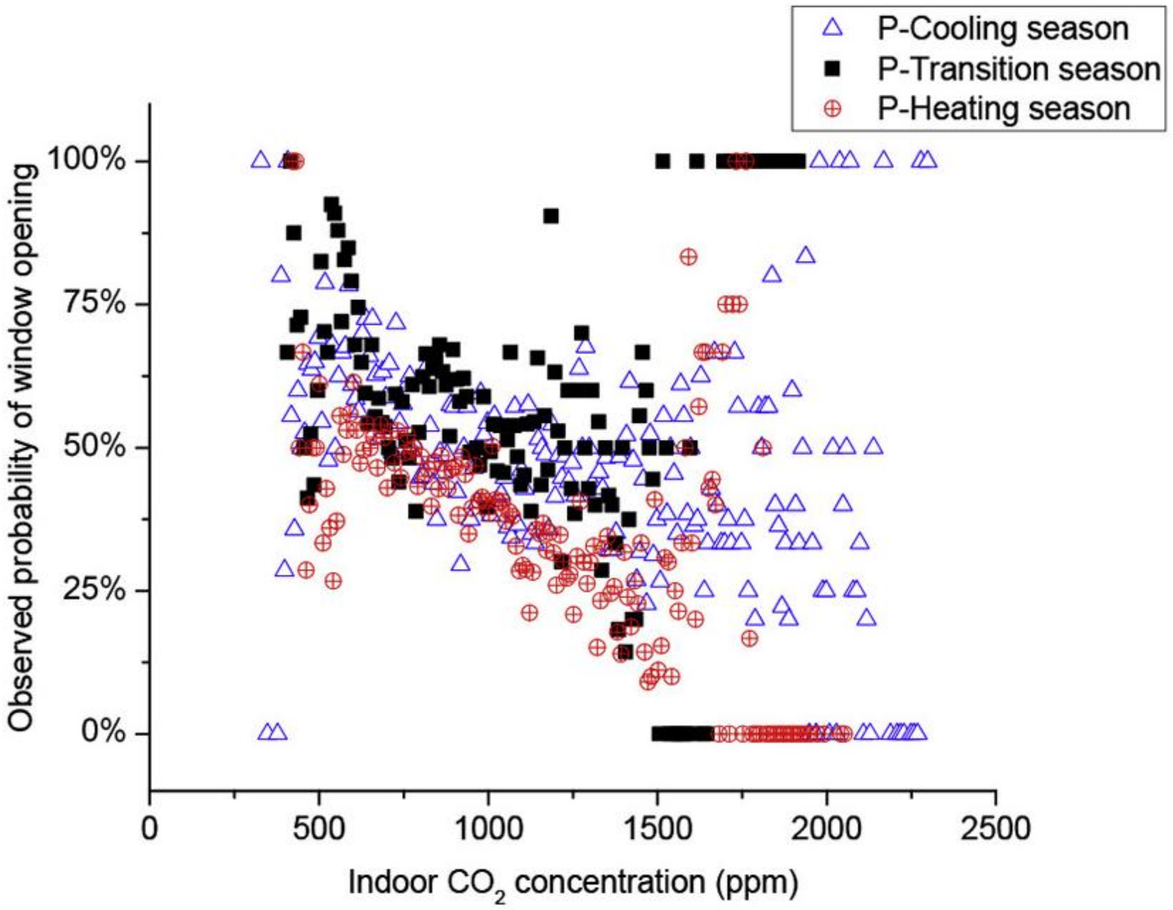
Significant behaviour dependence





Shi Z et al, Build Env 2018, 130:85-93

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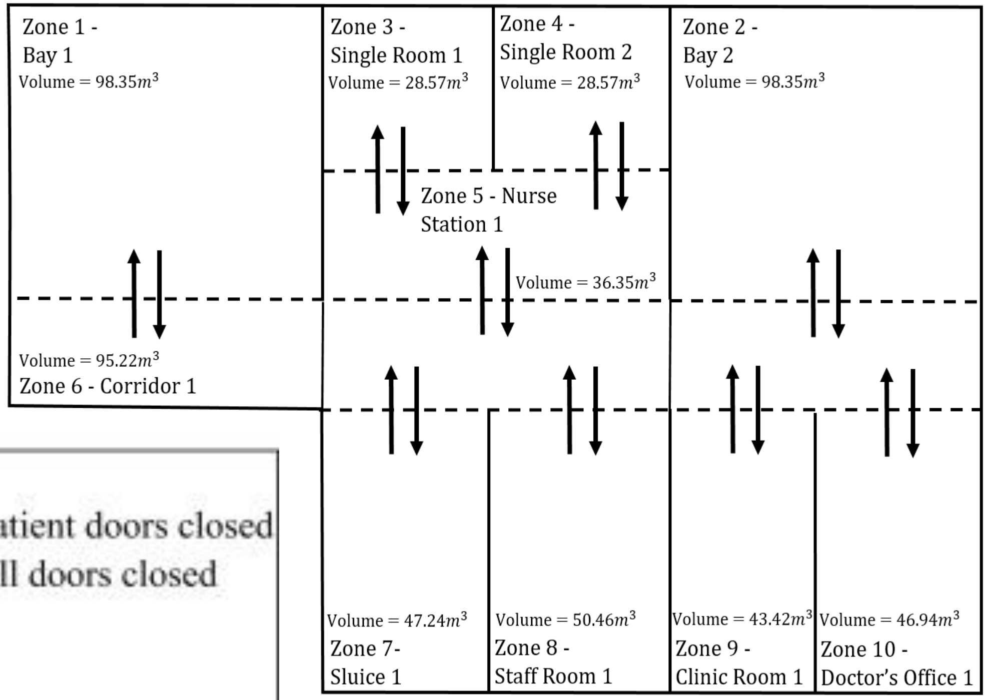
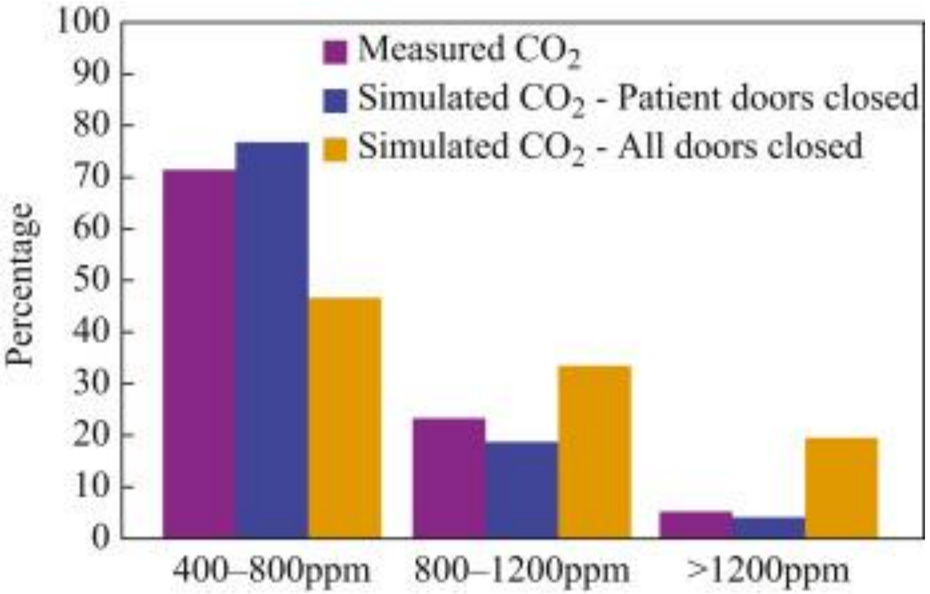
Assessing variability in multi-zone spaces

- Respiratory ward geometry and occupancy
- CONTAM airflow models with local weather
- Transient Wells-Riley infection model





Edwards et al, JHI, 2024

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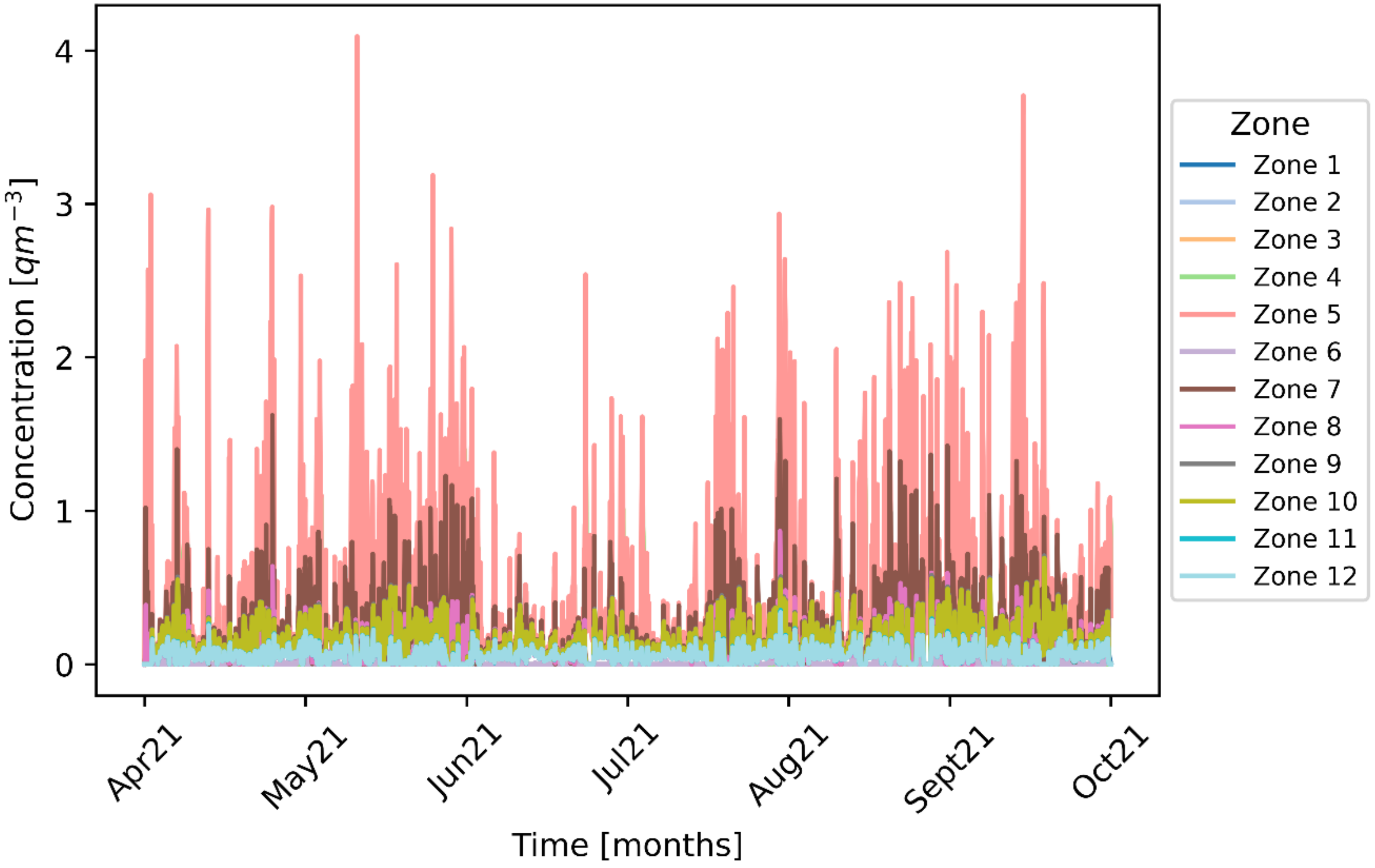
Transient fluctuation

- Infector in Zone 5 with constant emission rate ($30qhr^{-1}$)
- Only 4.57% above a concentration of $0.5qm^{-3}$
- Only 0.35% above a concentration of $1.5qm^{-3}$



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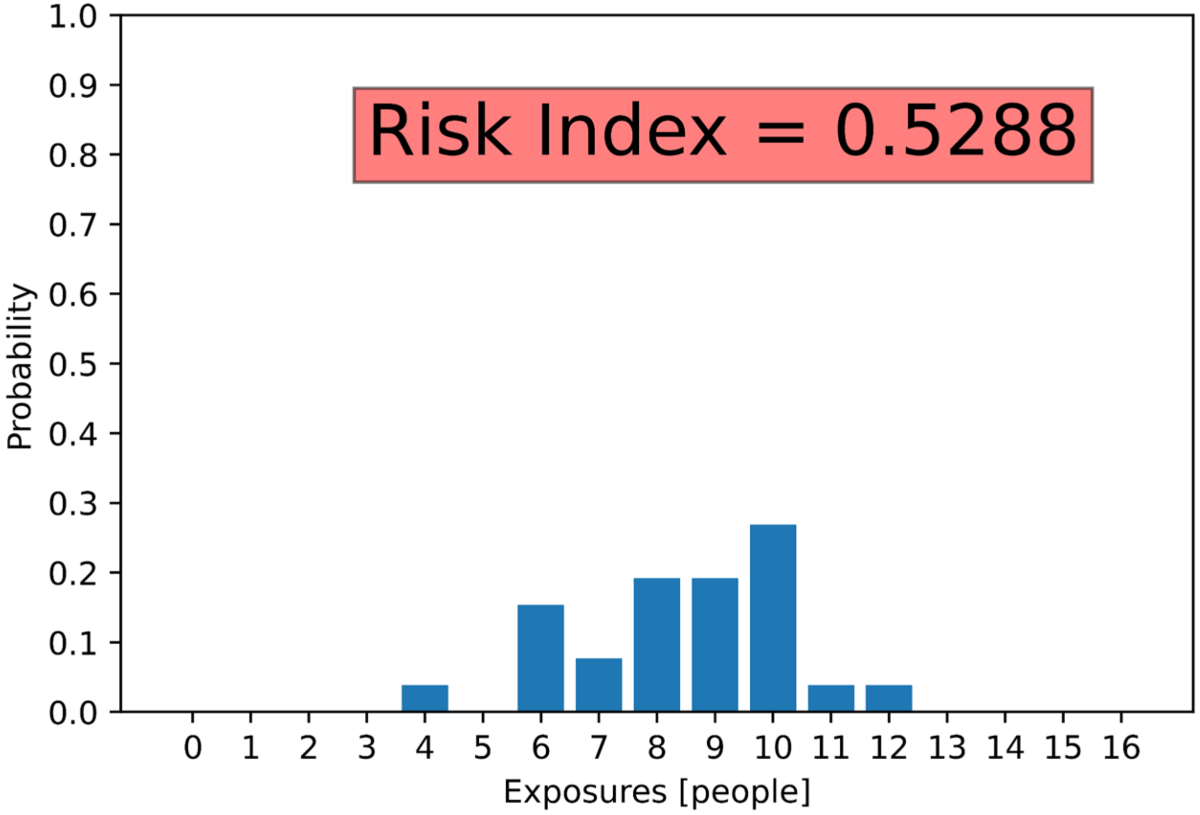
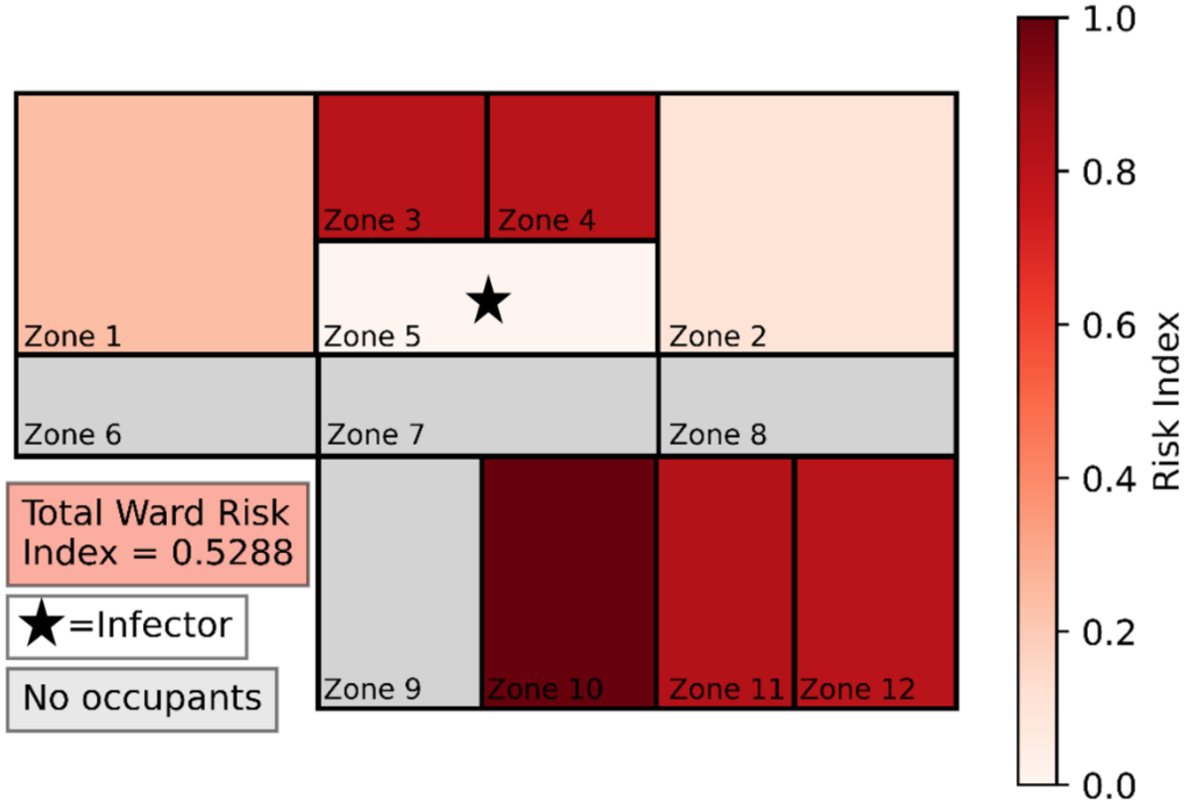
Natural Ventilation Only





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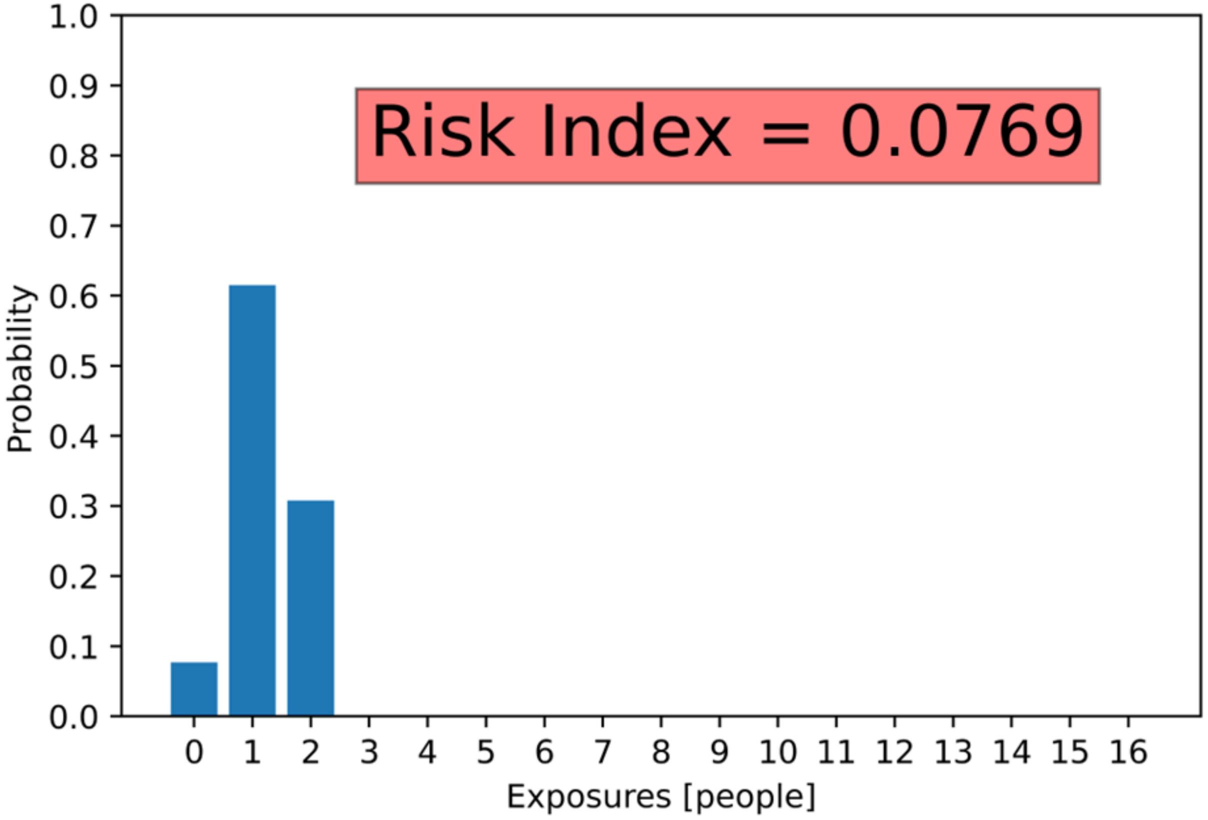
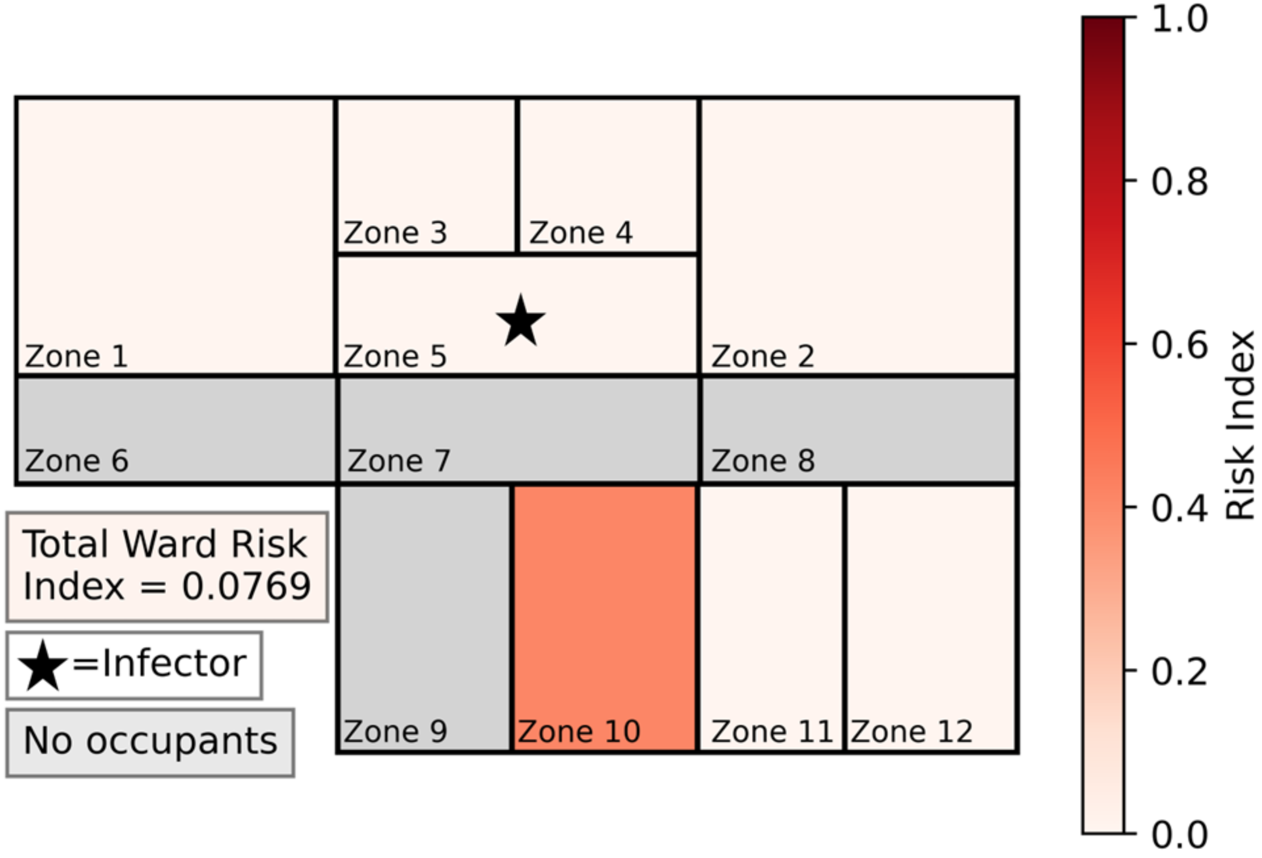
Addition of 3 ACH mechanical





Over 85% reduction in risk

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Case 3: Adding technologies

- Many hospitals have areas with inadequate ventilation or thermal control – costly to retrofit
- Addition of technologies is widespread
  - Local air conditioning units
  - Fans
  - Air cleaning technologies

- What is the goal of the technology device?
- Are there any negative impacts or risks?
- What is the cost, ease of use, practicality?

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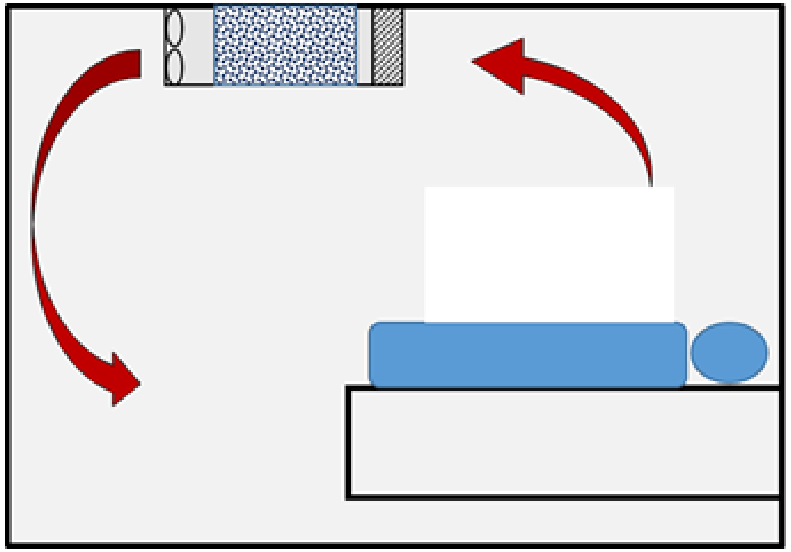
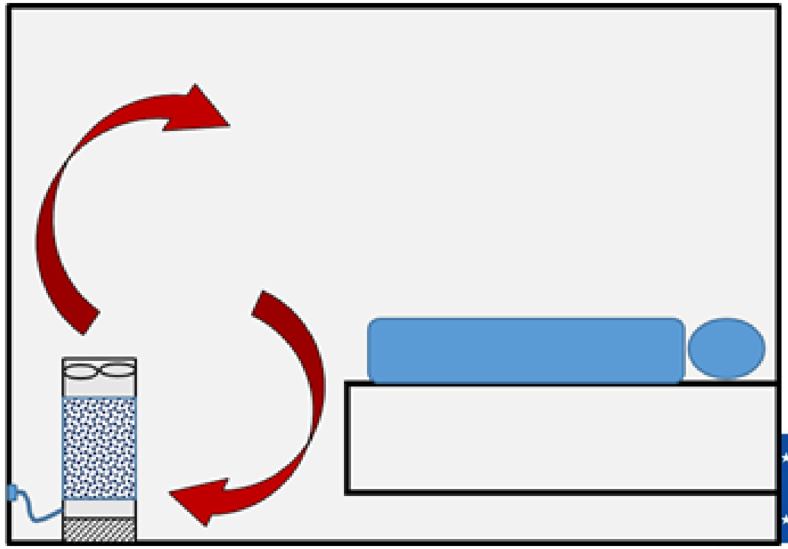
The Role of Air Cleaners

- Higher equivalent ventilation rate
  - Lower room concentration for constant occupancy
  - More rapid clearance rate for changing occupancy
- Change room air mixing
  - Potential to reduce stagnant zone
  - Could create directional flows?
- Zonal control
  - Less transfer of contamination to other spaces





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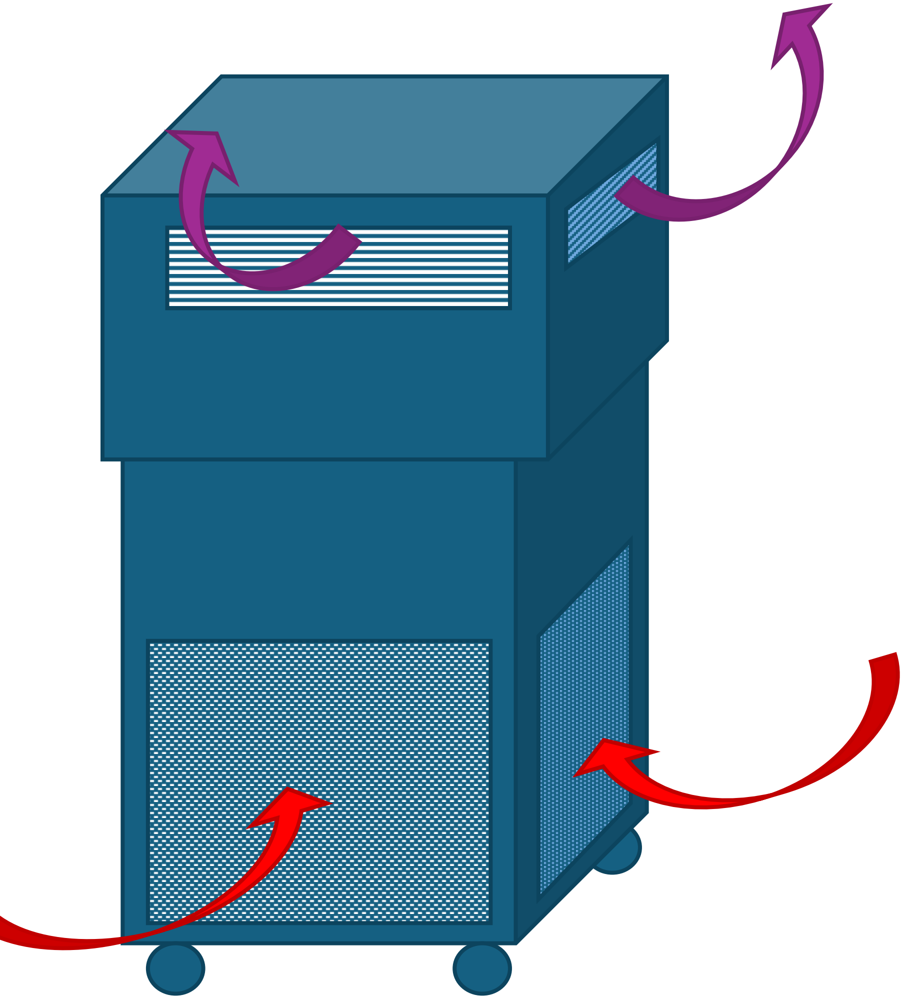
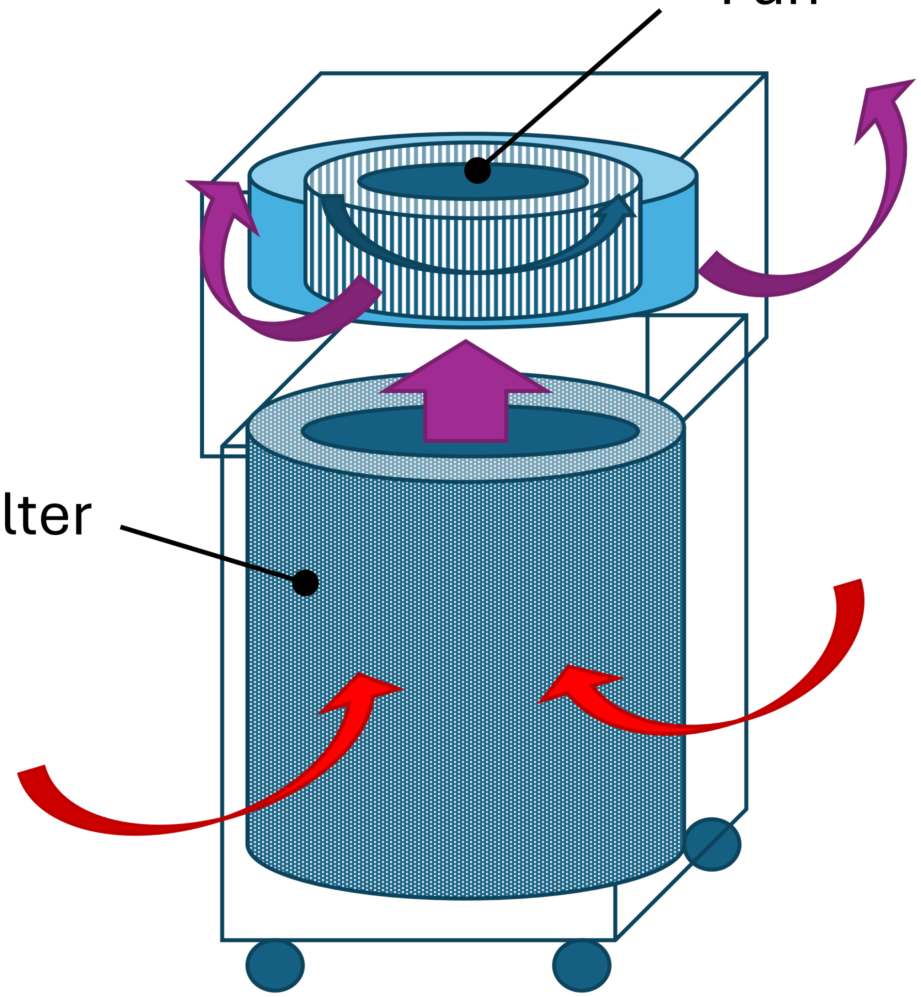
Filter based technologies





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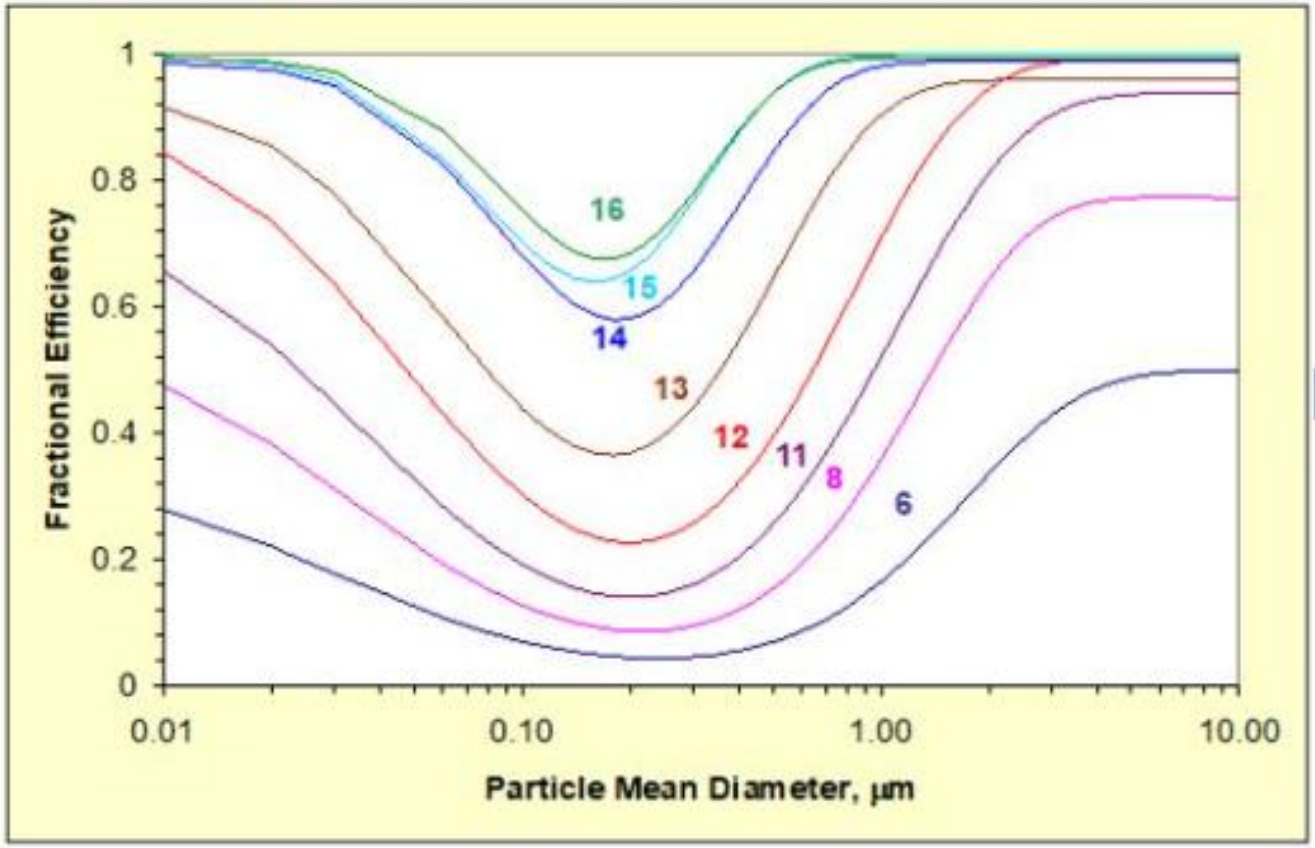
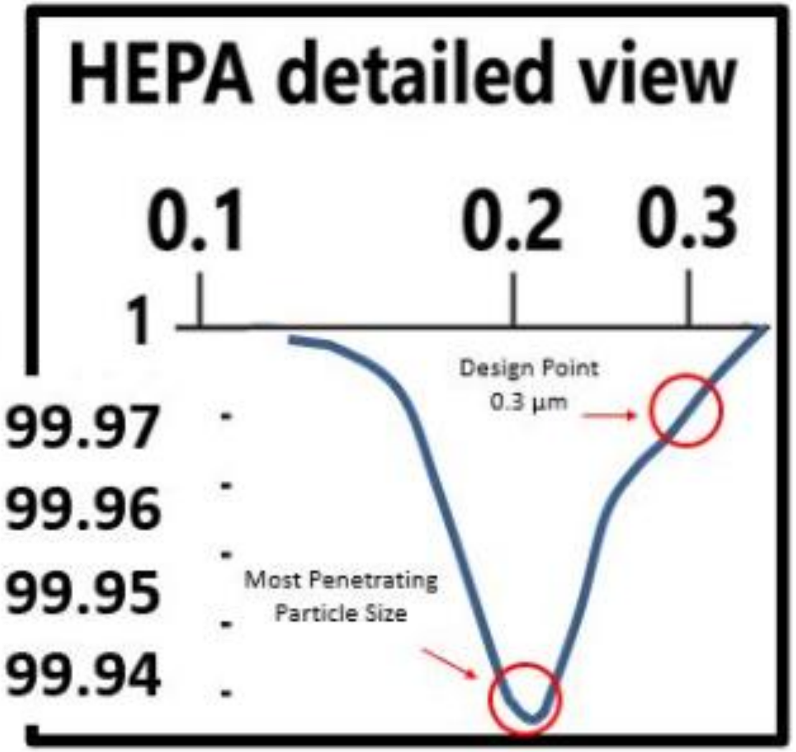
How a HEPA filter works





Note: Numbers in graph represent MERV values.

Kowalski, W.J. and Bahnfleth, W.P., 2002. MERV filter models for aerobiological applications. Air Media, Summer, 1.

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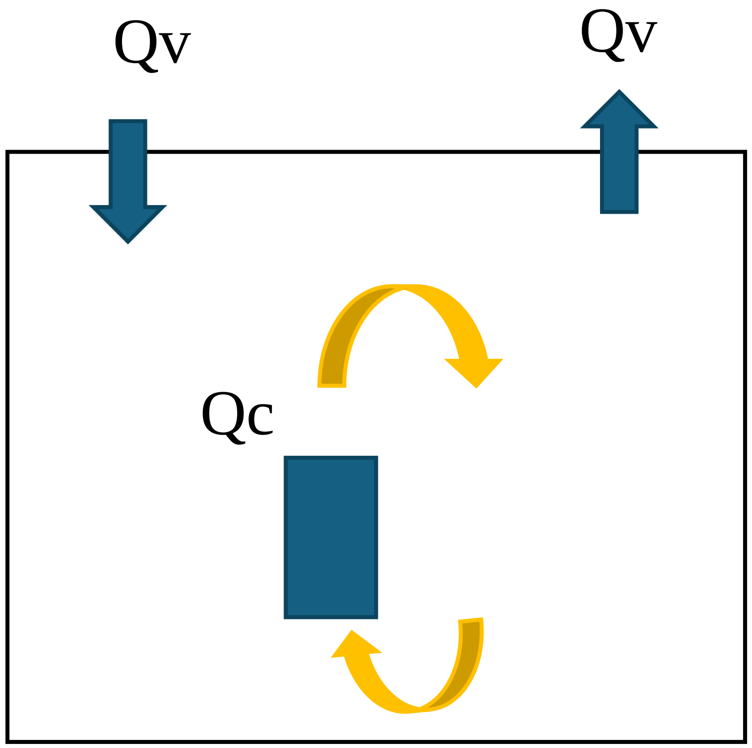
Sizing Air Cleaners

- Recirculating air cleaners pass through a filter/UV at Qc m3/h
- Clean Air Delivery Rate

  CADR = Qc * m*(1-E)

  E is filter efficiency, m is mixing
- For HEPA filter E >99%
- With good mixing, CADR ~Qc
- Overall ventilation removal rate for indoor source (assuming no recirc) = Qv + CADR



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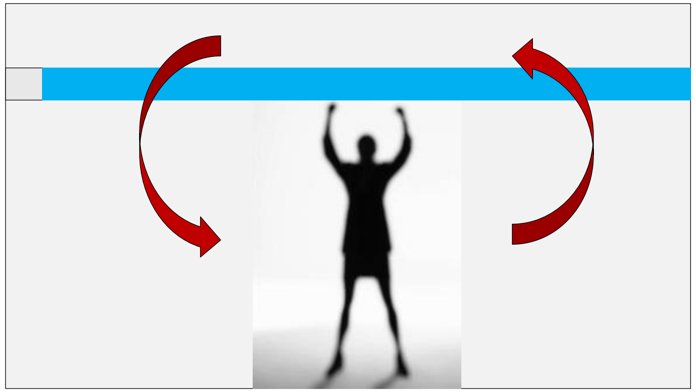
UV-C approaches

- UV-C light inactivates microorganisms
- Can be applied as upper room, recirculating or open unit
- Some wavelengths are hazardous to health – have to factor in shielding



Upper Room - UV

Recirculating

Disinfection unit

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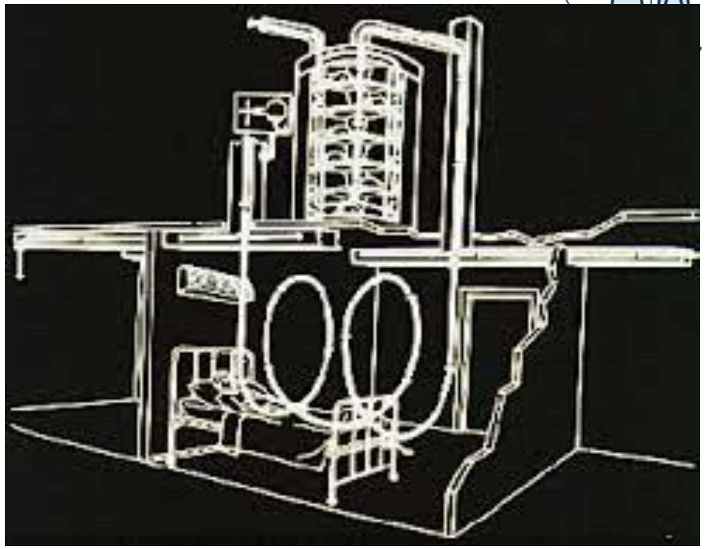
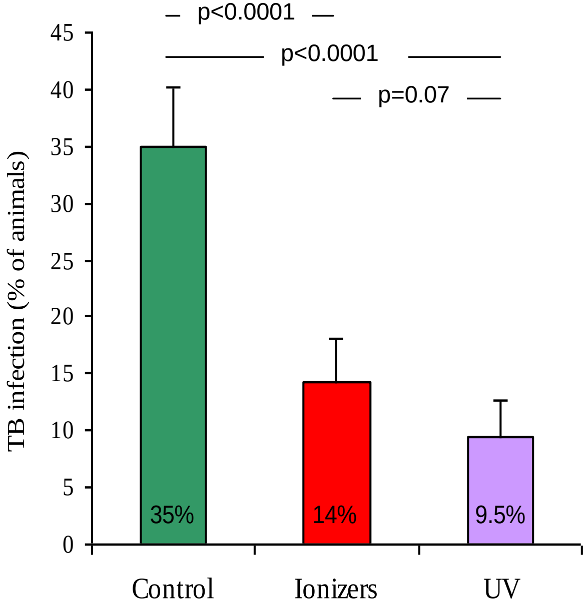
Evidencing Transmission and UV-C



- Riley and Wells TB – 1958-1962
  - Human to guinea pig, 134 infected over 4 years
  - Proof that TB is airborne
  - UVC air disinfection reduced transmission
- Escombe et al, 2009
  - Recreation of Riley & Wells
  - UV reduced infection by over 70%
  - Identified superspreaders



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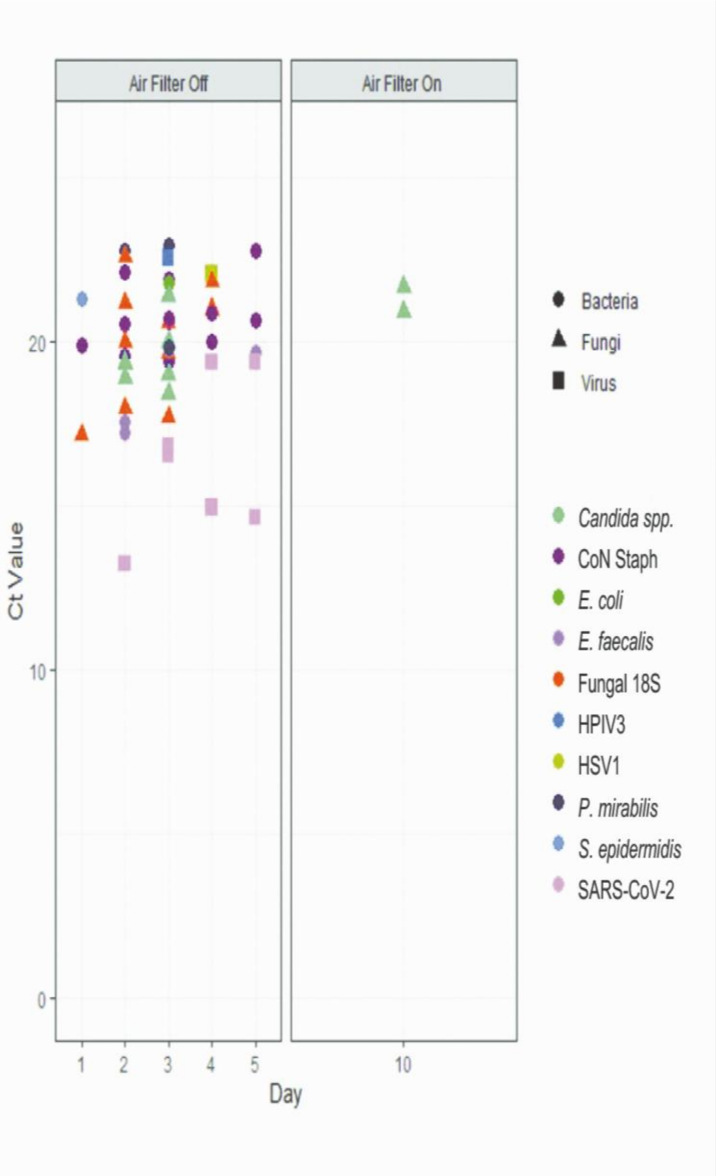
Air cleaner evidence

- Multiple chamber studies – particles and bioburden
- Addenbrookes HEPA/UV study (2021) – significant reduction in bioburden
- Singapore HEPA study (2010) – 50% reduction in aspergillous infection



Conway Morris, A, et al. *[The removal of airborne SARS-CoV-2 and other microbial bioaerosols by air filtration on COVID-19 surge units.](#)* *Clin Inf Dis; 30 Oct 2021; DOI: 10.1093/cid/ciab933*

Leeds Institute for Fluid Dynamics

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Selecting devices

Carry out with ventilation safety group and IPC considering:

- Performance (eACH) – including test data
- Noise
- Physical size
- Ease of use and maintenance
- Safety including secondary emissions
- Cost effectiveness

- Clean Air Delivery Rate (CADR) = equivalent ventilation rate (m3/h)
- Depends on device design:
  - Air flow rate through device
  - Device efficiency How well device mixes the room air

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Beware the test data

- Microbial only - specialist testing requiring custom facilities
- Test conditions matter
  - Microorganism species
  - Room ventilation, rate and strategy – or no ventilation
  - Temperature and humidity
  - Size of room – smaller rooms give better results
  - Device technology, device location
  - Sampling technique - decay or steady state, variability

99% reduction in airborne pathogen in 3 hours

Effective?

At 6 ACH 99% reduction in 46 min
At 2 ACH 99% reduction in 138 min
Device is ~ 1.5 ACH

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Locating and using

- Location
  - Airflow effectiveness to enable good flow
  - Practicality – power sockets, other items in room
  - Comfort
- Safety
  - Access, trip hazards, ligature risks, toppling
  - Remote controls and voice privacy
  - Checking filters are properly installed – pressure drop
  - Checking exposure for UVC

Training is Essential

- Why are devices present?
- Practicalities on how to use + labelling
- Day to day cleaning, managing any issues

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Portable air cleaner guidance

New Guidance from NHS England published May 2023

NETB 2023/01A
https://www.england.nhs.uk/publication/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/

NETB 2023/01B
https://www.england.nhs.uk/publication/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/

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Exercise 2: Measuring in hospitals

- You are part of a team who is planning to evaluate whether design changes to an emergency room in a hospital are likely to have an impact on thermal comfort or infection transmission risks.
- What type of information would you want to collect on the hospital environment to help carry out this evaluation?
- What parameters could you measure and what considerations in that measurement?

10 min discussion in groups then feed back

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The future

Airborne Transmission
- Respiratory infections
- Air-water interfaces
- Air-surface

Air pollution
- Outdoor sources
- Indoor sources
- Ability to reduce sources
- Ability to mitigate pathways

Climate change
- changes in pollution
- changes in disease patterns
- dealing with extreme heat
- dealing with extreme storms

"Effective ventilation, while minimising energy use and heat loss, is a priority for reducing air pollution, respiratory infections and achieving net zero" England Chief Medical Officers Annual Report 2022

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Designing your research

- Hospitals are complex places, and there is no single solution – essential to be aware of the context
- Lab-based and simulation-based studies – provide essential data but need to consider scale up and practical issues
- Hospital based measurement – provides real-world evidence but practical aspects and access can limit what and where can be measured
- Dissemination - HumanIC likely to input into future design and guidance, but this takes time

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Q&A

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