Risk-Based Selection of Respirators against Airborne Pathogens

Mark Nicas, PhD, CIH
School of Public Health
University of California, Berkeley
Some Pathogens Transmitted Person-to-Person via Air

- Mycobacterium tuberculosis
- Yersinia pestis (pneumonic plague)
- SARS corona virus
- Variola virus (smallpox)
- Influenza A virus
Routes of Exposure

(1) Inhalation of respirable (< 10 µm) and inspirable (10 to 100 µm) particles
(2) Droplet spray
(3) Surface-to-hand-to-eyes/lips/nose

For some pathogens (influenza A virus), all three routes apply. The following figure is from Ref. 1.
Influenza A Virus

• Human tests with influenza A strains show the infectious dose via inhaling virus on small particles is several hundred fold lower than via nasally instilling virus. (Ref 2)

• The outcome of a natural experiment involving a grounded airplane is most consistent with inhalation transmission. (Ref 3)

• Upper room-air UV irradiation has been effective in reducing transmission. (Ref 4)
Routes of Exposure

- Infection control practitioners usually assume that droplet spray and hand contact are the most important routes.

- In its planning document for avian flu, the CDC assumes that droplet spray and hand contact are predominant, despite admitting no knowledge of the relative importance of the three exposure routes.
Droplet Spray Exposure

• Droplet spray exposure requires “close contact” (e.g., within 3 feet of the case).

• But close contact maximizes inhalation exposure, and permits inhalation of inspirable as well as respirable particles.

• Ergo, droplet spray exposure does not occur without inhalation exposure.
Surgical Masks for Avian Flu

• The CDC recommends wearing a surgical mask as a “droplet precaution” when in close contact with an avian flu patient.

• Because inhalation exposure also occurs with close contact, the CDC recommends de facto that a surgical mask be worn for inhalation protection.
N95 FF Respirators for Avian Flu

• The CDC recommends a N95 filtering-facepiece “during procedures that may generate increased small-particle aerosols.”

• The CDC ignores inhalation exposure to large particles (10 to 100 µm).

• More importantly, the CDC fails to consider exposure intensity, exposure duration, infectivity, face seal leakage and, ergo, risk.
Points Worth Considering

• An influenza virus that causes a pandemic likely has high infectivity.

• Given high infectivity, a low virus concentration in air can impart a high risk of infection via inhalation.

• Because N95 FFRs permit about 10% leakage of contaminated air around the faceseal, residual infection risk may be substantial.
The One-Hit Infection Risk Model

- Each pathogen received has a probability denoted $\alpha$ of infecting the host.
- The expected inhaled (and deposited) dose is denoted $\mu_D$.
- Infection Risk $= 1 - \exp(-\alpha \times \mu_D)$
Example - Smallpox

• The smallpox virus adheres to the one-hit model with $\alpha \approx 0.1$. (Ref 5)

• The CDC recommends that health care workers attending smallpox patients (in the event of bioterrorism) use N95 FFRs.
The Expected Inhaled Dose

The expected deposited dose in the lungs:

\[ \mu_D = C_A \times B \times T \times f \]

- \( C_A \): concentration in air (# per m^3)
- \( B \): breathing rate (m^3 per hour)
- \( T \): exposure duration (hour)
- \( f \): fraction deposited
Hypothetical Example - Smallpox

Let $C_A = 1 \text{ m}^{-3}$, $B = 1 \text{ m}^3 \text{ hr}^{-1}$, $T = 5 \text{ hr}$

Consider 10-$\mu$m particles such that $f = 0.9$

$$\mu_D = (1 \text{ m}^{-3})(1 \text{ m}^3 \text{ hr}^{-1})(5 \text{ hr})(0.9) = 4.5$$

$$\text{Risk} = 1 - \exp(-0.1 \times 4.5) = 0.36$$
Respirators and Infection Risk

• A respirator permits some penetration $P$, primarily due to faceseal leakage: $(\text{Ref 6})$

$$\text{Risk} = 1 - \exp(-\alpha \times P \times \mu_D)$$

• A respirator reduces the expected dose and thereby reduces infection risk.
Hypothetical Example - Smallpox

• For a N95 FFR, the assumed value of P is 0.1 (10% leakage):

\[ \text{Risk} = 1 - \exp(-0.1 \times 0.1 \times 4.5) = 0.044 \]

• Is 4.4% an acceptable infection risk for smallpox? Public health agencies such as the CDC, OSHA, and NIOSH avoid addressing this issue.
Is There a Better Respirator Available?

• Yes. A hooded powered air-purifying respirator with a high efficiency filter.

• Tests of high-quality hooded PAPRs used in the pharmaceutical industry show that a typical $P = .001$ or less.\(^{(Ref 7)}\)

• Federal OSHA has designated $APF = 1000$ for certain hooded PAPRs.\(^{(Ref 8)}\)
Hypothetical Example - Smallpox

• For a hooded PAPR, assume $P = .001$:

$$\text{Risk} = 1 - \exp(-0.1 \times 0.001 \times 4.5) = .00045$$

• Is $.045\%$ an acceptable infection risk for smallpox? Maybe not, but it’s about 100-fold lower than $4.4\%$. 
Risk-Based Approach

The greatest sources of uncertainty in estimating infection risk are:

• the infectious dose model and its parameters

• the pathogen emission rate into air
Alternative Infectious Dose Models

- **One-Hit:** Each microbe has success probability $\alpha$ of causing infection.
  \[
  \text{Risk} = 1 - \exp(-\alpha \times \mu_D)
  \]

- **Threshold:** A person must receive $X$ number of microbes to be infected:
  \[
  \text{Risk} = \text{Probability}(\text{Dose} \geq X)
  \]
The Emission Rate

The **respirable** pathogen emission rate $E$ is the product of:

- cough rate $W$ (# per hr)
- respirable volume per cough $V_F$ (mL)
- concentration in resp. fluid $C_F$ (# per mL)

$$E (# \text{ per hr}) = W \times V_F \times C_F$$
Superspreaders and Dangerous Disseminators

These highly infectious source cases likely have high values for cough frequency, pathogen concentration in respiratory fluid, and aerosol volume per cough.
The Cough Rate W

Among 48 pneumonia patients: (Ref 9)

- 60% coughed > 12 times per hr
- 29% coughed > 24 times per hr
- 2% coughed > 48 times per hr
In a single cough, the initial volume in particles that have final diameters less than 10 µm is: \( V_F = 6 \times 10^{-8} \text{ mL} \)
Influenza A Titres in Nasal Fluid

- For 7 subjects who received H\textsubscript{3}N\textsubscript{2} virus via nasal inoculation, virus concentrations in nasal washings were assayed. Peak levels occurred two days later.\(^{(\text{Ref 11})}\)

- Range: \(1 \times 10^2\) to \(2 \times 10^7\) TCID\textsubscript{50} units per mL

- Geom. Mean: \(1 \times 10^5\) TCID\textsubscript{50} units per mL
Hypothetical Example – Avian Flu

- Assume high cough rate $W = 30 \text{ hr}^{-1}$
- Assume productive cough $V_F = 3.0 \times 10^{-7} \text{ mL}$
- Assume high pathogen $C_F = 5.0 \times 10^7 \text{ mL}^{-1}$

$$E = 450 \text{ respirable virus per hr}$$
$$= (30 \text{ hr}^{-1}) \times (3.0 \times 10^{-7} \text{ mL}) \times (5.0 \times 10^7 \text{ mL}^{-1})$$
Hypothetical Example – Avian Flu

• Consider a 50 m³ room receiving six ACH such that Q = 300 m³ per hour.

\[ C_{\text{room}} = \frac{450 \text{ hr}^{-1}}{300 \text{ m}^3 \text{ hr}^{-1}} = 1.5 \text{ m}^{-3} \]

• Near field exposure will be 2-fold greater.

• Strictly, we should consider virus loss due to particle settling and inactivation.
Hypothetical Example – Avian Flu

• Assume $f = 0.9$ and $T = 5$ hr:

$$\mu_D = 6.75 \text{ virus}$$

$$(1.5 \text{ m}^{-3}) \times (1 \text{ m}^3 \text{ hr}^{-1}) \times (5 \text{ hr}) \times (0.9)$$

• Assume $\alpha = 0.1$ (like smallpox):

$$\text{Risk} = 1 - \exp(-0.1 \times 6.75) = 0.5$$
What do we assume when $\alpha$ and $\mu_D$ are unknown?

- In my opinion, assume $\alpha = 1$, and assume $\mu_D = 1$ if there is no respirator use.

- Given these assumptions, the risk of infection without respirator use is 63%.

- For this risk level, use a hooded PAPR.
Why are PAPRs not recommended?

• The health care industry objects to the expense of using PAPRs.

• Other reasons cited are interference with communication, greater risk of sharps injuries, and scaring the patient.

• Risk calculations are avoided, and an “expert opinion” approach is used.
The Expert Opinion Approach

In general, the assumptions used and the decision logic are poorly documented, and acceptable risk is not specified.

“They took a calculated risk but forgot to do the calculation.”
The Interplay of Risk Analysis and Expert Opinion

- Given uncertainty in exposure intensity and infectivity, professional judgment (i.e., expert opinion) would always be involved in selecting a respirator.

- At a minimum, a risk analysis informs decision-making, makes the selection process transparent, and specifies the acceptable risk value.
References


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References

