Mechanistic transmission modeling of COVID-19 on the *Diamond Princess* cruise ship demonstrates the importance of aerosol transmission

Parham Azimi[a,1], Zahra Keshavarz[a], Jose Guillermo Cedeno Laurent[a], Brent Stephens[b], and Joseph G. Allen[a,1]

[a]Environmental Health Department, Harvard T.H. Chan School of Public Health, Boston, MA 02115; and [b]Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology, Chicago, IL 60616

Edited by Andrea Rinaldo, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, and approved January 7, 2021 (received for review July 22, 2020)

Several lines of existing evidence support the possibility of airborne transmission of coronavirus disease 2019 (COVID-19). However, quantitative information on the relative importance of transmission pathways of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) remains limited. To evaluate the relative importance of multiple transmission routes for SARS-CoV-2, we developed a modeling framework and leveraged detailed information available from the *Diamond Princess* cruise ship outbreak that occurred in early 2020. We modeled 21,600 scenarios to generate a matrix of solutions across a full range of assumptions for eight unknown or uncertain epidemic and mechanistic transmission factors. A total of 132 model iterations met acceptability criteria ($R^2 >$ 0.95 for modeled vs. reported cumulative daily cases and $R^2 > 0$ for daily cases). Analyzing only these successful model iterations quantifies the likely contributions of each defined mode of transmission. Mean estimates of the contributions of short-range, long-range, and fomite transmission modes to infected cases across the entire simulation period were 35%, 35%, and 30%, respectively. Mean estimates of the contributions of larger respiratory droplets and smaller respiratory aerosols were 41% and 59%, respectively. Our results demonstrate that aerosol inhalation was likely the dominant contributor to COVID-19 transmission among the passengers, even considering a conservative assumption of high ventilation rates and no air recirculation conditions for the cruise ship. Moreover, close-range and long-range transmission likely contributed similarly to disease progression aboard the ship, with fomite transmission playing a smaller role. The passenger quarantine also affected the importance of each mode, demonstrating the impacts of the interventions.

COVID-19 | transmission risk model | aerosol transmission | Diamond Princess Cruise Ship | built environment

Understanding the importance of each transmission pathway for COVID-19 is critical to informing public health guidelines for effectively managing the spread of the disease. Although information and guidance on the likely routes of transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) continue to evolve, quantitative information on the relative importance of specific transmission pathways remains limited (1). The current position of the World Health Organization (WHO) is that the COVID-19 virus is transmitted primarily through respiratory droplets (assumed >5 to 10 μm in diameter) and direct and indirect contact routes, while airborne transmission of the COVID-19 virus via smaller aerosols (assumed <5 μm) is likely not a major route of transmission other than in settings in which aerosol-generating procedures are occurring (2). Similarly, the US Centers for Disease Control and Prevention (CDC) has updated their position multiple times and currently maintains that "COVID-19 is thought to spread mainly through close contact from person-to-person" (which CDC defines as within about 1.8 m) and that fomite transmission and inhalation of respiratory droplets are likely not the main ways that the virus spreads (3). CDC has also acknowledged that airborne transmission by smaller droplets traveling more than 1.8 m away from infected individual(s) can sometimes occur (4).

Since the beginning of the pandemic, numerous researchers (5–15) and professional societies [e.g., American Society of Heating, Refrigerating and Air-Conditioning Engineers (16)] have raised concerns that transmission of SARS-CoV-2 can occur from both symptomatic and asymptomatic (or presymptomatic) individuals to others beyond close-range contact through a combination of larger respiratory droplets that are carried further than 1 to 2 m via airflow patterns and smaller inhalable aerosols that can remain suspended and easily transport over longer distances. These concerns arise from a growing understanding of human respiratory emissions (17, 18), known transmission pathways of other respiratory viruses (19), recent empirical evidence detecting SARS-CoV-2 in aerosol and surface samples in health care settings (20–25), and recent case studies demonstrating the likely importance of longer-range aerosol transmission in some settings (26–28).

In the absence of empirical studies using controlled exposures to elucidate transmission pathways (29), mathematical modeling approaches can offer insights into the likely importance of the different modes of disease transmission among human populations (30–34), provided that sufficiently accurate inputs are

Significance

We find that airborne transmission likely accounted for >50% of disease transmission on the *Diamond Princess* cruise ship, which includes inhalation of aerosols during close contact as well as longer range. These findings underscore the importance of implementing public health measures that target the control of inhalation of aerosols in addition to ongoing measures targeting control of large-droplet and fomite transmission, not only aboard cruise ships but in other indoor environments as well. Guidance from health organizations should include a greater emphasis on controls for reducing spread by airborne transmission. Last, although our work is based on a cruise ship outbreak of COVID-19, the model approach can be applied to other indoor environments and other infectious diseases.

Author contributions: P.A., B.S., and J.G.A. designed research; P.A., Z.K., and B.S. performed research; P.A., Z.K., J.G.C.L., B.S., and J.G.A. analyzed data; P.A., B.S., and J.G.A. wrote the paper; and P.A., Z.K., J.G.C.L., B.S., and J.G.A. reviewed the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: pazimi@hsph.harvard.edu or jgallen@hsph.harvard.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2015482118/-/DCSupplemental.

Published February 3, 2021.

2021 年 3 月 12 日　衆院厚生労働委員会提出資料②

出典：Parham Azimi, et al. "Mechanistic transmission modeling of COVID-19 on the Diamond Princess cruise ship demonstrates the importance of aerosol transmission", *PNAS*, 2021 Vol. 118 No. 8., p.1.

日本共産党　宮本徹