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Evaluation of intervention strategies in schools including ventilation for influenza transmission control

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Research Article

Indoor/Outdoor Airflow and Air Quality

Abstract

Many common respiratory infectious diseases transmit readily among school-age children. In major epidemics, school closures and class suspensions may be implemented to attempt to control transmission in the community. However, such intervention measures have been subject to an extensive debate as well as questions of its effectiveness and adverse social impacts. In the meanwhile, engineering intervention methods are also available, but their impacts at the community level were not well studied. A better understanding of how different school interventions contribute to the airborne disease prevention can provide public health officials important information to design infection control strategies, in particular how engineering control methods such as ventilation are compared to other intervention methods. In this study a hypothetical indoor social contact network was constructed based on census and statistical data of Hong Kong. Detailed school contact structures were modeled and predicted. Influenza outbreaks were simulated within indoor contact networks, allowing for airborne transmission. Local infection risks were calculated from the modified Wells-Riley equation, and the transmission dynamics of the disease were simulated using the SEPIR model. Both school-based general public health interventions (such as school closures, household isolation) and engineering control methods (including increasing ventilation rate in schools and homes) were evaluated in this study. The results showed that among different school-based interventions, increasing ventilation rate together with household isolation could be as effective as school closure.

Keywords

airborne infection,
social network,
engineering control,
school interventions,
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Article History

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1 Introduction

The epidemiological studies of the pandemic H1N1 outbreak 2009 have demonstrated a high attack rate to school-age population in many major outbreak countries or regions (Archer et al. 2009; CDC 2009a; Dawood et al. 2009; Fielding et al. 2009; Fraser et al. 2009; Gianella et al. 2009; Gilsdorf and Poggensee 2009; Health Protection Agency et al. 2009; Kelly and Grant 2009; Munayco et al. 2009; Nishiura et al. 2009; WHO 2009a; Wu et al. 2010a). Large school outbreaks have been reported (Calatayud et al. 2010; CDC 2009b; Dawood et al. 2009; Kawaguchi et al. 2009). The Hong Kong H1N1 influenza surveillance data in Year 2009 also showed an earlier and extensive outbreak in younger population (Wu et al. 2010b). The pattern of infection age distribution was believed to be caused by a higher susceptibility of younger population (Dawood et al. 2009; Mermel 2009; WHO 2009a).

School-age population was identified to have a significant impact on influenza pandemic (Kar-Purkayastha et al. 2009; WHO 2009b) and it has received a great intention for related interventions, such as school-age children vaccination (White et al. 1999; Hurwitz et al. 2000; Reichert et al. 2001; Jefferson et al. 2005; Longini and Halloran 2005; Weycker et al. 2005;

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King et al. 2006), closure of schools (Ferguson et al. 2006; Cowling et al. 2008; Cauchemez et al. 2009; Wu et al. 2010b), hand-hygiene (Dyer et al. 2000; White et al. 2001; Meadows and Le Saux 2004; Morton and Schultz 2004; Talaat et al. 2011) and air-hygiene etc. (Chen and Liao 2008) However, the understanding of school intervention policies is rather limited due to the insufficient understanding of school contact structure and the role of school intervention policies in influencing social distance (Cauchemez et al. 2009). On the other hand, engineering interventions such as increasing ventilation rate and applications of air-hygiene equipments were largely neglected in the comparison of different school interventions caused by the difficulty of evaluating engineering methods in epidemiology models.

In this study we develop an indoor social contact network based on the data of demographical, construction and population social behavior of Hong Kong and simulate airborne transmitted influenza outbreaks in a large city. Detailed simulation of school contact is included in order to evaluate the effectiveness of different school-based intervention policies. We compare general public health interventions such as increasing household isolation rate of symptomatic students, school closures and engineering intervention of increasing ventilation rate.

2 Methods

2.1 Collection of statistical data

Demographical data of Hong Kong such as the size of population, household size distribution, occupations, social behaviors and numbers of students in different types of schools are collected from the Census and Statistics Department of HKSAR (http://www.censtatd.gov.hk/home/index.jsp). Considering the potential difference in school contact behaviors of students at different education levels, we separate schools to 4 types as listed in Table 1.

Data of class size distributions and school size distributions of primary schools and secondary schools were provided by Education Bureau of HKSAR. As shown in Fig. 1, class sizes in both primary schools and secondary schools are found to be best fit to normal distribution.

However, the distribution of school sizes in different types of schools is found largely different. As shown in Fig. 2,

Table 1 Statistical data of different types of schools

School type	Number of students	Number of schools	Average class sizes	Number of classes
Kindergartens	147 496	964	20.3	7266
Primary schools	387 547	601	32.2	12036
Secondary schools and colleges	531 944	643	36.7	14495
16 higher degree institutions	284 550	16	40[#]	6940

[#] Assumed data.

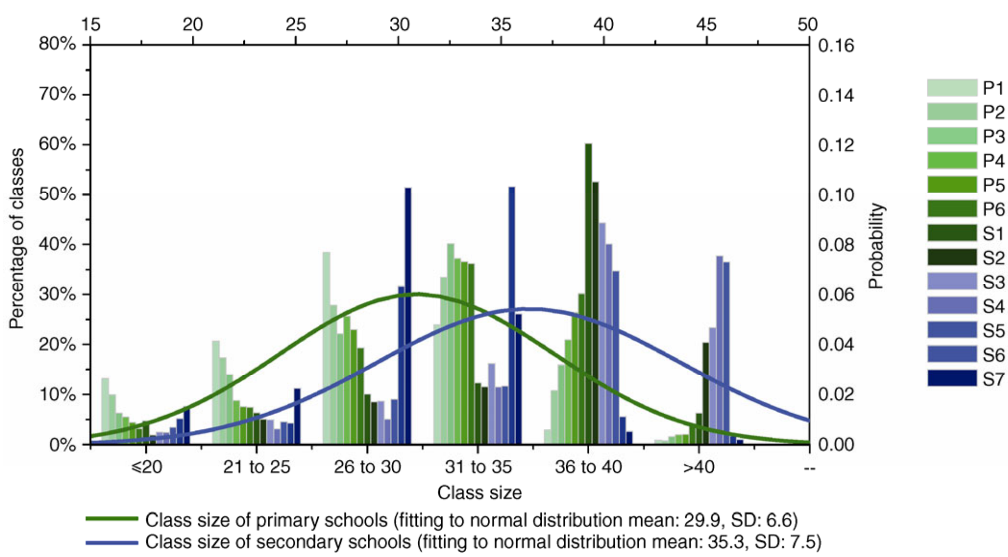

Fig. 1 Fitting of class size distribution of primary schools and secondary schools (P1—Grade 1 in primary school, S1—Grade1 in secondary school)

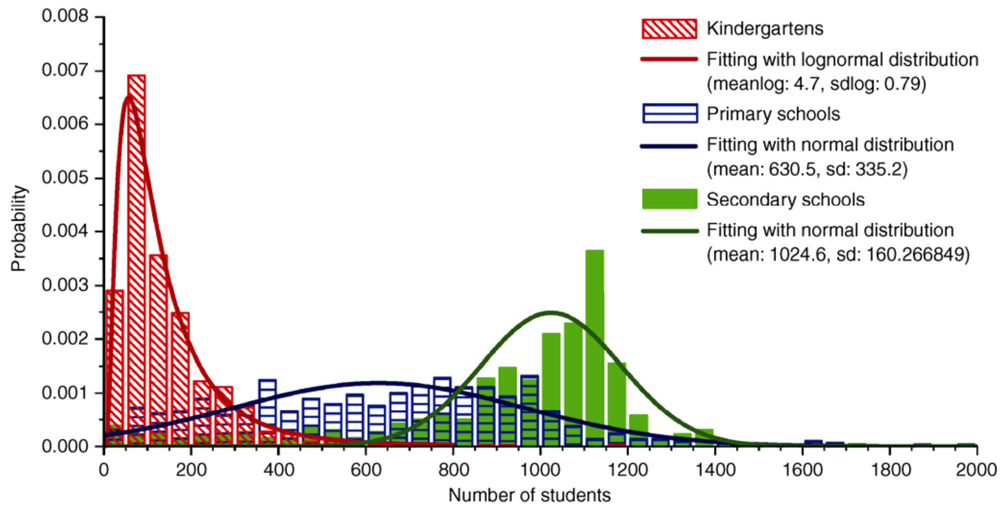

Fig. 2 School size distributions of kindergartens, primary schools, and secondary schools

school sizes in kindergartens are found best fitted with lognormal distribution, by contrast, school sizes in primary schools and secondary schools are best fitted with normal distribution.

Class size distributions in kindergartens and higher education level are not available. An average class size of 20.3 in kindergartens in Year 2003 is reported in the Hong Kong 2006 Population By-census (the Census and Statistics Department Hong Kong Government 2007), hence we assume that the distribution of class sizes in kindergartens also follows the normal distribution and the standard deviation is 5. Information of class sizes in higher institutions such as universities are not readily available. Considering that a small number of classes in universities might enrolled with a large number of audiences, we assume that the distribution of class sizes follows a lognormal distribution (meanlog: 3.69, sdlog: 0.6).

2.2 Building indoor social contact network

A synthetic population and a collection of all locations are first built according to the statistical data of Hong Kong as listed in Table 2. Individuals are first randomly assigned with a home. Connections can then be built between individuals and the rest of locations to represent contacts of individuals in different locations.

The contact structure of students is modeled in detail considering the inter-classroom contacts and the inter-school contacts. Connections between classrooms and students are built with the following steps:

(1) School sizes are first generated according to the school size distribution of Hong Kong.
(2) Classes are randomly assigned with a school that they belonged to.
(3) Students are first connected with schools.
(4) Students can only choose to attend classrooms within the same school they selected. Students who attend secondary schools and universities are assigned to multiple classrooms.

A recursion algorithm is applied to guarantee the selection of all classrooms and all individuals are independent and all locations are not overflowed.

Individuals in other groups other than students and home stayed individuals are first randomly assigned a work place according to their population group. Individuals working outdoors are not given any indoor locations that they work in. Other locations including restaurants, public places, shops and vehicles are connected with individuals with a

Table 2 Proportions of different types of locations and proportions of individuals work or study in each type of locations

Type	Homes	Schools	Offices	Restaurants	Public places	Shops	Vehicles	Outdoor Places
Locations	0.7518	0.0132	0.0113	0.0492	0.004	0.1193	0.0512	
Population	0.3334*	0.1849	0.2193	0.0287	0.0095	0.0513	0.0015	0.1714

* Representing home stayed individuals including housewives, retired people, pre-school age children, babies and domestic helpers.

selection algorithm based on their social behavior. The details of our social contact model are provided by Gao (2011). The predicted results such as the degree distributions of people-location graph and degree distributions of people-people graph are compared with those in Eubank (2004) and a good agreement was found.

2.3 Exposure risk and SEPIR model

Local exposure risks of individual i in different locations are estimated using the Wells-Riley model (Wells 1955). If we use $p_{i,l}$ to represent the possibility of individual i being infected in location l, the infection risk can be expressed as follows:

$$p_{i,l} = 1 - \exp\left(-\frac{QcI_l\tau_l}{q_l}\right) \quad (1)$$

where Q is the average number of infectious quanta generated by an infector (quanta/h), c the pulmonary ventilation rate (m^3/h). τ_l the duration of exposure of individual i in location l for infection (h), I_l the number of infectors in l and q_l the ventilation rate the location (m^3/h).

The overall infection risk of each individual is then integrated according to exposure risks of all locations that individual visited. The epidemic was simulated with the SEPIR (susceptible, exposure, pre-intervention-action infectious, infectious and recovery) model. The latent period and overall infectious period were estimated to be 2 days and 4 days, respectively (Longini et al. 2004). Pre-intervention transmission period in the study is defined as the period that infection occurs before any possible intervention actions. We assume a pre-symptomatic transmission period of 0.5 days (Wu et al. 2006) and a 0.5 day delay of possible intervention actions to comprise the pre-intervention transmission period. Hence the pre-intervention-action transmission period is assumed to be 1 day and the infectious period will continue for another 3 days. We assumed that 1/3 of all infectors will be asymptomatic. All input data for the baseline case simulation is summarized in Table 3 and Table 4.

2.4 Simulation of school-based intervention policies

School-based interventions are considered in this study including increasing the home isolation rate of symptomatic students, school closures at different infection thresholds, targeted school closures and increasing ventilation rates in schools. When adopted these school interventions, an increase of household exposure will be introduced, hence we also consider the effectiveness of increasing ventilation rates in both schools and households. All choices of intervention policies are listed in Table 5. Policy of increasing

Table 3 Input data for the model

	Data	Sources
Population size	700 000	Estimated
Number of locations	300 000	Estimated
Quanta generation rate, Q (quanta/h)	3.5	Estimated
Pulmonary ventilation rate, c (m^3/h)	0.38	Chen et al. 2006
Exposure time , τ_l (h)	$10^{\wedge}$, $8^{\&}$, 0.5^{+}	Estimated
Latent period (day)	2	Longini et al. 2004
Pre-intervention transmission period (day)	1	Wu et al. 2006
Infectious period (day)	4	Longini et al. 2004
Asymptomatic percentage of infectors	30%	Estimated

^ Household exposure period per day.
& Work-related exposure period per day.
+ Exposure period of other type of contact per day.

Table 4 Ventilation rate and population density of different locations

	Homes	Schools	Offices	Restaurants	Public places	Shops	Vehicles
Ventilation rate (ACH)	0.7	1	1	1	1	1	4
Population density (m^3/person)	30	6.5	13	5	7	13	2

Table 5 List of school-based intervention polices

Policy	Increasing home isolation rate of students	Closure of all schools (threshold percentage of symptomatic cases)	Closure of targeted schools (threshold percentage or No. of symptomatic cases)	Increasing ventilation rate in schools (ACH)	Increasing ventilation rate in both schools and households (ACH)
Code	A	B	C	D	E
1	60%	10%	10%	2	2
2	80%	5%	10	5	5
3	100%	1%	5	10	10
4		0.1%	1		

the home isolation rate of students here represents a restriction of probability of symptomatic students to visit all locations except their homes when they are discovered to be symptomatic. The targeted school closure policy (Policy C) is different from closing all schools at the same time (Policy B), as in Policy C only schools with any identified case or cases are closed.

3 Results

The baseline scenario is simulated and shown in Fig. 3. Assuming that the population is completely susceptible to the circulating virus, the outbreak will reach the peak of infectors after 23 days from the beginning of infectors introduced to the population. The peak infection rate is 26% of all individual. Assuming that the population is completely susceptible to the diseases, simulation results shows that 96% of all individuals will be infected under a quanta generation rate of 3.5 quanta/hour. Our results are in qualitative agreement with other predictions such as (Wu et al. 2006).

Effectiveness of different control parameters in different intervention policies were illustrated in Fig. 4. As shown in Figs. 4(a) and (b), increasing isolation rates to the infected and symptomatic students to 100% will introduce a 3% reduction of the peak infection rate and a delay of peak infection for 1 day. School closure policy, by contrast, shows a higher control effect (about 10% reduction of peak infection rate and 1 day delay of peak infection under Policy B3), especially in student population groups. However, the restriction of school closures, as shown in Figs. 4(c) and (d), is found to have a weakened ability of reducing the scale of outbreak. A change of threshold from 1% of all infectors to 0.1% of infectors did not show a significant delay of the outbreak peak, whereas, an increased peak infection rate in student population groups. Lower peak infection rates of students under Policies B2 and B3 are caused by the extended outbreak duration in the student groups; and the overall attack rates are still higher than the outbreak scenario under Policy B4. The targeted school closure policy shows a better control effect than when school closure threshold is 0.1% of overall infectors (Policy B4). The number of infectors discovered in a school as a control parameter of shutting down the school (Policy C, shown in Fig. 4(e) and (f)) is demonstrated to be less sensitive than the control threshold of shutting down all schools at the same time (Policy B).

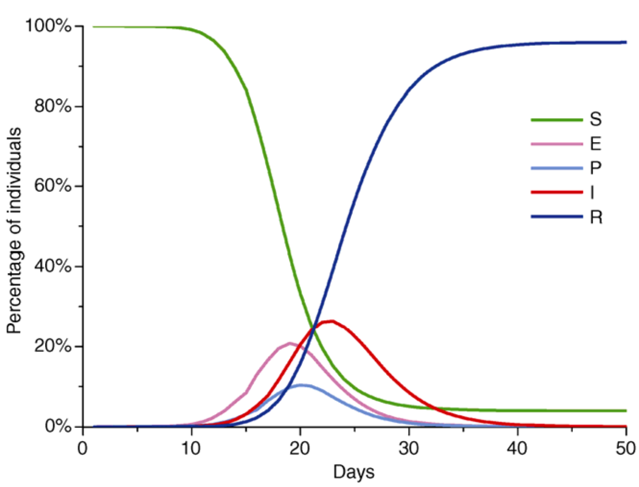

Fig. 3 Baseline outbreak scenario of influenza

Increasing ventilation rate to 10 ACH in schools will introduce a reduction of peak infection number by 9% and the peak of outbreak postponed for 3 days as shown Figs. 4(g) and (h). Increasing ventilation rates in both schools and homes shows the best control effect in both reducing the scale of infection and delaying the outbreak (34% and 41% of reduction of peak infection rate in overall population and students, respectively; 4 and 6 days delay of peak infection in overall population and students, respectively).

In reality, reaching an average air change rate of 10 ACH in homes and schools may be difficult to achieve as limited by many factors such as ventilation system and energy efficiency. However, such a ventilation rate or higher can be reached simply though open windows (Chao 2001; Escombe et al. 2007) if conditions permit. In addition, the school closure policy was also considered to have many potential social and economical influences to the society. Therefore here we compared the effectiveness of each single intervention policy with combinations of relatively-easily achieved policies (increasing ventilation rate to 5 ACH and isolation) and the results are plotted in Fig. 5.

In all school-based intervention policies, the targeted school closure policy has the best control effect in terms of reducing peak infection rate and delaying peak infection. Increasing ventilation rate also has the same ability to delay the arrival of peak infection. Furthermore, combining increasing ventilation rate and 100% isolation of symptomatic students (Policies A3 and D2) can achieve a similar control effect as school closures. Although increasing ventilation rate of both homes and classrooms to 10 ACH is hard to achieve in practice, similar control effect can be reached by combining policy of increasing home isolation rate of the symptomatic students and increasing ventilation rate of classrooms and homes to 5 ACH (Policies A3 and E2) and adding a additional school closure intervention (Policies A3, C3 and E2) did not change the dynamic significantly.

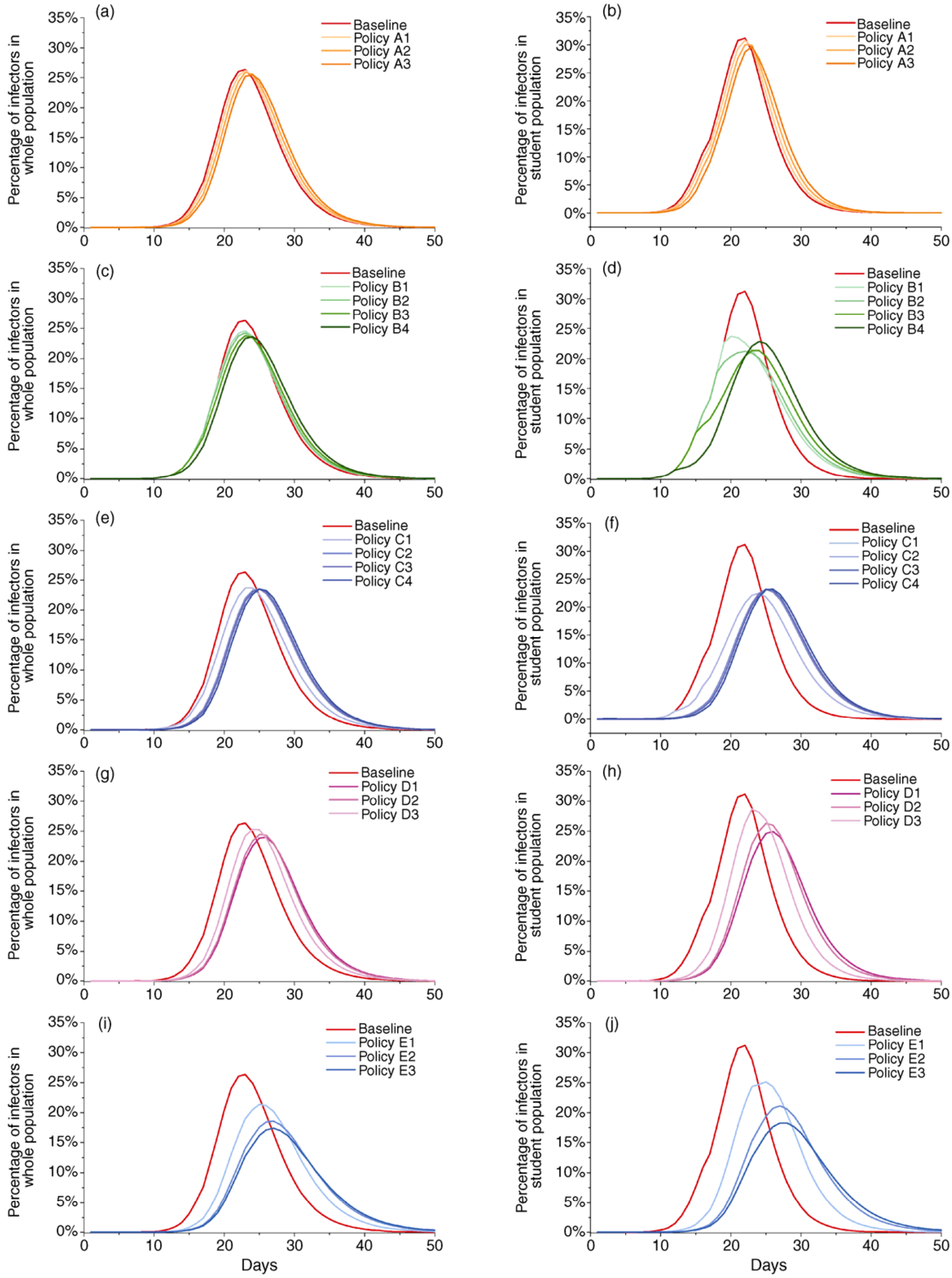

Fig. 4 Sensitivity of control parameters when different intervention policies are used. The left figures are for the percentage of infectors in the general population and the right figures for that in the student population. (a, b) Percentages of infectors in the general population (a) and in the student population (b) during the outbreak under the different household isolation rate of symptomatic students. (c, d) Percentage of infectors and infected students when all schools were shut down at different thresholds of overall infectors. (e, f) Percentage of infectors and infected students during the outbreak period when schools with more than 10, 5 or 1 symptomatic students. (g, h) Percentage of infectors and infected students changes with different ventilation rates in classrooms. (i, j) Percentage of infectors and infected students changed with increasing ventilation rates in both households and classrooms. Representing code names of all intervention policies are listed in Table 5

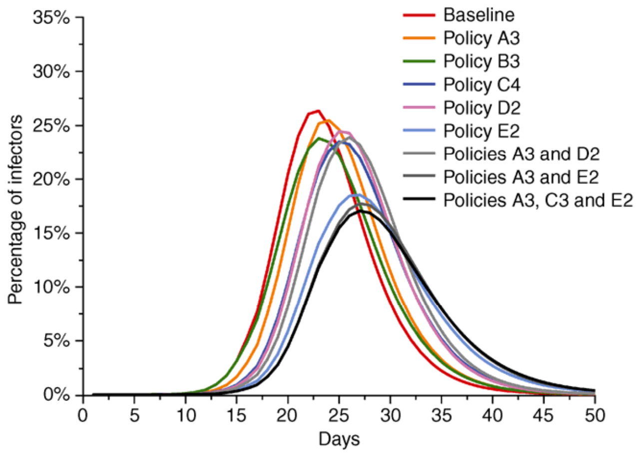

Fig. 5 Percentage of infectors changing with time under different control policies

4 Discussion

The school-based intervention policies discussed in this paper all demonstrated the ability to moderate the scale of influenza outbreak. However, their control effects are largely restricted by social behaviors, namely, household contacts and contacts introduced by other social activities such as eating in a restaurant, shopping etc. The basic disease transmission chains in the society are from large hubs (large crowed locations, where exposure times of individuals are longer and infection risks are higher) in the contact network to all ends of the network (homes) and go back to these large hubs again. In many cases each households connected with more than 1 large hub, mostly work places and schools. Cutting down one path of infection to reach homes will not have significant impact on stopping the circulation of the disease. By contrast, decreasing household and school transmission rate together trough increasing ventilation rates have demonstrated a good control effectiveness, due to the increased efficiency of blocking transmission chain of the infection in community.

The control parameter of targeted school closure policy was shown to have the least influence on the outcome of simulation results and demonstrated a better control effect than the most strict control policy of shutting down all schools at the same time. This indicated that in the community the transmission paths in the simulation model are scattering from one infection cluster to others. Hence the restriction of schools with infected cases serves the same purpose as the overall school closures at the very early stage of infection outbreak.

Comparing with other studies (Cauchemez et al. 2008; Lee et al. 2010), our simulation showed a lower control ability of school closures in mitigating the outbreak. This might be caused by several reasons. Firstly, our model simulated a network, where school contacts are not the only type of location dominated transmission risks in the transmission dynamic. Work places with potentially larger number of workers sharing the same room, such as large companies and factories, were also considered in our model (fitting from the structure of work places in Hong Kong). Secondly, children and students were assumed to have the same infectivity and susceptibility as the rest of population, which also eliminate the importance of inner-school transmission in the dynamic of the outbreak in our model. In the meanwhile, the pre-symptomatic transmission period and the delay of intervention actions of influenza were estimated to be 1 day, which is longer than the estimated value of other studies. The simulation case compared in this study adopted a quanta generation rate of 3.5 quanta/(h·person), which representing a highly infectious scenario, was suggested to be less likely controlled through shutting down schools (Halloran et al. 2008).

Comparing with other general public health school-based interventions such as household isolation and school closures, increasing ventilation rate also demonstrated the same ability of controlling the epidemic. Increasing ventilation in both homes and schools can achieve a higher control effect than other interventions. This is a very encouraging result. However, we considered that the disease is transmitted only via the airborne route, which might have magnified the importance of ventilation in controlling influenza outbreaks. Models simulating the multiple transmission routes of influenza should be adopted in future studies. There has been a continuing debate about the transmission routes of influenza. Even reviewing the same literature of evidence, different authors draw opposite conclusions with regard to the quality of evidence for airborne infection, e.g., Tellier (2006) and Brankston et al (2007) on influenza.

In our study, although school attendances of student to classrooms, changing of classrooms were simulated, detailed inner-school mixing patterns involving with peer groups, teachers, possible plenary meetings were not considered. These complex mixing patterns, together with the potential higher transmission rate of the disease among students, may enlarge the importance of inner-school transmission and might introduce a better control effect of school-based interventions.

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