A Metapopulation Model with Entry-Exit Screening Measure for the 2014-2016 West Africa Ebola Virus Outbreak

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Abstract

The Ebola Virus Disease (EVD), formerly known as the Ebola Hemorrhagic Fever (EHF), is a major public health disaster and threat to both affected Sub-Saharan Africa countries and other countries in the world, due to the wide-spread transmission during the epidemic. Since the first EVD cases identified in 1976 with two simultaneous outbreaks in Sudan and Zaire, now the South Sudan and the Democratic Republic of Congo, respectively, the 2014-2016 West Africa EVD remains the largest and severest outbreak. It had a significant impact on the world with a total of 28,616 cases and 11,310 deaths reported. One of the challenges of this outbreak is that it arose in three different countries, namely Guinea, Liberia and Sierra Leone, in which migrations and travel of people by road and air were considerable. We construct a metapopulation model to study the transmission dynamics as well as the control and management of the disease. In each patch, we consider an extended Susceptible-Exposed-Infective-Recovered ($SEIR$) type-model enriched by D, P and Q compartments that account for disease induced deceased, isolated and quarantined individuals, respectively. The next generation matrix method is used to compute the control reproduction number, $\mathcal{R}_c$, thanks to which the local asymptotic stability (LAS) and instability of the disease-free equilibrium (DFE) are established whenever $\mathcal{R}_c < 1$ and $\mathcal{R}_c > 1$, respectively. For global stability, we introduce an additional threshold number, $\mathcal{T}$ which ensures its global asymptotic stability (GAS) whenever it is less than one. The existence of patch boundary equilibria is also investigated. Moreover, we construct a nonstandard finite difference (NSFD) scheme that is dynamically consistent with the properties of the continuous model including the GAS of the DFE. Numerical simulations obtained from real data are provided to support the theory. Finally, we design two optimal control problems, the entry screening and the vaccination combined with exit screening as supplement measures. For each of this control, we construct a new Forward-Backward-Sweep-Method (FBSM) which has the following features: (1) The iterations $k = 0, 1, \cdots$ are clearly defined; (2) The state variable system of differential equations is approximated by a nonstandard forward Euler scheme, which is dynamically consistent with the properties of the continuous model; (3) The adjoint system of differential equations is discretized by the classical backward Euler scheme; (4) The FBSM is convergent. The numerical resolution of the optimal problems highlight the relevance of the controls defined.

Keywords: Ebola, Exit screening, Entry screening, Vaccination, Global stability, Optimal control, Nonstandard Forward Difference Method.