Interactive Agent Based Modeling of Public Health Decision-Making

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Abstract

Agent-based models have yielded important insights regarding the transmission dynamics of communicable diseases. To better understand how these models can be used to study decision making of public health officials, we developed a computer program that linked an agent-based model of pertussis with an agent-based model of public health management. The program, which we call the Public Health Interactive Model & simulation (PHIMs) encompassed the reporting of cases to public health, case investigation, and public health response. The user directly interacted with the model in the role of the public health decision-maker. In this paper we describe the design of our model, and present the results of a pilot study to assess its usability and potential for future development. Affinity for specific tools was demonstrated. Participants ranked the program high in usability and considered it useful for training. Our ultimate goal is to achieve better public health decisions and outcomes through use of public health decision support tools .

Introduction

Infectious disease threats vary from emerging pathogens, such as avian influenza; to endemic infections, such as pertussis; to potential bioterrorism agents, such as anthrax. Abundant resources have been allocated toward the development and implementation of biosurveillance systems geared toward early detection of these microbial hazards. However, more research is needed to develop tools that also enhance decision making and policy development by public health personnel when dealing with novel situations and large amounts of information.

Currently the application of models for public health purposes is virtually unchartered territory. Historically models have been developed and used for military applications. Similar to the military arena where testing strategies is not feasible (from ethical and economic perspectives), modeling has become an ideal means of exploring large scale policy decisions such as vaccination strategies, contact tracing and bioterrorism threats, for example.

Background

The Decision Support in Infectious Disease Epidemiology (DSIDE) project involves a multidisciplinary team of epidemiologists, physicians, computer scientists, and cognitive psychologists. The project addresses decision-making processes of public health officials in the context of uncertainty, resource constraints, and high stakes [1]. One of the project goals is to gain a deeper understanding of how to better assist decision makers in dynamic situations of high stress [2]. The overall goal is to develop decision support tools that improve situational awareness and decision making, enhance training of public health epidemiologists, and lead to improved public health outcomes. As a step toward accomplishing this aim, we created simulation tools with highly interactive interfaces. This paper focuses on an interactive agent-based model for public health management of pertussis, which we call PHIMs (Public Health Interactive Model & simulation). A notable feature of PHIMs is that it allows the user to make decisions interactively within a dynamic, stochastic setting. Pertussis was selected as the initial target communicable disease [3,4].

This pilot study was performed to begin testing PHIMs' ability to assess and improve public health decision-making. We designed this pilot study to evaluate usability and face validity, to target tools for further development, and evaluate PHIMs' potential as a decision support and training tool.

Finally, one of the goals of the pilot study was to explore potential differences between participants based in their expertise. One aspect of expertise is that experts are considered more effective in searching for relevant information and are more likely to develop and test specific hypothesis when performing information search [5].

Methods

Framework

The simulation architecture comprises three major levels (Figure 1). Various types of agents operate within these levels. Top Level is an omnipotent view, supporting batch runs, parameter exploration, and myriad "what-if ?" experiments. It stores data generated across multiple runs. Agents within the Ground Truth level include the constituents of the simulated community: individuals, households, schools, and day care centers. The Public Health level contains data filtered from Ground Truth, as well as events and actions that transpire within the Public Health environment. Agents within Public Health include reported cases and their households, schools, and day care centers; traced contacts; and public health epidemiologists. Decisions made within the Public Health environment are passed back to Ground Truth, where they exert consequences.

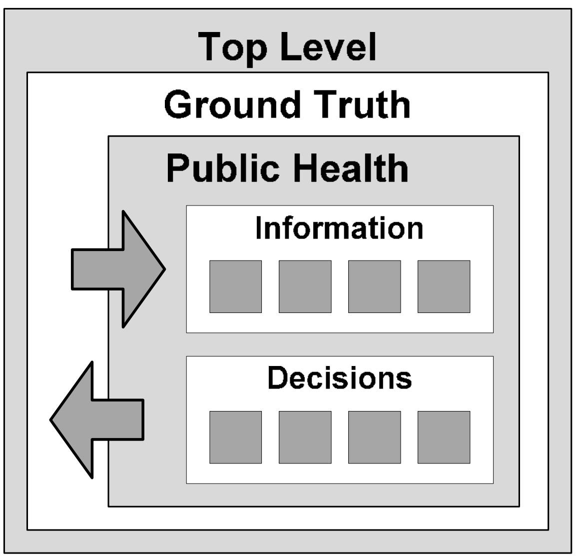

Figure 1. Basic architecture of AnyLogic model.

Programming environment

We created the agent-based models using AnyLogic 6.2 (XJ Technologies, St. Petersburg, Russia). AnyLogic is a simulation program that is designed to support agent-based models, discrete event simulation, and system dynamic models. It is based on Java and uses the Eclipse workbench as the programming interface. It includes many built-in graphical tools to facilitate creation of nested, replicated agents that interact according to their assigned rules. State charts and arrows are graphical objects used to model behaviors. Messages are used to transmit information between agents. Events and transitions may occur asynchronously or synchronously through specification of rates, timers, or custom functions. Numerous Java objects support interaction with the model at runtime.

Description of the simulated community

A generic community of size 13,876 was modeled. Age and gender were assigned to simulated individuals according to extrapolated Utah 2000 census data. Individuals were allocated to households to fit a size distribution calibrated to Utah census data. Nine percent of individuals were less than 5 years old, 26% were aged 5 to 18, and 65% were age greater than 18. Twenty-five percent of children less than 4 years of age were assigned to attend day care centers. Day care centers were assumed to vary in size from 6 to 25 children. Children between 5 and 18 years of age were assigned to schools, 450-500 students per school. Households were randomly assigned x and y coordinates in two-dimensional space.

Disease transmission and symptoms

A state chart was created to represent transitions between four states corresponding to infection status: Susceptible, Exposed, Infectious and Recovered. This structure, known as an SEIR compartmental model (figure 2), was used to model pertussis dynamics. "Susceptible" denotes risk of acquiring infection. "Exposed" denotes contact with an infected individual and latent, non-infectious infection. "Infectious" denotes the capability of transmitting infection to other individuals. "Recovered" denotes immunity from infection. Base case parameters for the distributions of latent, infectious, and recovered periods were drawn from communicable disease references and published models [5]. Susceptible individuals were assumed to occupy states of varying levels of natural and vaccine immunity, according to the timing and number of prior infections and vaccinations. Transfers between levels of natural and vaccine immunity were patterned after previously published compartmental models of pertussis [5].

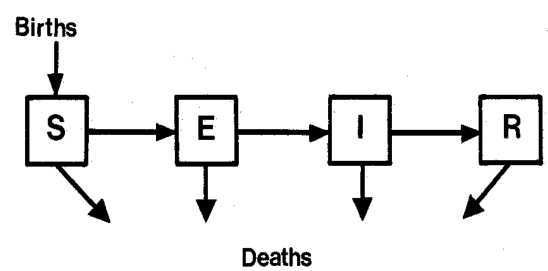

Figure 2. SEIR model.

A site-specific parameter assigned to households, school classrooms, and day care centers was used to define the rate with which infectious members contacted other members of the same household, school classroom, or day care center. Contact was assumed to be density dependent within households and frequency dependent within classrooms and day care centers. Community contact between individuals belonging to different households was assumed to follow a distance-based network structure. Contact between students belonging to different classrooms within the same school was also assumed to follow a network structure.

Three symptom states were modeled: asymptomatic, coryza and cough. These symptoms occurred in association with pertussis as well as non-pertussis illness. Among individuals with pertussis, we assumed that the transition from asymptomatic state to coryza was coincident with the onset of infectiousness. Composite states within the cough state included “mild” and “severe”. The severity and duration of disease symptoms were tied to states of pertussis immunity, following the Hethcote model [6]. Under base case conditions, we elected to not represent asymptomatic infection, because the frequency of asymptomatic infection is unknown and currently there is no reporting of these individuals to health departments. Even if asymptomatically infected individuals exist in appreciable numbers, their levels of infectiousness are unknown [7].

Disease reporting

Disease reporting was modeled as a series of decision (chance) nodes and time delays (Figure 3). Individuals, influenced by the severity of symptoms, either decided to seek medical care or not. For individuals who sought care, the time to care followed a triangular distribution. Similarly, the healthcare provider either decided to test for pertussis or not. The interval to completion of the test constituted another delay. It was assumed that PCR tests were ordered by clinicians only during the cough phase of illness. Conditional on testing, an individual’s probability of having a positive test was calculated according to disease status, test sensitivity, and test specificity. Individuals with positive tests were assumed to have a 90% probability of being reported, based on an analysis of Utah reporting rates. The time to reporting after a positive test also followed a triangular distribution.

Public health response

The public health response to reported pertussis cases was similarly modeled as a series of decision nodes and time delays. An initial delay occurred while the case was classified as confirmed or not. Participants then made a decision whether to trace contacts of the confirmed case. We assumed that the time delay to identify, reach, and evaluate household contacts was shorter than for school or community contacts. The possibility of error or incompleteness in the identification of school or community contacts was accommodated. In addition, participants were able to make decisions about use of antibiotic prophylaxis and booster vaccinations, either at a policy level or on a case-by-case basis. Contacts with symptoms that met case criteria for pertussis in epidemiologically linked individuals were classified as secondary cases and, in turn, optionally subjected to further contact tracing.

PHIMs

The Public Health Desktop provided central access for information search, case decisions, and policy decisions (Figure 4). Aggregated data were accessible in the form of an epidemic curve or as cumulative counts of events. Tabulations of cases were available in subcategories (e.g. adults, infants, etc.) Data about each case, such as (simulated) name, age, and reporting date, were available in a line list format, which is a spreadsheet of one row per case. Model times were presented in date format. Selecting individual cases opened up a case report form which presented additional case information and provided drill down access to a list of household members. Another view displayed the list of cases reported from each school. Other links supported navigation between index and secondary reported cases. Traced contacts were also viewable in a line list format. A pertussis reference library was also available with discretely categorized levels of information. The speed of the simulation could be slowed down, sped up, or paused at any time. Alternatively, the user could stipulate that the simulation pause at the time of reporting of each case. A map of the household locations of reported cases was optionally viewable.

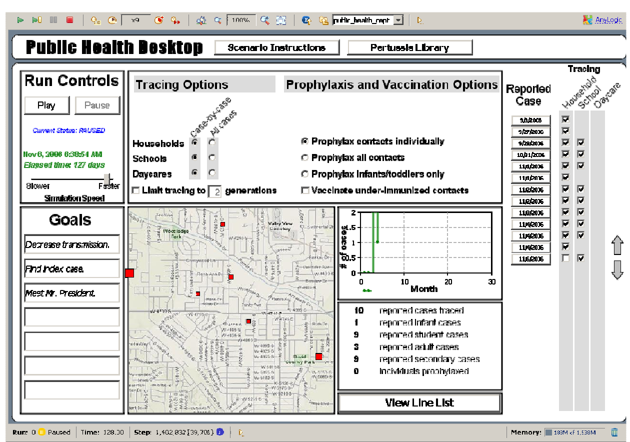

Figure 4. Public health desktop view for participants.

Participants

Participants of this pilot study were public health practitioners, or volunteers with training in public health. They were recruited by contacting epidemiologists in state and local health departments, directors of the

University of Utah's Public Health Program, and the University of Utah Division of Infectious Diseases. Participants received a recruitment letter describing goals of the study and the scope of the research project. Participants' level of expertise was determined based on two criteria: the Tier 2 Council of State and Territorial Epidemiologists (CSTE) Epidemiology Competency Form and Current Occupation Data. The later criterion included information on level of education, current position and years of experience in Public Health/Infectious Diseases. The level of expertise ranged from Public Health student to Epidemiologists with < 1 year - >30 years experience.

Study Design

The participants were asked to complete 6 scenarios with the parameters of each scenario being the same, e.g.,one scripted outbreak beginning at day 90. Participants were allotted 3 hours to complete the simulations; most participants were able to complete 3-5 scenarios within the time frame. The simulation was preceded by introductory information, instructions, a brief epidemiology primer and a survey. Questions were either answered using a 7-point Likert scale (1- completely disagree, 7- completely agree) or required an open-ended response. Next, participants selected initial policies and began the first simulation scenario. The scenario included an apparent school outbreak, which occurred during the 4^{th} month of follow-up. Questions regarding situation assessment and his/her mental model followed. At the end of the simulation, a post-survey occurred.

Assessment of information search

A log file of all user interactions with PHIMs was stored for each scenario run. The type of the interaction, the model time, and system time were saved. In addition, the model generated a set of tables containing detailed, time-stamped data about each individual in the population, including reported and non-reported pertussis cases. In addition, participants were able to enter their current goals in text box (Figure 4) to better assess the rationale for specific actions. Finally, the responses to the initial and the post-simulator survey and questions following the scripted outbreak were logged.

Results

Seven participants participated in the simulations; 4 participants were classified as novices, and 3 participants were classified as experts in epidemiology. A total of 27 runs were completed, generating 6,000 entries in the log files. The mean time to complete a scenario was 40 minutes. Experts spent less time gathering information than did novices, and demonstrated a more focused, goal-directed approach which is consistent with our initial hypothesis. Additionally, experts remarked that the simulations were useful for exploring aspects of prophylaxis and contact tracing, and tended to consider PHIMs a viable decision support tool. Experts ranked filtering and integration of information the highest among attributes as a decision support tool (all experts ranked it 6 or higher). Novices felt that the simulation made their jobs easier and more efficient; 75% ranked it at 6 or higher. Novices rated the geographical representations and the epicurve the highest and felt the ability to simulate and explore potential outcomes was the most helpful aspect of PHIMs. Clear differences in information search strategies were found, indicating that novices relied more on Reference data (1.37%) than experts (0.16%). One of the members of the novice group, described PHIMs as an engaging means of learning infectious disease transmission dynamics; she cited the ability to make 'test runs' on virtual communities---where she could realize her 'biggest errors' in a harmless manner---as being the greatest attribute. Across both groups, relatively little change occurred in post- as compared to pre-simulator survey responses, indicating that running the simulator did not change their attitudes. The perceived utility of implementing contact tracing varied widely, but was consistent within areas of expertise; experts uniformly ranked it at 5 (on a Likert scale of 1-7; 1 disagree, 7 agree), novices had varying responses (2-7).

Discussion

This pilot study assessed the usability of PHIMs and allowed a preliminary evaluation of how usage varied across individuals with different levels of expertise in epidemiology. PHIMs appealed to users in distinctly different ways, reflecting the nature of interaction associated with various levels of expertise. Experts appreciated the filtering and integration capabilities, characteristic of advanced, goal-directed decision making. Novices found the graphical representations amenable to facilitating comprehension of what can frequently be detailed and complex interrelated data sets. Accordingly, novices consistently ranked the utility of PHIMS as highest in its potential to make their jobs easier and more efficient. This is a reflection of learning styles as well, a significant driving force behind development of any graphical user interface; particularly so when involving simulated reality.

Regarding face validity, five participants scored the scenario as a highly "fair/accurate/plausible version of reality" (ranking 6 (response range 5-7) on the Likert scale), with two participants answering, "I don't know." Separately, participants generated a mean score of 72 (response range 50-100) on of a scenario realism assessment scale, with 1 being interpreted as "completely unrealistic," and 100 being interpreted as "highly realistic."

Particularly intriguing was the propensity across the groups to 'explore' the kinds of ideas generally limited in doing, either by economic, ethical or cognitive constraints. Experts commented that they enjoyed trying something 'I have always wondered about,' suggesting a PHIMs played a useful role in helping them explore their own mental models. Novices demonstrated much less intentionality and precision, but the evidence of exploring possibilities was present---novices had a much more exploratory type of approach where the approach experts used was more consistent with an approach of hypothesis development and hypothesis testing..

This present study is limited by the small sample size but provides useful data that can guide the conduct of a follow-up study. Larger sample studies are planned to analyze the information search strategies and heuristics that underlie public health decision making in a more comprehensive manner. We will incorporate additional interactive tools into the test environment to evaluate the impact of simulation-based decision support. PHIMs is sufficiently flexible to support development of scenarios for a variety of other communicable diseases.

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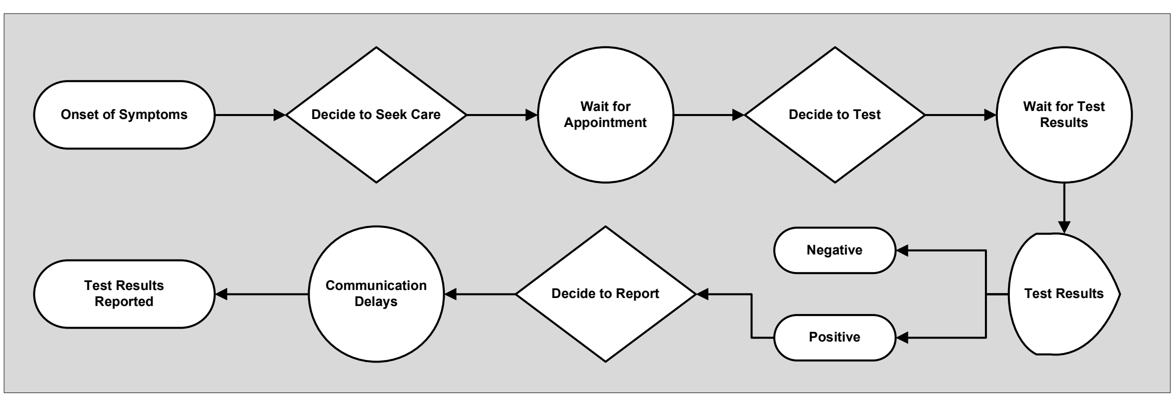

Figure 3. Information flow of disease reporting in our model.