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Optimal sequential management decisions for measles outbreaks

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Objective

Development of general methodology for optimal decisions during disease outbreaks that incorporate uncertainty in both parameters governing the outbreak and the current outbreak state in terms of the number of current infected, immune and susceptible individuals.

Introduction

Optimal sequential management of disease outbreaks has been shown to dramatically improve the realized outbreak costs when the number of newly infected and recovered individuals is assumed to be known (1, 2). This assumption has been relaxed so that infected and recovered individuals are sampled, and therefore the rate of information gain about the infectiousness and morbidity of a particular outbreak is proportional to the sampling rate (3). We study the effect of no recovered sampling and signal delay, features common to surveillance systems, on the costs associated with an outbreak.

Methods

We develop a stochastic compartment model for disease populations consisting of susceptible (S), infected (I), recovered (R) and deceased (D) individuals. This model contains four parameters determining the rates of these transitions: $S \rightarrow I$, $I \rightarrow R$, $I \rightarrow D$ and $S \rightarrow R$ (vaccination). While all vaccination and death transitions are observed completely, the infected and recovered transitions are observed through sampling possibly with a delay between the transition and when the information can be used in a decision.

Sequential inference of parameters is performed using Bayesian updating, which is available in closed form when independent gamma priors are assumed, and the current system state is known. For the two sampled transitions, the associated parameters are updated in a manner that is consistent with how information is gained during sampling so that the rate of information gain is proportional to the sampling rate.

A cost structure is developed to weigh the outbreak morbidity and mortality versus the cost of active outbreak control (isolation, vaccination and increased sampling). The morbidity cost is quadratic to account for increased costs that occur when many individuals are sick simultaneously. Control costs include fixed and running costs, which are a function of the current number of infected individuals (3).

The effect of recovered sampling and delay is primarily assessed by running separate scenarios that have combinations of sampling and delay and calculating the average outbreak cost under these scenarios. In addition, allowing recovered sampling in a control allowed analysis of how often and when the optimal outbreak management utilized this sampling.

Results

As a case study, we use a recent measles outbreak in Harare, Zimbabwe, as our basis. At outbreak onset, we assume 20,000 susceptible individuals ($\sim$1% of total population in accordance with vaccination coverage rates) and 20 infected individuals. Priors for outbreak parameters are vague but informative, e.g., a 95% interval for infectiousness is 4 to 11 days.

Relative to the base-case scenario where immediate sampling is performed on both newly infected and recovered individuals, the following results are observed. Eliminating recovered sampling increases average costs by 5%, a one-period delay between transitions and control action increases costs 6%, a two-period delay increases costs 14% and eliminating all sampling increases costs by 34%.

When allowing increased sampling as a possible outbreak control measure, the optimal decision was to utilize sampling of infected and recovered individuals about 20% of the time.

Conclusions

Typical syndromic surveillance systems have taken the first step, which is to provide a measure of the number of newly infected individuals. Costs being equal, this research suggests this was the best investment for surveillance. We hope future research with different diseases and surveillance possibilities will elucidate where money should be spent in improving surveillance practices.

Keywords

Optimal control; Bayesian; basic reproductive number; time series; statistical model

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