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Breaking down of the healthcare system: Mathematical modelling for controlling the novel coronavirus (2019-nCoV) outbreak in Wuhan, China

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Abstract

A novel coronavirus pneumonia initially identified in Wuhan, China and provisionally named 2019-nCoV has surged in the public. In anticipation of substantial burdens on healthcare system following this human-to-human spread, we aim to scrutinise the currently available information and evaluate the burden of healthcare systems during this outbreak in Wuhan. We applied a modified SIR model to project the actual number of infected cases and the specific burdens on isolation wards and intensive care units, given the scenarios of different diagnosis rates as well as different public health intervention efficacy. Our estimates suggest the actual number of infected cases could be much higher than the reported, with estimated 26,701 cases (as of 28th January 2020) assuming 50% diagnosis rate if no public health interventions were implemented. The estimated burdens on healthcare system could be largely reduced if at least 70% efficacy of public health intervention is achieved.

Keywords

2019-nCoV, novel coronavirus, Wuhan pneumonia, healthcare system, mathematical modelling

1. Background

A novel coronavirus pneumonia, initially identified in Wuhan, Central China and now named as 2019-nCoV[1], has surged in the public. With the increasing incidence of confirmed cases, corresponding spread control policies and emergency actions are taking place.

The symptom onset date of the first 2019-nCoV patient was identified in early December 2019 and the outbreak started in late December with most of cases epidemiologically connected to a

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seafood market in the city of Wuhan, Hubei province[2]. Following the cases reported in other Chinese cities and overseas, the National Health Commission (NHC) of People's Republic of China confirmed the evidence of human-to-human transmission of such viral pneumonia[3]. As of 28th January 2020, authorities had reported more than 4,515 confirmed cases across thirteen provinces in mainland China and confirmed 106 deaths. First laboratory-confirmed case was also reported in Taiwan on 21st January, and on the following day, both Hong Kong and Macao reported their first confirmed cases. Globally, Thailand, Japan, South Korea, Vietnam, Singapore, Malaysia, Nepal, France, Canada, Australia and the United States had reported cases infected by 2019-nCoV. All confirmed cases so far are travellers from or ever been to Wuhan or other Chinese cities. The number of confirmed cases is expected to increase given the availability of fast-track laboratory test and anticipated country-wide commute arising from Lunar New Year holidays.

Although the genetic relatedness of 2019-nCoV to previous viral outbreaks such as Severe Acute Respiratory Syndrome (SARS) in 2003 and Middle Eastern Respiratory Syndrome (MERS) in 2012 has been established, its details regarding age range, animal source of the virus, epidemic curve, transmission route, pathogenesis, autopsy findings and any treatment responses to antivirals amongst the severe cases are still limited.[4]

To combat the 2019-nCoV outbreak, authorities in China have implemented several preventive measures. Starting from 10am, 23rd January, all public transport has been temporarily suspended following by the lockdown on the city of Wuhan[5]. Neighbouring cities also announced a lockdown in sequence. Local residents were advised to remain at home and avoid gathering in order to contain the virus spread. Following the raise of protection standards

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instructed by NHC, prevention and control measures, such as disinfection for public facilities, have been strengthened and taking places in other cities[6]. For example, Hong Kong, a special administrative region of China, has undergone temperature screening of passengers at broader entries following the Prevention and Control of Disease Ordinance and the International Health Regulation[7]. The Centre for Health Protection of Hong Kong has also advised avoidance of close contact with animals and persons with fever or respiratory symptoms and recommended maintaining hand hygiene as well as wearing surgical masks for precaution and self-protection[8].

Facemask wear has been considered as one of the most cost-effective approaches in infectious disease prevention and control. A recent cluster randomised controlled trial[9], consisting of multiple region-varying medical settings, compared the effectiveness of preventing influenza and other viral respiratory infections between N95 respirators and medical masks and found both types of mask wear had comparable effects with no significant difference.

In anticipation of substantial burdens on healthcare system following this human-to-human transmissible epidemic, we aim to scrutinise the currently available information and evaluate the burden of healthcare system during the 2019-nCoV outbreak in China. We hope, by doing so, that the findings are able to provide efficacious suggestions on reducing the spreads on the large scale and help authorities formulate effective control measures on combating the emerging viral outbreak.

2. Methods

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In the classic SIR model, *S* represents the susceptible population, *I* represents the infected population, and *R* represents the recovered population. Susceptible population can be infected, who would be cured or died of the infection. The composition of susceptible, infected, recovered, deceased population is modelled based on a set of transition probabilities.

In this study, we applied a modified SIR model to evaluate the burden of healthcare system during the 2019-nCoV outbreak in China. Figure 1 shows the design of our model. Each cycle is one day in our model. The parameters used in the model were estimated based on the reported incidence released by the NHC of the People's Republic of China or recent investigation on the outbreak (Table 1). Daily reported incidence of confirmed 2019-nCoV cases, death, and recovery in China is available from 11 January, 2020.[10] However, given that the probability of misdiagnosis is likely to be high in the early stage of the outbreak, we used the reported incidence between 0:00-24:00 on 25 Jan 2020 (the most updated data when the analysis was performed).

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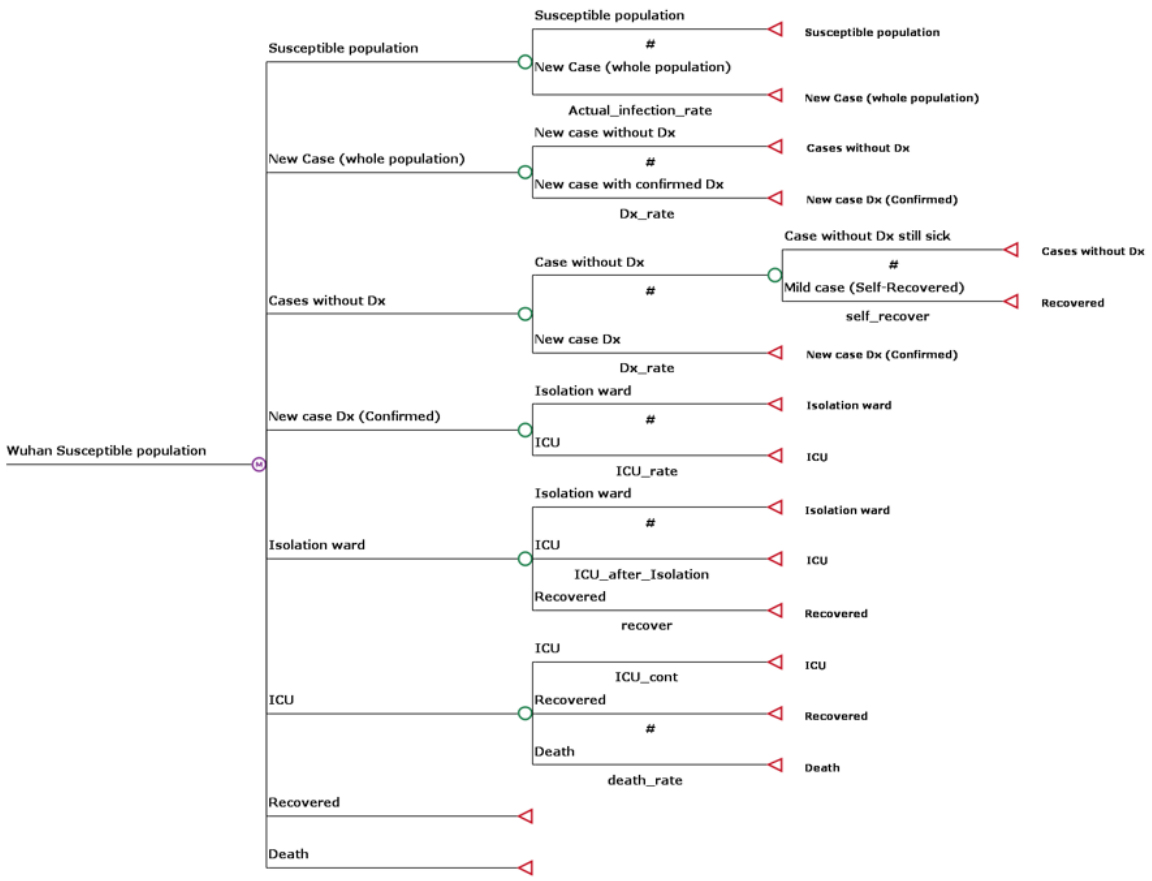

Figure 1 Design of the modified SIR model to evaluate the burden of healthcare system during the 2019-nCoV outbreak in China

The parameters included in the model were transition probabilities from one state to another in any given day. Briefly, we estimated the probability of being infected (Actual_infection_rate), the probability of being admitted to ICU if being a confirmed case (ICU_rate), and the probability of recovering from infection if being hospitalised (Recover_rate) according to the reported incidence and the total population in Wuhan. We further assumed that the probability of recovering from infection if not being hospitalised (SelfRecover_rate) would have been one-third of the Recover_rate. We also assumed that 2% of the confirmed cases admitted to isolation ward would experience deterioration of the symptoms and be admitted to ICU (ICU_After_Isolation). Probability of remaining in the ICU in the next day (ICU_cont) as estimated based on an assumption that a confirmed case can be discharged after receiving

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treatment for averagely 10 days in the ICU. We considered a 14% death rate among the hospitalised cases (Death_rate) according to the recent investigation by researchers from the University of Hong Kong.[11] Lastly, the report by the MRC Centre for Global Infectious Disease Analysis at Imperial College London suggests there were a total of 4,000 cases of 2019-nCoV in Wuhan City (uncertainty range: 1,000 – 9,700) by 18th January 2020.[12] Comparing to the number of cases released by the NHC of the People's Republic of China, this report suggests a diagnosis rate of less than 10%. Therefore, we considered multiple scenarios with different probabilities of being diagnosed if being infected (Dx_rate).

Table 1 Parameter for the SIR model

Parameter[a]	Meaning	Estimation[b]	Mean[c]	Model input[c]
Death_rate	Probability of death if being infected and hospitalised	$\text{Death_rate} = 14\%$ [11]	14%	14%
Dx_rate	Probability of being diagnosed if being infected	Assuming 10%, 50%, 90%, and 100% of the infected population can be accurately diagnosed.	10%, 50%, 90%, 100%	10%, 50%, 90%, 100%
ICU_rate	Probability of being admitted to ICU if being a confirmed case	Estimated based on data from National Health Commission of the People's Republic of China.[13] $\text{ICU_rate} = \frac{\sum(nNewICU/nNewCase)}{n}$	19%	12.6%
ICU_cont	Probability of remaining in the ICU in the next day	Assuming that a confirmed case can be discharged after receiving treatment for averagely 10 days in the ICU. $\text{ICU_cont} = \frac{1}{10} = 10\%$	10%	10%
ICU_after_Isolation	Probability of being admitted to ICU after admitted to isolation ward	$\text{ICU_After_Isolation} = 2\%$	2%	2%
Actual_infection_rate	Probability of being infected	Estimated based on data from National Health Commission of the People's Republic of China.[13] $\text{Acutal_infection_rate} = \frac{\sum(nNewCase/nPopulation)}{n}$	0.0042%	0.0063%
Recover_rate	Probability of recovering from infection if being hospitalised	Estimated based on data from National Health Commission of the People's Republic of China.[13] $\text{Recover_rate} = \frac{\sum(nNewRecover/nNewCase)}{n}$	1.5%	1.6%
SelfRecover_rate	Probability of recovering from infection if not being hospitalised	Assuming that the probability of recovery among the infected persons who were not hospitalised is 1/3 of those being hospitalized. $\text{SelfRecover_rate} = \frac{\text{Recover_rate}}{3}$	0.5%	0.53%

[a] All probabilities are probabilities in each day

[b] n is the number of days of which the data were used for estimating the parameter; nNewDeath is the number of newly reported death each day; nNewCase is the number of newly reported cases each day; nNewICU is the number of newly reported cases admitted to ICU each day; nPopulation is the number of population, in this analysis we used the number of population in Wuhan city, i.e., ~11 million; nNewRecover is the number of newly reported recovered patients each day;

[c] Mean values were based on the reported incidence between 0:00-24:00 on 23, 24, and 25 Jan 2020 (n=3); model input were based on the reported incidence between 0:00-24:00 on 25 Jan 2020 (n=1)

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3. Results

Figure 2 depicts our estimated numbers of cases using a modified SIR model based on the currently available information. We generated curves of four hypothesised diagnosis rates to project the developments of reported cases. For diagnosis rates of 100%, 90% and 50%, the projections are expected to lower than 25,000 cases with noticeable increases during the early stage (<50 days). However, under the condition of only 10% diagnosis rate, the case number at the early stage is expected to soar and exceed the threshold of 25,000 much sooner compared with other scenarios with higher diagnosis rate.

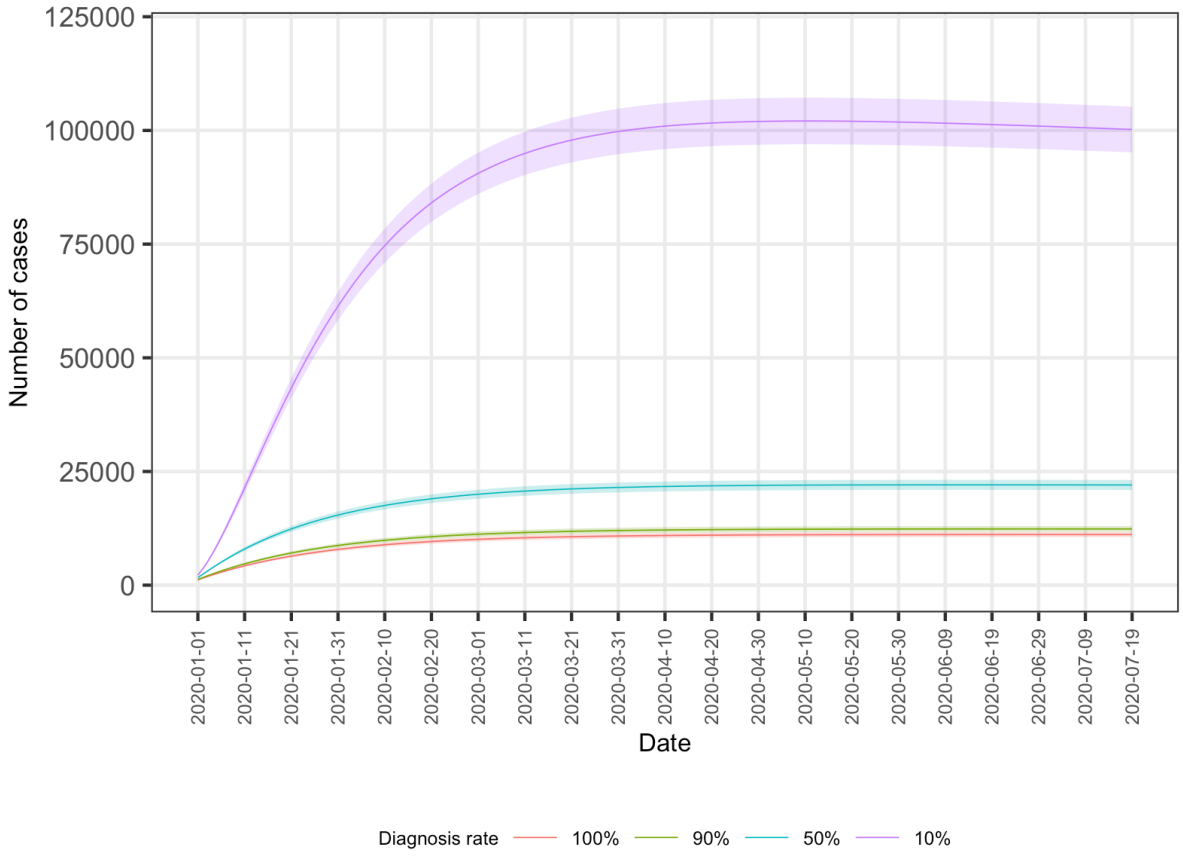

Figure 2 Estimated numbers of cases under scenarios with different diagnosis rates

As of 28th January, it is estimated that there were 95,933 cases given a 10% diagnosis rate whilst being 26,701 and 15,332 cases given diagnosis rates of 50% and 90%, respectively, if

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no public health interventions were implemented (see Table 2). We further estimated the number of cases with public health intervention efficacy of 70%, 80% and 90%, assuming a 50% diagnosis rate (Scenarios 4, 5 and 6). If 70% efficacy rate could be achieved (Scenario 4), the forecasting number of cases would drop dramatically to 11,056 as of 7th February when compared with 36,809 predicted without public health interventions (Scenario 2). It is expected that greater benefits with fewer cases can be obtained if higher efficacy (e.g., 80% or 90%) is reached.

Table 2 Estimated total number of cases in six different scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Diagnosis rate	10%	50%	90%	50%	50%	50%
Public health intervention efficacy	No public health intervention	No public health intervention	No public health intervention	70%	80%	90%
Estimated total number of cases on 28 Jan 2020	95,933	26,701	15,332	8,017	5,345	2,673
Estimated total number of cases 10 days later (7 Feb 2020)	143,165	36,809	20,969	11,056	7,372	3,686

We also investigated the specific burdens on isolation ward (Figure 3) and intensive care unit (ICU, Figure 4) assuming a 50% diagnosis rate, given public health intervention scenarios of baseline (no intervention), 70%, 80% and 90% efficacy rate. If 70% efficacy rate of public health intervention could be achieved, the number of cases being admitted to isolation wards and ICU would drop to a large extent throughout the course of outbreak. Similarly, greater benefits for healthcare system are expected to obtain if higher efficacy can be achieved (e.g., 80% or 90%).

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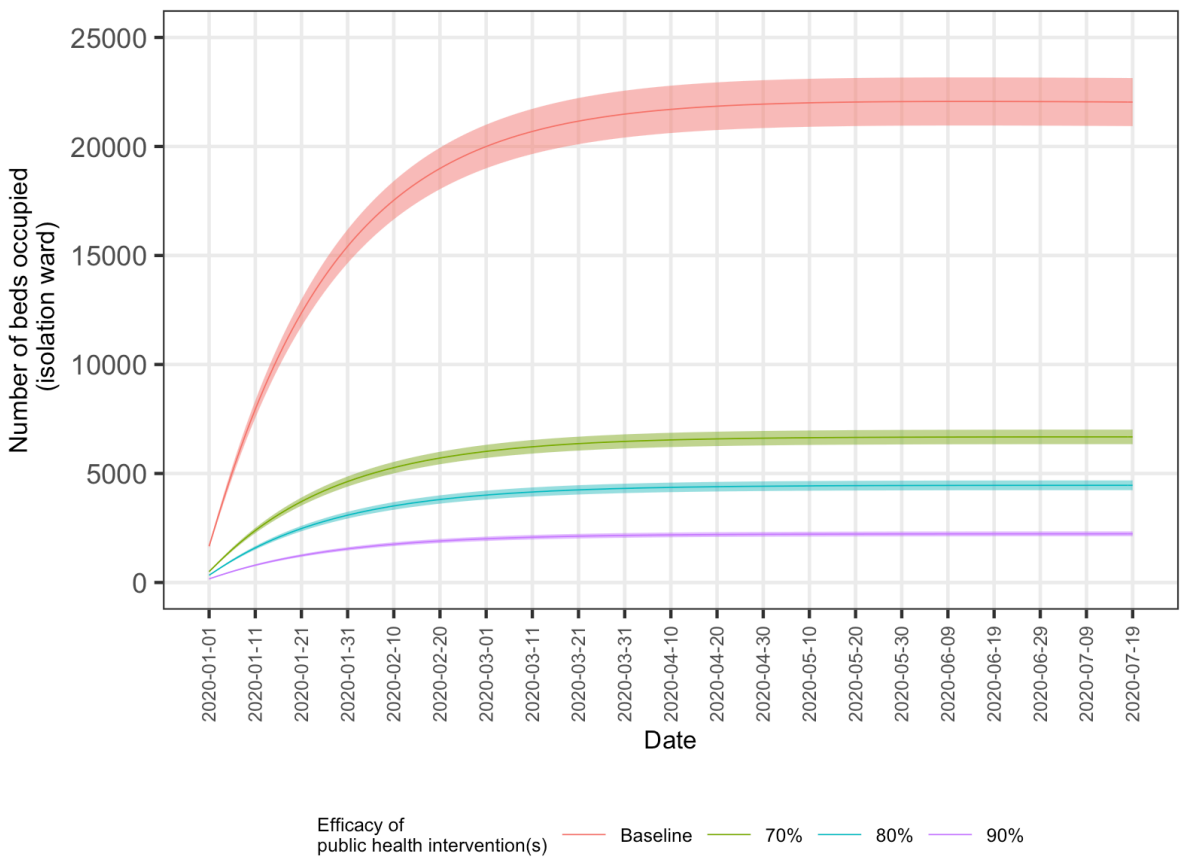

Figure 3 Number of beds occupied in the isolation wards under different scenarios of public health intervention efficacy (assuming a 50% diagnosis rate)

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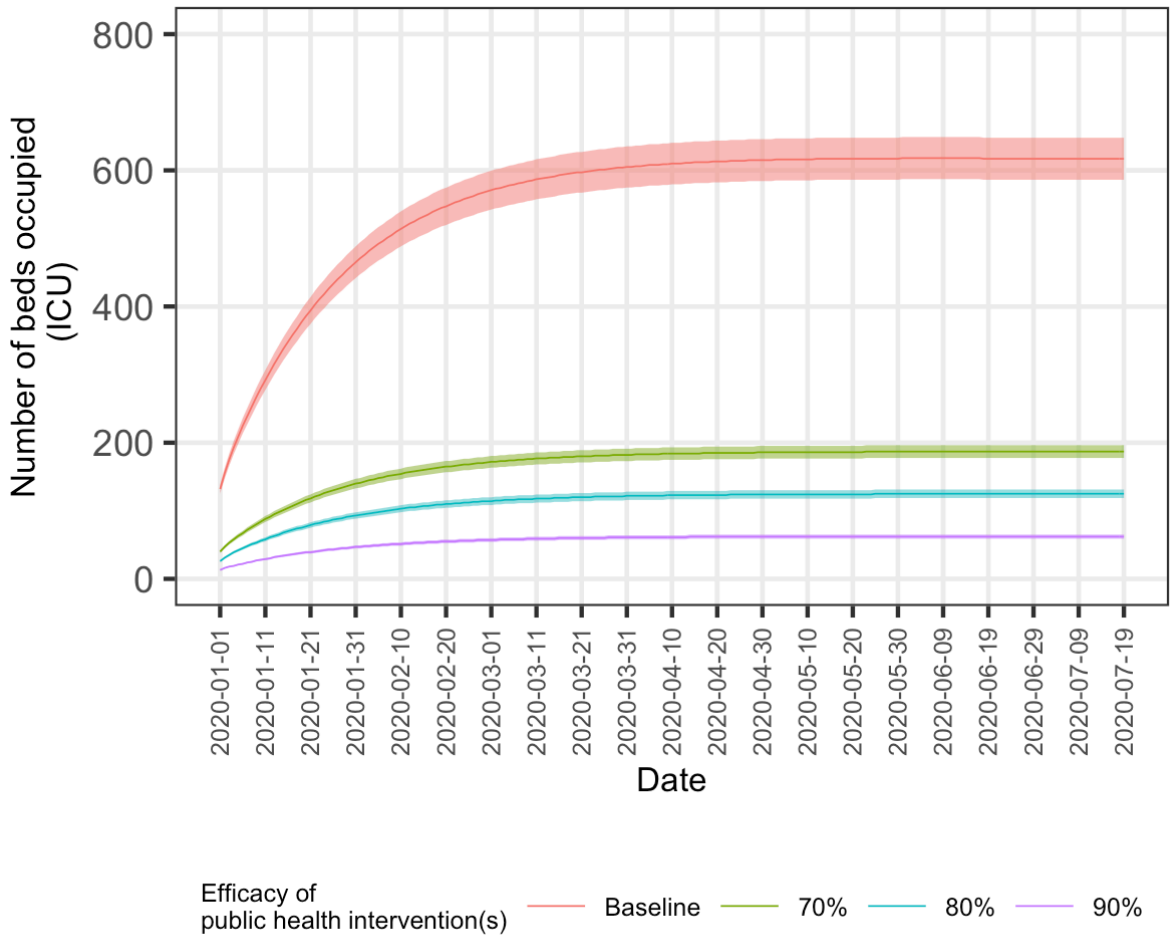

Figure 4 Number of beds occupied in the intensive care unit (ICU) under different scenarios of public health intervention efficacy (assuming a 50% diagnosis rate)

4. Discussion/Interpretation

In this study, we synthesised available information during the 2019-nCoV outbreak occurring in Wuhan city, China, and estimated the burden on healthcare system effected by the increasing numbers of cases using a modified SIR model. Our results suggest the actual number of infected cases could be much higher than the reported as the spread continues. Therefore, the burdens on healthcare system would be substantial, particularly for the isolation wards and ICU, if no effective public health interventions were implemented.

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Our analysis is limited by the availability of data and the lack of understanding of 2019-nCoV. First, SIR model can be substantially affected by the input parameters, i.e., the transition probabilities, which were estimated based on either the data released by the NHC of the People's Republic of China or other recent investigations. Only the reported incidence between 0:00 and 24:00 on 25 Jan 2020 was used at this stage. As more data become available, further investigation should be considered. Second, classic SIR model assumes a constant infection rate, which is not likely to be true as interventions being implemented. Therefore, in this study, we constructed an SIR model with multiple efficacy rates of public health interventions as proxy for the change of infection rate. Third, the estimated case numbers can be influenced by the diagnosis rate. Therefore, we simulated a number of scenarios with different hypothesised diagnosis rates of 10%, 50% and 90% to estimate the actual number of infected cases. For the reason of mild or moderate symptoms reported by part of infected cases and the relatively long incubation period observed, it is reasonable to model a context of low diagnosis rate. In fact, recent investigation also suggests the current diagnosis rate could be low and likely lower than 10%.[14] Our estimates appear to be close to the recently published estimates[14].

Our results emphasised the vital importance of efficacious public health interventions during the course of outbreak. Established human-to-human transmissibility of this novel coronavirus can be one of epidemiological factors that contribute to the accelerated spreads within the epicentre Wuhan and towards cities and regions via transports of those with no or only subclinical symptoms. It is likely that sustained human transmission (i.e., basic reproduction number $R_0 > 1$) is sufficiently supported by the confirmed human-to-human transability.[14] Therefore, upstream measures that are able to limit or block the viral transmission between individuals within and across cities are urgently needed. Fortunately, the lockdown of Wuhan city has taken place and is believed to have largely minimised the spreads from the epicentre

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to other areas. However, the mayor of Wuhan later announced approximately five million of residents had left the city ahead of the implementation of lockdown[15], which may compromise the anti-spread effect of such city lockdown measure as to spreads to other cities. To date, information on transmission modes and severity of this novel coronavirus is still limited [16]. Further preventive measures to diminish the contact between persons in avoidance of healthcare system breakdown should be implemented, such as school closure, public transport shutdown, common activities suspension, etc.

To achieve higher efficacy of the public health interventions, efforts from individuals should not be neglected. In light of no available specific vaccines and treatments for such novel coronavirus thus far, a range of precautionary behaviours between individuals at homes and in communities are essential and vital to obtain proper control of the spreads in public and likely preventing superspreading events. Personal prevention strategies for seasonal influenza and other viral infections are still applicable during the present outbreak, inclusive of restricting ill residents from common activities, excluding symptomatic persons from entering homes/facilities, limiting visit especially of wet markets, live poultry markets or farms. Maintaining personal hygiene (e.g., frequently performing hand hygiene, washing hands with soap and water) and cough etiquette (e.g., covering nose and mouth when coughing, correctly disposing wasted tissues after coughing) are also beneficial.

Amongst these preventive practices, facemask wear appears to be the most operationalised and thus effective since it is observable from other members of the public. Apart from facemask wear being required in public of the epicentre in Hubei province, it has also been mandated by the Guangdong provincial government that facemasks should be worn in public with effect

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from 26th January, four days after the implementation in Wuhan. The Centre for Disease Control and Prevention, the United States, also emphasised the importance of wearing a facemask at all times when staying with infected individuals in shared spaces as specified in their interim guidance for prevention for 2019-nCoV from spreading in home and communities[17]. All these are extremely important in raising awareness in the public as to personal preventive steps given the present situation (mild or subclinical symptoms observed in many cases and observed long incubation period). Operational issues associated with wearing disposable facemasks to maximise their preventive effectiveness should be also publicised and educated to the general public including correct ways of wearing facemask, hygiene practices across the procedure of mask wearing, disposal of used masks.

Volunteering from healthcare professionals appears to play a major role in reduction of fears amongst the public. Imported healthcare support from other cities are certainly vital to the healthcare system in Wuhan during the present outbreak.[18] It is also noteworthy that volunteers with medical backgrounds (e.g., medical trainees, health science students) are actively instilling scientific insight and evidence-based knowledge via the Internet to eliminate rumours spread across Chinse social media [19]. We believe that these volunteering activities can contribute to a successful delivery of public health principle and, in turn, efficacious interventions.

The basic reproductive number of this novel coronavirus has been estimated in recent studies (range from 2.6 to 6.47)[14 20-24], suggesting its spread being as similar as or more efficient than seasonal influenza. Our estimates also indicate that a country-wide outbreak or even an international outbreak is foreseeable. It is thus essential to implement effective public health

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measures to curb this very outbreak without delay. Otherwise, the current healthcare system would not be able to sustain. Once the breakdown occurred, mortality would be expected to soar due to lack of medical resources. Home isolation for mild patients could be one of possible managements if the ultimate limit of isolation beds at the city or province level was exceeded

To conclude, our estimates of the healthcare systems burdens arising from the actual number of cases infected by the novel coronavirus appear to be considerable if no effective public health interventions were implemented. We call for continuation of implemented anti-transmission measures (e.g., lockdown of city, closure of schools and facilities, suspension of public transport) and further effective large-scale interventions spanning all subgroups of populations (e.g., universal facemask wear) with an aim to obtain overall efficacy with at least 70%-90% to ensure the functioning of and avoid the breakdown of healthcare system.

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