Predicting SARS-CoV-2 transmission probabilities through expiratory aerosol modeling

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Abstract

Efforts to halt the COVID-19 pandemic are divided between understanding its transmission and producing an effective vaccine. The former pursuit has largely been viewed as a set of temporary measures to maximize while waiting for the vaccine 'silver bullet' solution. This perspective has detrimental public health consequences, since the vaccine will be less effective the more severe the pandemic is during implementation. Minimizing airborne transmission of the SARS-CoV-2 virus through studying expiratory aerosol behavior thus remains imperative. Utilizing the aerosol expertise and quadrature-based modeling methods already well-developed within the Environmental & Climate Sciences Department at Brookhaven National Laboratory, combined with continued development of jet plume and evaporative process modeling, we predict the risk of infection based on the length and proximity of encounters between infected and susceptible individuals. We further estimate the risk reductions of different mitigation strategies to inform the behaviors essential to reducing the severity of the COVID-19 pandemic.

Introduction

- Human expirations create aerosols (<5 μm) & droplets (>5 μm) which may carry viral RNA that can spread viruses like SARS-CoV-2
- Particulate creation, behavior, and deposition is variable and size dependent
- Environmental conditions and mask wearing alter particle behavior and thus infection risk

Hypothesis

- Airborne transmission is an important component of coronavirus spread
- Mask wearing, social distancing, ventilation each reduce the risk of initial infection
- Accurate modeling of particulate behavior will provide the best possible estimates of the probability of infection

Methods

- Literature review of expiratory distributions, mask efficacy, particulate behavior, respiratory deposition, particle evaporation, viral loading, and infection
- Reproduce and compare models of particle evaporation; model P(infection) based on viral load
- Add these small modeling efforts to the overall framework to predict overall probability of infection

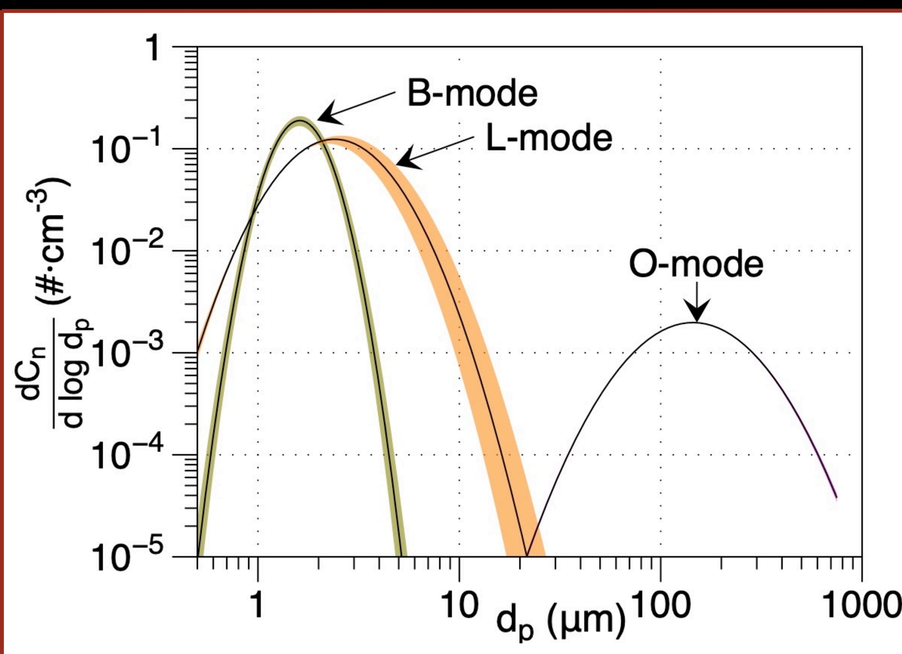


Fig 1. Trimodal expired aerosol distribution showing the concentration of each particle size produced through each mechanism (Johnson et al. 2011)

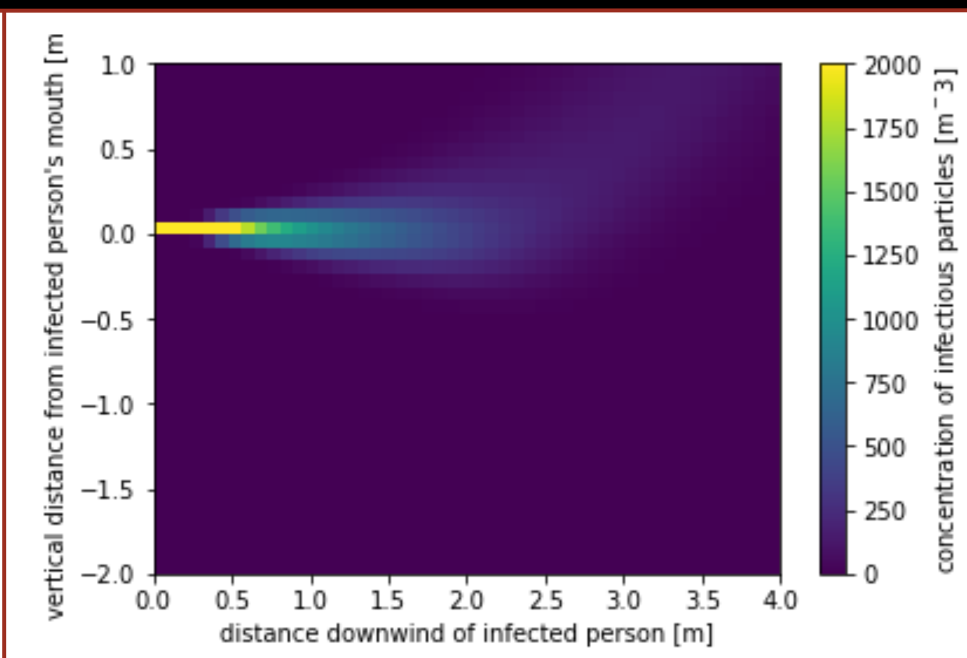


Fig 2. Example of an output from our jet plume model during speech by an infectious individual; shows the concentration of infectious particles after 2 seconds (inspired by Wei 2015)

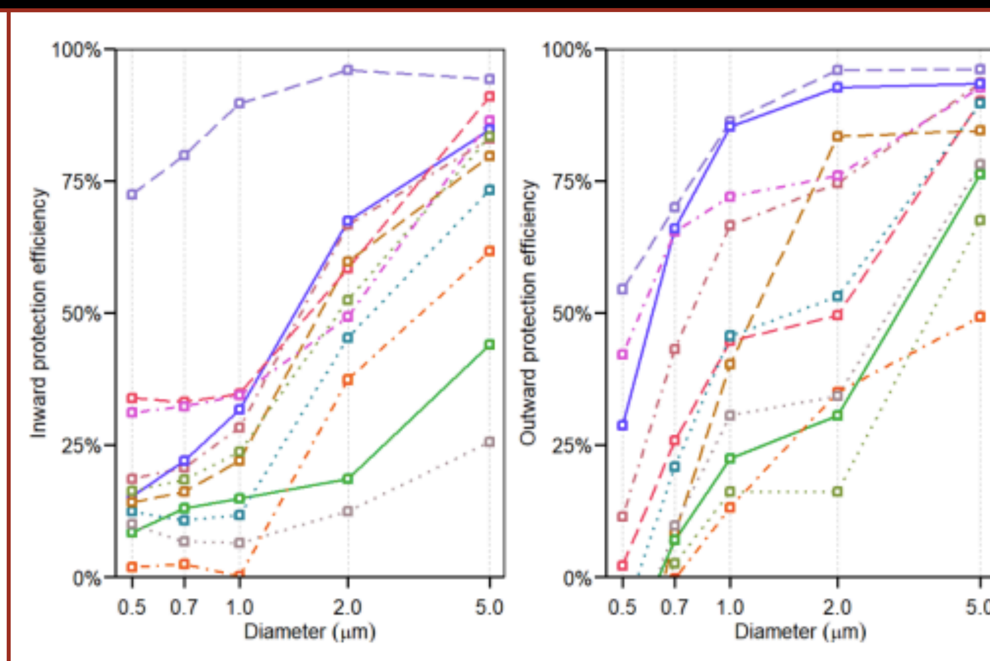


Fig 3. Comparison of inhalation and exhalation efficiencies at each particle size for different mask types; we focused on surgical masks, the pink line (Pan et al. 2020)

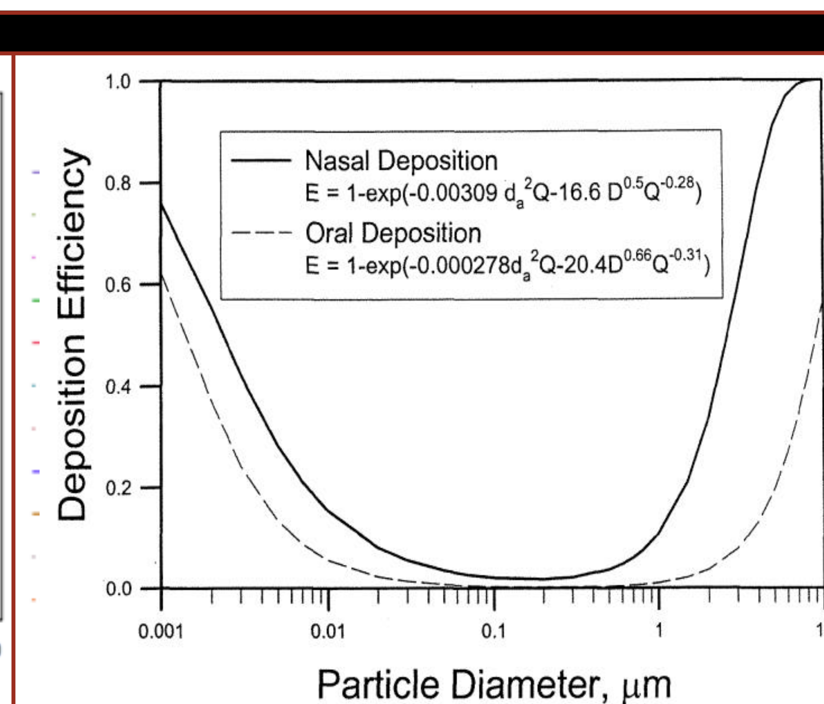
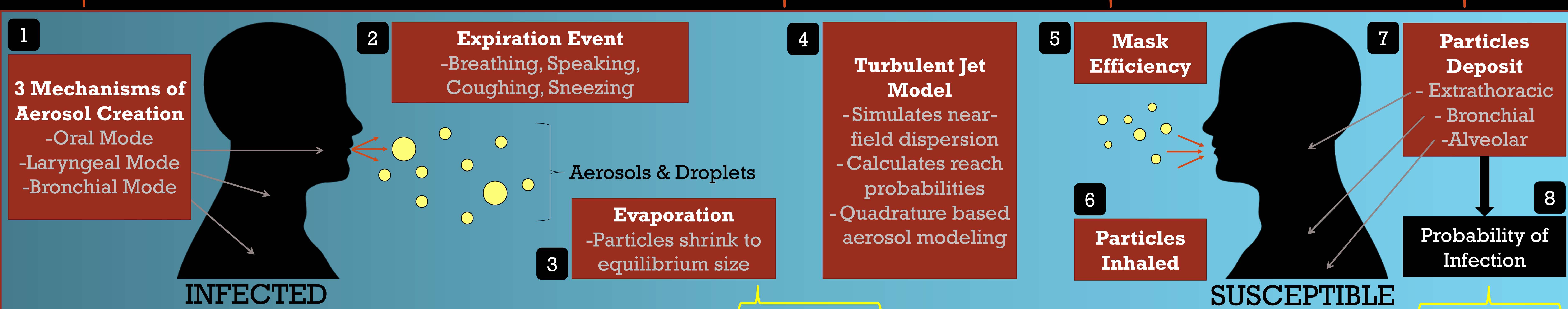
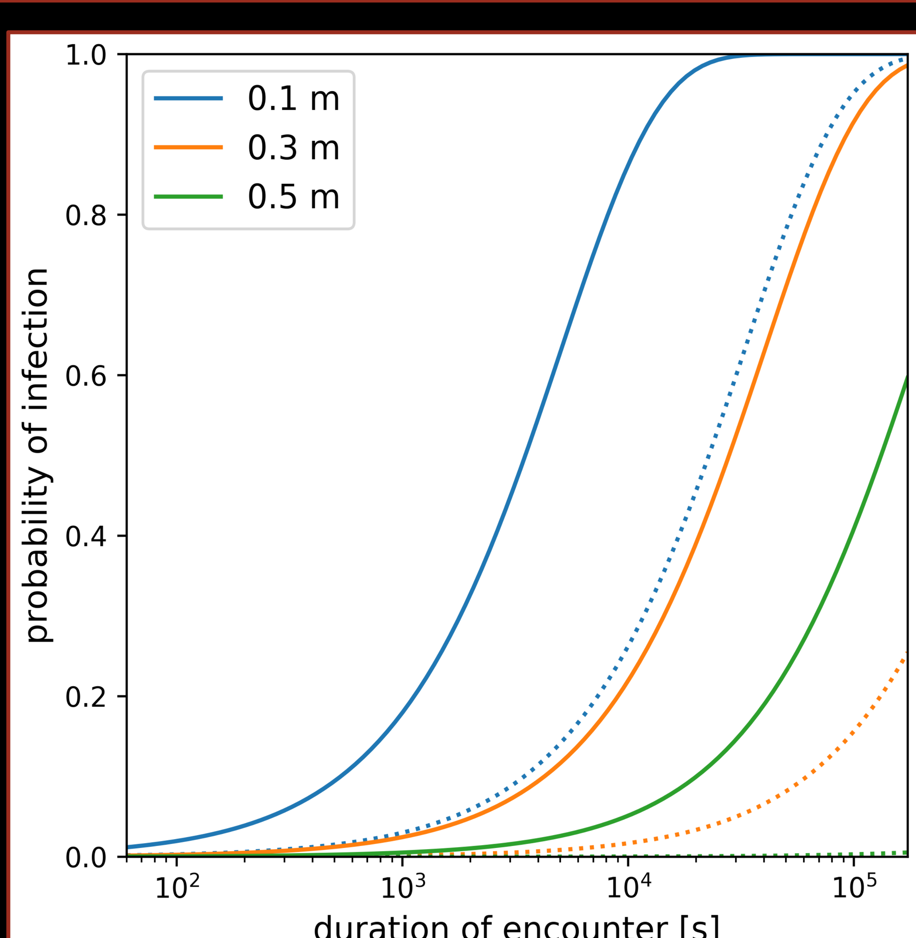


Fig 4. Extrathoracic particle deposition by size (Cheng 2003), relevant due to indications that the nasal epithelium is likely the initial infection site





Results

The final model predicts the probability of infection in a given scenario, either with a specific set of assumptions or over the probability space spanned by our assumptions. Its best use is predicting the difference in risk between different scenarios.

Fig 9. Example code output: the probability of infection given the duration of an encounter for one set of parameter assumptions. The different colors represent different distances between the infectious and the susceptible individual; the solid lines represent an unmasked situation, while the dotted lines represent a situation where both individuals wear a well-fitted surgical mask.

Focus area:

3. Particle Evaporation

Particles are expired at a certain size, but to accurately model their motion, we need their equilibrium size (after evaporation) and how quickly they come to that equilibrium.

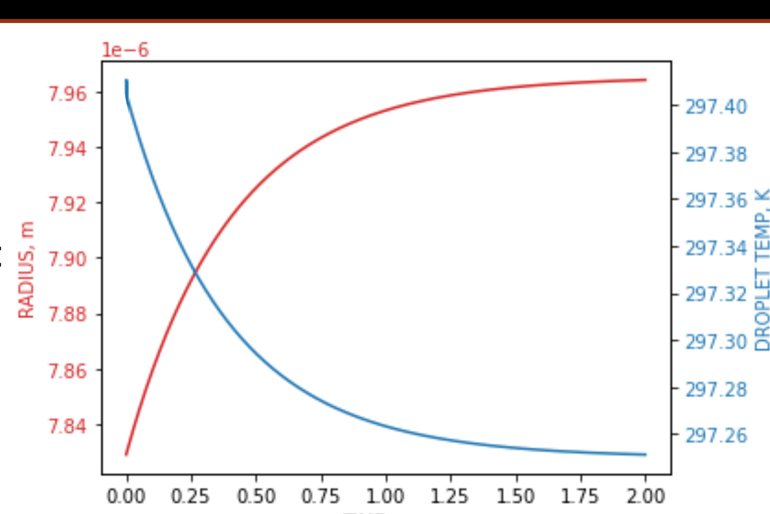
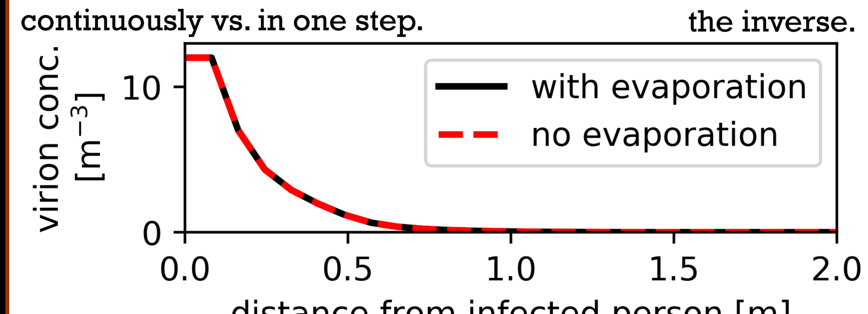


Fig 5. Reproduced results of mass and heat transfer showing a particle coming to equilibrium size through condensation (Richardson et al. 1986); evaporation is the inverse.

Fig 6. Demonstration of similar results modeling evaporation continuously vs. in one step.



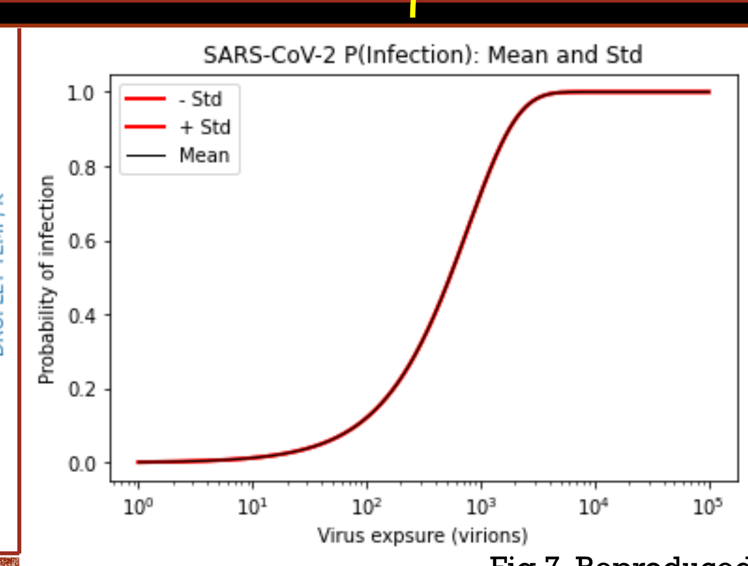


Fig 7. Reproduced results of the Gale 2020 infection model; assumes initial infection in ACE2 of nasal epithelium.

Focus area:

8. Probability of Infection

Once we know where particles end up, we need to know how much virus they carry and how infectious it is.

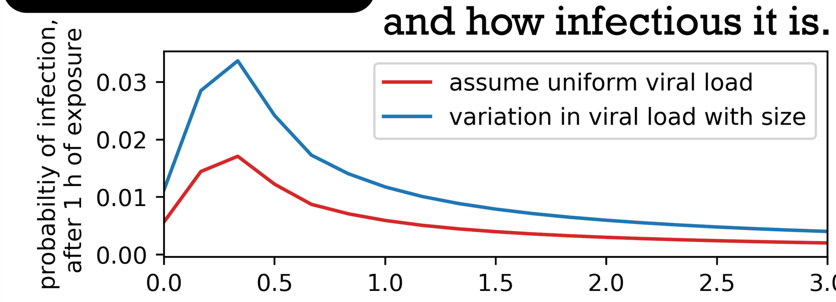


Fig 8. Importance of assumptions about viral loading by size. We assume higher loads on aerosols based on influenza data.[7,8]

Acknowledgements

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Next Steps

How can we use our understanding of infection probability and risks to a) inform individual and collective actions aimed at minimizing the number of sick individuals and b) contribute to the growing body of epidemiological models of SARS-CoV-2 by refining R0 (reproductive rate) values to reflect the different infection risks possible under different mitigation scenarios?

Conclusions

Understanding aerosolized transmission of COVID-19 is key to protecting the lives and health of as many people as possible, particularly during the wait for and implementation of coronavirus vaccines, which will be more effective the lower the current spread rate of SARS-CoV-2 is. We add to that effort research on the effect of evaporative modeling and risk predictions based on the combination of quadrature-based aerosol and near-field dispersion models.

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