ENVE 576
Indoor Air Pollution
Fall 2014

Week 13: November 18, 2014
Airborne infectious disease transmission

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Course update

- Take-home exam returned and graded

Topics covered last week:

- IAQ in developing countries
- IAQ measurements

This week

- Airborne infectious disease transmission

Introduction and motivation

- Communicable respiratory illnesses have significant economic impacts in the U.S.
  - 43 common colds per 100 people
  - 26 cases of influenza per 100 people
  - Healthcare costs, absence from work, lost worker productivity
    - Total cost was ~$70 billion in 2000 Fisk 2000 *Ann Review Energy Environ* 25:537-566

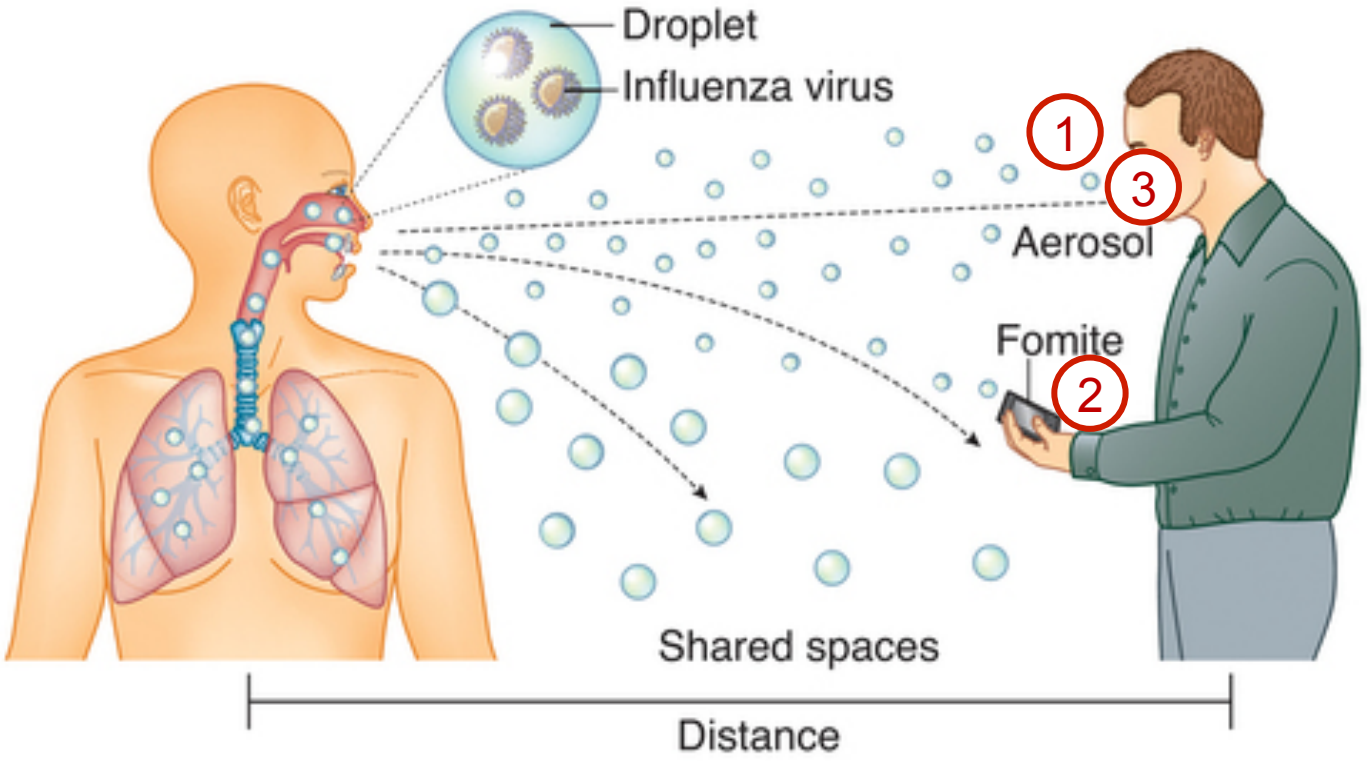
- Airborne transmission of respiratory pathogens is complex
  - Continuing debate about transmission modes
    - Inhalation, direct contact, indirect contact (e.g., surfaces)

Objectives for this lecture

- Explore modes of infectious disease transmission
- Infectious aerosols: particle sizes and emissions
  - Including viruses/bacteria within aerosols
- Methods of estimating disease risks
- Methods of infection control

MODES OF INFECTIOUS DISEASE TRANSMISSION

Primary modes of disease transmission



1. Direct contact with pathogen sources
2. Contact with contaminated object surfaces (“fomite”)
3. Inhalation of airborne infectious aerosols (often longer distances)

Lakdawala and Subbarao 2012 *Nature Medicine* 18:1468-1470

Diseases spread by airborne transmission

Disease	Organism	Clinical manifestations
Adenovirus	Adenovirus	Rhinitis, pharyngitis, malaise, rash, cough
Influenza*	Influenza virus	Fever, chills, malaise, headache, cough
Measles*	Rubeola virus	Fever, rash, malaise, conjunctivitis
Meningococcal disease	Neisseria meningitides	Fever, headache, vomiting, confusing
Mumps*	Mumps virus	Pain/swollen salivary glands
Pertussis	Bordetella pertussis	Malaise, cough, coryza, “whooping cough”
Parvovirus B19	Parvovirus B19	Rash, anemia, arthritis
Respiratory syncytial virus	RSV	Often asymptomatic
Rubella	Rubella virus	Fever, malaise, rash
Tuberculosis*	Mycobacterium species	Fever, weight loss, fatigue, night sweats, pulmonary disease
Varicella	Human herpes virus 3	Chicken pox

ASHRAE Position Document on Airborne Infectious Diseases (2014)

Evidence of airborne transmission

An absurd experiment…

Aerosol Transmission of Rhinovirus Colds

Elliot C. Dick, Lance C. Jennings, Kathy A. Mink, Catherine D. Wartgow, and Stanley L. Inhorn

Rhinovirus infections may spread by aerosol, direct contact, or indirect contact involving environmental objects. We examined aerosol and indirect contact in transmission of rhinovirus type 16 colds between laboratory-infected men (donors) and susceptible men (recipients) who played cards together for 12 hr. In three experiments the infection rate of restrained recipients (10 [56%] of 18), who could not touch their faces and could only have been infected by aerosols, and that of unrestrained recipients (12 [67%] of 18), who could have been infected by aerosol, by direct contact, or by indirect fomite contact, was not significantly different ($\chi^2 = 0.468$, $P = .494$). In a fourth experiment, transmission via fomites heavily used for 12 hr by eight donors was the only possible route of spread, and no transmissions occurred among 12 recipients ($P < .00$ results suggest that contrary to current opinion, occurs chiefly by the aerosol route.

ments. Twenty-seven to 34 men >18 years of age were inoculated intranasally with 560–2,400 $TCID_{50}$ of safety-tested RV16 [5] by pipette and spray on two successive days. On the third day, eight men with the most severe colds (donors) played stud and draw poker with 12 antibody-free (no neutralization of virus by the undilute [1:1] serum specimen against a 20–25 $TCID_{50}$ challenge) men (recipients) between hours of 8 a.m. and 11 p.m. The ending hour was

Dick et al. 1987 *J Infectious Diseases* 156:442-448

Evidence of airborne transmission

In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

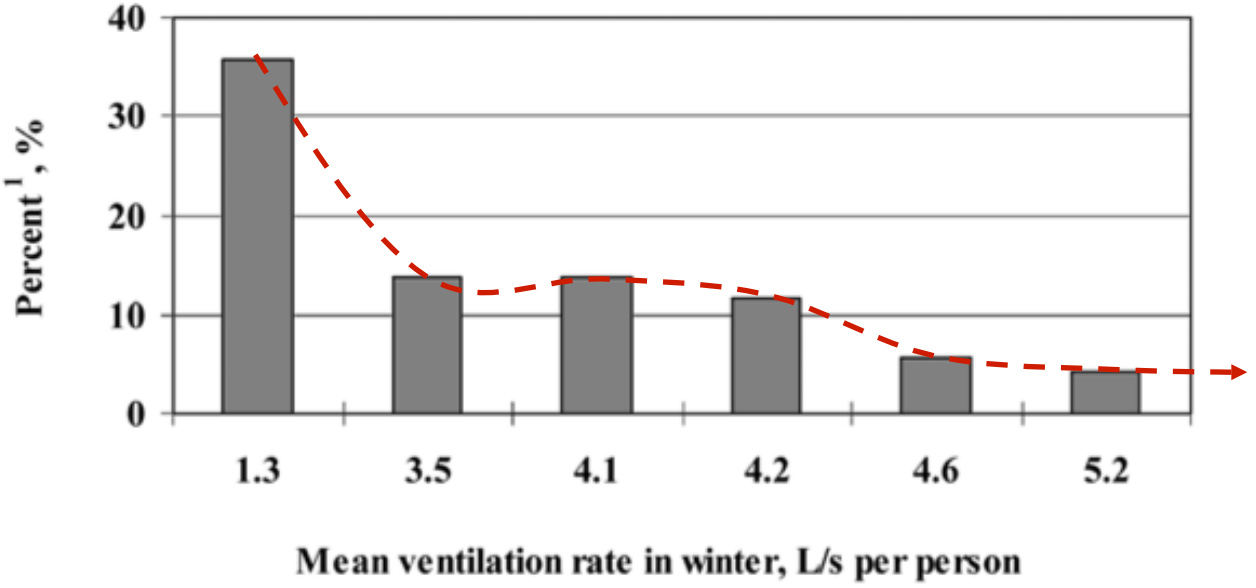


Figure 4. Associations between common cold infection rates and mean ventilation rate in winter in buildings constructed after year 1993. [1] Proportion of occupants with ≥6 common colds in the previous 12 months.

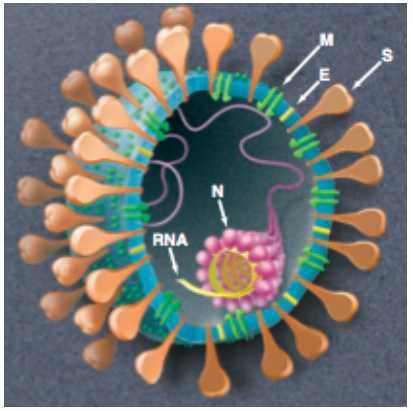
Sun et al. 2011 *PLoS ONE* 6:e27140

Evidence of airborne transmission

Severe acute respiratory syndrome (SARS)

- 10 years ago: global outbreak of SARS
  - In 8 months, 8100 people in 29 countries were infected
    - 774 died

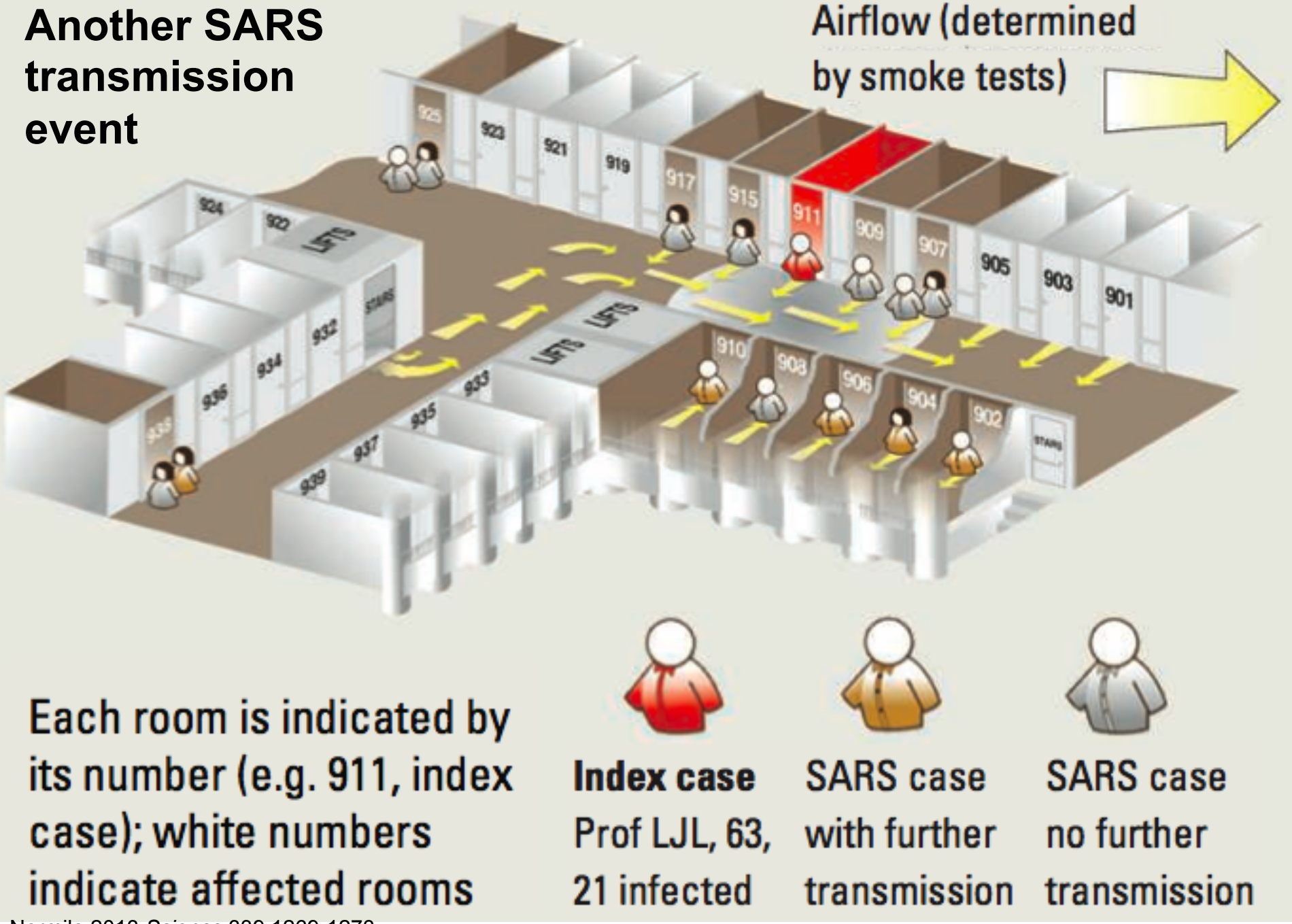
- In one high profile spreading event in Hong Kong, it became clear that transmission by airborne particles was substantial
  - One infected man suffering from diarrhea was linked to 300 SARS cases in one apartment building
  - Investigators concluded that diarrhea from the patient flushed into common plumbing system between units produced aerosols that traveled through piping and into other bathrooms
  - From there, both aerosol and subsequent person-to-person contact transmission likely occurred



SARS virus

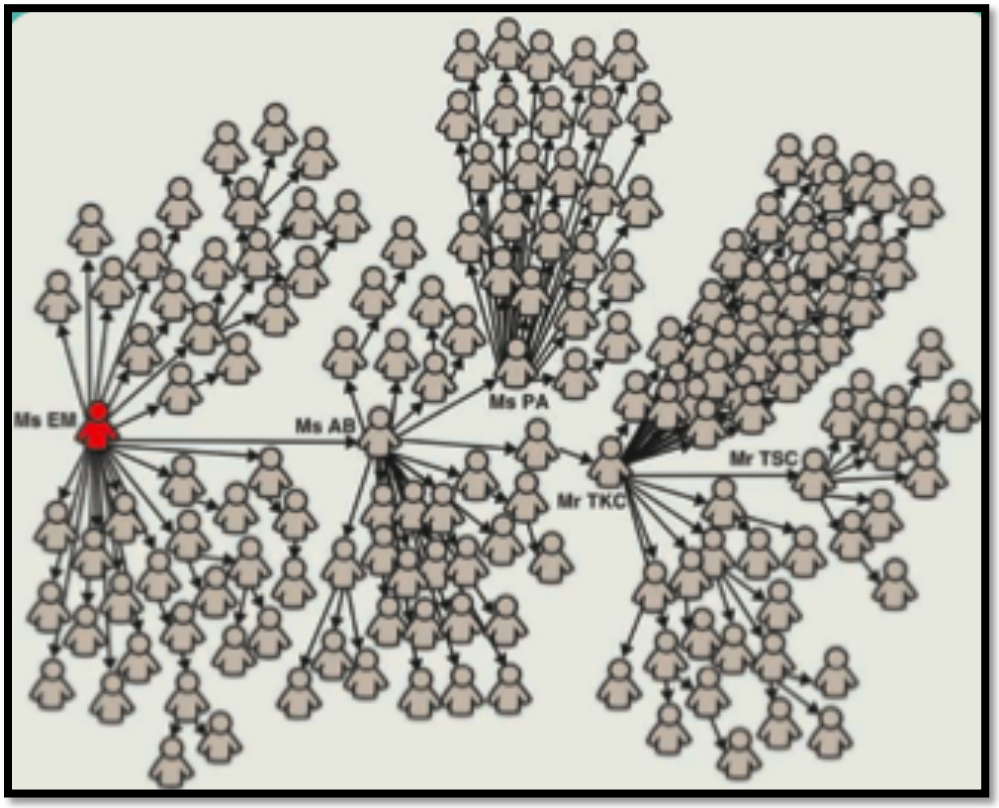
Normile 2013 *Science* 339:1269-1273

Another SARS transmission event



Normile 2013 *Science* 339:1269-1273

Importance of “super spreaders”

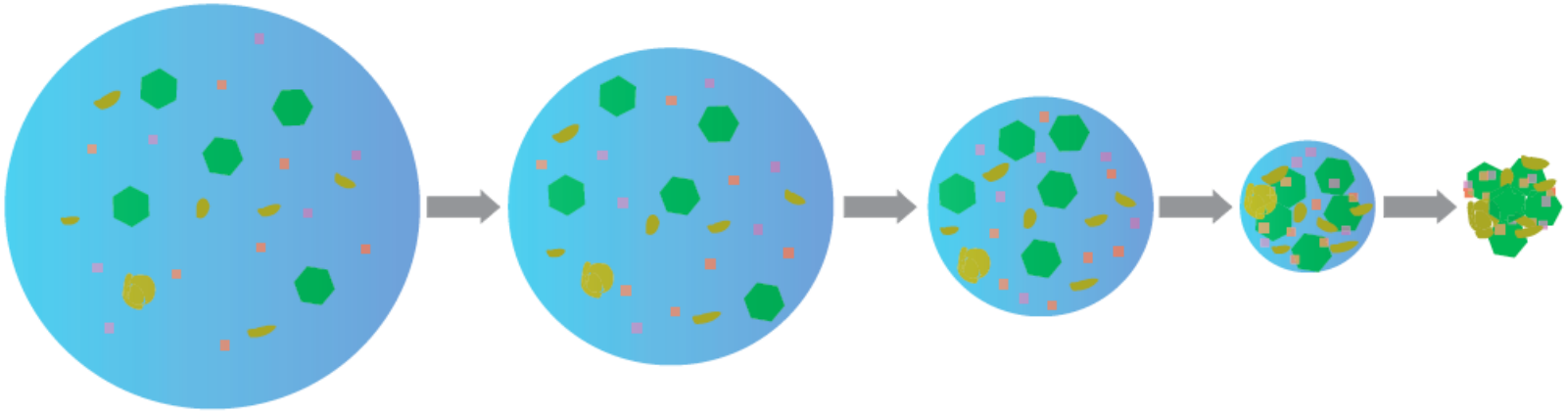


144 of Singapore’s 206 SARS cases were traced to 5 individuals

Normile 2013 *Science* 339:1269-1273

"Spreading": Expulsion of droplets

- When a person coughs, sneezes, speaks or even breaths:
  - Particles of liquid water, proteins, salts, and other matter are expelled
    - These are called droplets
    - These particles may contain smaller infectious organisms
  - Droplets rapidly deposit to surfaces and/or decrease in size as the surrounding liquid evaporates
    - Droplet nuclei remain after evaporation
    - Typically 40-50% smaller diameter (d_p) than original droplets
      - Still contain infectious organisms



Verreault et al. 2008 *Microbiology and Molecular Biology Reviews* 72:413-444; Nicas et al. 2005 *J Occup Environ Hyg* 2:143-154; Chen and Zhao 2010 *Indoor Air* 20:95-111; Yang and Marr 2011 *PLoS ONE* 6:e21481

Rapid evaporation of droplets brought to you by *Mythbusters*

Droplet evaporation is nearly instantaneous

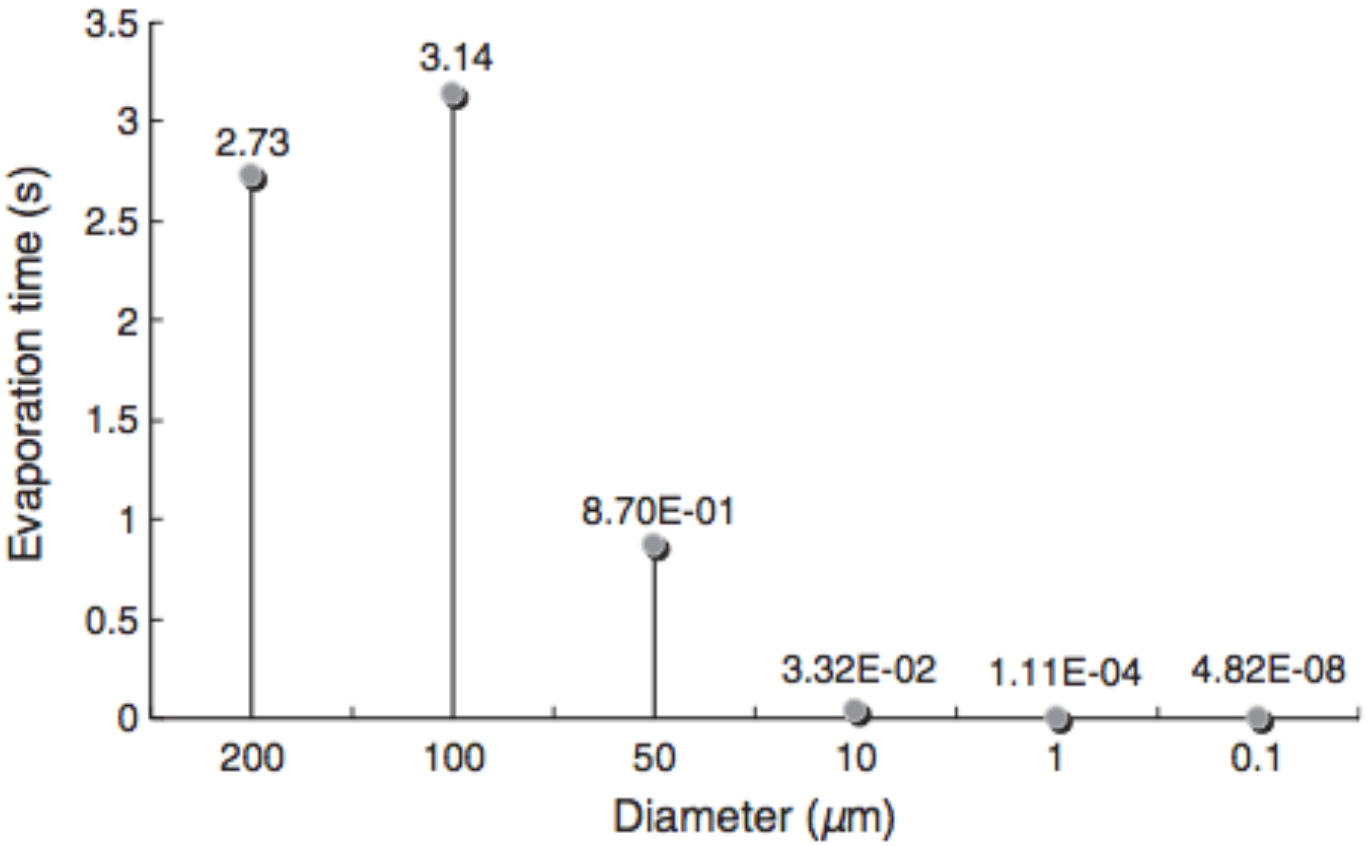


Fig. 5 The evaporation time of droplets with different diameters

Chen and Zhao 2010 *Indoor Air* 20:95-111

Airborne transmission and particle size

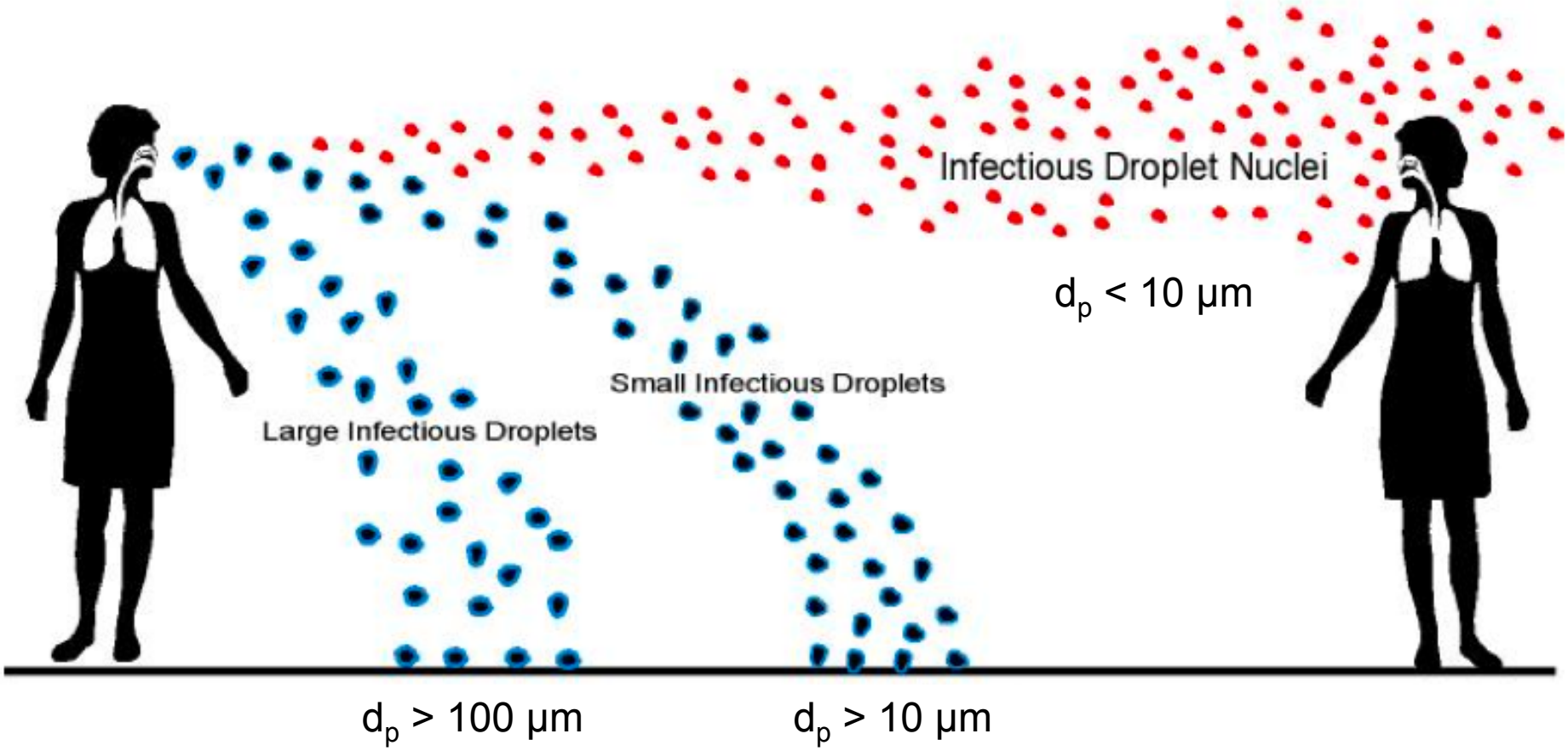
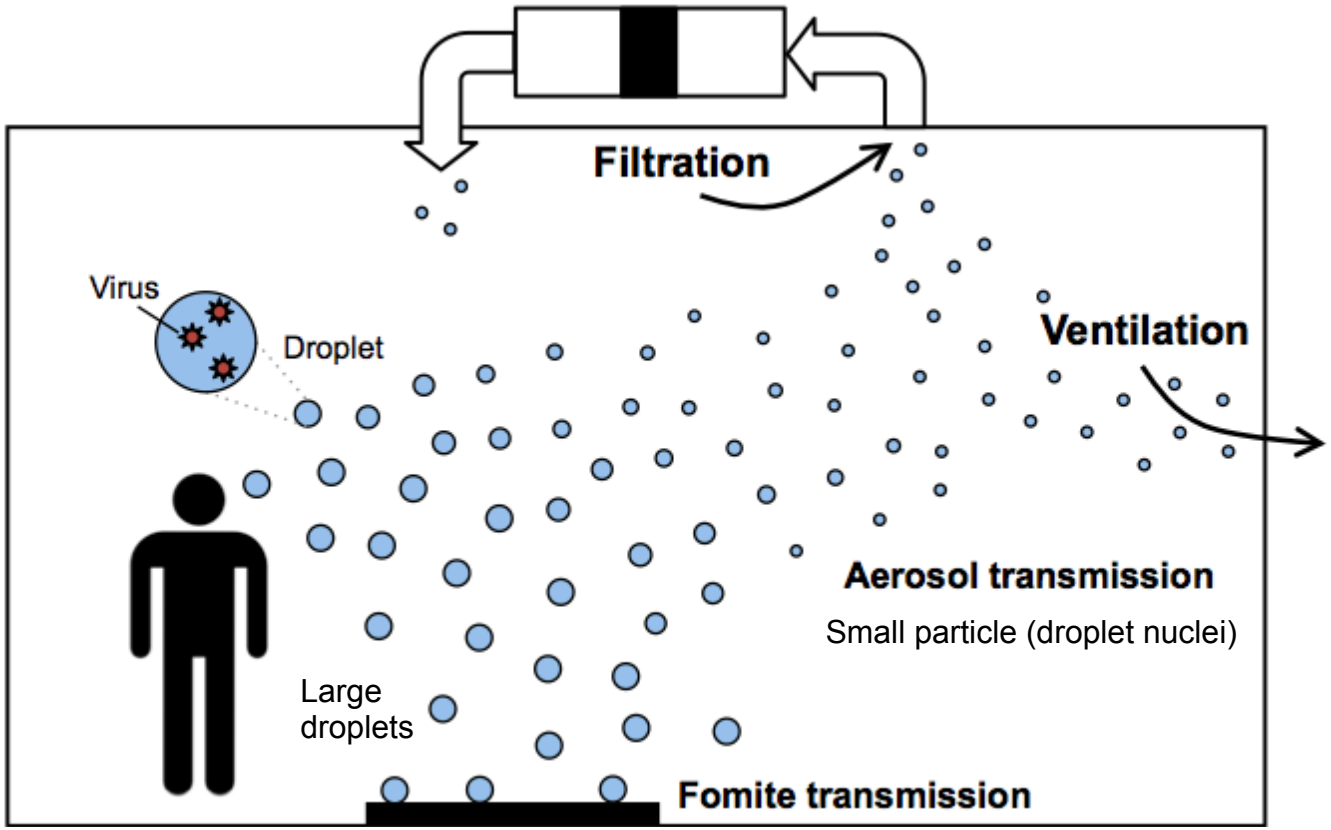
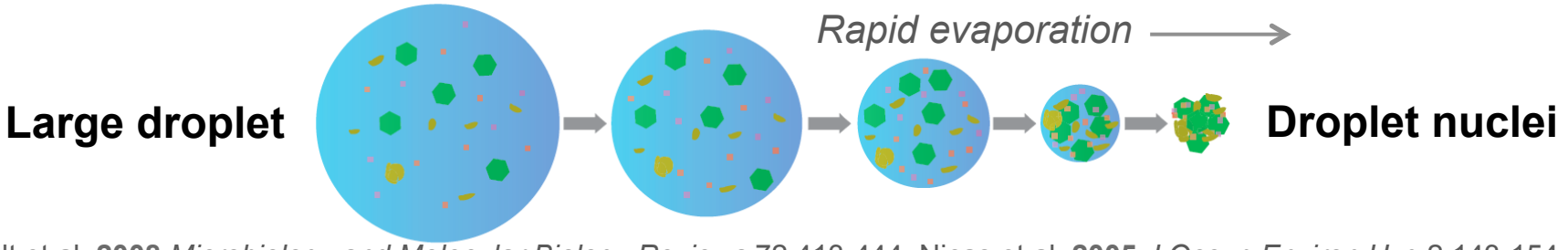


Figure taken directly from Welty 2009 presentation to FIC for IAQ, US EPA

Aerosol transmission: Particle size is crucial





Verreault et al. **2008** *Microbiology and Molecular Biology Reviews* 72:413-444; Nicas et al. **2005** *J Occup Environ Hyg* 2:143-154; Chen and Zhao **2010** *Indoor Air* 20:95-111; Yang and Marr **2011** *PLoS ONE* 6:e21481; Lakdawala and Subbarao **2012** *Nature Medicine* 18:1468-1470

Droplet nuclei can mix rapidly

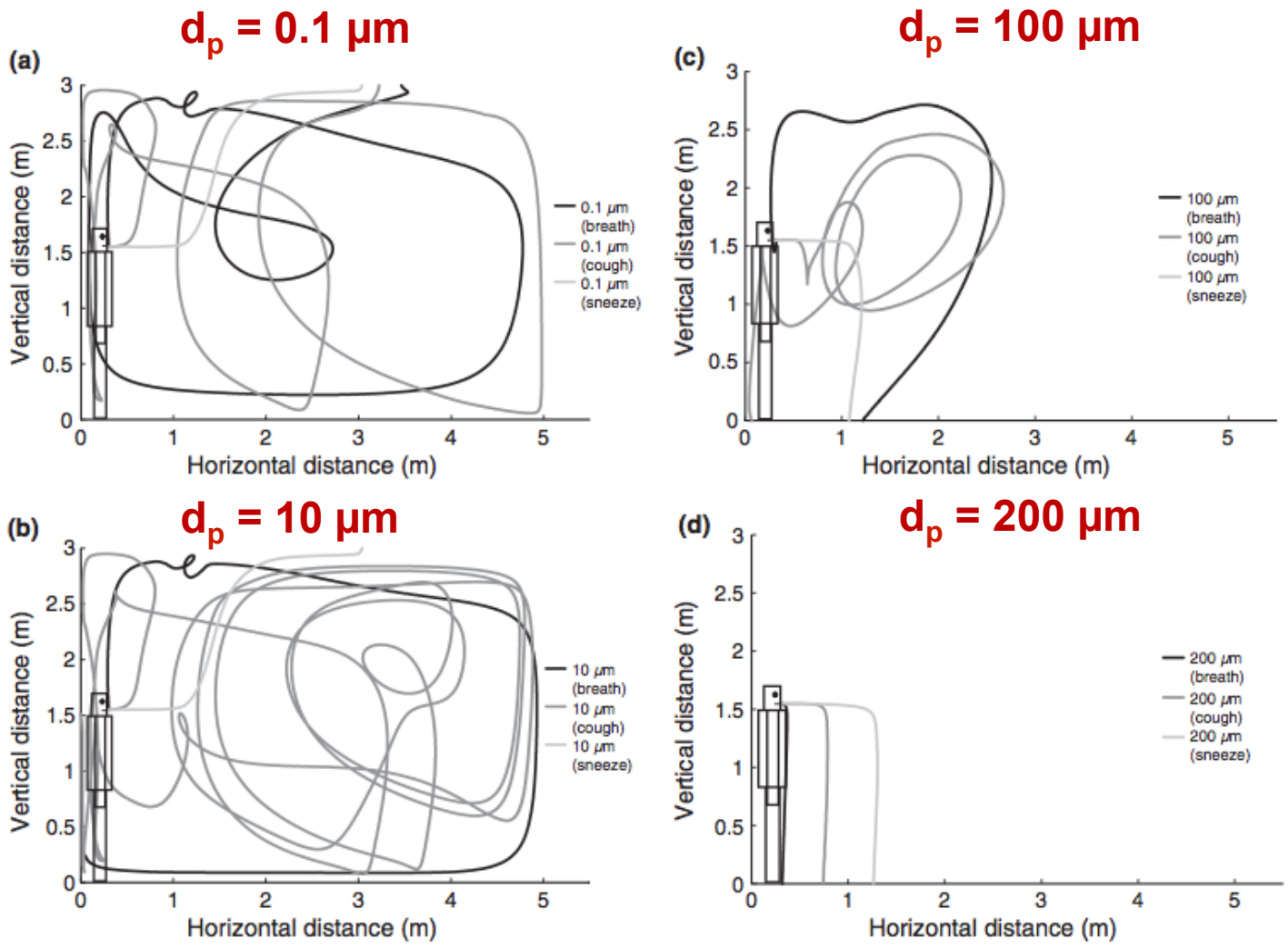


Fig. 13 Comparison of trajectories of droplets at different initial exhaled velocities. (a) initial diameter 0.1 μm, (b) initial diameter 10 μm, (c) initial diameter 100 μm, (d) initial diameter 200 μm. z = 2 m

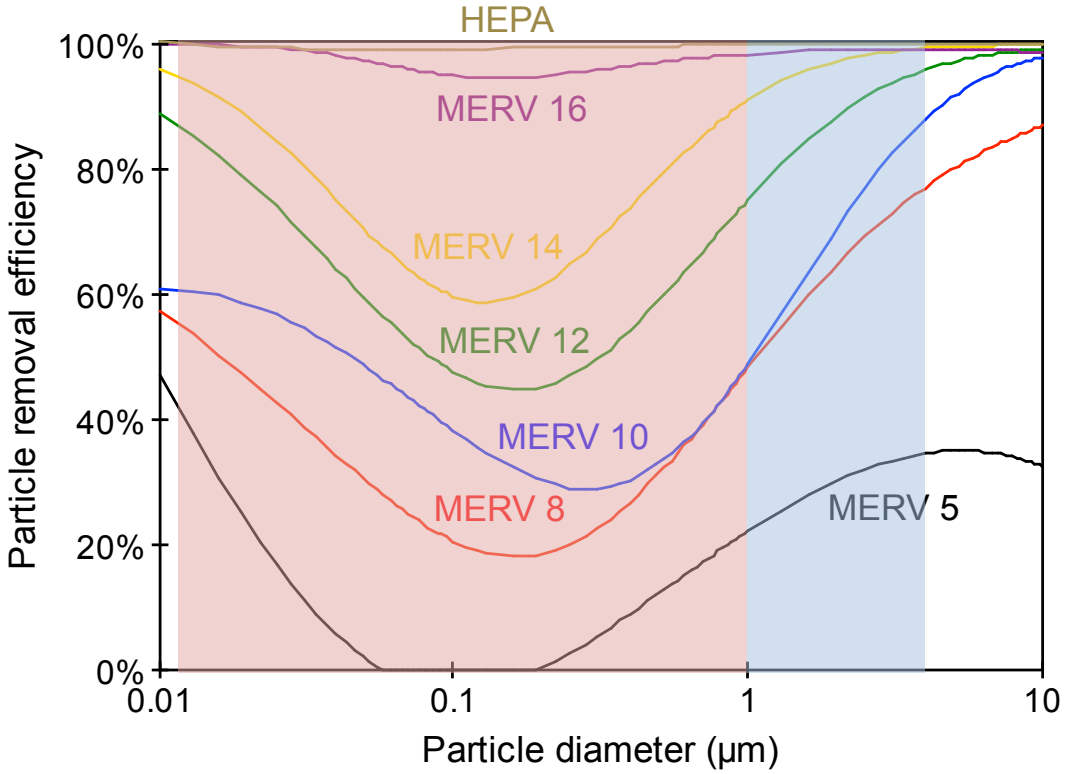
Chen and Zhao 2010 *Indoor Air* 20:95-111

INFECTIOUS AEROSOLS

Size distributions and infectious organism content

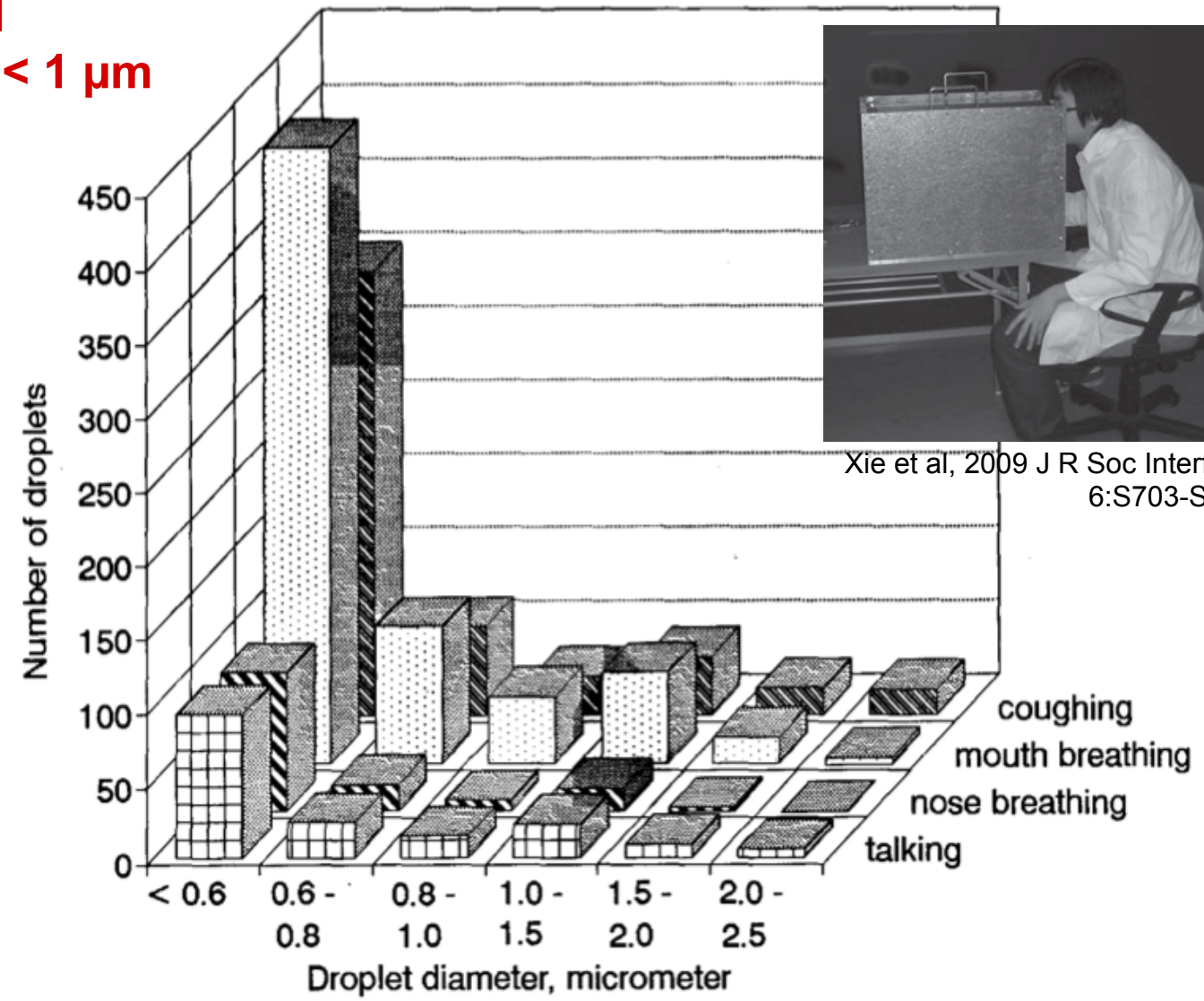
What particle sizes are actually emitted by humans?

- Commonly believed that droplet nuclei average 1-3 μm
  - Recent studies show that 80-90% of particles expelled during human activities are actually smaller than 1-2 μm
- When considering dynamics of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols



Emissions from coughing subjects

Nearly all particles < 1 µm

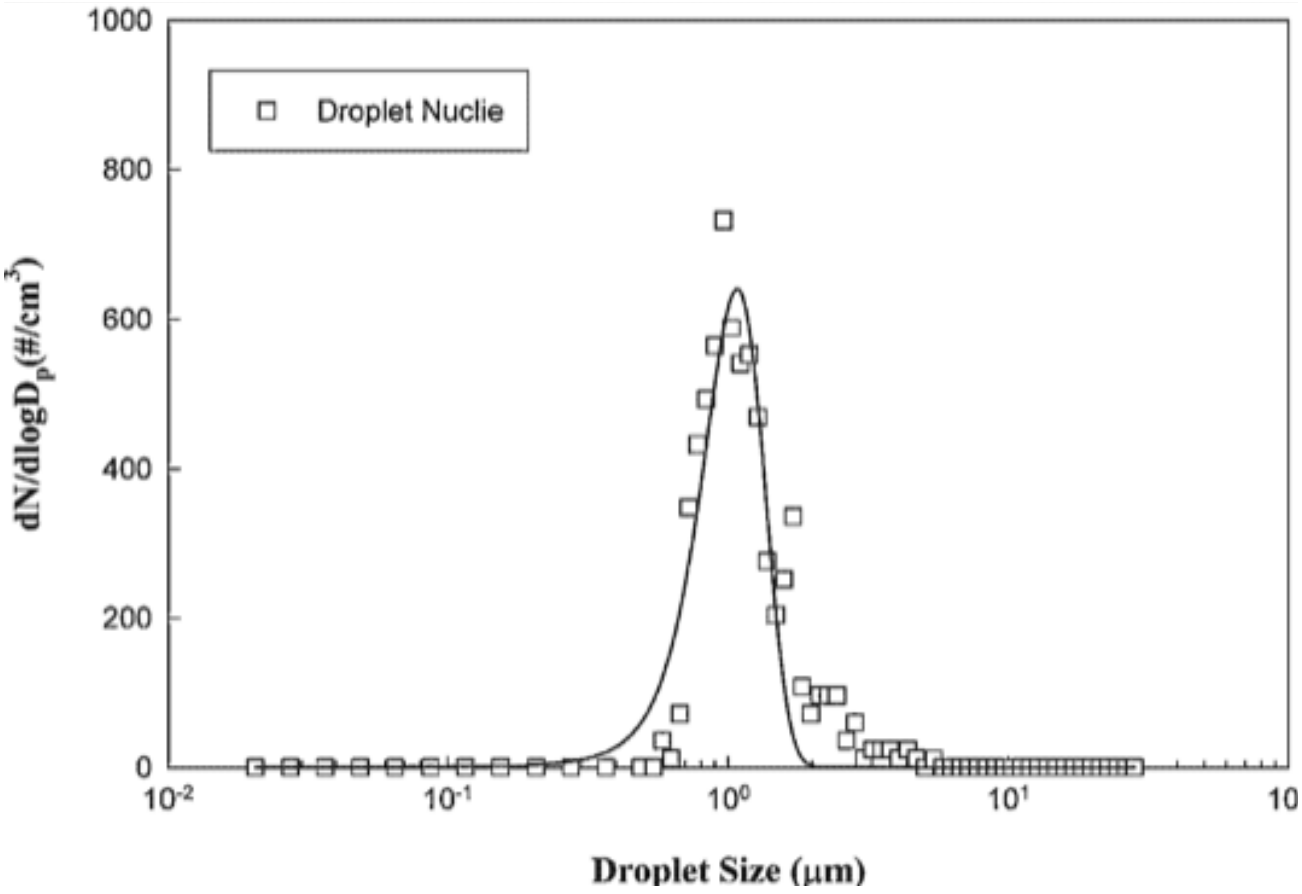


Xie et al, 2009 J R Soc Interface 6:S703-S714

Papineni and Rosenthal 1997 *J Aerosol Medicine* 10:105-116

More emissions from coughing subjects (n = 54)

- 82% of particles in the 0.7-2.2 μm size range

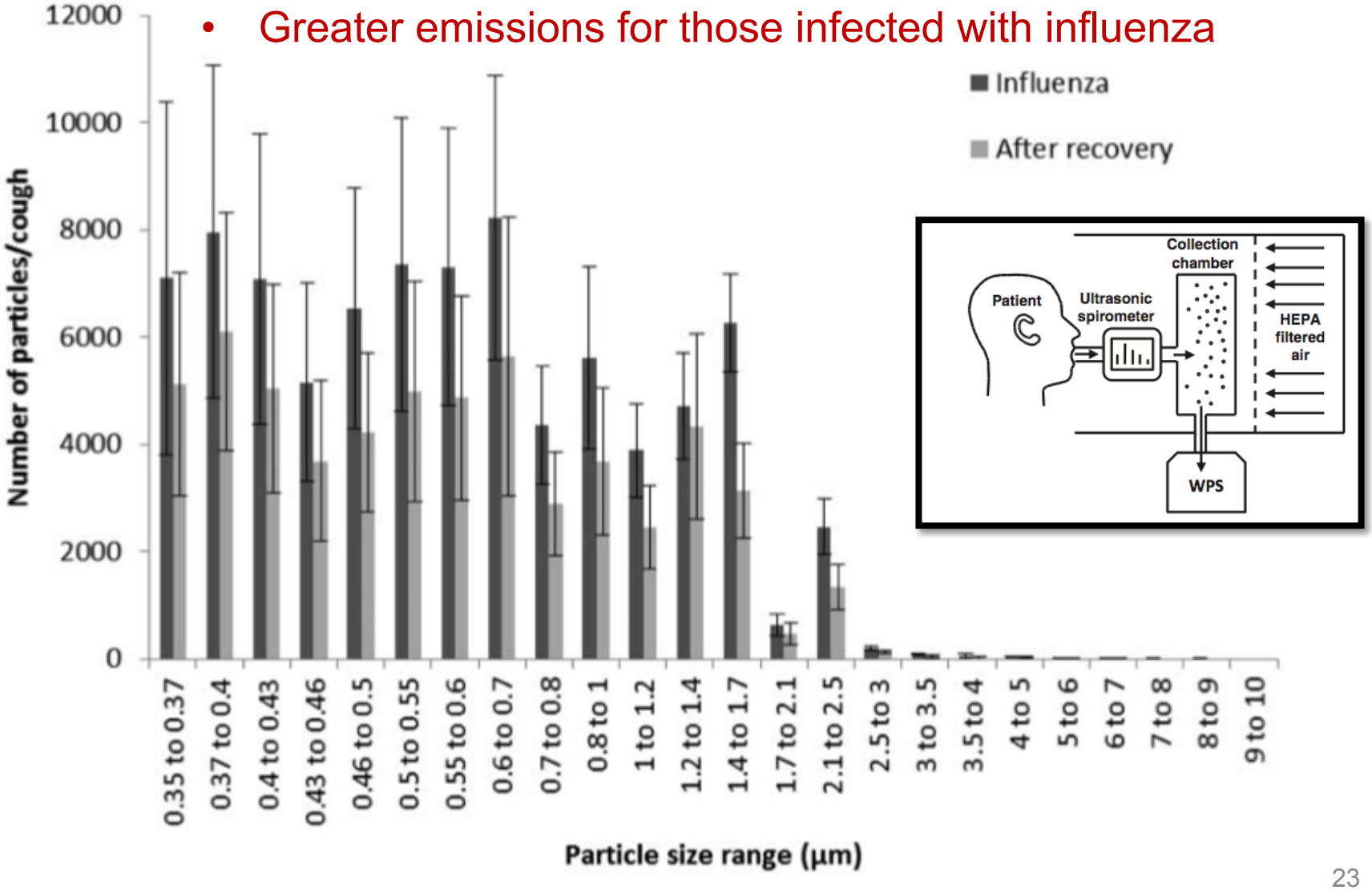


Yang et al., 2007 *J Aerosol Med* 20:484-494

Coughing subjects with and without influenza

Most emitted particles < 1 µm

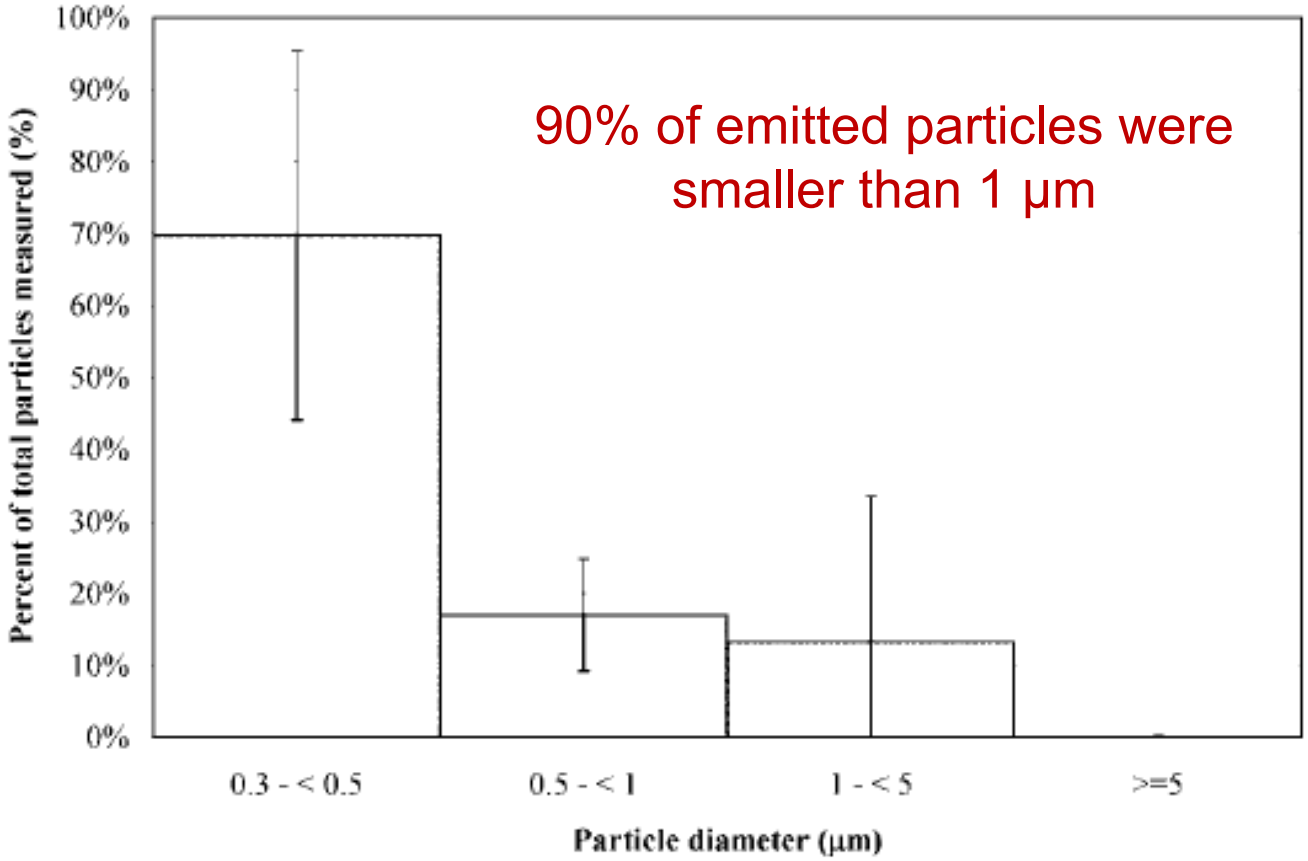
- Greater emissions for those infected with influenza



Lindsley et al., 2012 *J Occup Environ Hygiene* 9:443-449

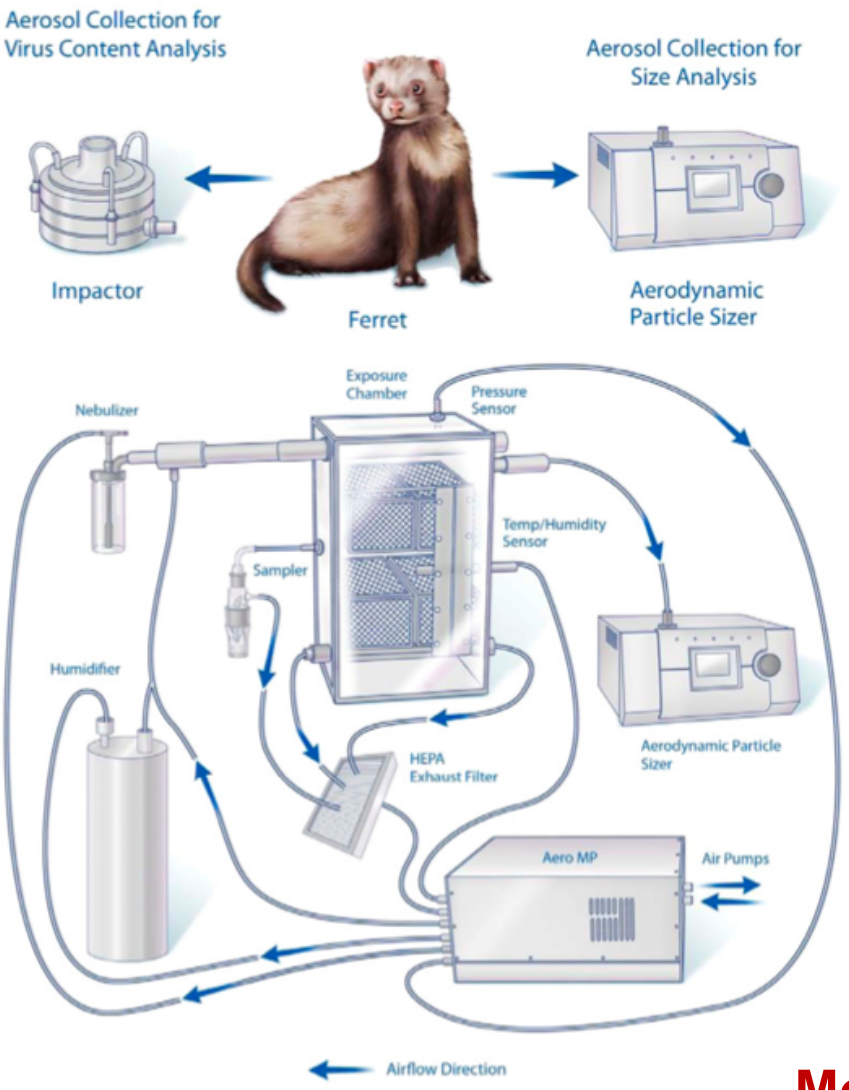
Emissions from breathing subjects

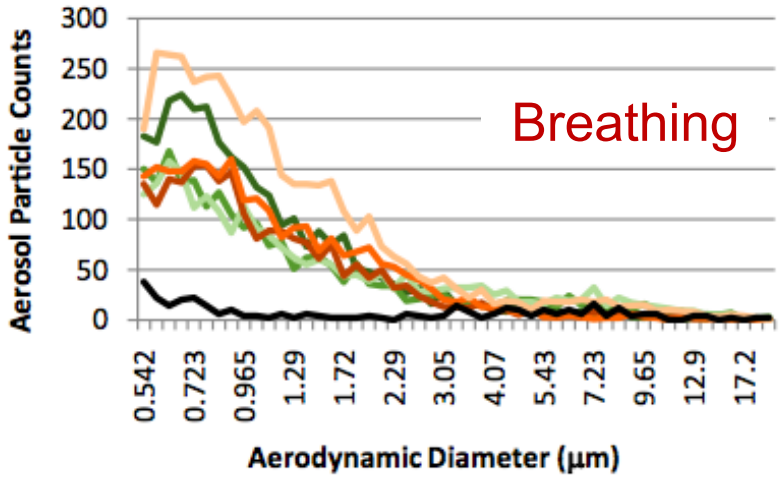
- Typically much smaller number concentrations than during coughing

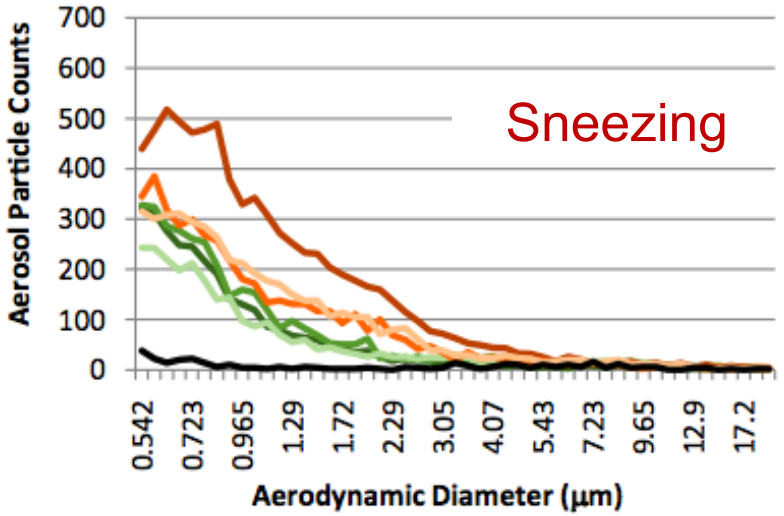


Fabian et al., 2008 *PLoS ONE* 3:e2691

Emissions from ferrets (yes, ferrets)





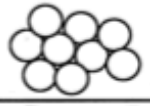
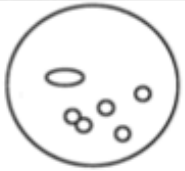


Most particles < 2 µm

Gustin et al., 2011 *PNAS* 108:8432-8437

What about infectious organisms within particles?

Shape and Aspect Ratios of Microorganisms

Shape	Type	Description	AR
	Icosahedral Helical	All respiratory viruses, whether icosahedral or helical, are so much smaller than filter fibers that they can be considered spherical for filtration calculations.	1
	Spherical	Most bacteria and spores are approximately spherical.	1
	Ovoid	Some bacteria and spores are ovoid.	1-3
	Rods	Bacteria classed as bacilli are rod-shaped.	1-10
	Diplo-cocci	Certain bacteria normally occur in pairs.	1-3
	Strepto-cocci	Some bacteria occur in strings (i.e. strepto-coccus) but are likely to break up on impact with filter fibers.	NA
	Staphylo-cocci	Some bacteria occur in bunches (i.e. staphylo-coccus) but are likely to break up on impact with filter fibers.	NA
	Flagella	Some bacteria have flagella, enabling motility.	NA
	Capsule	Some bacteria have hydrophobic capsules that can be shed or regenerated depending on the environment.	1-3
	Slime layer	Some microbes produce slime layers in addition to capsules that can be shed at any time.	1-3
	Droplets & Droplet Nuclei	Aerosolized droplets, typically 20-100 microns, may contain numerous microbes and other particles. These evaporate to condensation nuclei that may contain several viable microbes and residue. These will break up upon impact with filter fibers.	1-3

Kowalski et al., 1999 *ASHRAE Transactions*

What about infectious organisms within particles?

Pathogen	Mean size, μm
Influenza	0.098
Smallpox	0.22
C. burnetti	0.283
R. prowazeki	0.283
L. pneumophila	0.520
M. tuberculosis	0.637
C. diphtheria	0.700
S. pneumoniae	0.707
R. rickettsii	0.85
N. asteroides	1.12
Bacillus anthracis	1.12
H. capsulatum	2.24
Botulinum toxin	2.24
B. dermatitidis	12.6

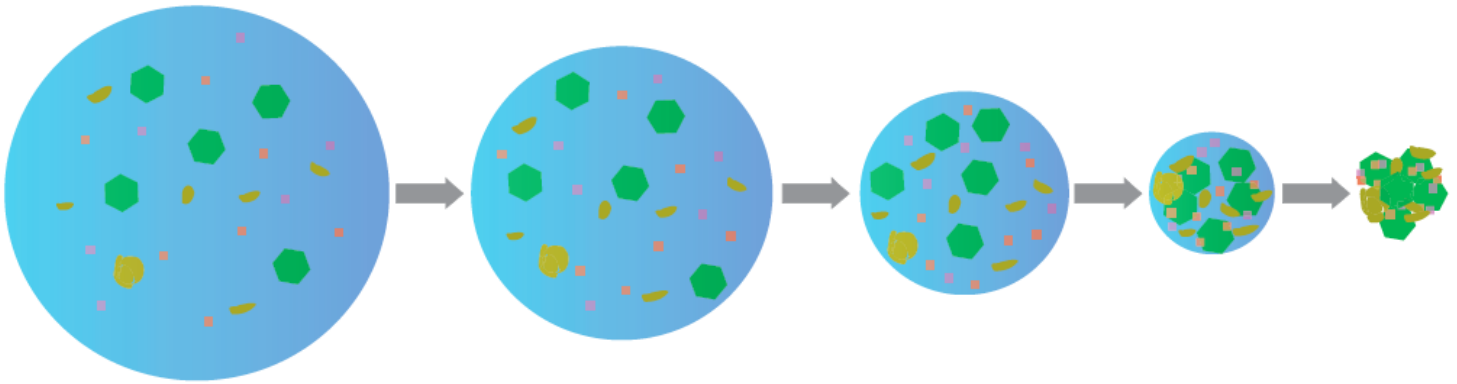
Airborne Respiratory Pathogens—Sizes and Dimensions

AIRBORNE PATHOGEN	AVG DIA	DIA/WIDTH		LENGTH		AR	EQUIV DIA	LOGMEAN DIAMETER	LN STDEV
		MIN	MAX	MIN	MAX				
Parvovirus B19	0.022	0.018	0.026			1		0.022	0.074
Rhinovirus	0.023	0.018	0.028			1		0.022	0.088
Coxsackievirus	0.025	0.02	0.03			1		0.024	0.081
Echovirus	0.025	0.02	0.03			1		0.024	0.081
Hantavirus	0.06	0.05	0.07			1		0.059	0.067
Togavirus	0.063	0.05	0.075			1		0.061	0.081
Reovirus	0.073	0.07	0.075			1		0.072	0.014
Adenovirus	0.08	0.07	0.09			1		0.08	0.050
Orthomyxovirus	0.1	0.08	0.12			1		0.10	0.081
Coronavirus	0.11	0.08	0.13			1		0.10	0.097
Varicella-zoster	0.15	0.1	0.2			1		0.14	0.139
Arenavirus	0.18	0.05	0.3			1		0.12	0.358
Francisella tularenis	0.19	0.08	0.3	0.2	0.7	2.4	0.13	0.15	0.264
Morbillivirus	0.2	0.1	0.3			1		0.17	0.220
Respiratory Syncytial Virus	0.22	0.14	0.3			1		0.20	0.152
Parainfluenza	0.23	0.15	0.3			1		0.21	0.139
Poxvirus - Vaccinia	0.23	0.2	0.25	0.25	0.3	1.2	0.08	0.22	0.045
Mycoplasma pneumoniae	0.23	0.15	0.3			1		0.21	0.137
Paramyxovirus	0.23	0.15	0.31			1		0.22	0.145
Bordetella pertussis	0.25	0.2	0.3	0.5	1	3	0.21	0.24	0.081
Chlamydia pneumoniae	0.3	0.2	0.4			1		0.28	0.139
Chlamydia psittaci	0.3	0.2	0.4			1		0.28	0.139
Klebsiella pneumoniae	0.4	0.3	0.5			1		0.39	0.102
Haemophilus influenzae	0.43	0.2	0.3	1	1.5	5	0.43	0.35	0.081
Coxiella burnetii	0.5	0.45	0.55			1		0.50	0.040
Pseudomonas aeruginosa	0.57	0.3	0.8	1	3	3.6	0.57	0.51	0.209

Kowalski et al., 1999 *ASHRAE Transactions*

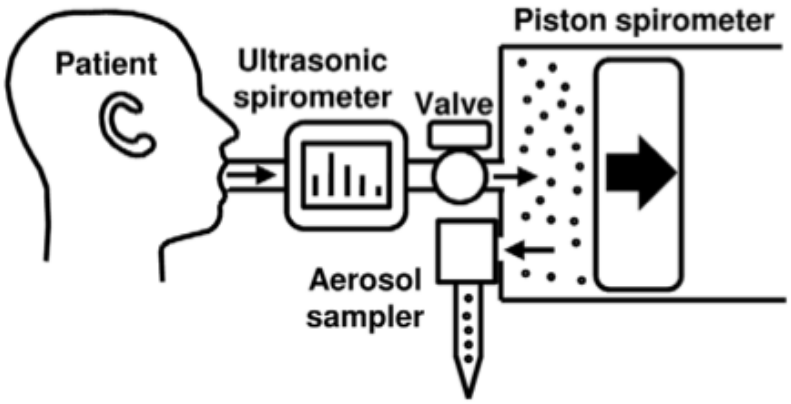
What about infectious organisms within particles?

- Most particles emitted during human activities are smaller than 1-2 μm
  - But particle volume scales with d_p^3
  - Does the amount of viral or bacterial material contained in droplet nuclei scale similarly?



- Recent measurements have shown this to be ~true

Viral RNA contained in size-resolved aerosol samples



qPCR reveals influenza viral RNA size distribution in human coughs:

- 42% < 1 μm
- 23% 1-4 μm
- 35% > 4 μm

Table 1. Influenza viral RNA detected in the NIOSH two-stage aerosol sampler.

Aerosol particle size range (aerodynamic diameter)	*Median # of viral copies per cough*	*% of viral RNA contained in particles in this size range*	*% of subjects whose cough aerosol contained viral RNA-laden particles in this size range*
>4 μm	6.3 (SD 9.0)	35%	90%
1 to 4 μm	3.3 (SD 6.9)	23%	81%
<1 μm	3.7 (SD 23.7)	42%	75%
All particles	15.8 (SD 29.3)	100%	100%

Although ~90% of emitted particles (number concentrations) are < 1 μm

- Only ~40% of viral RNA is contained in that fraction

Lindsley et al., 2010 *PLoS ONE* 5:e15100

Size-resolved influenza virus indoors

Distribution of Airborne Influenza Virus and Respiratory Syncytial Virus in an Urgent Care Medical Clinic

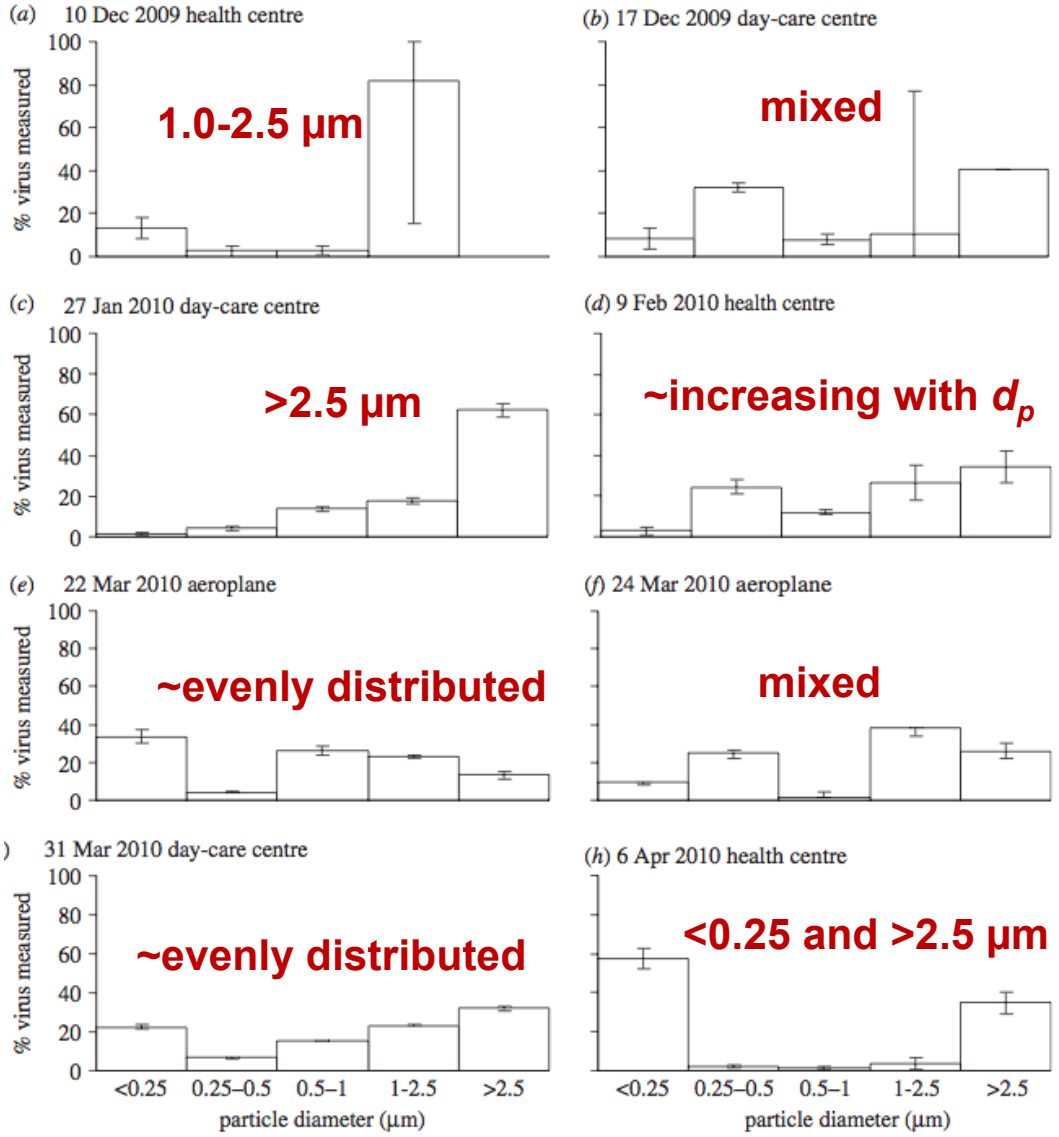
qPCR reveals influenza viral RNA size distribution in an urgent care clinic:

- ~10-20% < 1 μm
- ~20-40% 1-4 μm
- ~50-60% > 4 μm

Sampling Location	Distribution of viral RNA		
Personal samplers	< 1.7 μm 32%	1.7-4.9 μm 16%	> 4.9 μm 52%
Lower stationary samplers	< 1 μm 13%	1-4.1 μm 37%	> 4.1 μm 50%
Upper stationary samplers	< 1 μm 9%	1-4.1 μm 27%	> 4.1 μm 64%

Lindsley et al., 2010 *Clinical Infectious Diseases* 50:693-698

Other mixed results for viral distributions



Yang et al., 2011 *J R Soc Interface* 8:1176-1184

ESTIMATING RISKS OF INFECTIOUS DISEASES

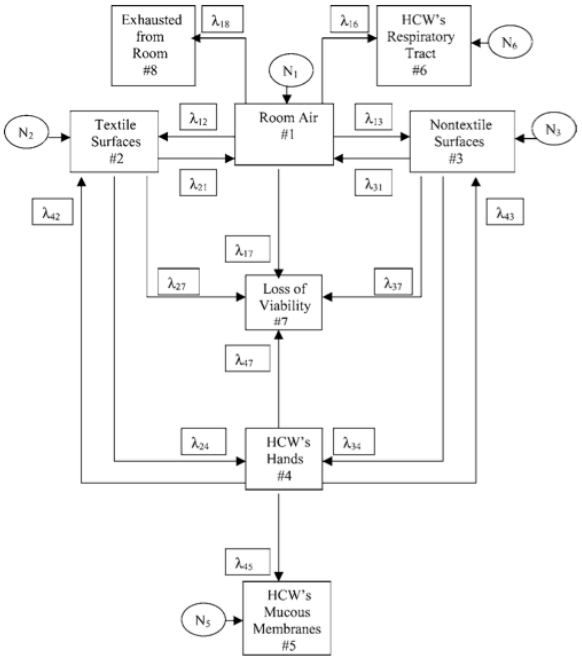
Methods of estimating infectious disease risks

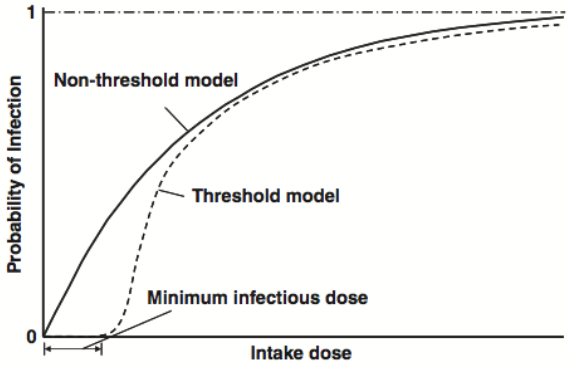
Wells-Riley model

$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

$P_{\text{infection}}$ = 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)

Markov chain combined with dose-response models





Wells-Riley model

$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\overline{\mu}}$$

- μ = average number of "quanta" breathed by a susceptible person, assuming probability of infection fits a Poisson distribution
- "quantum" = number of infectious droplet nuclei necessary to initiate infection based on the assumption that infection requires at least one organism
  - Function of type of infectious agent (more on that later)

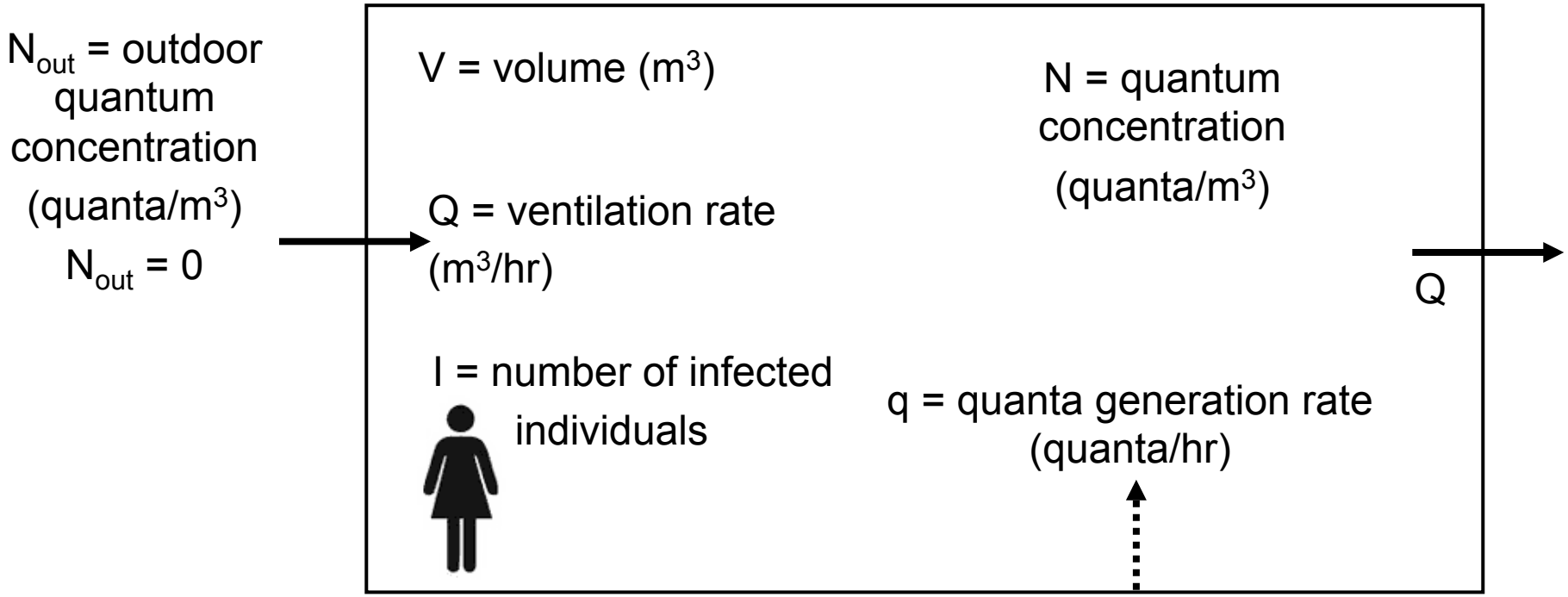
- If μ = 1 quanta breathed, risk of infection = $1 - e^{-1} = 1 - 1/e$ = ~63%

$$\overline{\mu} = p_b t \overline{N}$$

p_b = breathing rate (m^3/hr)
t = total time of exposure (hr)
$\overline{N}$ = average quantum "concentration"

Wells-Riley model

- Simplest mass balance on “quanta”, assuming:
  - Well-mixed space
  - AER is much greater than loss of agent viability, loss by filtration, loss by deposition



$$V\frac{dN}{dt} = Iq - NQ \quad \rightarrow \quad \overline{N}_{\text{at steady state}} = \frac{Iq}{Q}$$

Wells-Riley model

- Average # of quanta breathed:

$$\overline{\mu} = p_b t \overline{N}$$

p_b = breathing rate (m^3/hr)
t = total time of exposure (hr)
$\overline{N}$ = average quantum "concentration"

- Average quanta concentration:

$$\overline{N}_{\text{at steady state}} = \frac{Iq}{Q}$$

- Poisson risk model:

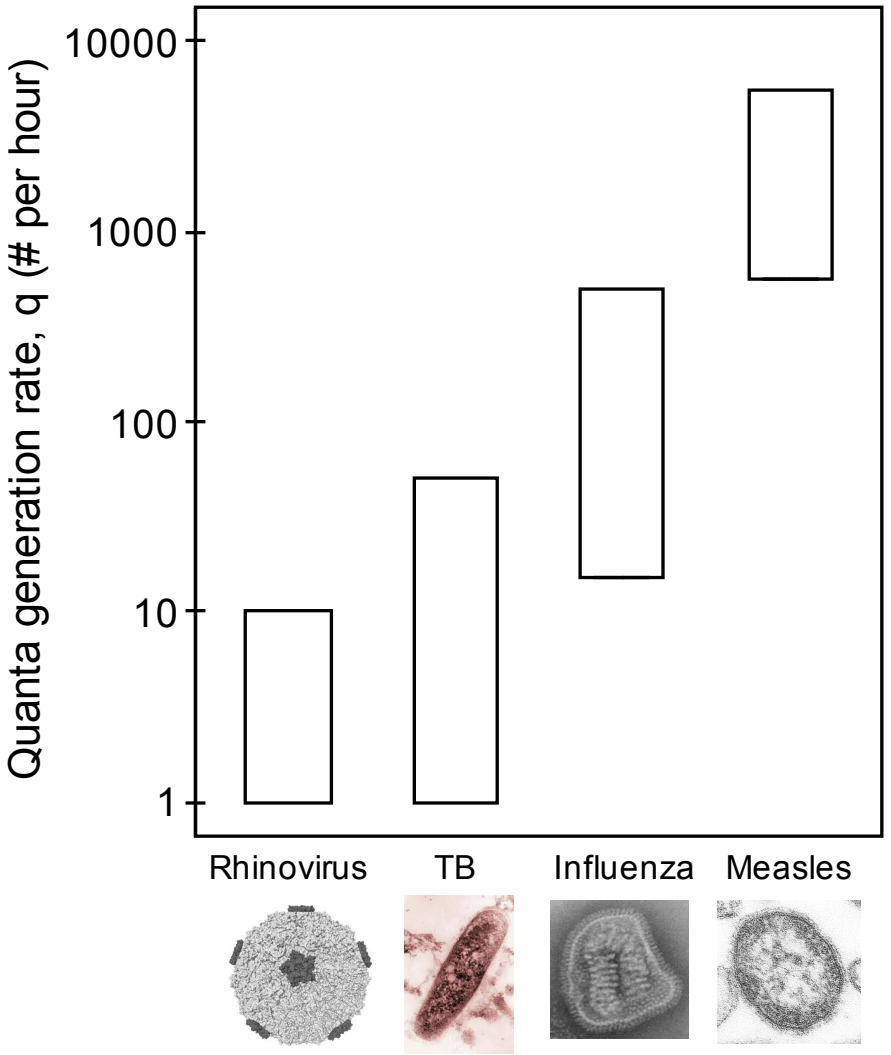
$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\overline{\mu}}$$

$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

$P_{\text{infection}}$ = 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)

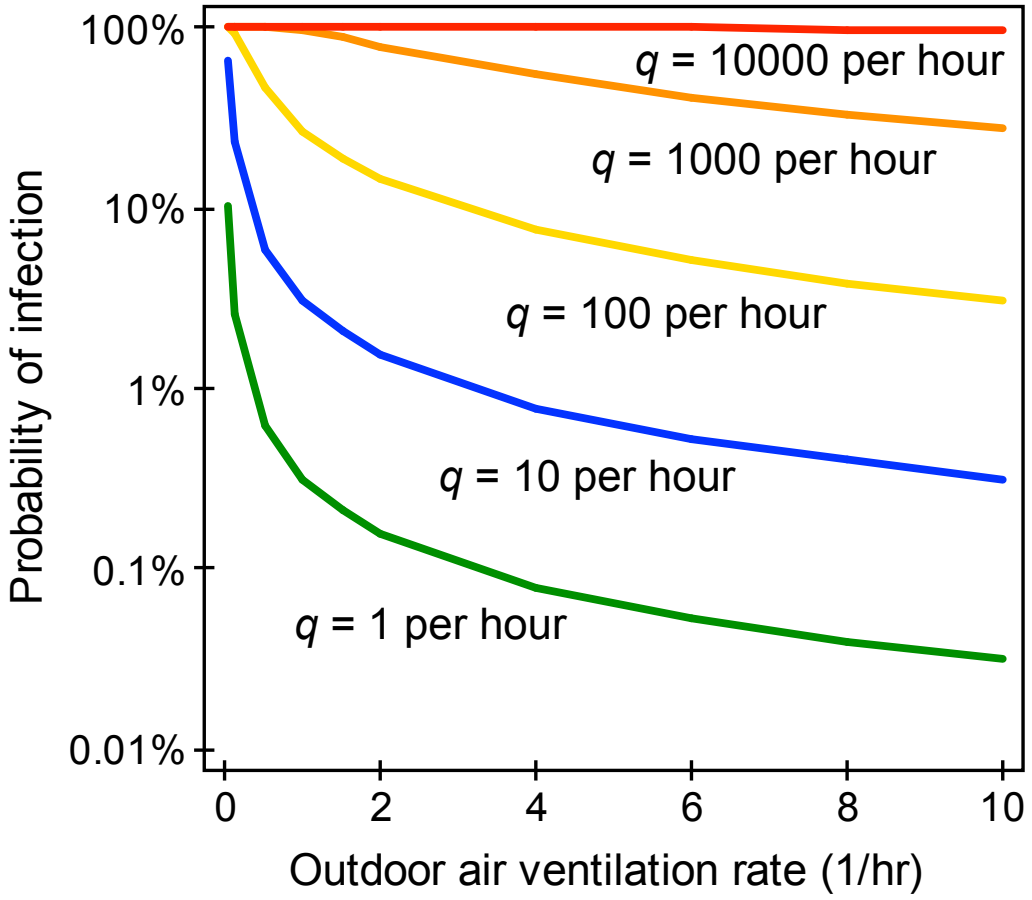
Concept of quanta generation

- The unit *quantum of infection* is not an actual physical unit
- It is a hypothetical infectious dose
  - Back calculated from epidemiological studies
- Accounts for emissions, transport, inhalation, infectivity, and susceptibility all in one term



Riley et al., 1978 *Am J Epidemiology* 107:421-432 (and many others for quanta estimates)

How do quanta generation and ventilation rates affect risk?

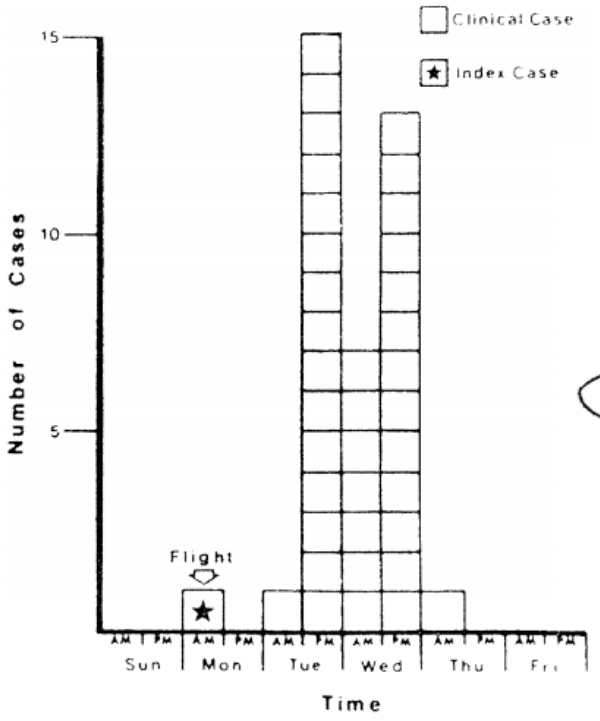


- Example 500 m^2 (5,300 ft^2) building with 1 infector
  - Containing adults with 0.48 m^3/hr breathing rate
- Depends strongly on value of *q*

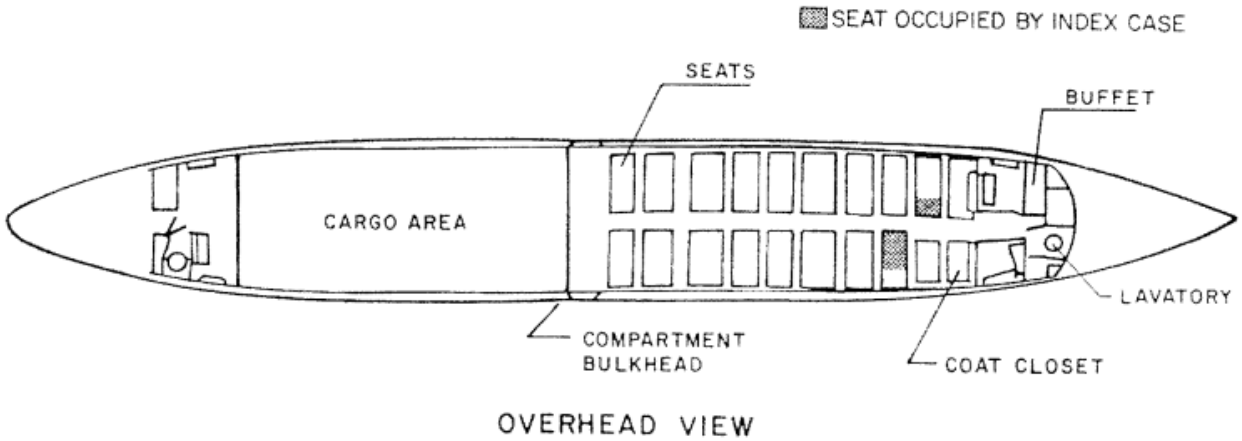
$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

Example of quanta generation rate calculation

- Passenger plane grounded for 4.5 hours
  - One known infector and 29 other uninfected passengers
    - 25 (86%) contracted influenza within 2 days
  - Rudnick and Milton made assumptions of breathing rates and air exchange rates to yield *q* of 15-128 per hour



$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$



Buxton Bridges et al. 2003 *Clinical Infectious Diseases* 37:1094-1101; Rudnick and Milton, 2003 *Indoor Air* 13:237-245

INFECTION CONTROL

In indoor environments

Airborne infection control

Surface disinfection and hand hygiene

Procedural controls and isolation

Treatment, prophylaxis, and vaccination

Engineering controls and air disinfection

Engineering controls and disinfection

- Control of airborne infectious disease transmission
  - Studies suggest building characteristics such as outdoor air ventilation rates and lower occupant density can reduce respiratory illnesses 15-76%

Langmuir et al. 1948 *Am J Hyg*; Brundage et al. 1988 *JAMA*; Drink a et al. 1996 *Am Geriatr Soc*; Fisk 2000; Li et al. 2007 *Indoor Air*

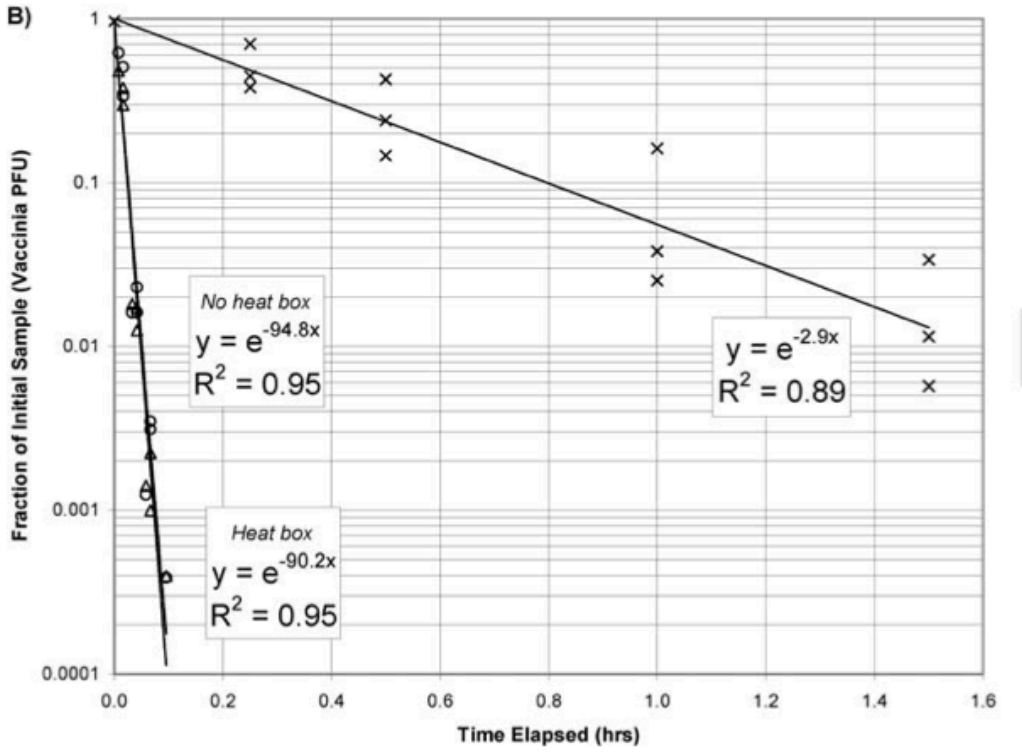
- Other engineering controls include:
  - Ultraviolet germicidal irradiation (UVGI)
  - Facemasks
  - Isolation rooms (dedicated HVAC)
  - Flow control (pressure differentials and flow regime control)
  - HVAC filtration

- These only work for diseases that are primarily spread via airborne routes (not through surface contamination)

ASHRAE Position Document on Airborne Infectious Diseases (2014)

UVGI

Inactivation of Poxviruses by Upper-Room UVC Light in a Simulated Hospital Room Environment



McDevitt et al. **2008** *PLOS ONE* 3(9):e3186

HVAC filtration and infectious disease transmission?

- What impact can HVAC filtration have on infectious disease transmission probability?
  - At what costs relative to increased ventilation?

- We used a modified Wells-Riley equation to explore influenza transmission risk reductions by HVAC filtration in a hypothetical office environment

Azimi and Stephens **2013** *Build Environ* 70:150-60

Incorporating other loss terms into Wells-Riley model

$$P_{\text{infection}} = 1 - \exp\left[-\frac{Iqpt}{V} \Big/ \left(\lambda_{\text{ventilation}} + k_{\text{filtration}} + k_{\text{deposition}}\right)\right]$$

Loss by HVAC filtration (1/hr)

Loss by particle deposition (1/hr)

$$k_{\text{filtration}} = f_{\text{HVAC}} \frac{Q_{\text{filter}} \eta_{\text{filter}}}{V} = \lambda_{\text{recirculated}} \eta_{\text{filter}}$$

f_{HVAC} = fractional HVAC operation time (-)
Q_{filter} = airflow rate through filter (m^3/hr)
η_{filter} = particle removal efficiency of the filter (-)
$\lambda_{\text{recirculated}}$ = recirculation rate through the HVAC filter (1/hr)

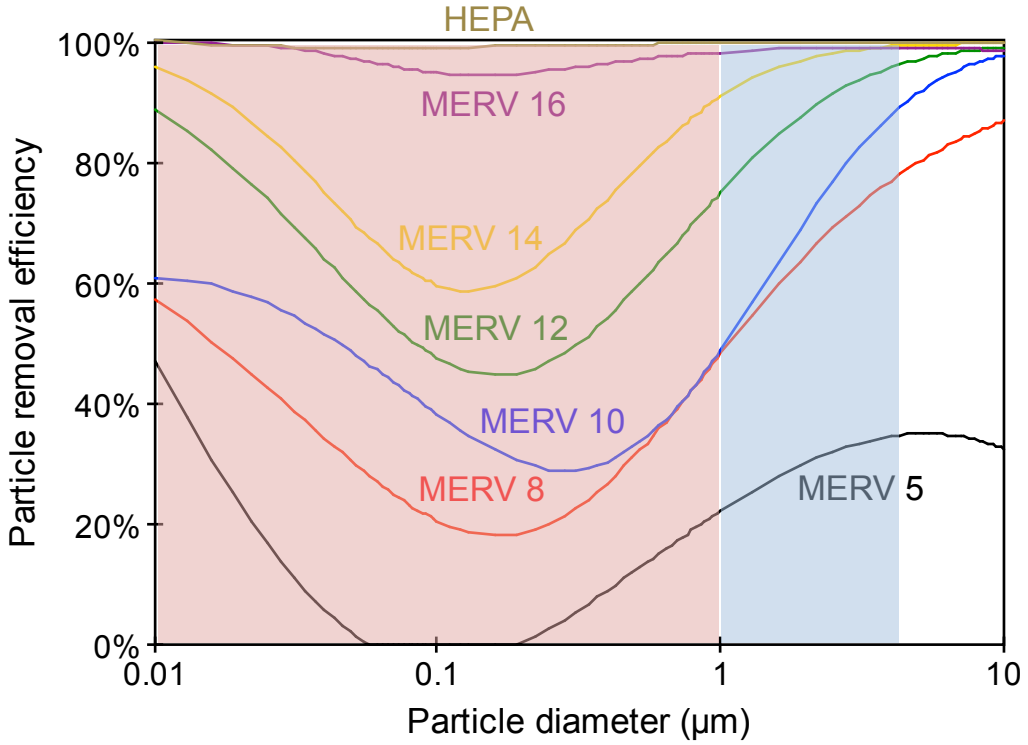
To connect Wells-Riley with filtration, we need to know several specific building characteristics, as well as:

- Size-resolved quanta generation rates
- Removal efficiency of HVAC filters for infectious aerosols

Azimi and Stephens **2013** *Build Environ* 70:150-60

What particle sizes are emitted and remain airborne?

- When considering particle filtration of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols



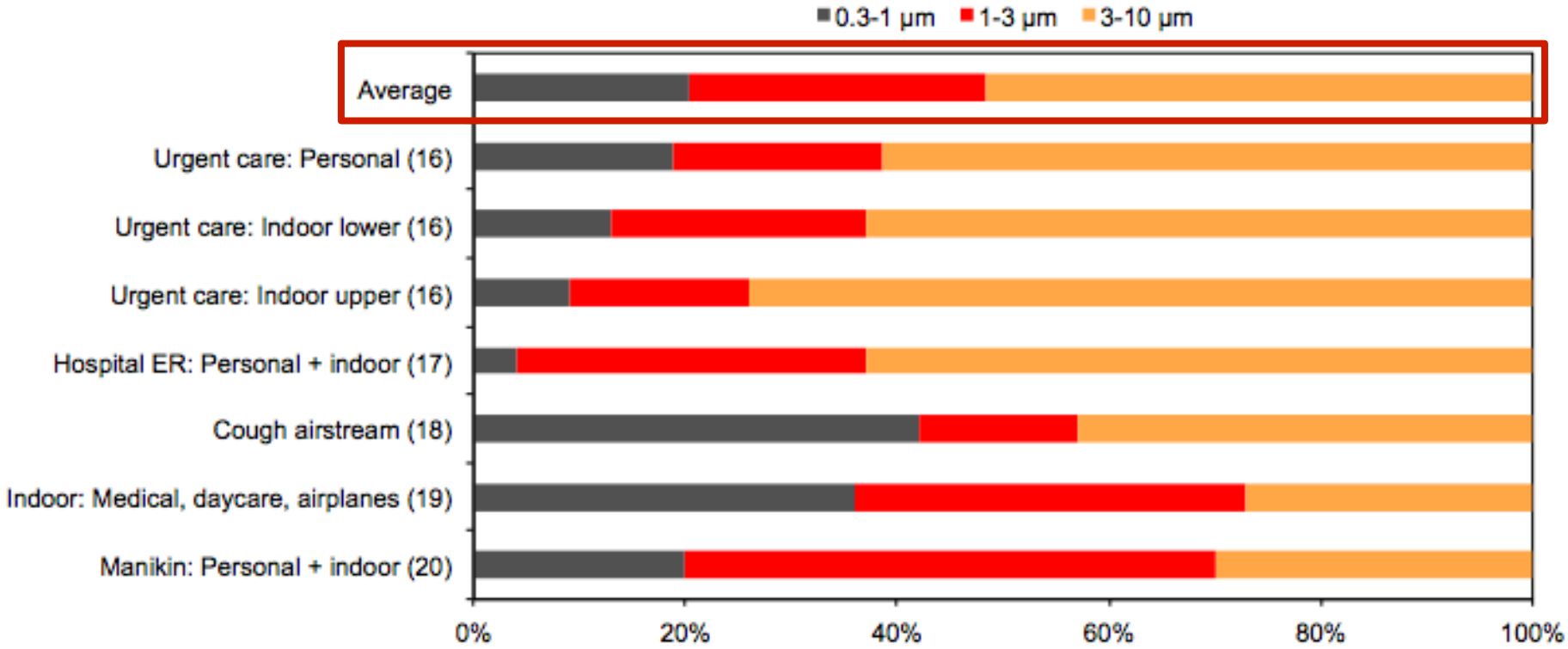
- Commonly believed that droplet nuclei average 1-3 μm
  - Recent studies show that 80-90% of particles expelled during human activities are actually smaller than 1-2 μm

Papineni and Rosenthal **1997** *J Aerosol Medicine* 10:105-116; Yang et al., **2007** *J Aerosol Med* 20:484-494; Lindsley et al., **2012** *J Occup Environ Hygiene* 9:443-449; Fabian et al., **2008** *PLoS ONE* 3:e2691

Size-resolved influenza virus indoors: Summary

Recent measurements of influenza RNA in size-fractioned indoor aerosols:

- Healthcare centers, ER, cough airstreams, daycare, airplanes, manikins
- Manually adjusted to fit into ASHRAE Standard 52.2 size bins



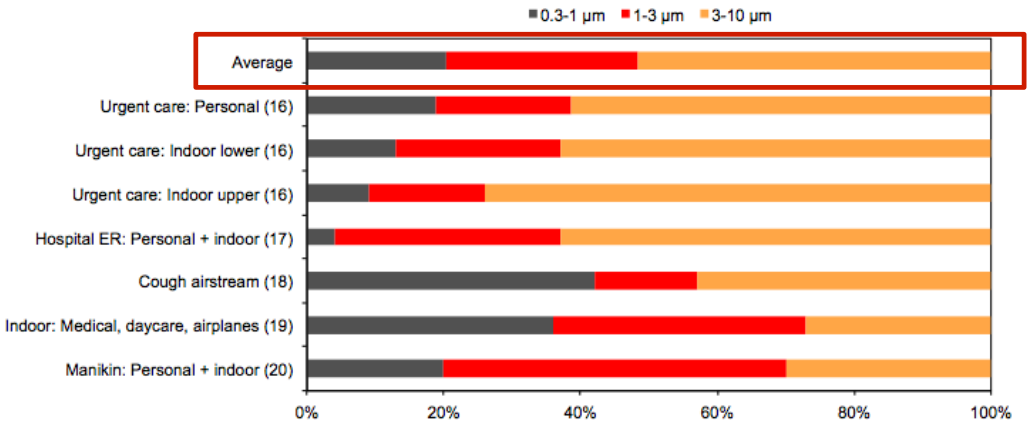
Average influenza RNA size distribution:

20% <1 µm **29% 1-3 µm** **51% >3 µm**

[16] Lindsley et al., **2010** *Clin Infect Dis* 50:693-698; [17] Blachere et al., **2009** *Clin Infect Dis* 48(4):438-40
[18] Lindsley et al., **2010** *PLoS ONE* 5:e15100; [19] Yang et al., **2011** *J R Soc Interface* 8:1176-1184;
[20] Noti et al. **2012** *Clin Infect Dis* 54(11):1569–77

Mapping viral size distributions to filtration efficiency

Viral size distributions ----→ Filtration Efficiency



Average influenza size distribution:

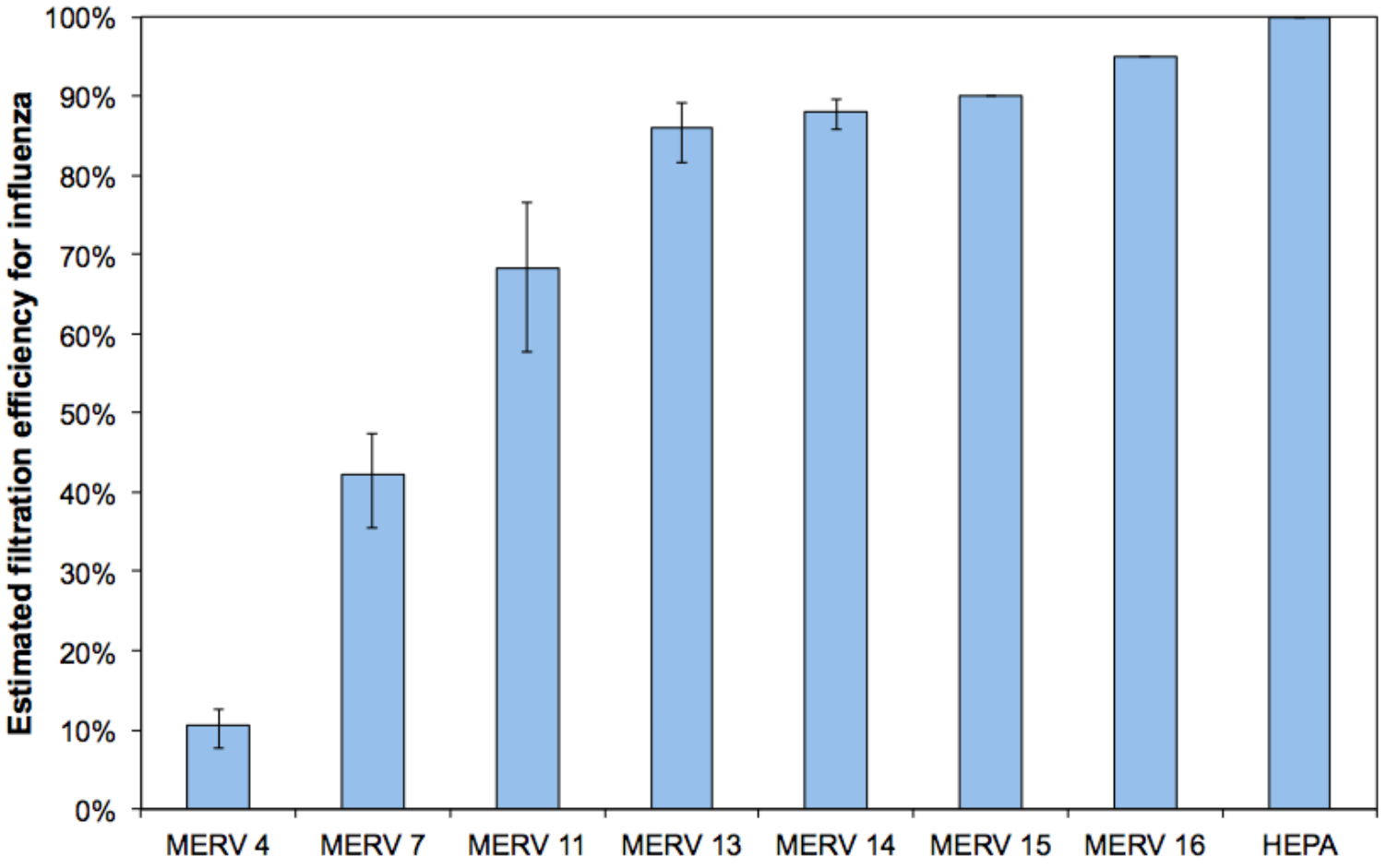
20% <1 µm **29% 1-3 µm** **51% >3 µm**

MERV table from ASHRAE 52.2

	Composite particle removal efficiency (%)		
MERV	0.3-1 µm	1-3 µm	3-10 µm
1			<20
2			<20
3			<20
4			<20
5			20-35
6			35-50
7			50-70
8			70+
9		<50	85+
10		50-65	85+
11		65-80	85+
12		80+	90+
13	<75	90+	90+
14	75-85	90+	90+
15	85-95	90+	90+
16	95+	95+	95+

Estimated airborne influenza removal efficiency

Assuming these viral size distributions, we can estimate the size-weighted removal efficiency of a range of filters for infectious aerosols (w/ uncertainty):

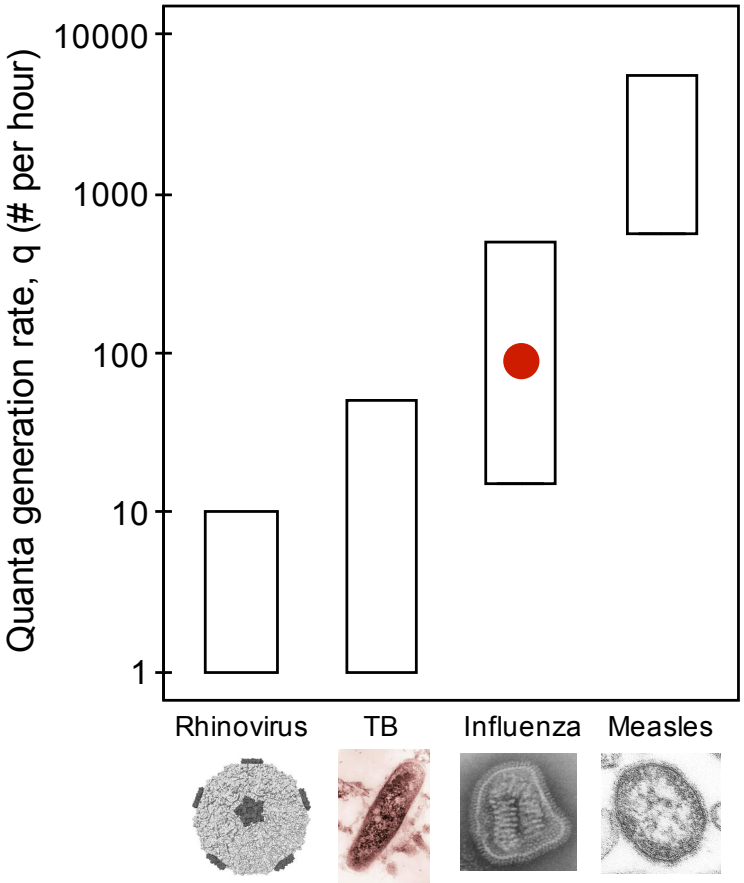


Azimi and Stephens **2013** *Building and Environment* 70:150-160

Case study: Influenza in an office environment

- Hypothetical office environments with 1 infector:
  - A = 500 m^2
  - V = 1500 m^3
  - 25 adult occupants
  - ASHRAE 62.1 minimum ventilation rates
  - 25% OA
  - $Q_{HVAC,total}$ = 3044 m^3/hr
  - 8 hours of occupancy per day

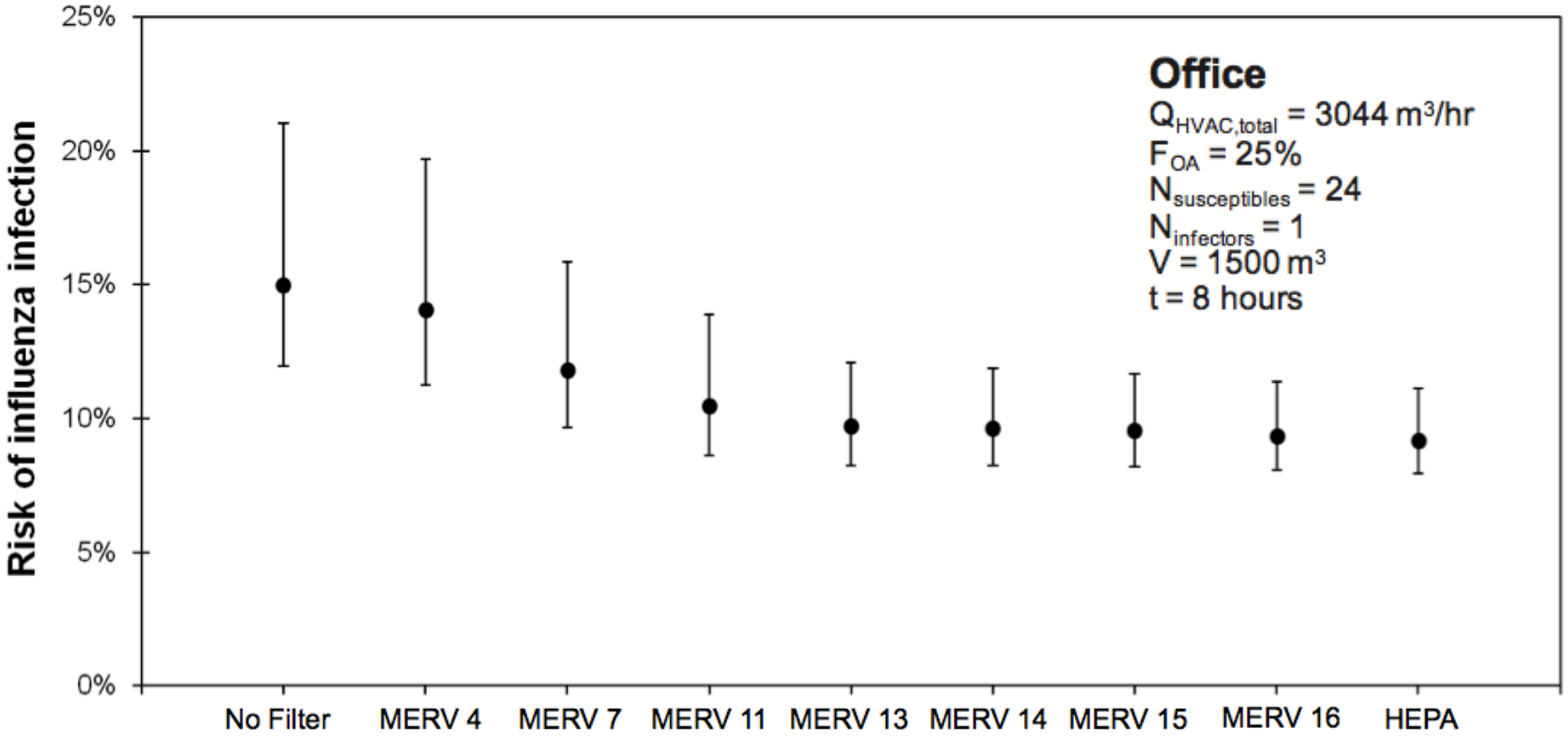
- Used mean quanta generation rate from previous studies
  - Influenza (q = 100/hr)



Riley et al., **1978** *Am J Epidemiology* 107:421-432
(and many others for quanta estimates)

Azimi and Stephens **2013** *Building and Environment* 70:150-160

Estimated probability of infection with HVAC filtration



From no filter to MERV 13 or greater:
From 4 out of 24 occupants infected w/ influenza to 2 out of 24

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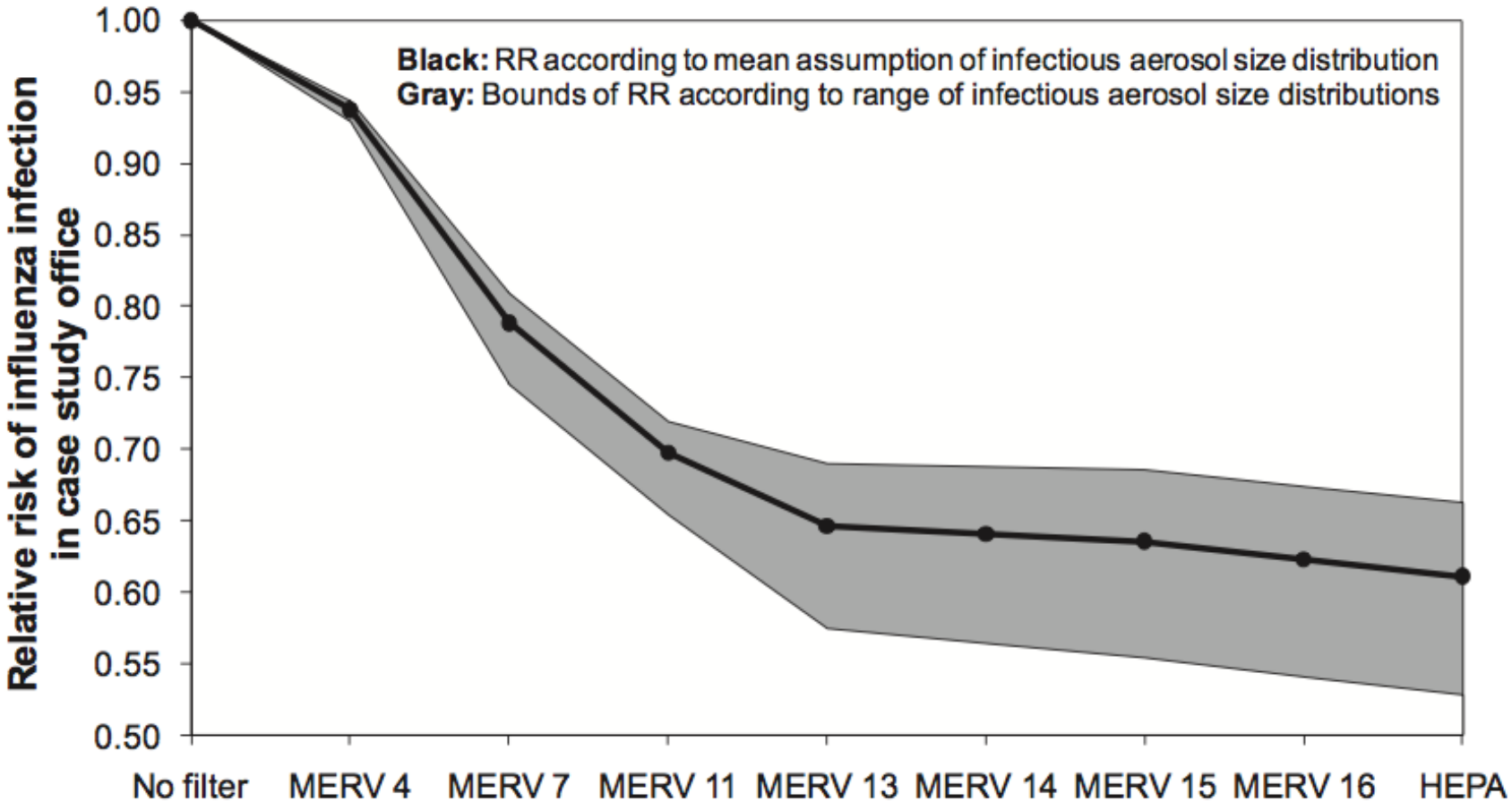
Generalizing results

- Using relative risks across all estimates of influenza aerosol size distributions and all HVAC filters, we can generalize results



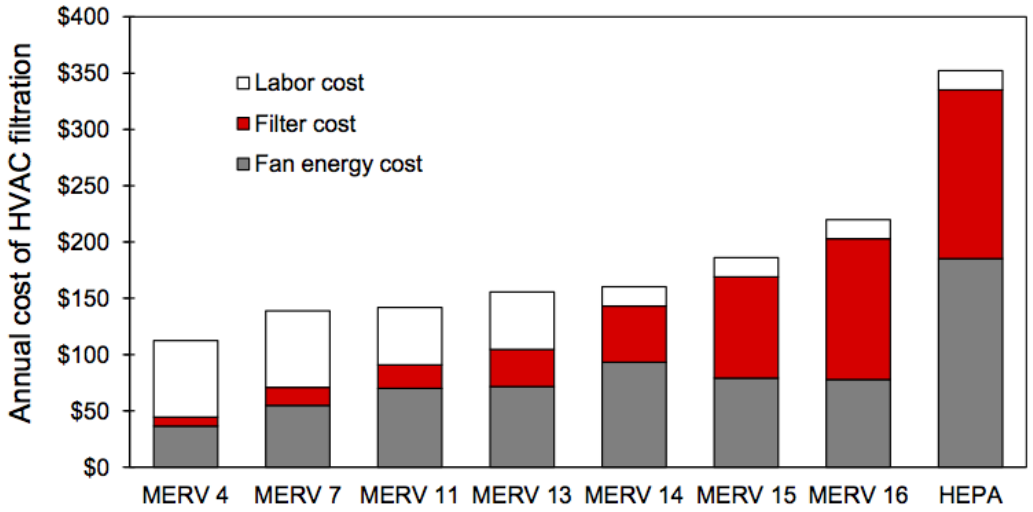
Azimi and Stephens **2013** *Building and Environment* 70:150-160

Estimating costs of filtration and ventilation

- Making assumptions about operational periods in each building type, costs of natural gas and electricity, and HVAC equipment efficiency we estimate the cost of conditioning each unit of outdoor air ventilation rate delivered in each of four cities:
  - Chicago, Charlotte, Houston, and Phoenix

$$E_{\text{heating}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{\text{p,air}} HDD \frac{1}{\eta_{\text{heating}}} \alpha \qquad E_{\text{cooling}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{\text{p,air}} CDD \frac{1}{\eta_{\text{cooling}}} \beta$$

- We can also estimate the cost of filtration by combining filter costs, fan energy costs, and replacement costs (labor)



$$W_{\text{filtration}} = \frac{Q_{\text{recirculated}} \Delta P_{\text{avg}}}{\eta_{\text{fan}} \eta_{\text{motor}}}$$

$$C_{\text{filtration}} = W_{\text{filtration}} t_{\text{operating}} P_{\text{electric}}$$

Procedure similar to Bekö et al. **2008** *Building and Environment*

Azimi and Stephens **2013** *Building and Environment* 70:150-160

Table 5
Climate conditions (HDD and CDD) and annual cost of outdoor air delivery used for the office environment under the assumed operational schedule in each location.

	Chicago	Charlotte	Houston	Phoenix
Heating degree days, HDD (K-day)	893	461	204	159
Cooling degree days, CDD (K-day)	300	415	713	1011
Annual cost of air delivery per unit removal rate ($ per 1/hr)	$469	$367	$416	$543

Table 6
Assumptions used in estimating the annual costs of HVAC filtration.

Filter	Depth (cm)	Purchase cost	Initial pressure drop (Pa)	Final pressure drop (Pa)	Average pressure drop (Pa)	Expected filter life
MERV 4	5.1	$2	22	125	73	3 months
MERV 7	5.1	$4	72	149	111	3 months
MERV 11	5.1	$7	95	187	141	4 months
MERV 13	5.1	$11	102	187	144	4 months
MERV 14	30.5	$50	127	249	188	12 months
MERV 15	30.5	$90	70	249	159	12 months
MERV 16	30.5	$125	65	249	157	12 months
HEPA	30.5	$150	249	498	374	12 months

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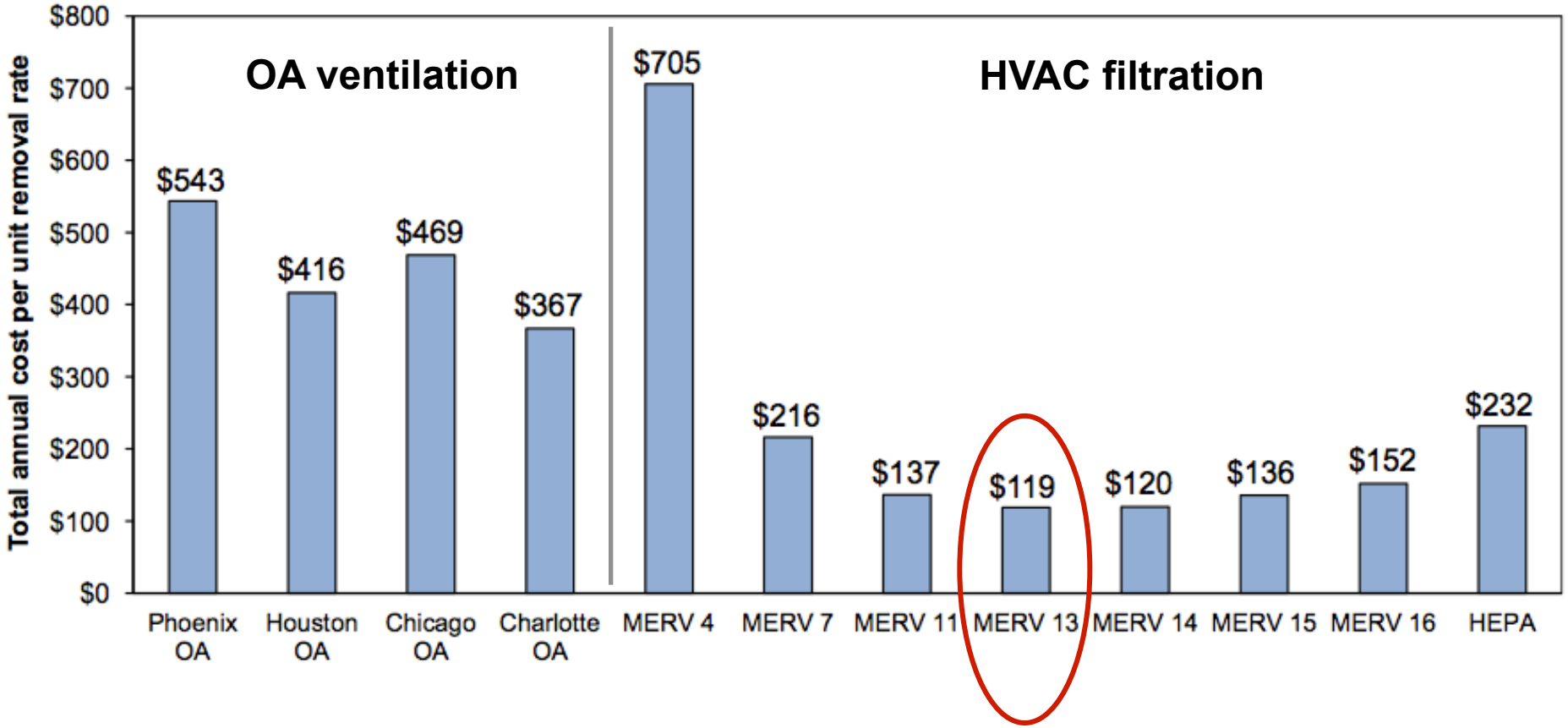
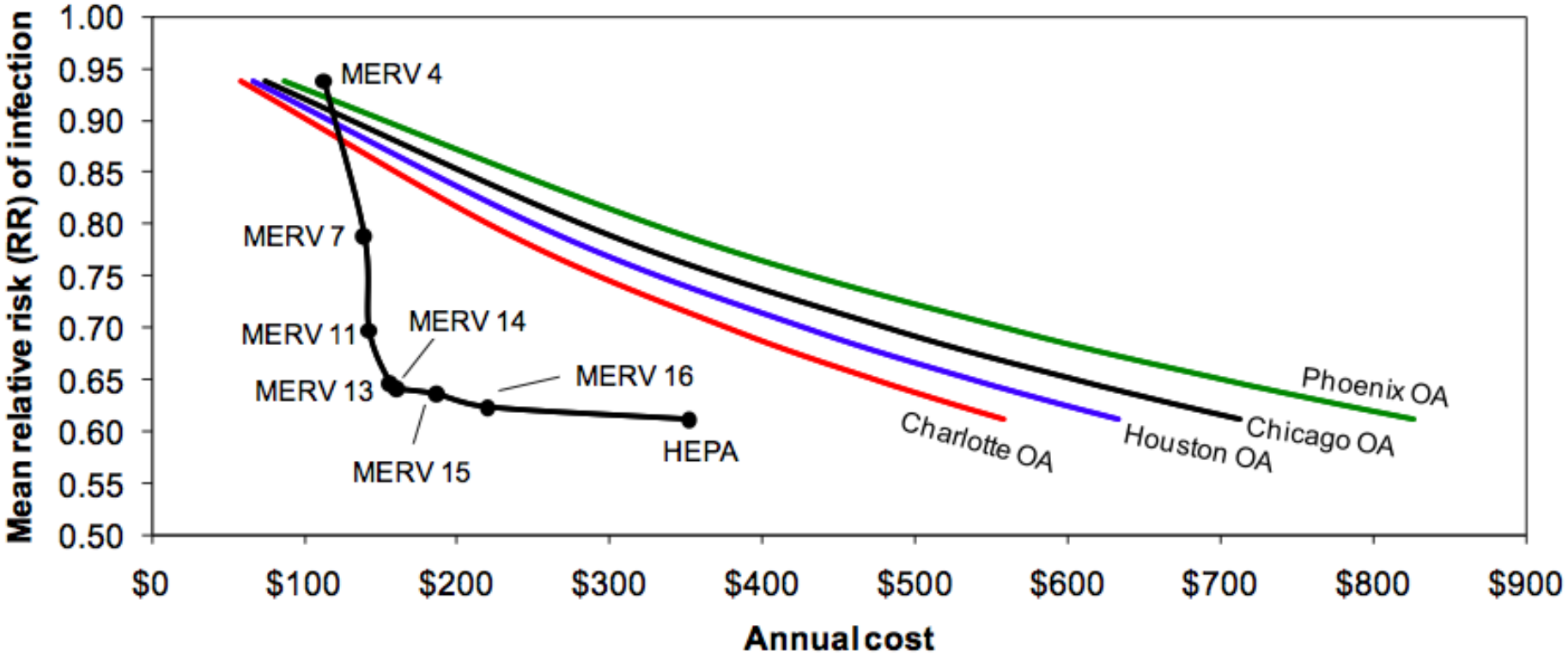
Estimated annual costs per unit removal rate ($ per 1/hr)



Azimi and Stephens **2013** *Building and Environment* 70:150-160

Relative risk vs. estimated annual cost: Filtration vs. OA



MERV 13-14 predicted to offer greatest risk reduction at lowest cost

Azimi and Stephens **2013** *Building and Environment* 70:150-160

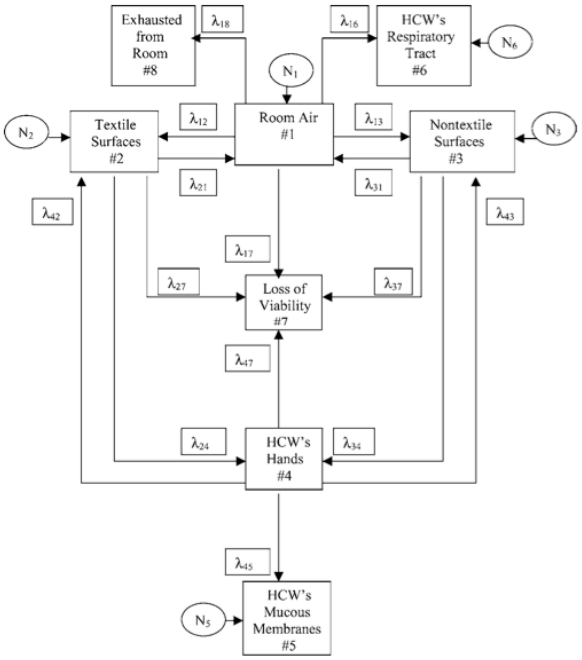
Methods of estimating infectious disease risks

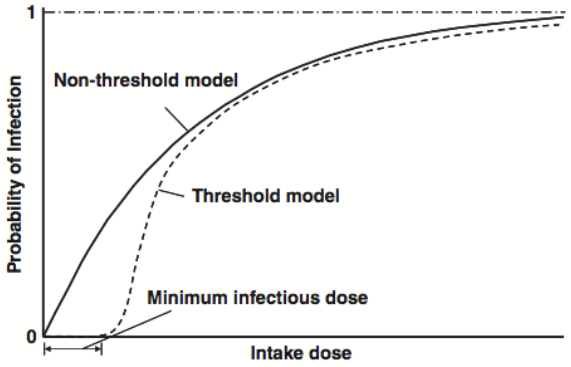
Wells-Riley model

$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

$P_{\text{infection}}$ = 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)

Markov chain combined with dose-response models





Parham Azimi, PhD Candidate ENVE