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Equilibrium vaccination patterns in incomplete and heterogeneous networks

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ABSTRACT

Under-vaccination is a usual concern of disease control studies, but this paper employs a simultaneous-move game in a three-agent contagion network to show that it is only one of the three inefficient patterns. When the network structure is incomplete or individual characteristics are heterogeneous, there exist new types of Nash equilibrium outcomes with either the right number but wrong set of people getting vaccinated or too many vaccinations, and these equilibria are robust to standard refinements. While untargeted policies can correct the standard under-vaccination problem, targeted policies are more palatable for correcting the new inefficiencies. Universal mandates can never improve on any Nash equilibria.

1. Introduction

When it comes to vaccinations, the primary focus of the general public, the medical profession, and academic researchers tends toward the problem of too few vaccinations.[2] For economists, under-vaccination is a straightforward example of free-riding. The individual receiving the vaccination bears the cost of the vaccination, but by keeping him from getting the disease, the benefits go not just to him but also to others with whom he interacts.[3] Free-riding provides one explanation for

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[2] For instance, in 2015 the journal *Vaccine* published a special issue on the topic of vaccine hesitancy, the tendency of both patients and caregivers to become "hesitant" about vaccinations (see Hickler et al., 2015).

[3] That vaccinations have a public-good component and lead to free-riding behavior was already well-known in public finance textbooks (Stiglitz, 1988), but Brito et al. (1991) were among the first to provide a formal treatment. Their paper looks at tax and subsidy schemes to get the socially-optimal number of vaccinations, and it was built upon by Geoffard and Philipson (1997) and Francis (1997). Ward (2014) and White (2017) find empirical evidence of vaccination externalities using data on influenza vaccines.

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why too few individuals receive vaccinations, but some recent economic research has moved into other factors that might exacerbate this effect, with individuals not receiving vaccinations because of misinformation or behavioral biases.[4]

This paper focuses on a different problem. We show that in incomplete and heterogeneous contagion networks, not only can too few people get vaccinated, but also the right number but the wrong set of people could get vaccinated, and the possibility even arises that too many people get vaccinated. As with free-riding, the intuition is straightforward. Suppose the socially-optimal vaccination pattern dictates that one particular individual should be among those vaccinated, perhaps she has the lowest vaccination cost or the highest likelihood to spread the disease, but in equilibrium, that person does not get vaccinated. Her forgoing the vaccine leads others with smaller network externalities to get vaccinated as the best response, and sometimes it takes more than one person to make up for the missing vaccination. These new results show the importance not just of incentivizing vaccinations, but also of targeting the incentives to the right individuals in incomplete and heterogeneous networks.

The typical large, stochastic network models capture situations where diseases spread through random strangers. To analyze those models, researchers run simulations to find both the socially-optimal vaccination rate and the equilibrium vaccination rate in the presence of free-riding (see Britton et al., 2007 or Miller and Hyman, 2007 for examples from the mathematics literature; see Goyal and Vigier, 2015 for an example from the economics literature).[5] In contrast, we adopt small, deterministic networks to describe situations where diseases spread among members who expect to interact. Though the networks are small, each member can be treated as a representative agent from a well-defined group. We then explicitly solve a non-cooperative game for the social optima and all pure-strategy Nash equilibria.[6] These depend on the structure of the network, the cost of vaccination, the probabilities that the individuals become infected from outside the network, and the interpersonal transmission probabilities for the disease in the network.

Consistent with the goal of demonstrating that the problem exists, we establish it in the simplest possible cases. Three-person networks prove sufficient. We begin with a baseline case, a complete network in which three identical agents all have direct connections to each other. The only deviations from the socially optimal vaccination pattern arise when too few individuals get vaccinated in an equilibrium, which is the standard free-riding result. We then introduce asymmetry in the network structure by removing a link, creating a star network in which two peripheral individuals are connected only through a central one. Vaccination for the central player generates a larger external benefit than vaccination for a peripheral player, and this asymmetry in the externalities leads to two new equilibrium outcomes.

In this 3-person star network, no one should get vaccinated when vaccinations are prohibitively expensive. As the costs come down, though, the central player should be the first to get vaccinated because he can spread the disease directly to two individuals whereas the peripheral players can spread to just one person. However, we show that there exist equilibria in which one of the peripheral players gets vaccinated instead of the central one. Thus, the right number but the wrong set of people get vaccinated. Moreover, there also exist equilibria in which both of the peripheral players get vaccinated while the central player does not. They do so because getting vaccinated is the best response to the central player remaining unvaccinated, while the central player's choice is the best response to both peripheral players getting vaccinated. Under such circumstances, too many people get vaccinated.

These new patterns of wrong-vaccination and over-vaccination arise in cases where there are multiple equilibria, with the best equilibrium being the efficient one in which the central player takes the vaccine. However, we show that except on a set of measure zero the inefficient equilibria are trembling-hand perfect, and therefore survive the most common equilibrium refinement for normal-form games. Moreover, the same patterns can arise when the network is complete, but the individual parameters differ. Finally, we show that in a star network in which the central player is a healthy carrier, that is, one who can transmit the disease but suffers no ill effects of it herself, the new patterns uniquely emerge because a healthy carrier has no incentive to vaccinate.

All of this suggests that a successful pro-vaccine program must target the agent with the largest externality. We consider two targeted policies for the 3-person star network, a targeted subsidy which subsidizes the vaccine for the central agent, and a targeted fine which penalizes her for failure to vaccinate. Both policies, when administered appropriately, can achieve the social optimum, and they avoid the problems of too many or the wrong set of vaccinations by making vaccination a dominant strategy for the central player. We go on to show that untargeted policies can also achieve the social optimum, but they do so in a much less-straightforward way. They address the problem of free-riding with a small subsidy or fine, but they address the problem of too many or the wrong set of vaccinations by *rewarding* nonvaccination (i.e., a negative untargeted fine) or *taxing* vaccination (i.e., a negative vaccination subsidy). These policies work by making nonvaccination a dominant strategy for the peripheral players, in which case the central player best-responds by vaccinating. However, policies incentivizing nonvaccination are unlikely to be palatable, either to policymakers or the public at large. Surprisingly,

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[4] Some recent experimental evidence includes Ibuka et al. (2014), which finds evidence of free-riding but also recency bias, and Bronchetti et al. (2015), which looks at attention, planning, and follow-through for vaccination behavior.

[5] Rao et al. (2007) looks at a different question concerning vaccinations and networks, finding evidence of peer effects in vaccination behavior.

[6] Mixed-strategy equilibria also exist, but we do not pursue them in this paper for purposes of brevity, but the results are simple to summarize. As with the game of chicken, each individual prefers others to vaccinate so he can free ride. If individuals cannot coordinate, they must randomize between vaccinating and not. Then all possible outcomes arise with some probability, including the right set of vaccinations, too few, too many, and the right number but the wrong set. Furthermore, the mixed-strategy equilibrium has the same total payoff as the allocation under universal mandates because individuals are indifferent between vaccinating and not. Also, the total payoff in the mixed equilibrium is smaller than in pure ones.