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Disease risk mitigation: The equivalence of two selective mixing strategies on aggregate contact patterns and resulting epidemic spread ☆

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HIGHLIGHTS

- We study two mitigation strategies over a suite of epidemic models.
- We construct a change of variables between contact and affinity mitigation.
- Models including both are underdetermined.
- Models with asymptomatically infectious individuals violate this equivalence.

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ABSTRACT

The personal choices affecting the transmission of infectious diseases include the number of contacts an individual makes, and the risk-characteristics of those contacts. We consider whether these different choices have distinct implications for the course of an epidemic. We also consider whether choosing contact mitigation (how much to mix) and affinity mitigation (with whom to mix) strategies together has different epidemiological effects than choosing each separately. We use a set of differential equation compartmental models of the spread of disease, coupled with a model of selective mixing. We assess the consequences of varying contact or affinity mitigation as a response to disease risk. We do this by comparing disease incidence and dynamics under varying contact volume, contact type, and both combined across several different disease models. Specifically, we construct a change of variables that allows one to transition from contact mitigation to affinity mitigation, and *vice versa*. In the absence of asymptomatic infection we find no difference in the epidemiological impacts of the two forms of disease risk mitigation. Furthermore, since models that include both mitigation strategies are underdetermined, varying both results in no outcome that could not be reached by choosing either separately. Which strategy is actually chosen then depends not on their epidemiological consequences, but on the relative cost of reducing contact volume versus altering contact type. Although there is no fundamental epidemiological difference between the two forms of mitigation, the social cost of alternative strategies can be very different. From a social perspective, therefore, whether one strategy should be promoted over another depends on economic not epidemiological factors.

1. Introduction

The behaviors behind contacts through which infectious diseases are spread may be divided into those affecting the number of contacts a susceptible person makes (how much they mix), and those affecting the nature of contacts (with whom they mix) (Mercer et al., 2009; Oster, 2005). The choice between behaviors depends on the value of contacts relative to the cost of disease. Mercer et al. observe that the value of contacts within partnerships determines the probability of illness (see also Mah and

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Halperin, 2010; Morris, 2001). For example, a monogamous couple engaged in a certain volume of sexual contacts carries less risk than couples engaged in fewer overall contacts with some of these being extra-relational (Morris, 2010). It has been shown that changes in the selective mixing strategy of individuals have been sufficient to cause epidemics to peak, Chan et al. (1997). From this, it would appear that the choice between a reduction in contact volume or an alteration in contact types may significantly affect the course of an epidemic.

There is a growing body of research on the effect of risk management behaviors on the course of epidemics (Gross et al., 2006; Plowright et al., 2008; Leach et al., 2010; Chowell et al., 2009; Herrera-Valdez et al., 2011). A number of studies have done a *post hoc* estimation of these behaviors in order to improve the fit of models to observed data. A subset of these studies model behavior as the outcome of a goal-seeking, decision process in which individuals select either a reduction in contact volume or an adjustment of contact type so as to maximize the discounted stream of net benefits of contacts or, equivalently, to minimize the discounted net cost of disease and disease avoidance. This approach has been characterized as epidemiological economics (Fenichel et al., 2011; Morin et al., 2013; Fenichel and Wang, 2013). There are two ways in which private individuals are able to manage infection risk during an epidemic: *adaptation* and *mitigation*. Each addresses a different component of infection risk – the product of the probability of infection and the cost of infection. Adaptation affects the cost of infection and mitigation the probability of infection. The specific behaviors considered here are designed to reduce the probability of infection by reducing the likelihood that the individual susceptible (or otherwise ignorant of their immunity/infection) to a disease will encounter one who is symptomatically infectious.

Amongst mitigative behaviors we define *contact mitigation* as the alteration of an individual's contact volume in order to avoid infection (e.g., staying home from work or school and avoiding social interactions or public transportation). This form of mitigation is a common response to epidemics (Castillo-Chavez et al., 2003; Hethcote, 2000; Arino et al., 2007; Merl et al., 2009). By contrast, *affinity mitigation* is the alteration of contact type, i.e., the probability that a susceptible individual mixes with an infectious individual (e.g., by avoiding particular individuals or locations while engaging in a normal amount of contacts). The difference between the two approaches is that affinity mitigation seeks to lower risk by reducing not the level of activity, but the likelihood that contacts will be infectious. Similarly, *infection mitigation* occurs where the susceptible individual takes precautionary measures designed to reduce the probability of infection given infectious contact. While we do not study the third here explicitly, we note that it is closely related to affinity mitigation and has frequently been identified as the mechanism driving the reduction of disease incidence as in Gregson et al. (2010).

To evaluate the relative effects of contact and affinity mitigation we first characterize the probability of contact between two types of individuals (the target of selective mixing) derived by Castillo-Chavez et al. (1991), Busenberg and Castillo-Chávez (1991), Blythe et al. (1991). We then present an intuitive argument for the equivalence between contact and affinity mitigation in the absence of asymptomatic individuals. We show, for example, that the quarantine of infectious individuals may be accomplished with affinity mitigation without any individual reducing contact volume to 0. We conclude the argument by showing the non-equivalence of the two types of mitigation when there are individuals who are asymptomatic and infectious. Our Results section presents the full change-of-variables formula for models including compartments for susceptible, latently infected (asymptomatic and noninfectious), symptomatically infectious, and recovered/immune individuals (i.e., *SI*, *SIR*, and *SEIR* models) with and without reentry into susceptibility.

2. Methods

2.1. Model formulation

There is a large class of models for which the individual contact mitigation and affinity strategies are interchangeable. Some of these are depicted in Fig. 1. We adopt the convention that state variables represent proportions of the population within a particular state: S for susceptible, E for latently infected (noninfectious and asymptomatic), I for symptomatically infectious, and R for recovered/immune individuals. We model epidemics using a system of differential equations describing the change of each epidemiological compartment. Infection within these models is generated by an incidence function of the form:

$$c_s S(t) \sum_Y \beta_Y P_{SY}(t), \tag{1}$$

where c_s denotes the per-unit time contact/activity rate for susceptible individuals, β_Y is the probability of infection due to a susceptible mixing with an infectious individual of type Y (with Y including both symptomatic and asymptomatically infectious individuals), and $P_{SY}(t)$ is the conditional probability of a susceptible-infectious mixing pair at time t. Traditional forms for $P_{SY}(t)$ include mass-action, $Y(t)$, standard incidence/proportionate mixing, $Y(t)/N(t)$ where $N(t)$ is the total population, and conditional proportionate mixing, $c_y Y(t)/\sum_j c_j J(t)$.

Disease-risk mitigation is represented by either reducing contact volume, c_x, or committing effort to avoiding contact with high-risk groups, altering $P_{XY}(t)$. We assume that mitigation is action intended to reduce the risk of infection so as to minimize the cost (disutility) of illness and illness avoidance. The only individuals engaged in mitigation are those who are either susceptible or unaware of their infectiousness/immunity; we call these individuals "reactive". In the models described in Fig. 1 they comprise the S and E compartments (and to a lesser degree the R compartment in the presence of loss of immunity). Furthermore, we assume that all individuals within a particular compartment behave identically (we describe the behavior of a representative individual). Finally, we assume that all individuals are aware of their own symptomatically infectious status, and that these symptoms are readily recognizable by others.

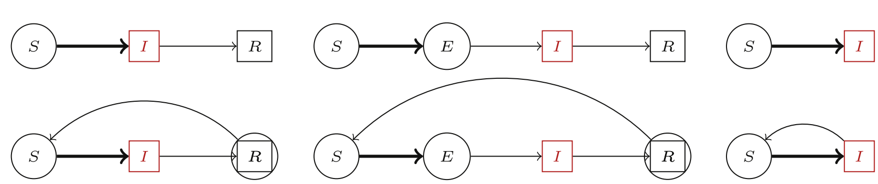

Fig. 1. The models studied in this paper. Circles indicate the individuals who engage in mitigation behaviors. The I and A compartments indicate infectious individuals. Thick arrows indicate non-linear flow rates. Within the context of loss of immunity the recovered individuals may engage in some limited mitigation due to their inability to assess their own immunity.