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New Agent-Based Model for Influenza Epidemic Dynamics in Cities

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ABSTRACT

The currently standard agent-based model involves setting probabilities of infection during contacts of residents. This means the unknown of the epidemic, the dynamics of which we are going to model. New agent-based model capable to predict a real dynamic of the influenza epidemic in city under consideration and efficiency of possible non-pharmaceutical interventions was proposed.

Keywords: Influenza; Epidemic Dynamics; Agent-Based Model

Introduction

The famous idea of using a computer to simulate the daily life of city's residents during an influenza epidemic was only realized at the beginning of this century, when powerful computers with large memory became available. In 2005-2006, several pioneering papers appeared that described a new statistical agent-based model (ABM) for calculating epidemic dynamics (Eubank S, et al. [1-4]). Using this model, we expect to obtain a fairly accurate estimate of the number of urban residents who will be able to fall ill during the epidemic and their distribution through age groups. To my opinion there are three shortcomings of this model. It can be used after end of an epidemic; it contains a lot of parameters most part of which cannot be measured and may be evaluated from indirect considerations only and it cannot be adapted to analysis of non- pharmaceutical interventions. In this paper we propose a new agent- based model that to a large extent reduce these shortcomings.

Short Description of the Standard ABM

We will use a very short description of the standard model, sufficient to understand the proposed one and analyze its capabilities. On a computer, each resident has a sign of the state at the considered point in time (healthy, infected, infectious, restored) and age. Every work morning, any resident can either come to his/her workplace or stay at home. Workplaces (day cares, kindergartens, schools, universities, companies, etc.) have to be defined and then populated according to the demographic and infrastructure information for the city under consideration. The same is true for households and places of entertainment in the evenings and on non- working days. All possible contacts for all residents together form a set of contacts. During any contact healthy resident with infectious one the first one can get infected with some given probability (in general, different for different age groups). After sometime this resident becomes infectious, and then for a while the infectious resident returns to the healthy status. All such probabilities by contact in all age groups form a set of infection probabilities. In the process of coming to workplaces and returning to households, the total number of residents who came in and the number of infectious among them are counted. Thus, we determine the total number of contacts of healthy residents with infectious ones and, having "performed" these contacts, we obtain the total number of newly infected residents in all workplaces and households during a day. This number forms the daily value of the functions describing the dynamics of the epidemic in all age groups and, consequently, their sums too.

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It is clear that an implementation of the standard ABM requires knowledge of the set of contacts and the set of infection probabilities. The set of contacts is easy to build from demographic and infrastructure information for the city under consideration. As a rule information concerning the set of infection probabilities is absent and it have to be prescribed a priori. Probabilities given in such a set cannot be measured and may be evaluated from indirect considerations only. It means that an accuracy of results obtained will be unknown and therefore the standard ABM cannot be used for an analysis of different medical interventions.

Description of Ideas of the New ABM

Since the probabilities of infection are determined only by the type of virus and do not depend on the set of contacts, the additional information can be taken from the real epidemic dynamics (i.e. received from the epidemic surveillance center) in another city. Such a possibility is realized, for example, in the case of a regional epidemic, in which there are always cities in which the outbreak has already passed, but in the city under consideration it is still only expected. Let us show that such information makes it possible to determine the set of infection probabilities for the considered virus. First, let's formulate the problem mathematically. We want to use integral data at the lower level (epidemic dynamics in age groups) to obtain data at a higher level (infection probability through contact in the same groups). Such problems, called ill-posed ones, may have one solution, or have many solutions, or have no solution at all. Moreover, numerical solution of such problems can be unstable. Mathematicians who have studied such problems have shown (Tikhonov AN, et al. [5]) that the problem we are considering here has an unique solution if the epidemic dynamics in age groups is represented by increasing functions of time. Of course, the results obtained can be presented in any form.

The described algorithm for determining was tested on the example of influenza epidemic in Dresden, Germany (Perminov VD, et al. [6,7]). The test's scheme:

1. Creation of the set of contacts for Dresden.
2. Writing down the real epidemic dynamics in a source city (that is received from an epidemic surveillance center).
3. Calculation of epidemic dynamics in the city by the standard ABM for given set of contacts and any values of infection probabilities in age groups.
4. Calculation of real infection probabilities in age groups.
5. New modeling of the epidemic dynamic based on these real calculated probabilities. If ABM's algorithm is working correctly and the real set of contacts in the city was approximated properly, the real epidemic dynamics in age groups as well as in the city as a whole should coincide with the simulation results (Perminov V [7]).

Before presenting the results obtained, several remarks should be made. These remarks are based on a comparison of parameters describing the standard algorithm and the algorithm proposed in this article.

1. Both models specify the infection probabilities of healthy residents at the time of contacts. In the standard ABM they proceed from the assumption (probably, medical?) that these probabilities depend not only on the ability of a healthy resident to become infected, but also on the infectious one. It leads to a necessity to set up entire table of probabilities, each element of which is given with an unknown accuracy (for example, (Cooley P, et al. [8]) used 12 of such elements and their values are written out with three or even four decimal places!?). In the new ABM each resident in the age group has the same probability to get infected by contact and it does not depend on who infects them. This change in the standard ABM is due to two reasons. First, in the proposed modeling algorithm, the probabilities are calculated from a comparison of the obtained results with real data for the source city. Secondly, according to our purpose of modeling with ABM, we are only interested in the distribution of those infected among age groups (see above). Moreover, the new model supposes that the number of age groups and their parameters are the same as being used by surveillance centers.
2. One should add parameters that characterize a scheme of the disease (for example, the length of the latent period, the time of visiting a doctor, and, possibly, others) and the residents' response to infection (for example, what part of new infected residents visit a doctor.) The listed parameters are sufficient for implementing both ABM.To restore the real values of the infection probabilities in age groups (point 3) in the book (Tikhonov AN, et al. [5]) a regularizing procedure was proposed. According to this procedure, recovery is reduced to the problem of minimizing the functional, which is the integral quadratic difference between the functions (and their derivatives too) that determine the dynamics of the epidemic and obtained in points 2 and 5 (Perminov VD, [6]). At the same time, the proven uniqueness of the solution of the inverse problem transforms into uniqueness of the functional minimum value.

Therefore, for minimization of the functional it is possible to use any procedure supporting control of admissible values of infection probabilities in age groups. Since the infection probabilities are determined only by the type of virus and do not depend on the set of contacts, we can use the new ABM to obtain results for different sets of contacts. In particular, for the city under consideration we can see the effect of changing the date of school closures, the duration of closures, effect of the transfering a certain proportion of employees of various companies to remote work, and many other interventions. The results obtained in this way can be used to select among them and their combinations, optimal non-pharmaceutical interventions for different efficiency parameters (for example, the total number of infected residents during the epidemic) or change its dynamics (for example, a shift in the maximum on the dynamics of the epidemic) and so on.Result obtained are presented at the figure (source data for 4 different age groups presented by different types of curves and data, obtained at the step 5, by different types of icons) (Figure 1). Such analysis of the effectiveness of possible interventions can be done before the outbreak in the city is under consideration. In other words, you can prepare the city for a future outbreak!

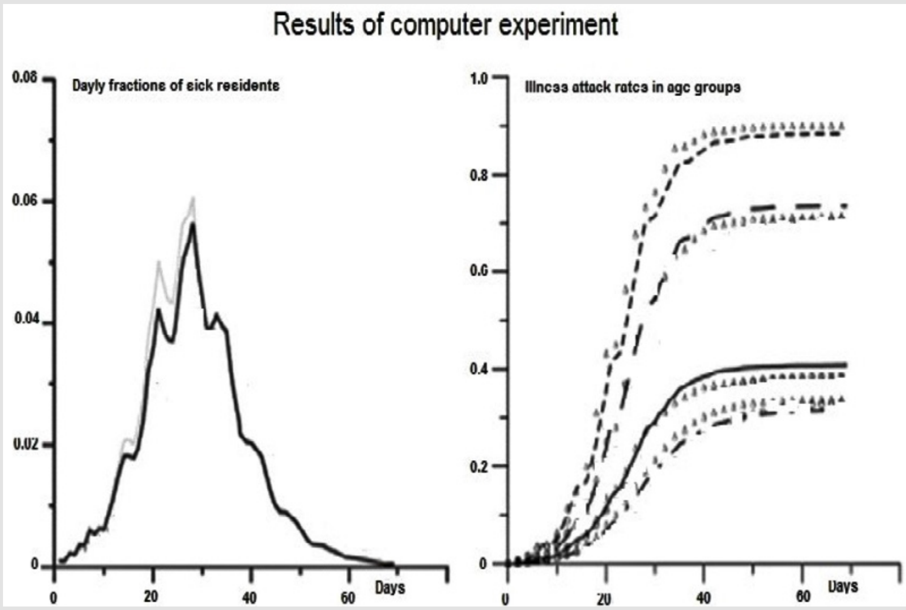

Figure 1: Result of computer experiment.

From what has been said, it is clear that in terms of the possibilities for practical application, the new ABM certainly occupies the first place. Among the shortcomings of new ABM, one should first of all note the huge amount of demographic and infrastructure data required for both ABM's implementation (some of them are quite difficult to find or calculate). Currently, there are databases adapted for use in ABMs, but usually they are strongly associated with the city under consideration, and their structure is also determined by the set of interventions considered.

Concluding Remarks

The new ABM described above was a result of studying advantages and disadvantages of the standard ABM. The first mention of it was made in the article (Perminov VD [6]). The implementation of the idea for a small town (Perminov V [7]) required a significant revision of the program created for the standard ABM. It turned out that in order to use all capabilities of the new ABM for a fairly large city, a new program is needed. Thinking through the logic of this new program has begun. At this time, the project which was created to master the standard ABM has ended. The new project could not be found. Therefore, it would be useful to share the accumulated experience. The following remarks are devoted to various aspects of this experience:

1. When distributing residents to different workplaces and households and for their identification in various parts of the model, a database is needed. Such databases were created for the standard ABM, but it's are tied to an unchanged set of contacts (for example, Cooley P, et al. [8]). In the new ABM, an analysis of interventions has become available. Most of such interventions require changing set of contacts and, therefore, principal correction of these databases is necessary.
2. Obviously, the most time-consuming process in the model is the procedure for minimizing the functional, since in it, at each new step, it is necessary to solve the problem of determining the step of the epidemic dynamics.
3. Therefore, it is preferable to use a small city as a source city.
4. Mortality can also be evaluated if we assume that it is proportional to the total number of infections during each day of epidemic and take the proportionality coefficients from the documented epidemic in a source city.
5. If the corresponding prices are known, the model can be modified to estimate the total cost of fighting the epidemic in the city under consideration.
6. Since the presence of a time gap between the end of the epidemic in the source city and its beginning in the city under consideration is not essential for testing the proposed model, this testing can be performed on the results of any past epidemic. The only condition is the identity of the schemes for fixing the results in the observation centers of the selected cities.

7. In principle, all of the above is also true for a pandemic (at least within the first wave). As a rule, a pandemic is characterized by significantly higher infection probabilities in all age groups. This, in turn, leads to a dramatic reduction in the time to make the necessary number of simulations, the value of which greatly increases. New parameters, compared to a pandemic case, can become more important (for example, the time necessary for creation of a vaccine, a scheme of its distribution, a speed of commissioning additional clinics, and the influence of many other factors).

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