Effectiveness of Vaccination Strategies for Infectious Diseases According to Human Contact Networks

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SUMMARY: Mathematical modeling of infectious disease transmission aims to predict the spread of infection and the effectiveness of containment strategies. For the case of infectious diseases that transmit between human, one key factor becomes the modeling of contacts between individuals through which the disease is potentially transmitted. We review several formulations of such contacts with emphasis on the recently investigated scale-free network, and also discuss the effectiveness of vaccination strategies.

Mathematical modeling of infection transmission among individuals in a society basically comprises of two factors: who contacts who, and how the infection transmits during contact. We here focus on the first factor, the modeling of contacts that potentially transmit the disease. Such contacts are formalized as a human contact network, in which individuals are called ‘nodes’, and two nodes are defined to be ‘linked’ if they are in contact. The most important question we want to know from infection transmission modeling is whether an infectious disease outbreak spreads widely as an epidemic or extinguishes.

Homogeneous mixing

In the simplest and traditional homogeneous mixing model, we assume that all nodes are linked to a constant number of other nodes, and that the links among the nodes are random. Under this model, there exists a threshold value in ‘transmissibility’, the probability that an infected node transmits the infection to a linked susceptible node, less than which an outbreak immediately extinguishes (1).

Social structure

However, the homogeneous mixing assumption is sometimes too much naïve. For example, the number of contacts per a person for influenza transmission would be significantly higher for healthcare workers in a hospital than for the remaining population in society. In such cases, nodes are categorized into several types according to the social structure, while still the links between the nodes are assumed to be random.

Scale-free networks

In network theory, the number of nodes linked to a node is defined as its ‘degree’. While the social structure model assumes several values of degree, networks having nodes with a much wider range of degree have been featured recently. In the typical scale-free network the frequency of high degree ‘hub’ nodes decreases only by the power of the degree (Figure 1) (2). It allows a larger number of high degree nodes than the above two models or the case with normal distribution in nodes’ degree. In contrast to the homogeneous mixing case, a series of scale-free contact networks of fixed mean degree asymptotically keeps a stationary number of infected nodes thus does not lead to the extinction of infection (under the SIS model where nodes transit between susceptible and infected), even for pathogens of infinitely weak transmissibility (3). Since sexual contacts are known to follow the scale-free degree distribution (4), sexually transmitted diseases can fit such cases.

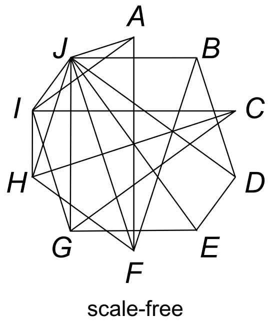

Fig. 1. An example of a scale-free network with 10 nodes. While the mean degree is four, the degree varies widely from the lowest degree three in nodes *A*, *B*, *C*, *D*, *E* to the highest degree eight in node *J*. Node *J* is a hub node connected to many other nodes, thus can become a super-spreader that transmits the disease to numerous neighboring nodes.

Effectiveness of vaccination

The primary measure for containing infection is vaccination, either preventive or post-outbreak. The effect of vaccination varies according to which node the vaccination is implemented; vaccination of hubs is generally more effective than vaccination of lower degree nodes. The epidemic mentioned above under SIS model was for scale-free networks, and cannot be stopped by preventive mass vaccination of randomly selected nodes even of a large proportion, but can be halted by prioritized vaccination of hub nodes (5,6). However, for vaccination in case of infectious diseases in human, the latter hub vaccination is difficult to implement, because the contact network is not apparent and potential hubs are not evident. On the other hand, among post-outbreak vaccination strategies, the one important in practice is the ring vaccination, in which the susceptible individuals in contact with an infected individual are vaccinated. Thus for practice, quantitative (i.e., not asymptotic) evaluation of the effectiveness of the combination of the two practical containment strategies – mass and ring vaccinations – is important, but is remaining to be resolved.

ACKNOWLEDGMENTS

This study was partly supported by a grant of Japan Science and Technology Agency.

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REFERENCES

1. Anderson, R. M. and May, R. M. (1991): Infectious diseases of humans: dynamics and control. viii, 757 p. Oxford Science Publications. Oxford University Press.
2. Albert, R. and Barabasi, A. -L. (2002): Statistical mechanics of complex networks. Rev. Modern Phys., 74, 47-97.
3. Pastor-Satorras, R. and Vespignani, A. (2001): Epidemic spreading in scale-free networks. Phys. Rev. Lett., 86, 3200-3203.
4. Liljeros, F., et al. (2001): The web of human sexual contacts. Nature, 411, 907-908.
5. Pastor-Satorras, R. and Vespignani, A. (2002): Immunization of complex networks. Phys. Rev. E, 65, 036104.
6. Cohen, R., Havlin, S. and ben-Avraham, D. (2003): Efficient immunization strategies for computer networks and populations. Phys. Rev. Lett., 91, 247901.