A NEW CONCEPT OF INTERVENTION GAME BASED ON MATHEMATICAL EPIDEMIOLOGY AND EVOLUTIONARY GAME THEORY

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（数理疫学と進化ゲームに基づく新概念 Intervention game`）

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論 文 内 容 の 要 旨

Thesis Summary

Evolutionary game theory (EGT), a well-recognized framework to explain diverse aspects of human behavior, has become an extensively popular concept in the context of social and environmental structures. The scientific community has witnessed an incredible growth of EGT in the last two decades, especially in tracing the evolution of human decision-making regarding the selection of control interventions during an epidemic outbreak. Implementation of EGT in modeling the transmission dynamics of seasonal epidemics has gained global attention as the most tractable means of capturing the complex interplay between epidemic prevalence and human behavior dynamics. Evolutionary game-theoretic models indeed confer a fertile terrain for illustrating the time trajectories of an epidemic resurgence within the populations or societies and expose the relative prevalence of behavioral propensities to portray existing conditions. Numerous endeavors to study human behavior in the context of epidemics have primarily concentrated on assessing the efficacy of several voluntary provisions such as vaccination and self-protection, as well as institutionally imposed measures like hospitalization, forced quarantine, or self-isolation, school closures, work from home, travel restrictions, etc. Within a large group of mutually interacting individuals, the interaction time, the number of contacts, the pattern of interactions, etc., may fluctuate significantly, and this diversity is usually represented by complex networks, intending to capture the nuances of the interaction patterns perfectly. Recently, the influence of self-protective actions on the dynamics of infectious diseases has gained considerable attention. In fact, spontaneous human responses to an epidemic can remarkably affect the infection spread, and their interactions with disease dynamics require a proper investigation in order to better understand what happens when a disease spreads through human populations. In this connection, mathematical and computational approaches are crucially important for estimating epidemic dynamics and recommending health interventions to control its rapid transmission. Epidemiological modeling paves the way to investigate infectious diseases, providing valuable predictions about the potential transmissibility of disease and the effectiveness of possible control measures.

This thesis aims at conjecturing the potential mechanisms of epidemic transmission, endurance, and control interventions, entangling EGT with mathematical epidemiology. The work is truly dedicated to extending the emerging aspects of intervention games, a modern concept to epidemic modeling that includes both evolutionary and vaccination games, highlighting the complex interaction among epidemic dynamics, behavioral attributes, and intervention strategies. The proposed vaccination game models in this thesis present a deterministic compartmental framework to explain the disease dynamics and control provisions. These models cover the epidemic dynamics on both homogenous well-mixing populations and heterogenous networked populations. Model evaluation relies on mean-field approximation (MFA) for theoretical prediction of the homogeneous well-mixed population, while a multi-agent simulation (MAS) approach is employed to estimate the case of a spatially structured heterogeneous population. However, each model illustrates the complex interplay between cost and efficacy of a particular health intervention observed in the evolutionary process. We consider vaccination, self-protection triggered by intermediate defense measure (IDM), and a combination of these two as distinct pre-emptive intervention strategies, whereas quarantine, isolation, and taking them together are categorized as distinct forced intervention policies to suppress the epidemic prevalence. Incorporating these two-types of intervention strategies under a suitable compartmental epidemic framework, the proposed game-theoretic models, tackling both spatial and non-spatial populations, have been dedicated to comparing, planning, implementing, evaluating, and optimizing various health interventions employing the central aspect of EGT.

As a general introduction, Chapter 1 clarifies the historical background and motivation behind conducting this study. Besides, it provides some fundamental ideas regarding the history of mathematical modeling in epidemiology, an introduction to evolutionary game theory in coupled disease-behavioral dynamics, and some relevant definitions to address the modern concept of intervention game. In Chapter 2, the influence of various noise models in bringing enhanced network reciprocity is deeply studied in a spatial prisoner's dilemma (SPD) game. This chapter comes out as an application of evolutionary game theory to a spatially structured network soliciting enhanced cooperation among neighboring agents. Motivated by the seminal work of Kermack and McKendrick, Chapter 3 proposes a novel deterministic framework of vaccination game, allowing three different pre-emptive provisions against the epidemic upsurge. Employing an SVMBIR epidemic model, this study further illustrates the evolutionary consequences of adopting multiple health interventions solely relying on a mean-field approximation on a homogenous well-mixing population. As a sticking aspect of the vaccination game, Chapter 4 elucidates the positive secondary effect of voluntary vaccination policy, expanding the theoretical framework of an SVIR epidemic model to expose the crucial advantage of committing vaccination, especially for the missed out immune individuals. Relying on mean-field approximation (MFA) and multi-agent simulation (MAS) approaches, this study justifies that the proposed model can somewhat ameliorate the situation even though vaccination does not work perfectly yet minimizing the social dilemma situation from the costeffective viewpoints. In Chapter 5, we turn our attention to portray the complex interplay between forced and voluntary provisions observed in a usual vaccination game model. To this aim, a novel game-theoretic framework is designed by incorporating forced interventions like quarantine and isolation as well as their joint implementation besides pre-emptive vaccination. Applying an MFA for a homogenous well-mixing population, the proposed SVEIJR epidemic model explicates the epidemic consequences observed in a repeated season model. Chapter 6 primarily focuses on the spatial and non-spatial evolution of epidemic diseases employing multiple health interventions like vaccination and self-protection. After a careful examination of three different underlying topologies, this study emphasizes two specific evolutionary phenomena, namely the abrupt emergence of stain points and the appearance of strategy coexistence, observed during the course of an epidemic propagation. A quantitative assessment shows that self-protection brings better societal payoff than that of vaccination, especially for lattice networks. Also, the strain points are frequently viewed in the border regions between the two-different strategy fractions. Meanwhile, the coexistence of strategies happens to see in scale-free and well-mixed populations. Finally, Chapter 7 summarizes the results obtained throughout this thesis, pointing out some novel contributions to the field of epidemiology and public health-related issues. Besides, some recommendations and a brief outline of future works have been reported in the latter part of this chapter.