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A human behavior integrated hierarchical model of airborne disease transmission in a large city

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ABSTRACT

Epidemics of infectious diseases such as SARS, H1N1, and MERS threaten public health, particularly in large cities such as Hong Kong. We constructed a human behavior integrated hierarchical (HiHi) model based on the SIR (Susceptible, Infectious, and Recovered) model, the Wells-Riley equation, and population movement considering both spatial and temporal dimensions. The model considers more than 7 million people, 3 million indoor environments, and 2566 public transport routes in Hong Kong. Smallpox, which could be spread through airborne routes, is studied as an example. The simulation is based on people's daily commutes and indoor human behaviors, which were summarized by mathematical patterns. We found that 59.6%, 18.1%, and 13.4% of patients become infected in their homes, offices, and schools, respectively. If both work stoppage and school closure measures are taken when the number of infected people is greater than 1000, an infectious disease will be effectively controlled after 2 months. The peak number of infected people will be reduced by 25% compared to taking no action, and the time of peak infections will be delayed by about 40 days if 90% of the infected people go to hospital during the infectious period. When ventilation rates in indoor environments increase to five times their default settings, smallpox will be naturally controlled. Residents of Kowloon and the north part of Hong Kong Island have a high risk of infection from airborne infectious diseases. Our HiHi model reduces the calculation time for infection rates to an acceptable level while preserving accuracy.

1. Introduction

Infectious diseases are a severe threat to public health. The severe acute respiratory syndrome (SARS) epidemic affected about 30 countries and resulted in 8422 cases and 916 deaths globally between November 1, 2002, and August 7, 2003 [1]. According to the data provided by the Centers for Disease Control and Prevention (CDC), from April 12, 2009, to April 10, 2010, approximately 60.8 million H1N1 cases and 12,469 deaths occurred in the United States [2]. The Middle East respiratory syndrome coronavirus (MERS-CoV) also causes severe respiratory illness with a high case-fatality rate in humans [3]. As of July 21, 2017, it had attacked 27 countries and induced 2040 cases, including at least 712 deaths [4]. Viral or bacterial respiratory infections are the cause of more than 10% of the 6 million global annual deaths [5]. Hong Kong has a high population density and has been badly affected by SARS [6], H1N1 [7], and H7N9 [8]. For example, from November 1, 2002, to August 7, 2003, approximately 20.8% of the global SARS cases and 32.8% of the SARS deaths occurred in Hong Kong [9]. Therefore, a study of airborne infectious disease transmission at the city level in Hong Kong can provide information that the local government needs to plan for, and deal with, emergencies.

There are two types of models of infectious disease transmission: mathematical and behavior models. Simulation of infectious disease transmission based on mathematical models such as SIR [10], SEIS [11], SIRS [12], SEIR [13], and complex networks [14] is generally very fast, but these models do not reflect micro-patterns such as personal contact, which are essential for studying the effects of intervention at the personal and building levels. Models based on human behavior use simulated human activity at hourly intervals to calculate infection probabilities [15,16], but are significantly limited by computational power. Most studies of human behavior and infectious disease transmission have focused on a single space, such as a hospital [17], a cruise ship [18], or an office [19]. The total population considered in these studies is usually no more than 50,000; when the total population in a study is several million, it is very computationally complex to simulate all human behavior that occurs in many different indoor environments. For a large city such as Hong Kong, the computer storage requirement alone can be formidably large if detailed behaviors

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are to be simulated [20]. However, if we combine these two types of models, most of their disadvantages can be solved and simulations can be accurately conducted within an acceptable amount of time.

Many precautions can be taken to reduce risk of infection, such as increasing ventilation [21], wearing a mask, washing hands, and isolation. Models that could simulate human behavior in detail for every room and building and consider many environmental factors would help governments to make more effective intervention plans. This study builds such a model using smallpox as a typical airborne infectious disease. We constructed a human behavior integrated hierarchical (HiHi) model to simulate airborne infectious disease transmission in Hong Kong, which has more than 7 million people, 2.5 million homes, 700,000 offices, 30,000 classrooms, 30,000 restaurants, 54 hospitals, and 2566 public transportation routes. For indoor environments, the simulation accounts for human behaviors and considers transmission patterns in a typical home, office, school, restaurant, hospital, and on public transportation. To reduce computer storage requirements, we determined mathematical patterns for indoor infectious disease transmission in each different type of indoor environment. Airborne infectious disease transmission at a city level was then simulated by combining mathematical equations for locations at a more granular scale (building and room) with daily human behavior.

2. Methods

2.1. Study area, data resources, and setting

The Hong Kong Census [22] shows that Hong Kong occupies an area of 1105.7 km^2 and hosts 7.1 million people [23], giving a population density of roughly 6395 people/km^2. There are four primary districts (Hong Kong Island, Kowloon, New Territory, and Outlying Islands) and 18 secondary districts (Central and Western, Eastern, Southern, Wan Chai, Kowloon City, Kwun Tong, Sham Shui Po, Wong Tai Sin, Yau Tsim Mong, Island, Kwai Tsing, North, Sai Kung, Sha Tin, Tai Po, Tsuen Wan, Tuen Mun, and Yuen Long) covering 412 blocks. In this study, we divided Hong Kong into a grid of 4649 squares that are 500 × 500 m in size.

Hong Kong has 2.5 million homes, 700,000 offices, 30,000 classrooms, 30,000 restaurants, 54 hospitals, and 2566 public transportation routes. For this study, Hong Kong residents are divided into four types: worker (office), student (kindergarten, primary/middle/high school, university), patient (hospital), and unemployed, which includes children under 4 years of age and people over 60 years of age (home). The Hong Kong Census provides data on residents' age, gender, household size, employment rate, and percentage attending a kindergarten, primary/middle/high school, or university (KSU) for the 412 blocks [22]. Fig. 1(A) shows the distribution map of hospitals and KSUs. The statistics collected by the Hong Kong government [24] and the Baidu map were used to obtain the coordinates of all 54 private and public hospitals and institutions, 196 kindergartens, 302 primary schools, 370 middle and high schools, and 25 universities.

Public transportation, which plays a critical role in infectious disease transmission, connects most people's homes with their work or place of study. Hong Kong has 2566 public transportation lines with 4760 stops, including buses, subways, trams, and ferries [25]. Fig. 1(B) shows the distribution of public transportation.

All of Hong Kong's residents were assigned to the 4649 grids based on the population distribution given in the Hong Kong Census [22]. The census also indicates the probability of a person living in a certain block going to a certain office location or KSU (i.e., a person living in a particular block has a greater probability of going to a nearby block to work or study.) Therefore, office distribution was also obtained from this dataset.

Our simulation of airborne infectious disease transmission was based on the dynamic population flow of 7 million Hong Kong residents among the six functional areas (home, office, school, restaurant, hospital, and public transportation/private car). We only considered weekdays in this study; weekends were not modeled.

2.2. Airborne infectious disease transmission model

In this study, we regarded the outdoors as an infinite space and assumed that people cannot be infected outdoors; thus, all airborne infectious disease transmission events occur in indoor environments. We used the Wells-Riley [26] equation (Eq. (1)) to simulate airborne infectious disease transmission in indoor environments:

$$P = 1 - \exp\left(-\frac{pQ\tau}{q}\right) \tag{1}$$

where P is the infection probability per person per hour; Q is the average number of infectious quanta generated by an infector with Q set to 2 quanta/h (20); p is the pulmonary ventilation rate, set at 0.38 m^3/h [27]; τ is the duration of exposure to infection (h); and q is the ventilation rate of the location (m^3/h).

According to the known progression of smallpox infection, the latent period is the initial 11.6 days and the infectious period lasts from day 11.6 to day 32.39, including the first 2.49 days of the symptomatic period [28]. Infected people usually show symptoms during the

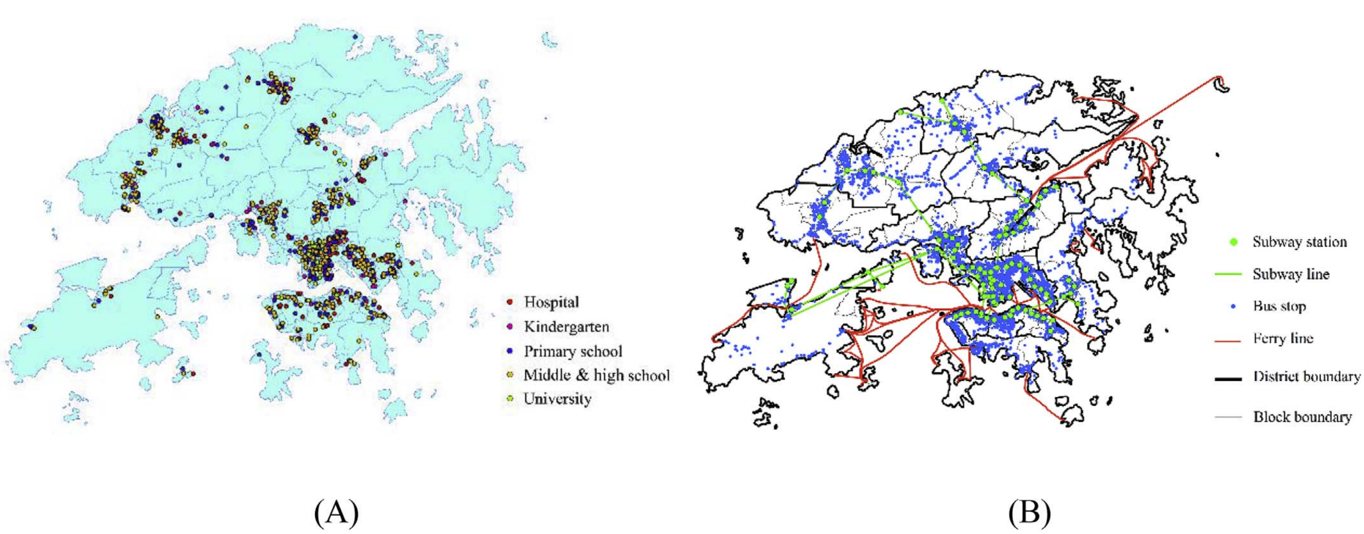

Fig. 1. Hong Kong: (A) Distribution of hospitals and KSUs; (B) Distribution of public transportation stops and routes.