Filtration for the prevention of airborne infectious disease transmission

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Introduction and motivation

- Communicable respiratory illnesses have significant economic impacts in the U.S.
  - 43 common colds and 26 cases of influenza per 100 persons
  - 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
- Control of airborne infectious disease transmission
  - Studies suggest building characteristics, 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*

- Others: UVGI, facemasks, isolation … HVAC filtration?

Objectives

1. Explore modes of disease transmission

2. Infectious aerosols: Particle sizes and emissions
   - Including influenza viruses within size-fractioned indoor aerosols

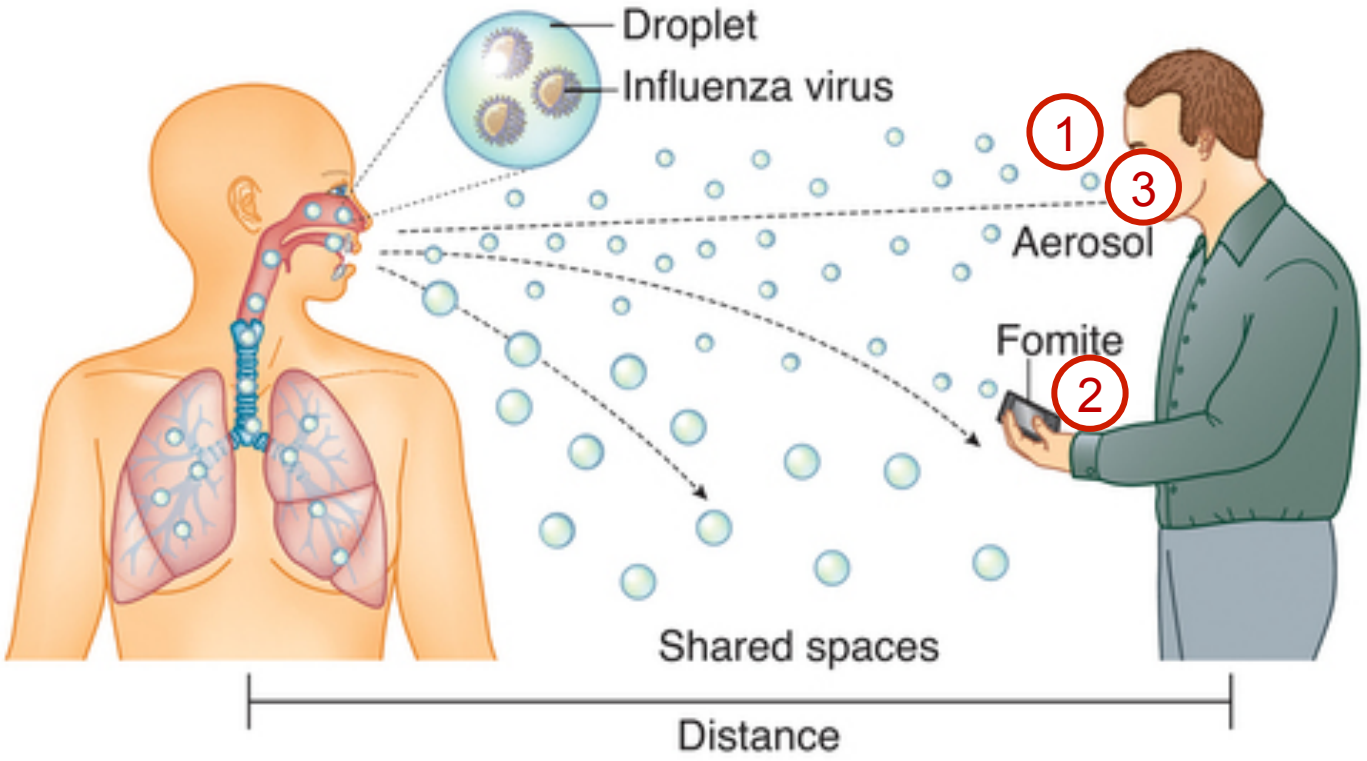
3. Methods of estimating disease risks
   - Linking HVAC filtration to a particular method: Wells-Riley model

4. Case studies
   - Influenza risks in a hypothetical office environment
   - Various levels of filtration (MERV)

5. Cost effectiveness of filtration vs. outdoor air ventilation

1. MODES OF INFECTIOUS DISEASE TRANSMISSION

Primary modes of disease transmission

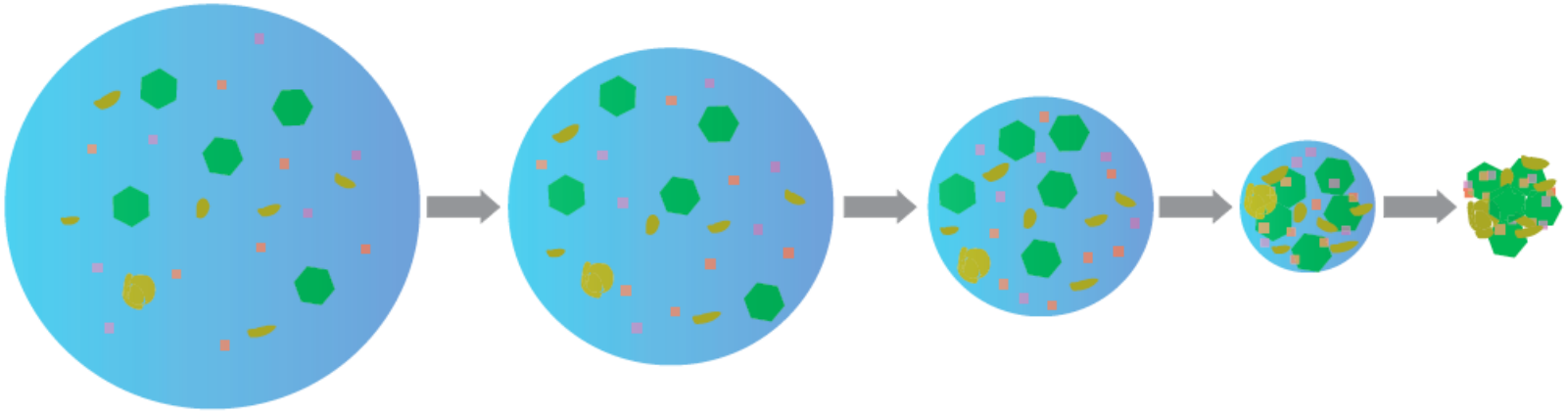


1. Direct contact with pathogen sources
2. Contact with contaminated object surfaces (“fomite”)
3. Inhalation of airborne infectious aerosols (often longer distances)

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

"Spreading": Expulsion of droplets

- When a person coughs, sneezes, speaks or 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, *Mythbusters*

Droplet evaporation is nearly instantaneous

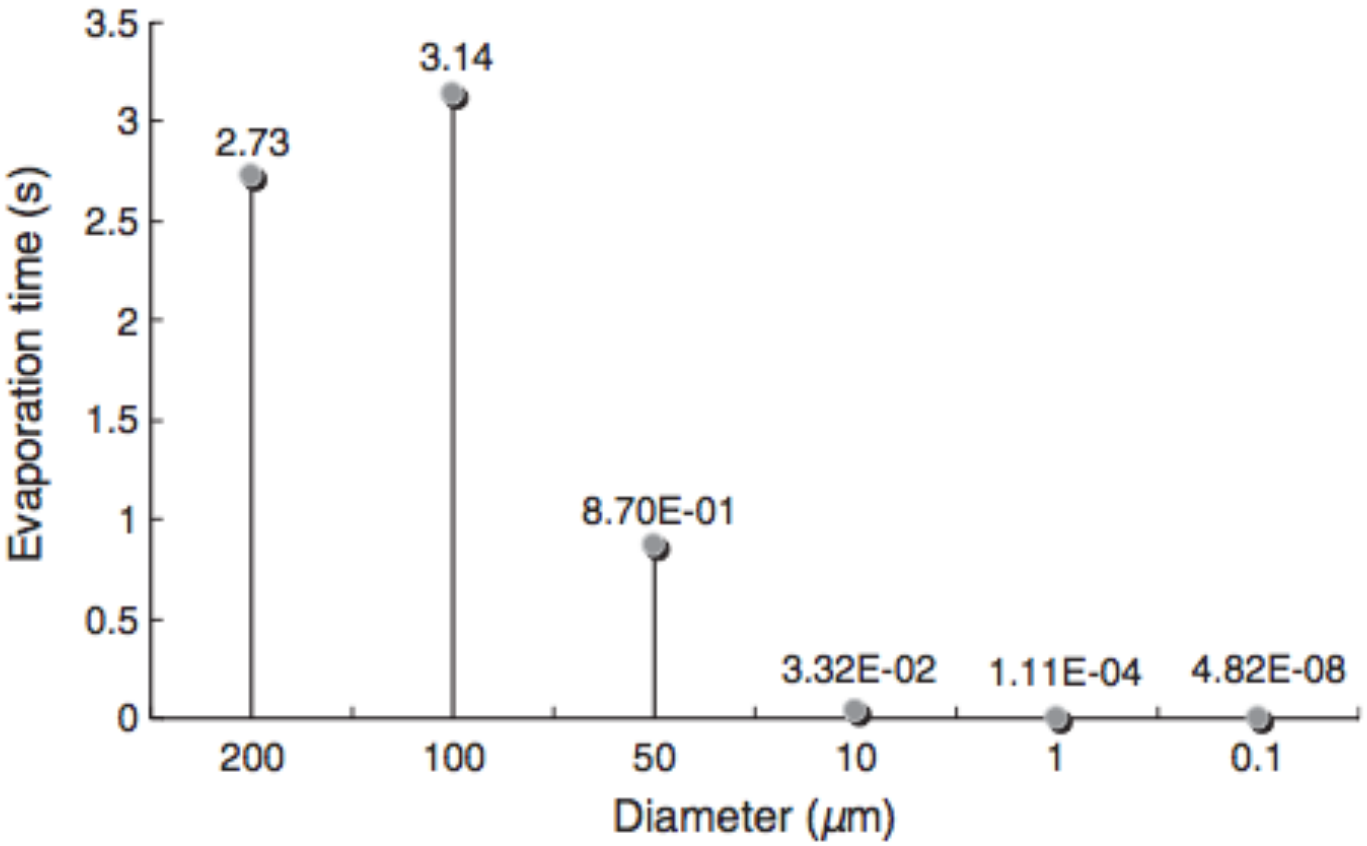


Fig. 5 The evaporation time of droplets with different diameters

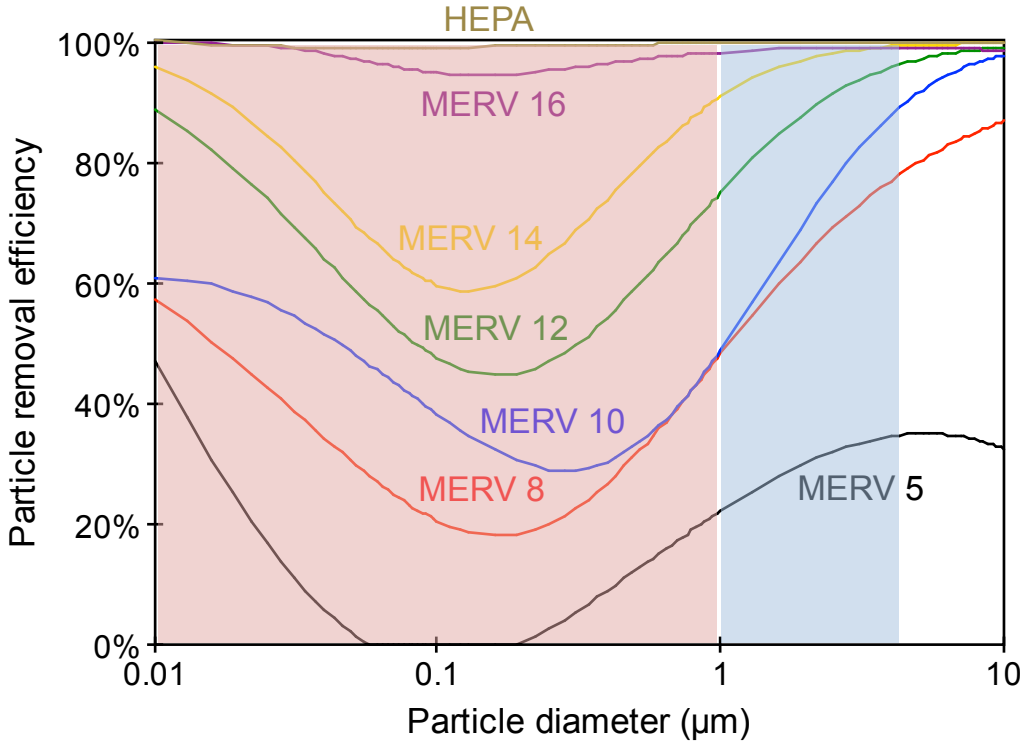
Chen and Zhao 2010 *Indoor Air* 20:95-111

2. INFECTIOUS AEROSOLS

Size distributions and infectious organism content

What particle sizes are actually emitted by humans?

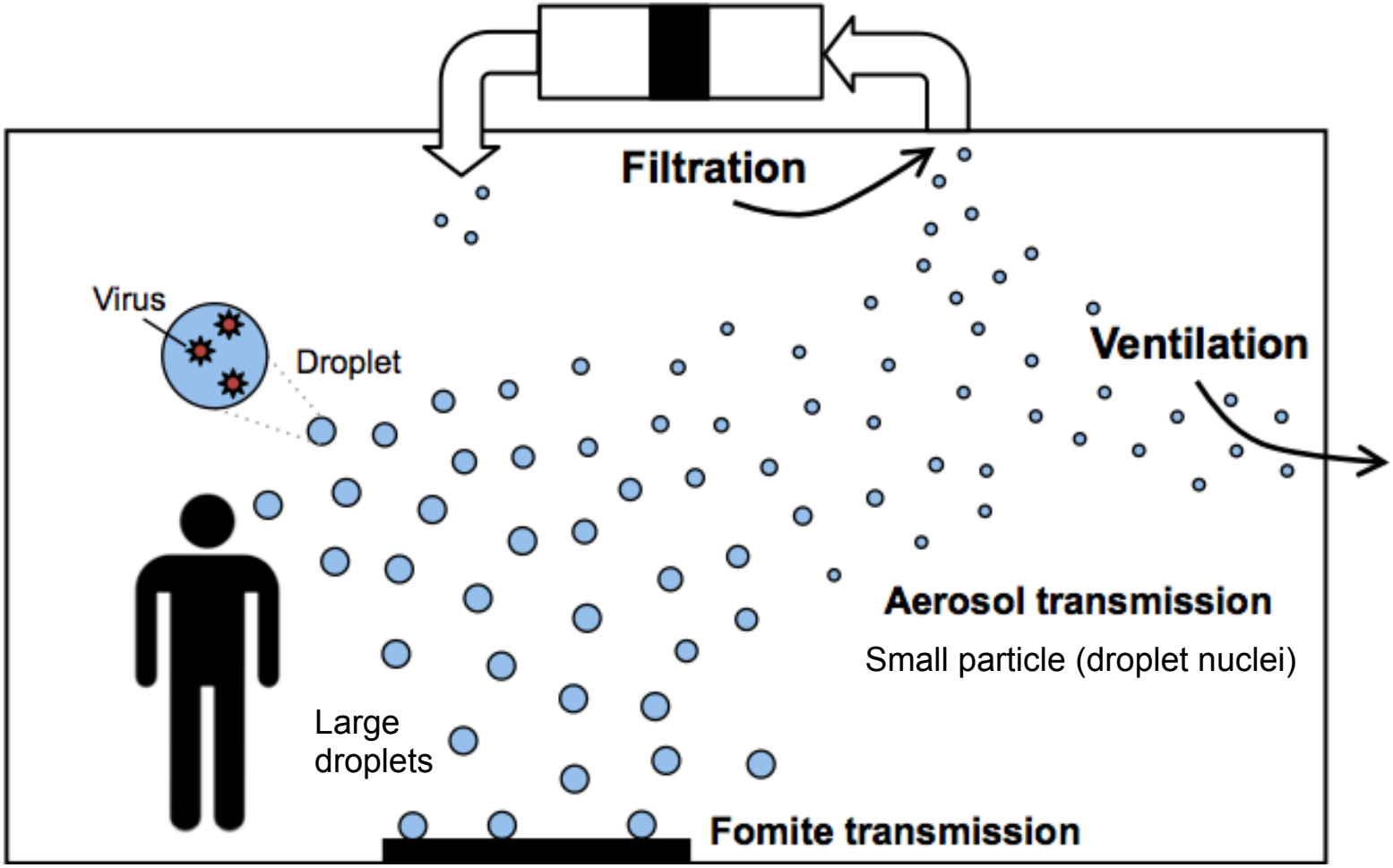
- When considering particle filtration of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols



- 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

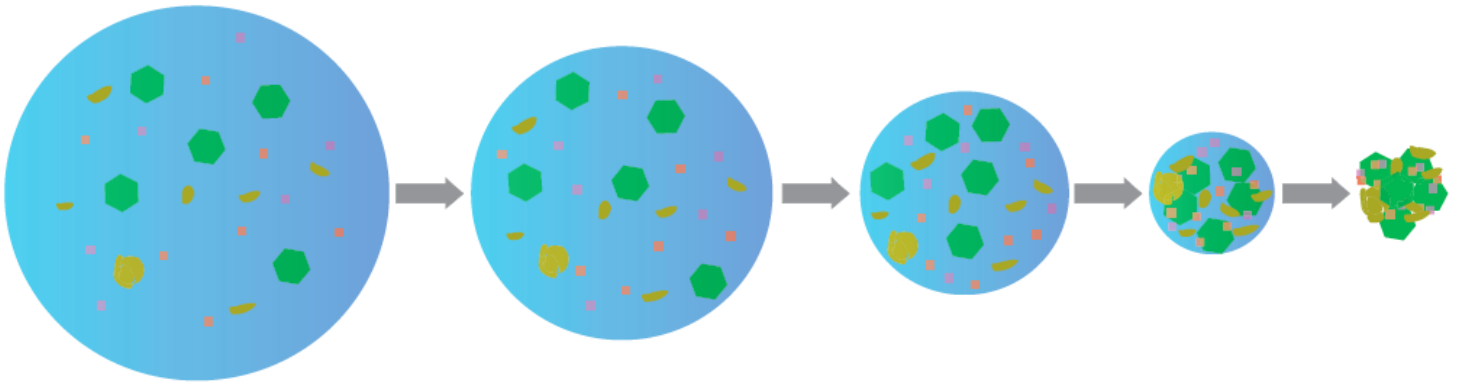
Papineni and Rosenthal 1997 *J Aerosol Medicine* 10:105-116; Yang et al., 2007 *J Aerosol Med* 20:484-494; Lindsley et al., 2012 *J Occup Environ Hygiene* 9:443-449; Fabian et al., 2008 *PLoS ONE* 3:e2691

Particle size is important for distribution and removal



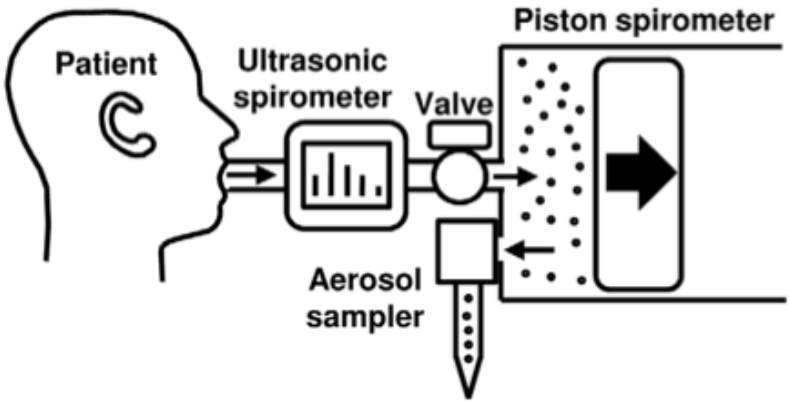
What about infectious organisms within particles?

- 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?



- Several recent studies have measured influenza virus content in size-fractioned indoor aerosols…

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

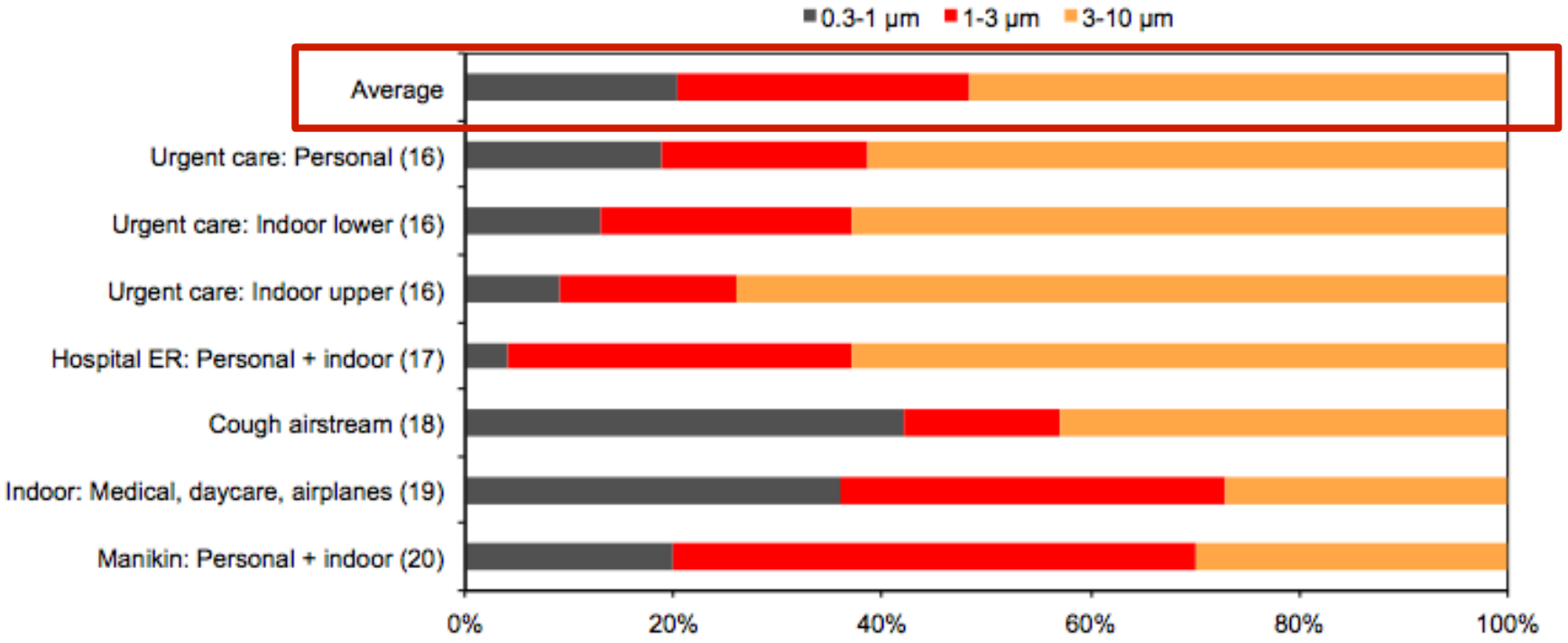
- Only ~40% of viral RNA is contained in that fraction

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

Size-resolved influenza virus indoors: Summary

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

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



Average influenza 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

3. ESTIMATING RISKS

And linking to HVAC filtration

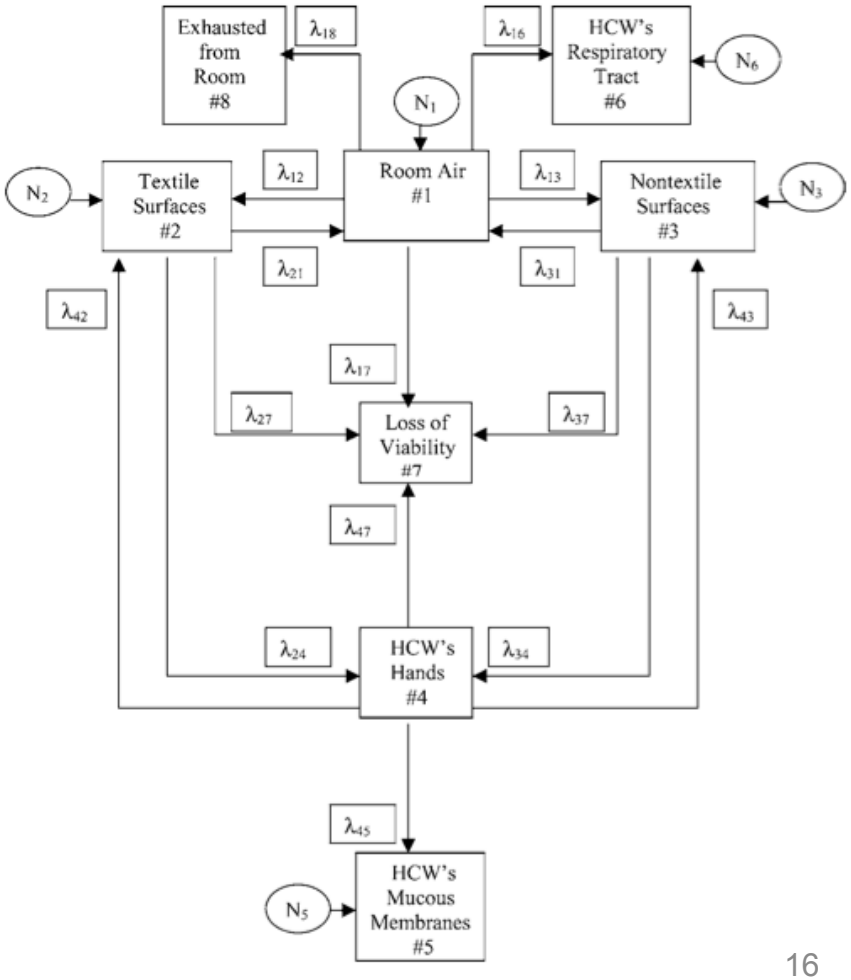
Methods of estimating infectious disease risks

Wells-Riley model

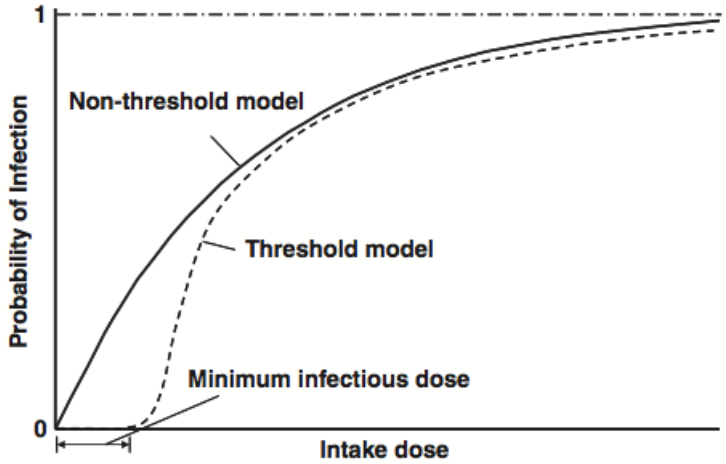
$$P_{\text{infection}} = \frac{cases}{susceptiles} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

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

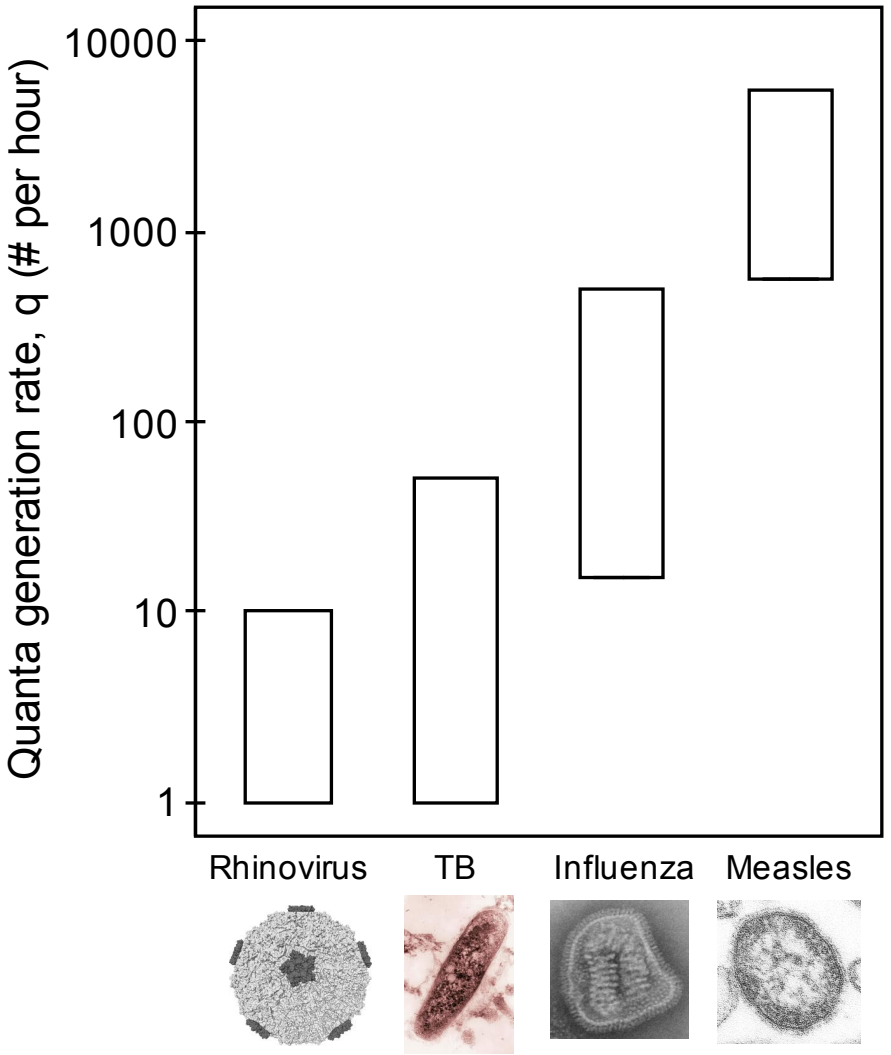


Dose-response models



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)

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

MERV and infectious aerosols

- Using previous data on influenza virus in size-resolved particle samples taken in real indoor environments, we assume the following infectious particle size distribution:
  - 20% exist in the 0.3-1 μm range
  - 29% exist in the 1-3 μm range
  - 51% exist in the 3-10 μm range

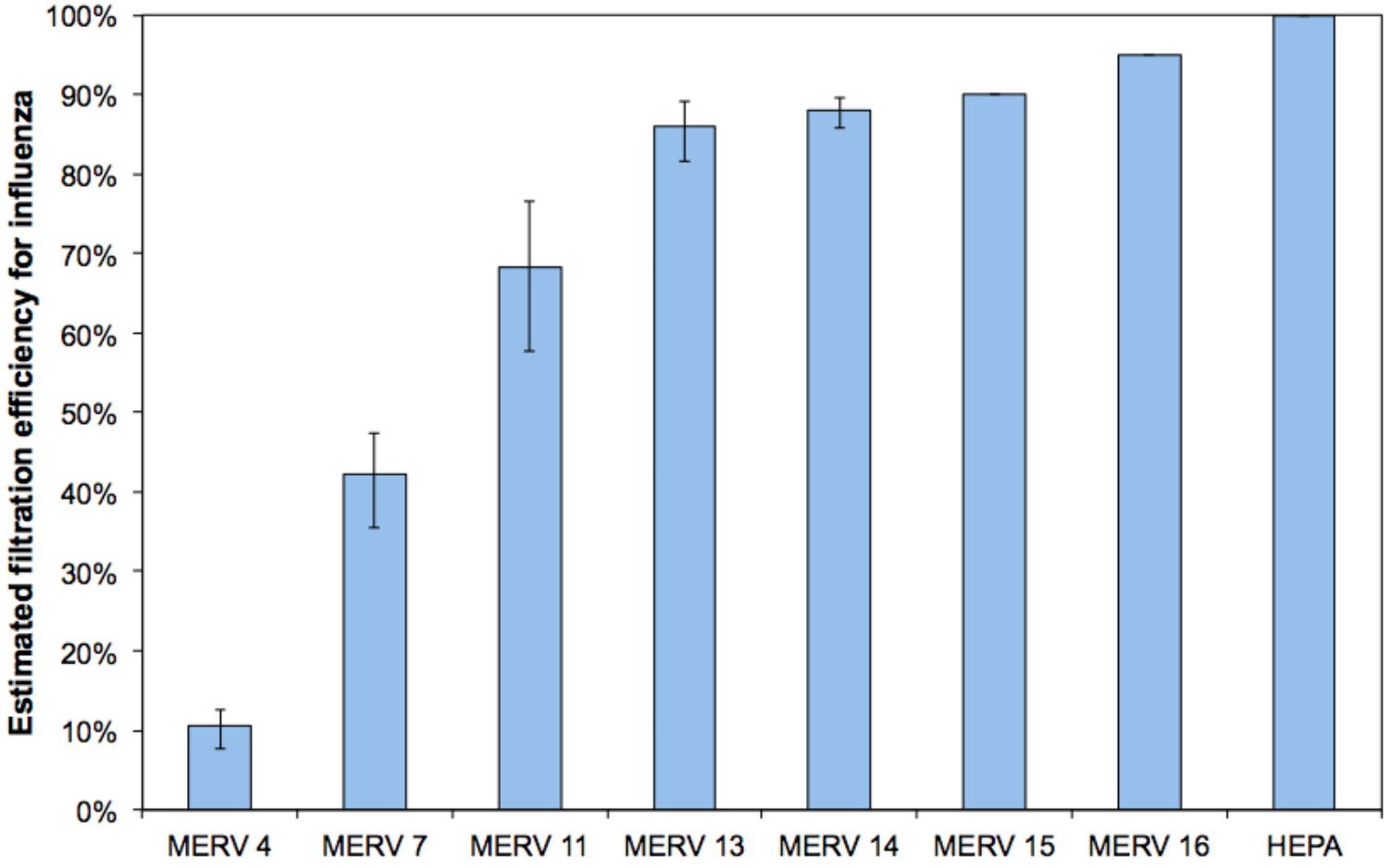
- Provides a reasonable estimate
  - Can also explore sensitivity

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+
Assume:	**~20%**	**~29%**	**~51%**

MERV and infectious aerosols: Removal efficiency

- Assuming that infectious size distribution, we can estimate the size-weighted average removal efficiency of a range of filters for infectious aerosols:



4. CASE STUDIES

Estimating risks with various level of MERV filtration

Case study: Influenza in an office environment

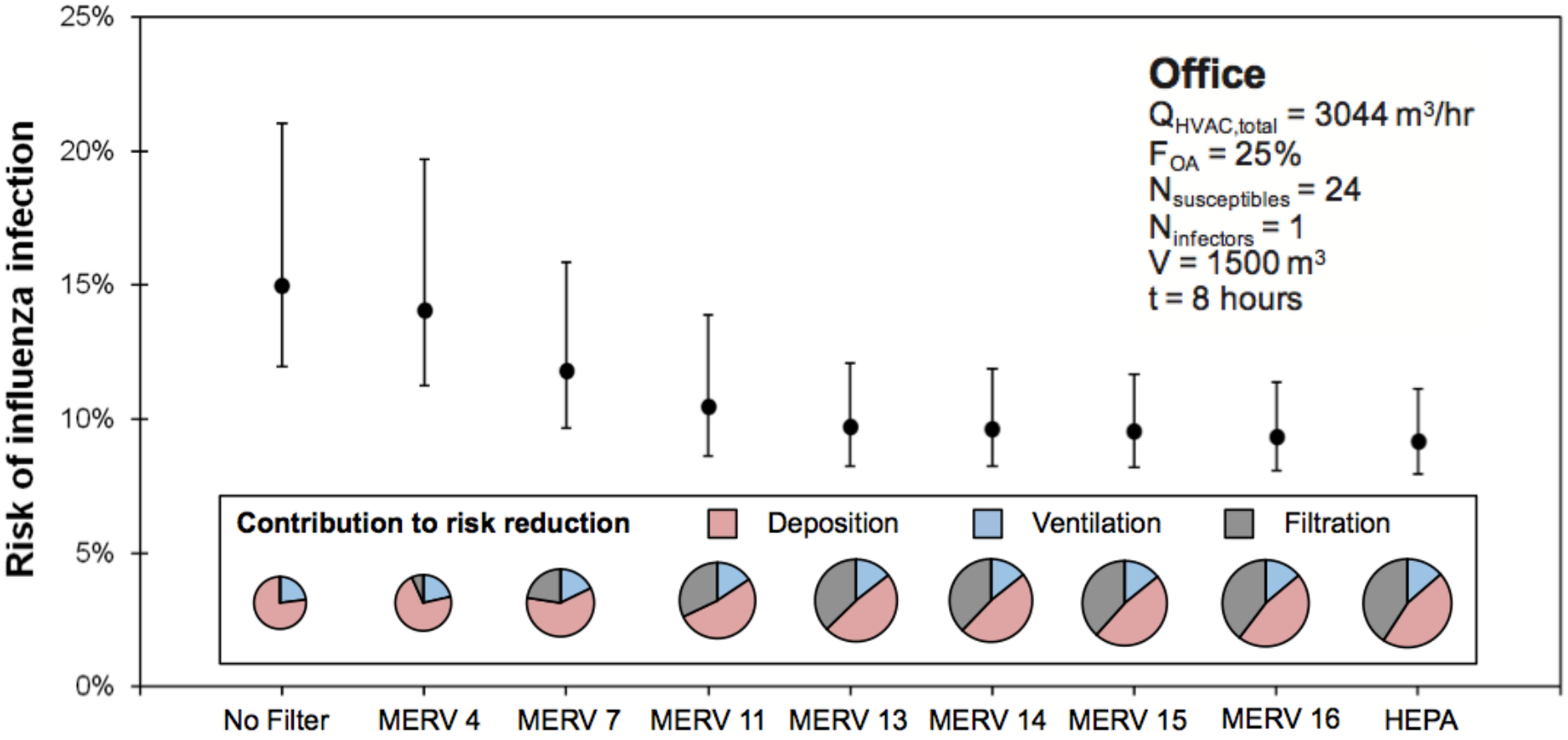
- Because the Wells-Riley model utilizes building volume, we must rely on case studies to explore possible impacts of filtration
  - Cannot generalize entirely because filtration effectiveness is a function of not only removal efficiency but recirculation rates through HVAC filters (flow vs. volume)

- We chose a hypothetical office environments with 1 infector:
  - 500 m^2
  - 25 adult occupants
  - ASHRAE 62.1 minimum ventilation rates
  - 25% OA
  - 8 hours of occupancy

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

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

Estimated risk of infection with HVAC filtration: Office

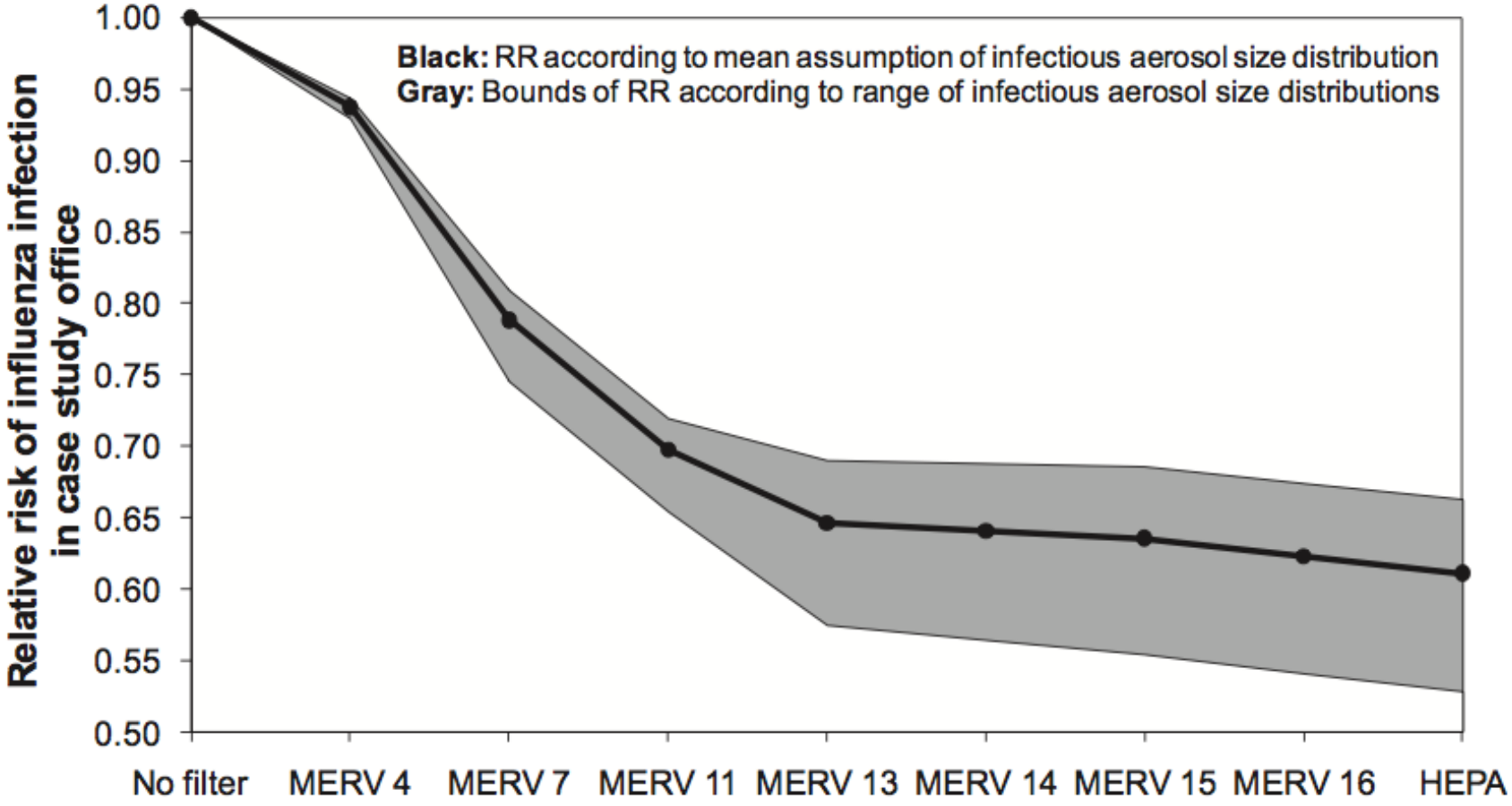


From no filter to MERV 13 or greater:
From 4 out of 24 occupants infected w/ flu to 2 out of 24

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

Generalizing results

- Using relative risks across all estimates of influenza aerosol size distributions and all HVAC filters allows us to identify trends and generalize results



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

5. COST COMPARISONS

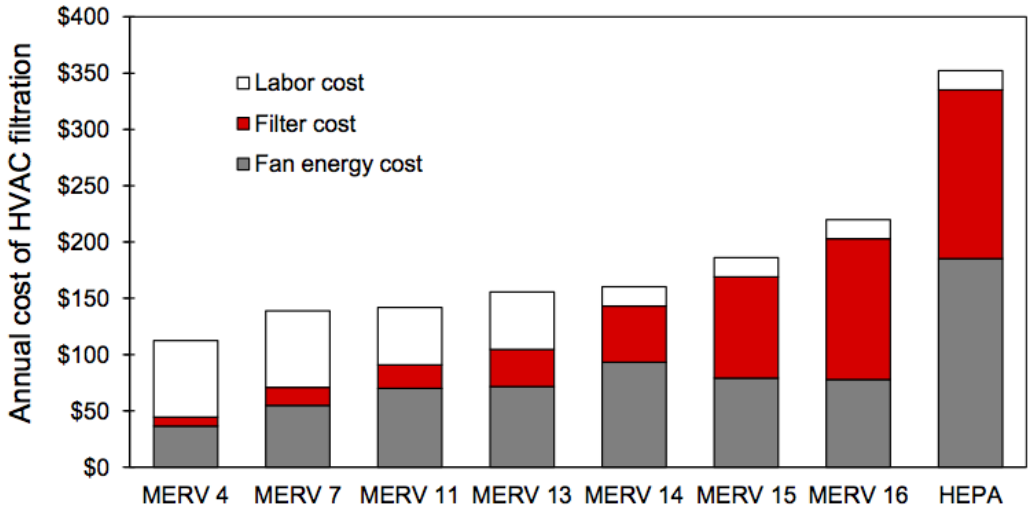
Filtration vs. outdoor air

Estimating outdoor air costs

- 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)



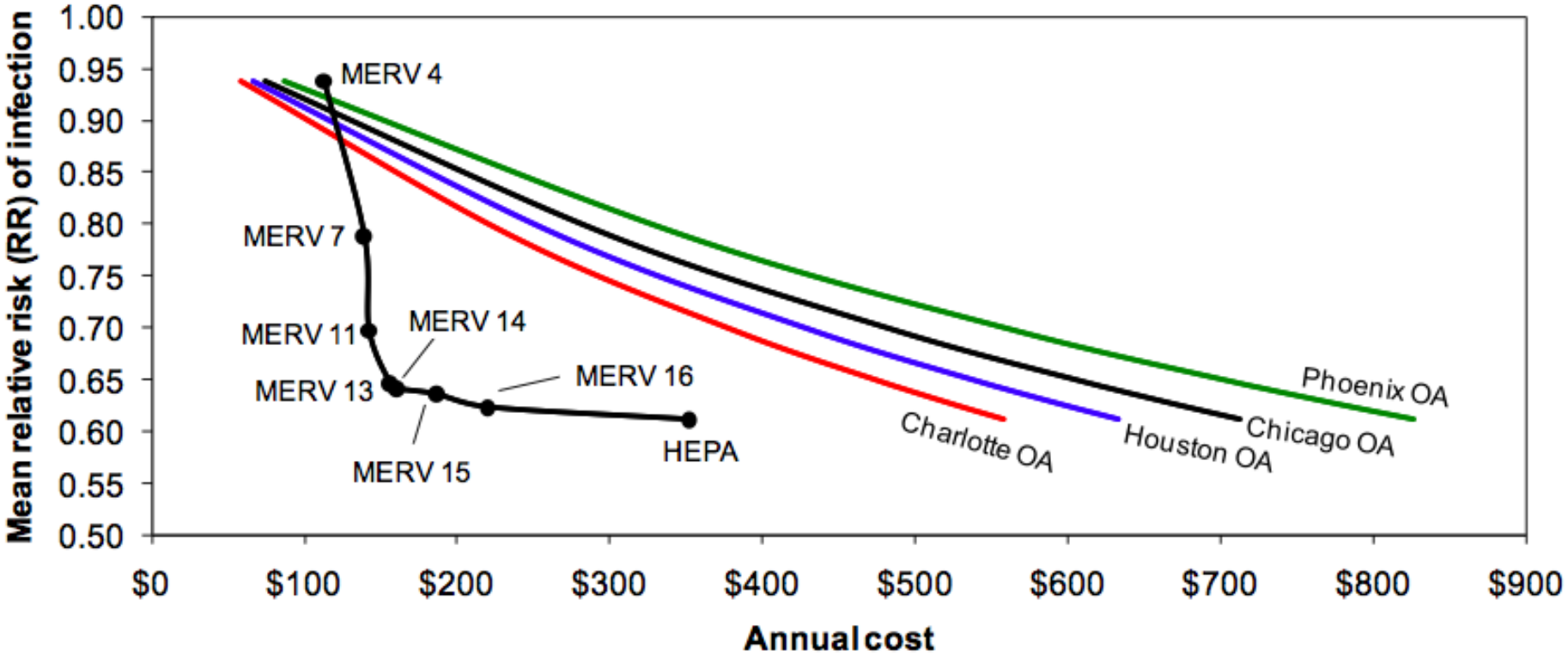
$$W_{\text{filtration}} = \frac{Q_{\text{recirculated}} \Delta P_{\text{avg}}}{\eta_{\text{fan}} \eta_{\text{motor}}}$$

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

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

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

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

6. LIMITATIONS AND FUTURE WORK

Important limitations and future research needs

- Need to identify the relative importance of large droplet vs. small droplet nuclei transmission for overall transmission of a range of infectious diseases

- Need to compare Wells-Riley model to other modeling methods (e.g., Markov chain and dose-response methods)
  - *PhD student Parham Azimi currently working on this*

- Need validation with real data
  - Observational studies of offices with various HVAC filters
  - More measurements of infectious aerosol size distributions

  - *Will be working with a Sloan Foundation post-doctoral fellow Stephanie Kunkel next year to experimentally validate this model*

Acknowledgements

- This work was supported by the NAFA Foundation
- Thanks to:
  - The NAFA Foundation Board
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  - Parham Azimi, Ph.D. candidate in environmental engineering, IIT

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