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Bidirectional impact of imperfect mask use on reproduction number of COVID-19: A next generation matrix approach☆

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ABSTRACT

The use of masks as a means of reducing transmission of COVID-19 outside healthcare settings has proved controversial. Masks are thought to have two modes of effect: they prevent infection with COVID-19 in wearers; and prevent transmission by individuals with subclinical infection. We used a simple next-generation matrix approach to estimate the conditions under which masks would reduce the reproduction number of COVID-19 under a threshold of 1. Our model takes into account the possibility of assortative mixing, where mask users interact preferentially with other mask users. We make 3 key observations:
1. Masks, even with suboptimal efficacy in both prevention of acquisition and transmission of infection, could substantially decrease the reproduction number for COVID-19 if widely used.
2. Widespread masking may be sufficient to suppress epidemics where R has been brought close to 1 via other measures (e.g., distancing).
3. “Assortment” within populations (the tendency for interactions between masked individuals to be more likely than interactions between masked and unmasked individuals) would rapidly erode the impact of masks. As such, mask uptake needs to be fairly universal to have an effect.
This simple model suggests that widespread uptake of masking could be determinative in suppressing COVID-19 epidemics in regions with R(t) at or near 1.

Background

The use of masks as a means of reducing transmission of COVID-19 outside healthcare settings has proved controversial. Available evidence suggests that masks and other face coverings reduce both transmission and acquisition of droplet-borne respiratory viruses in healthcare settings (Chu et al., 2020; Leung et al., 2020; Offeddu et al., 2017) but evidence outside healthcare is limited. Ecological evidence suggests that countries where mask use is widespread have controlled COVID-19 epidemics more rapidly (Kai, Goldstein, Morgunov, Nangalia, & Rotkirch, 2004), and models suggest that even imperfect

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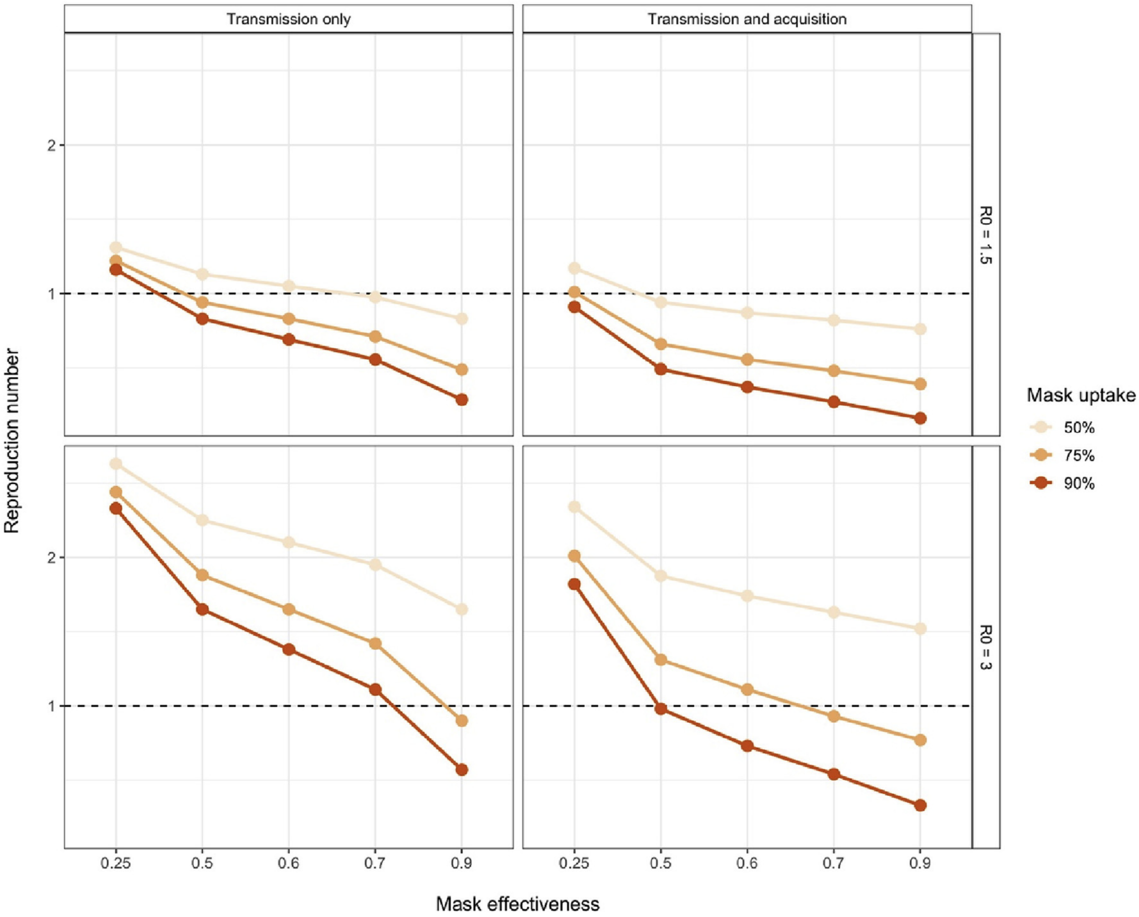

Fig. 1. Effect of Mask Uptake and Effectiveness on Reproduction Number of COVID-19
Effective reproduction number (R) is plotted on the Y-axis and increasing mask effectiveness is plotted on the X-axis in both figures. Curves represent 50% (light), 75% (medium) or 90% (dark) uptake of masks in the population. Top panels represent a scenario with baseline R = 1.5; and masks reducing transmission only (left), or both transmission and acquisition of infection with equal effectiveness (right). Bottom panels are identical, but use a baseline R = 3.

use of masks and other face coverings could be a potent disease control intervention, due to the bidirectional effects of masks on disease transmission (Eikenberry et al., 2020).

Objective

To use a simple, "next generation matrix" approach to explore the impact of masks on epidemic reproduction numbers under varying assumptions around effectiveness, uptake, and population mixing patterns.

Methods and findings

We can represent mask use in a population using a simple mixing approach whereby the "force of infection" (rate of infection of susceptibles) in masked (λ_m) and unmasked (λ_u) individuals is:

$$\begin{pmatrix} \lambda_m \\ \lambda_u \end{pmatrix} = \begin{pmatrix} \beta_{mm} & \beta_{um} \\ \beta_{mu} & \beta_{uu} \end{pmatrix} \begin{pmatrix} I_m \\ I_u \end{pmatrix}$$

Here I_m and I_u represent prevalent infections among masked and unmasked individuals. Each β_{ij} represents the product of contact rate and transmission probability from an infectious individual with mask use status *i*, acting on a susceptible person with mask use status *j*. Population mixing may be random, but assortativity is also possible, in which case masked individuals would interact predominantly with other masked individuals, and vice versa. Assortativity would manifest as zeroes in the

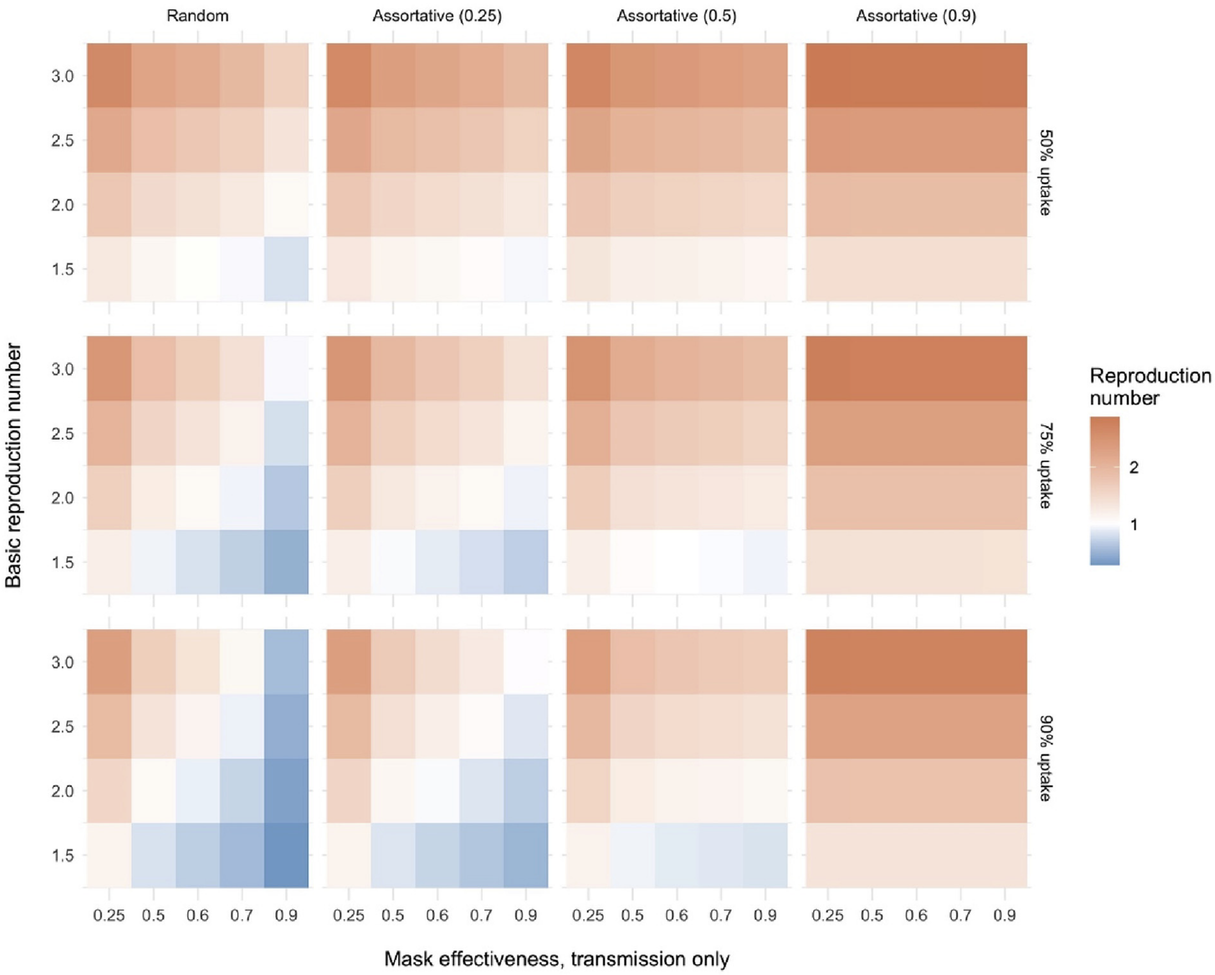

Fig. 2. Diminished Effect of Masks on Reproduction Number of COVID-19 with Assortative Mixing.
Baseline effective reproduction number (R) is plotted on the Y-axis and increasing mask effectiveness is plotted on the X-axis, across four different scenarios with respect to assortativity. Left handed panels show random mixing, while the three right hand panels show progressive increases in assortativity (coefficients of 0.25, 0.5 and 0.9, based on the approach of Garnett and Anderson (Garnett & Anderson, 1996)). The effective reproduction number, R, in each scenario is represented by color coding, with red areas signifying R > 1, white signifying R = 1, and blue areas signifying R < 1. It can be seen that R falls below 1 more easily with random mixing than with assortative mixing; when assortativity is extreme (far right panel), R cannot be brought below 1, even when R_0 is low, mask use is widespread, and masks are highly efficacious. Note that simulations in this figure consider only reduction of transmission risk, and assume that masks do not prevent acquisition of infection.

anti-diagonal of the matrix (Garnett & Anderson, 1996). This simple model is available as a Microsoft Excel spreadsheet at: https://figshare.com/articles/Next_Generation_Matrix_Approach_to_Mask_Use_for_COVID-19/12279266. Reproduction numbers (the number of new cases created by prevalent cases) can be estimated as the largest non-negative eigenvalue of the next-generation matrix:

$$\begin{pmatrix} R_{mm} & R_{um} \\ R_{mu} & R_{uu} \end{pmatrix} = \begin{pmatrix} \beta_{mm} N_m D_m & \beta_{um} N_m D_u \\ \beta_{mu} N_u D_m & \beta_{uu} N_u D_u \end{pmatrix}$$

Here N is population size and D is duration of infectivity; contact numbers and disease duration are equivalent for masked and unmasked individuals such that differences in β_{ij} relate entirely to the effectiveness of mask use for transmission (E_T) and for prevention of acquisition of infection (E_A). For example, β_{mm} would be estimated as $\beta_{mm} \cdot (1 - E_T) \cdot (1 - E_A)$. Using this simple model, we see that widespread adoption of partially effective masks can reduce R from a high baseline value (e.g., 3) to below 1, provided mask use is widespread and masks impact both transmission and acquisition of infection (Fig. 1, bottom panels). If R is closer to 1 (e.g., 1.5) as may be the case following social distancing, limited mask uptake with effects limited entirely to reduced transmission may be sufficient to drive R to values below 1 (Fig. 1, top panels).

Assortative mixing diminishes the impact of masking (Fig. 2), concentrating the epidemic in non-masked segments of the population. Assortativity is modeled using the approach of Garnett and Anderson (Garnett & Anderson, 1996), by adding an assortativity constant (η) to the matrix; values of η closer to 0 approximate random mixing while values closer to 1 represent extreme assortativity.

Discussion

Recommendations for the public use of masks and other face coverings for prevention of COVID-19 transmission have proven surprisingly contentious in high-resource countries. The reasons for this are likely varied and include concerns about diminished mask supply for healthcare workers and false reassurance for masked individuals with diminution of social distancing. Nonetheless, as we demonstrate here, even modest mask effectiveness for reduction of transmission of COVID-19 could have important effects on epidemic dynamics, especially given that pre-symptomatic transmission of disease is an important feature of COVID-19 epidemiology, and may account for over 40% of all transmission events (He et al., 2020). Even a partial reduction of this burden of transmission may be sufficient to drive reproduction numbers below 1, especially when they have been brought close to 1 by other non-pharmaceutical epidemic control measures such as aggressive physical distancing. While we used a slightly different mathematical approach, our findings are consistent with those published by Eikenberry et al. (Eikenberry et al., 2020), and provide a degree of cross-validation of those findings. We also show here that the benefit of masks may be diminished via assortative mixing patterns, if mask-users predominantly contact other mask users. As such, the impact of masks and other face coverings in reducing COVID-19 transmission is likely to be greatest if attention is paid to ensuring availability for disadvantaged populations.

Our analysis has several limitations, including the model's simplicity and the lack of precise estimates for mask effectiveness in the context of COVID-19. However, it should be noted that our model is likely conservative; a recent systematic review suggested, based on the best available evidence, that face masks reduce the risk of acquisition of viral infection by 85% (95% CI 66–93%) (Chu et al., 2020); as we note here, the impact of masking is markedly enhanced if both acquisition and transmission are reduced. In a health emergency like the current pandemic, decisions may need to be made on the basis of best available information, even if that information is imperfect. In the absence of evidence of harms done by masking, and with even preliminary evidence that they could influence epidemic growth, we suggest that their more widespread use be considered by jurisdictions which have not yet advocated this intervention.

Declaration of competing interest

The research was supported by a grant to DNF from the Canadians Institutes for Health Research (2019 COVID-19 rapid researching funding OV4-170360). None of the authors has any conflict of interest to declare.

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