The Limits of Ventilation for Airborne Infection Control

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Context

- TB is spread by the airborne transmission route
  - Consider the healthcare occupational risks[1,2]

Work / Location	Relative Prevalence (worker relative to general population)
Healthcare students (High Burden Countries)	115
All Health Care workers (SA)	119

1. WHO Global Tuberculosis Report 20th ed, 2015
2. Nasreen S, Shokoohi M, Malvankar-Mehta MS (2016) Prevalence of Latent Tuberculosis among Health Care Workers in High Burden Countries: A Systematic Review and Meta-Analysis. PLoS ONE 11(10): e0164034. https://doi.org/10.1371/journal.pone.0164034

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CONTEXT

South Africa's oldest hospital:

Somerset Hospital. Circa 1890

Photo: Etienne du Plessis

- A 2012 study by University of Oregon proved that while clinics with open windows had more microorganisms, closed window environments were more pathogenic[2]
- Ventilation method accounts for a greater variance in airborne bacterial pathogenicity than ventilation rates alone[2]

[2]Kembel, S. W., Jones, … Green, J. L. (2012). Architectural design influences the diversity and structure of the built environment microbiome. *The ISME Journal*, *6*(8), 1469–79.

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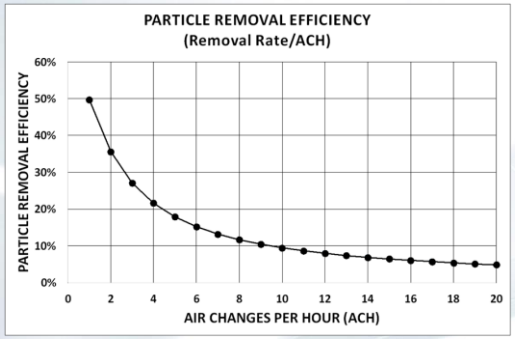
DEFINITIONS AND PRINCIPLES

- Ventilation (Q)
  - The supply of **fresh air** to a room for **diluting** or flushing **airborne contaminants**.
  - 12 ACH for airborne precaution rooms (WHO, CDC)

Image: T van Reenen 2017

DEFINITIONS AND PRINCIPLES

- **Ventilation (Q)**
  - Indoor contaminant concentration (C_{room}) is a function of the rates at which the room contaminants are generated and removed from the room



$$C_{room} = \frac{C_{exhaled} \cdot Q_{breath}}{Q_{supply\ air}} + C_{outdoor}$$

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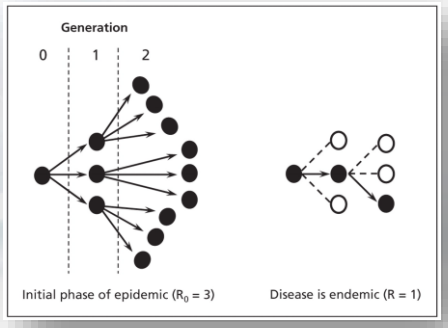
DEFINITIONS AND PRINCIPLES

- **Environmental Reproductive Number (R_{0E})**
  - the number of secondary infections that arise from each index case **in a space** *
  - When $R_{0E} > 1$ the space conditions **amplify the disease** and may contribute to an outbreak

* Rudnick, S. N., & Milton, D. K. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air, 13(3), 237–245. http://doi.org/10.1034/j.1600-0668.2003.001

* LIAO, C. M., CHEN, S. C., & CHANG, C. F. (2008). Modelling respiratory infection control measure effects. *Epidemiology and Infection*, *136*(3), 299–308. http://doi.org/10.1017/S0950268807008631



- Image: http://www.writeopinions.com

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PROBABILITY OF AIRBORNE TRANSMISSION

Equation for probability of airborne infection:

$$P_{inf} = \frac{new\ cases}{susceptibles} = 1 - e^{\frac{-Iqpt}{Q_{oa}}}$$

Where:

$P_{infection}$ = the probability of infection

Cases = the number of infection cases

Susceptibles = number of susceptible individuals

I = number of infector individuals

p = pulmonary ventilation rate of a person (m^3/hour)

q = quanta generation rate (1/hr)

t = exposure time (hr)

Q_{oa} = room ventilation rate with clean air (m^3/hour)

Source: Riley et al., 1978

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PROBABILITY OF AIRBORNE TRANSMISSION

- There can therefore be no ethical lower limit for rates of airborne transmission.
- Ventilation rates can be prescribed to prevent a congregate space from contributing to the prevalence of a disease within the population during room occupancy.
- When limiting the environmental reproduction number to less than 1, the disease's incidence rate within the resident population will not be amplified by that environment. [5,6]
    - the boundary of the transmission model is the room under consideration for the period occupied daily.
- It is proposed that an appropriate ventilation rate target would achieve the lower limit for transmission associated an $R0_E$ of 1 or less.

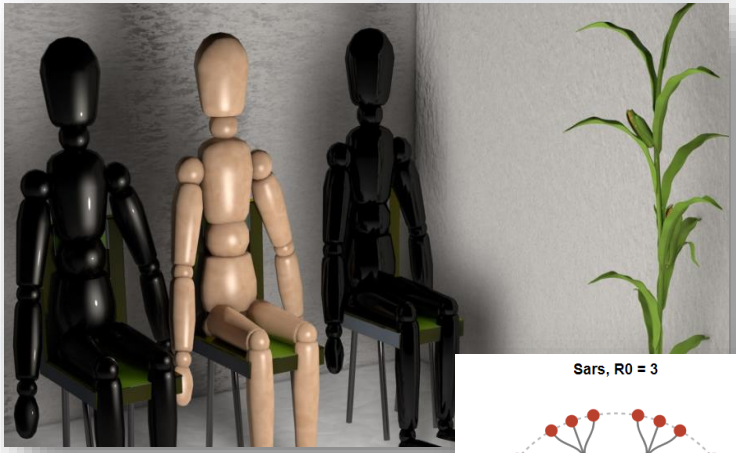
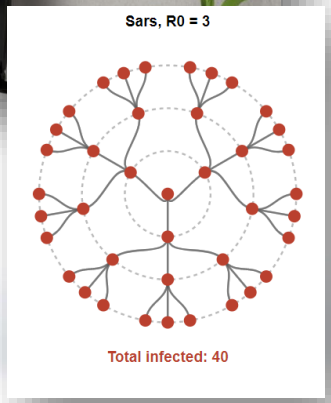


Image by kalhh from Pixabay



https://www.theguardian.com/

5. Van Den Driessche & Watmough, 2002

6. Rudnick & Milton, 2003

Probability of Airborne Transmission

From:

$$Q = {npqt} \Big/ {\varepsilon_v \cdot ln\left[\left(\frac{n-1}{n-(1+R_{0E})}\right)^n\right]}$$

We can calculate a ventilation rate Q_{oa} equivalent to the transmission rate limit (R_{0E}) for any:

1. limiting transmission rate (R_{0E})
2. Disease (q)
3. number of occupants (n)
4. exposure time (t)

- Rudnick, S. N., & Milton, D. K. (2003).

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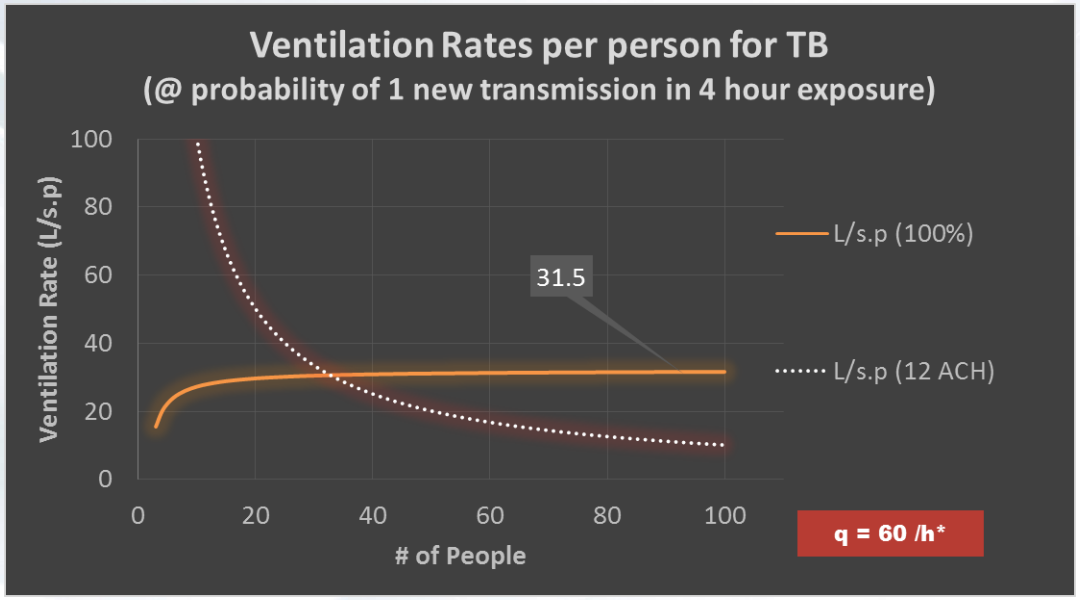
How much Ventilation? (100 person waiting room)



1 PATIENT WITH UNDETECTED LARYNGEAL TB (*Catanzaro, 1982)

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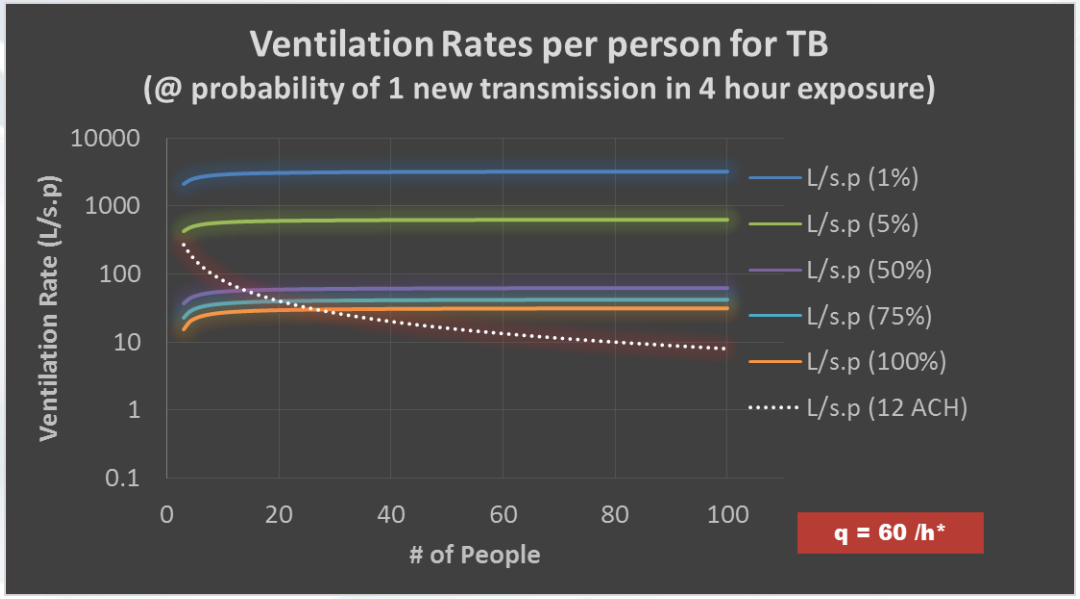

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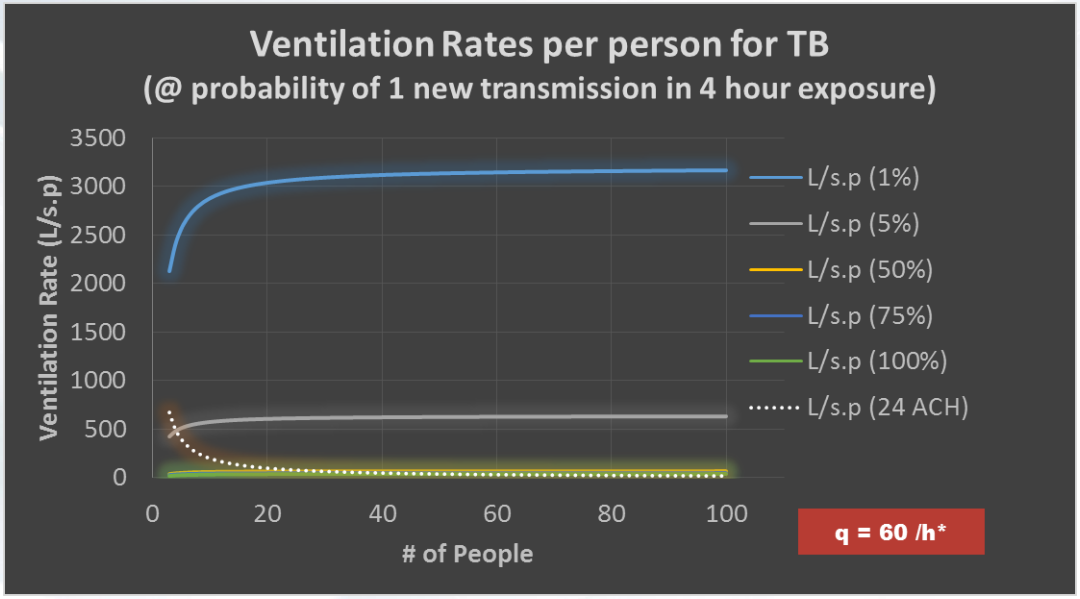

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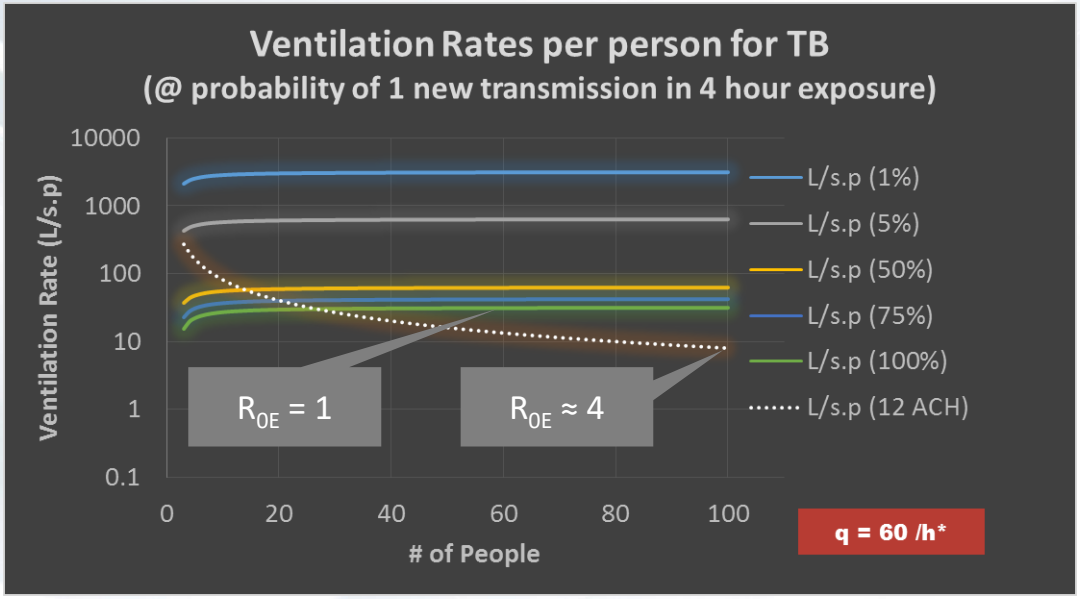

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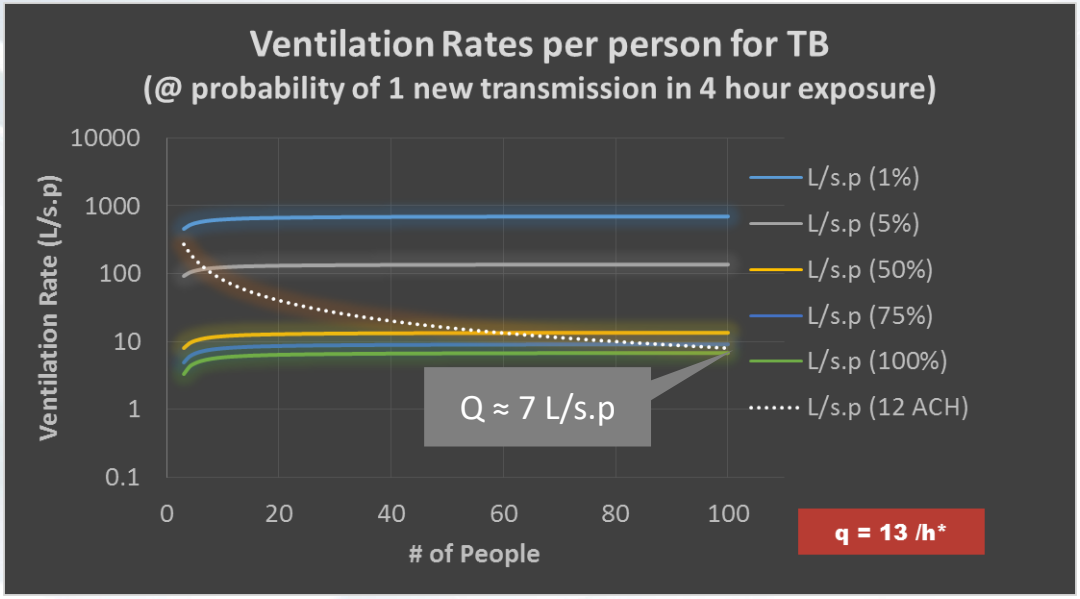

1 PATIENT WITH UNDETECTED PULMONARY TB (*Nardell et al., 1991)

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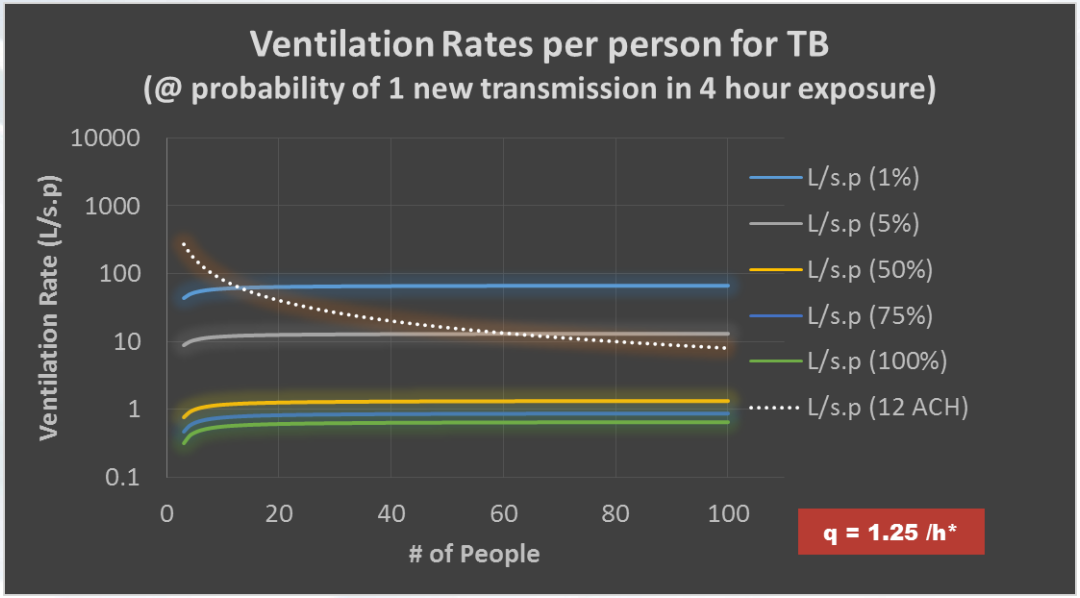
How much Ventilation?



1 PATIENT ON TREATMENT FOR PULMONARY TB (*Nardell et al., 1991)

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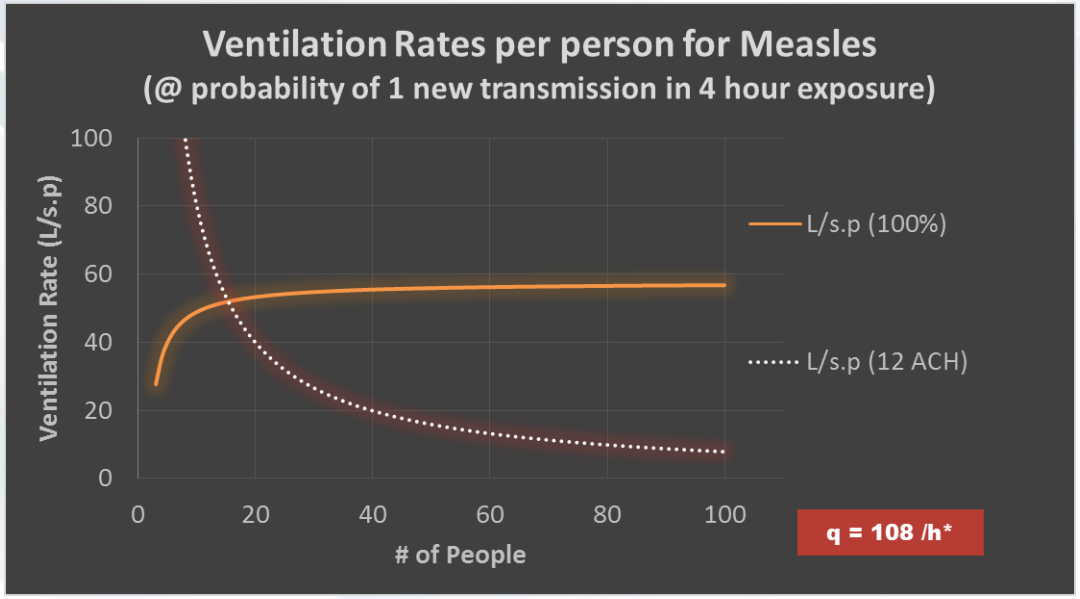
How much Ventilation?



INDEX CASE WITH MEASLES (*Liao et al, 2008)

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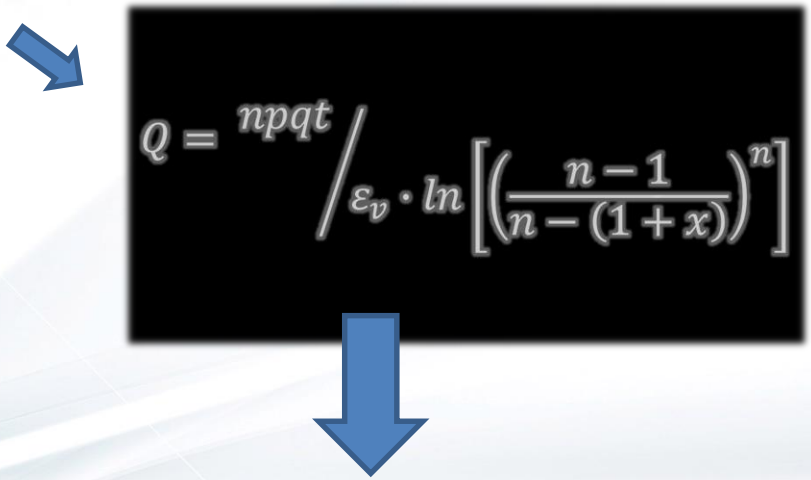
How much Ventilation?

Assumptions (For a 100 person waiting room)

a. $R_{OE} < 1$ (x)
b. Exposure time = 4h (average)
c. q = 60 /h
d. p = 0.13 l/s
e. n = 100



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How much Ventilation? (for a 100 person waiting room)

$$/\varepsilon_v \cdot ln\left[\left(\frac{n-1}{n-(1+x)}\right)^{n}\right]$$

Ventilation Rate ≥ 3200 L/s

Mechanical Ventilation	Room Air Cleaners	Natural Ventilation
• Full Fresh Air	• Particle Removal	• Fully Passive
• Recirculation	• Pollutant Destruction	• Mixed Mode

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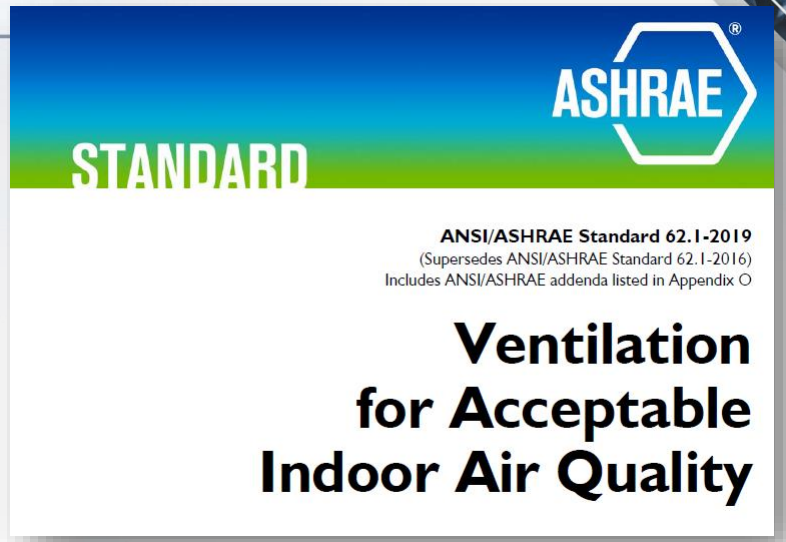
Mechanical Ventilation (3 200 L/s)

- Q= 3200 L/s
  - ≈ 727 person waiting
  - ≈ 1450 m² waiting
  - 145 kW cooling
  - 5 kW fan power
- 75 kW total electrical

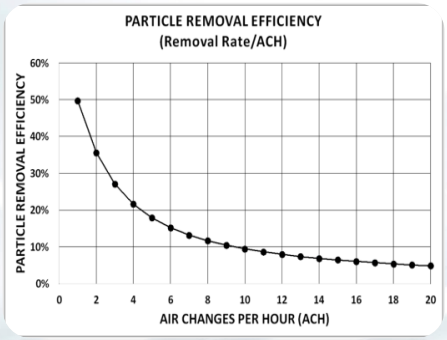


How much Ventilation is "enough"?

- Ventilation alone cannot protect against **long term exposure**:

  1% risk in a work year (q=13):

  - Q = 3,300,000 L/s (≈55M air changes per hour)



Rockstar Games - Grand Theft Auto 5- 2013

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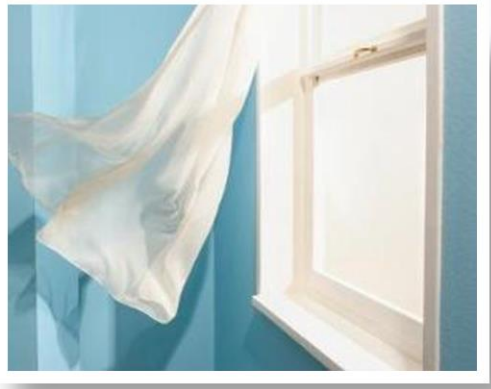
Natural Ventilation

- Capacity Benefits:
  - Windows **≥ 5%** floor area
  - 100 person waiting:
    100*0.9 = 90 m² (floor area)
  - Window area = 4.5 m²
  - + Doors = 8.3 m²
  - **Imperceptible** breeze
    = 0.25 - 0.6 m/s
  - = 1 035 – 2 484 L/s (**17 – 41 ACH**)
    (using only half the openable area)



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Impact of Proximity and Design

- Nardel et al 1991
  - Ventilation levels *inadequate for comfort* greatly contribute to transmission
  - protection from ventilation levels Above comfort levels may be inherently limited
- Liu et al 2016
  - Like droplet transmission, the risk of “airborne” transmission is greatly reduced with increased distance (>1.5m)
- Memarzedah et al 2012
  - the most important contributing factor is the airflow path between the contaminant source and the exhaust, not the ACH

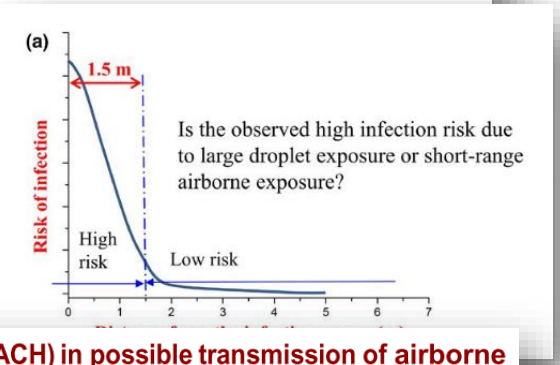
Theoretical Limits of Protection Achievable by Building Ventilation[1,2]

EDWARD A. NARDELL

as infectiousness rises, ventilation would offer progressively less protection. We conclude that outdoor air ventilation that is inadequate for comfort may contribute to airborne infection but that the protection afforded to building occupants by ventilation above comfort levels may be inherently limited, especially when the level of exposure to infection is high.

Short-range airborne transmission of expiratory droplets between two people

L. Liu[1,2] | Y. Li[1] | P. V. Nielsen[2] |



Role of air changes per hour (ACH) in possible transmission of airborne infections

Farhad Memarzadeh (✉), Weiran Xu

Department of He

source and exhaust. Contaminants are better controlled when this path is uninterrupted by an air stream. This study illustrates that the ventilation system design ,i.e., when it conforms with the hypothesized path principle, may be a more important factor than flow rate (i.e., ACH). A secondary

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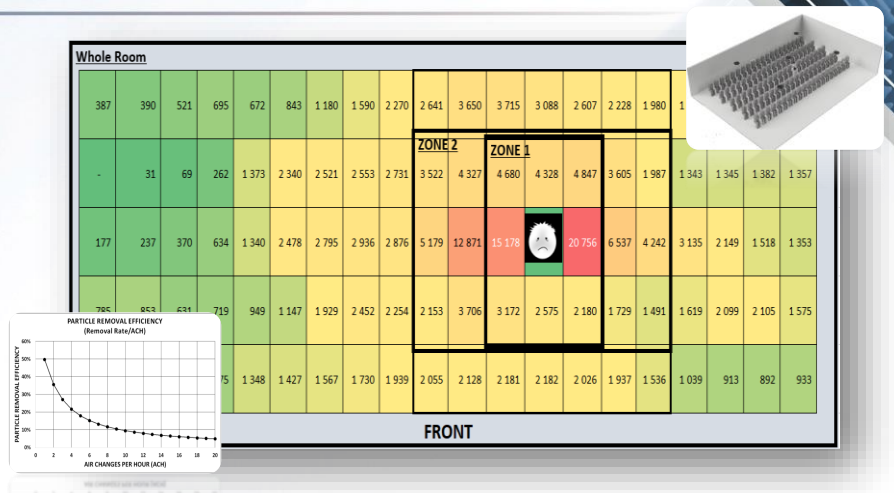
Impact of Proximity

Proximity vs Whole-Room

- Separation between the source and the target is fundamental in reducing airborne contaminant exposure levels
- Increasing ventilation reduces cumulative exposure for both the whole room and far field transmission zones
- A more rapidly diminishing benefit is seen within the near field zones than far field zones



Cumulative Transmission Risk*	2ACH	6ACH	12ACH
Zone1 (adjacent)	100%	52%	44%
Zone 2 (<4 seats away)	100%	44%	34%
Whole Room	100%	44%	33%
Far Field (>1 seat away)	100%	42%	30%
Far Field (>3 seat away)	100%	35%	19%

*Cumulative Exposure (PPM.s) after 3600 seconds in each zone

(J Grobler, T van Reenen (CSIR) 2020)

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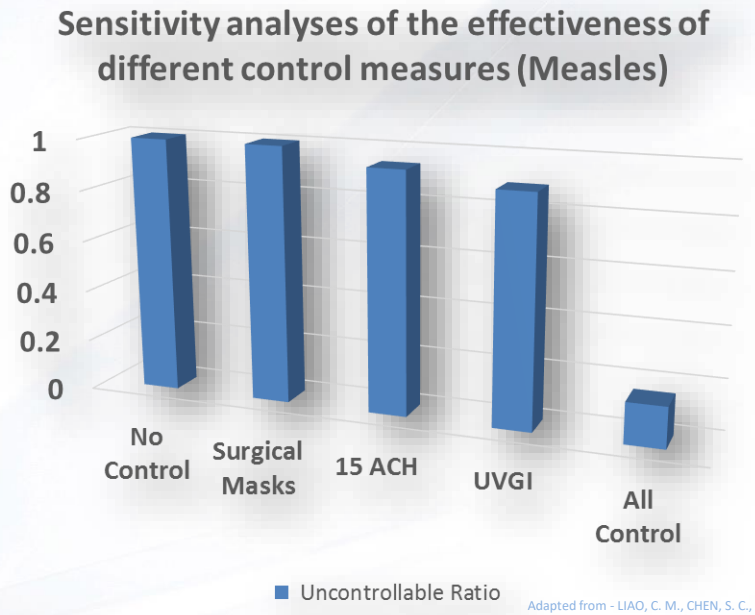
Conclusion

- Ventilation is important to control airborne transmission
- Ventilation is not the panacea often promised
  - Often higher rates are required than feasible
  - 12 ACH may not be sufficient
- A combination of controls is greater than the sum of its parts



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Thank you

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