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Transmission dynamics and the effects of non-pharmaceutical interventions in the COVID-19 outbreak resurged in Beijing, China: a descriptive and modelling study

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ABSTRACT

Objective To evaluate epidemiological characteristics and transmission dynamics of COVID-19 outbreak resurged in Beijing and to assess the effects of three non-pharmaceutical interventions.

Design Descriptive and modelling study based on surveillance data of COVID-19 in Beijing.

Setting Outbreak in Beijing.

Participants The database included 335 confirmed cases of COVID-19.

Methods To conduct spatiotemporal analyses of the outbreak, we collected individual records on laboratory-confirmed cases of COVID-19 from 11 June 2020 to 5 July 2020 in Beijing, and visitor flow and products transportation data of Xinfadi Wholesale Market. We also built a modified susceptible-exposed-infected-removed model to investigate the effect of interventions deployed in Beijing.

Results We found that the staff working in the market (52.2%) and the people around 10 km to this epicentre (72.5%) were most affected, and the population mobility entering-exiting Xinfadi Wholesale Market significantly contributed to the spread of COVID-19 (p=0.021), but goods flow of the market had little impact on the virus spread (p=0.184). The prompt identification of Xinfadi Wholesale Market as the infection source could have avoided a total of 25 708 (95% CI 13 657 to 40 625) cases if unnoticed transmission lasted for a month. Based on the model, we found that active screening on targeted population by nucleic acid testing alone had the most significant effect.

Conclusions The non-pharmaceutical interventions deployed in Beijing, including localised lockdown, close-contact tracing and community-based testing, were proved to be effective enough to contain the outbreak. Beijing has achieved an optimal balance between epidemic containment and economic protection.

INTRODUCTION

The COVID-19 pandemic, caused by SARS-CoV-2, is the most significant public

Strengths and limitations of this study

► We established the database including 335 confirmed cases of COVID-19 with detailed information.
► We comprehensively assessed epidemiological and spatiotemporal characteristics of COVID-19 outbreak in Xinfadi Wholesale Market.
► We developed a modified epidemiological model with time-variant parameters inferred from data for in-depth analysis on the effects of non-pharmaceutical interventions.
► Our model did not contain the spatial transmission of the epidemic due to the lack of inter-regional migration data.
► Our model only compared the most important interventions out of tens of control measures implemented in Beijing.

health crisis in a century and has infected >135 million people with nearly 3 million dead worldwide.[1] SARS-CoV-2 was initially thought to be linked to Huanan Seafood Wholesale Market in Wuhan, China,[2] although multiple origins later suggested for the human emergence.[3 4] Recently, another Chinese market, Xinfadi Wholesale Market, has been in the hot topic. The market is linked to a surge in COVID-19 cases in Beijing after 56-day stretch without any local transmitted cases,[5] triggering fears of a second wave of COVID-19 in mainland China. WHO called the new cluster in Beijing 'a significant event' that needs to be investigated and controlled.[6]

This event has further raised a critical question, why the wholesale market is frequently associated with the emergence of a human infection outbreak, as observed in SARS-CoV-2, SARS-CoV[7] and avian influenza A (H7N9).[8] Identifying factors that promote

maintenance, amplification and dissemination of virus occurred in the wholesale market has significant public health consequences. Additionally, it is sophisticated to develop control strategies to curtail the transmission of COVID-19, which fit the epidemiological situations, capacities and values of each country. The wholesale market characterises as the complex and high density of stalls, relatively poor environmental sanitation and daily crowded human activities. The virus might be quickly transmitted either by extensive exposed human or contaminated goods. How to promptly contain the disease spread, return to a normal life and keep the local economy alive is a difficult trade-off problem.

In this study, we aimed to describe the epidemiological characteristics of COVID-19 outbreak linked to Xinfadi Wholesale Market in Beijing, and to analyse the key factors that contributed to prompt local transmission. We also built a modified transmission model, which is more in line with the real dynamic epidemic prevention and control, to evaluate the effect of non-pharmaceutical interventions (NPIs) implemented in Beijing, including localised lockdown, close-contact tracing and community-based nucleic acid testing (NAT).

METHODS
Data collection
Individual records on COVID-19 cases were collected from official reports by Beijing Center for Disease Prevention and Control (https://www.bjcdc.org) from 11 June 2020 to 5 July 2020. Demographic characteristics (age, sex, occupation and residence location), exposure history, identification approach, clinical classification and key time points, including date of exposure to Xinfadi Wholesale Market, symptom onset, hospital admission and reporting were extracted. Data on visitor and goods flow volume from Xinfadi Wholesale Market to each district were obtained from Aurora Big Data (Shenzhen Hexun Huagu Information Technology) and Liu's thesis (online supplemental table S1, online supplemental table S2).[9] Aggregated and anonymised traffic volumes of all subdistricts in Beijing were collected from an online ride-hailing platform. Data of NPIs were obtained from the National Health Commission of the People's Republic of China (http://en.nhc.gov.cn) and Beijing Municipal Health Commission (http://wjw.beijing.gov.cn/).

Spatiotemporal analyses
Thematic maps showing the distribution of confirmed cases in Beijing, and visitor and goods flow from Xinfadi Wholesale Market to each district or subdistrict were produced by ArcGIS V.10.2 software (ESRI, Redlands, California, USA). We measured the commuting distance between each COVID-19 case and Xinfadi Wholesale Market based on city's transportation network. Particular locations of residential communities of 292 confirmed cases were extracted for mapping, and administrative agency of subdistricts where other 43 cases lived were used

when exact locations were not available. The distance-date-case matrix was used to illustrate the relationships between the number of confirmed cases and commuting distances from Xinfadi Wholesale Market and the date of symptom onset.

Estimation of effective reproduction number
We estimated the effective or net reproduction number on day t (R_t), which is defined as the mean number of secondary cases generated by one primary case with illness onset on day t using the method developed by Cori *et al* (online supplemental text 1).[10] CIs of R_t were quantified using a bootstrap procedure.[11]

Simulation model
We adopt a modified susceptible-exposed-infected-removed (SEIR) model to simulate the effects of different NPIs (online supplemental figure S1). This model divides the population into six compartments, that is, the susceptible population *S*, the exposed population *E*, the presymptomatic population *P*, the symptomatic but unconfirmed population *I*, the symptomatic but previously isolated population *IS* and the removed population *R*, which contains individuals removed from the disease transmission due to death/recovery and includes individuals that are isolated once they obtain laboratory confirmation. The extension on the definition of compartment *R* is based on the actual situation in China, where once the infected persons obtain laboratory confirmation, they will be quarantined and would not cause secondary infection anymore. The dynamics of these compartments across time *t* could be summarised by the following set of ordinary differential equations in Eq. (1):

$$
\begin{aligned}
\frac{dS_t}{dt} &= -\beta_t \frac{S_t}{N} I_t - q\beta_t \frac{S_t}{N} P_t & (a)\\
\frac{dE_t}{dt} &= \beta_t \frac{S_t}{N} I_t + q\beta_t \frac{S_t}{N} P_t - \gamma_e E_t & (b)\\
\frac{dP_t}{dt} &= \gamma_e E_t - \gamma_p P_t & (c)\\
\frac{dI_t}{dt} &= (1 - \alpha_t^1 - \alpha_t^2)\gamma_p P_t - \sigma_t I_t & (d)\\
\frac{dIS_t}{dt} &= (\alpha_t^1 + \alpha_t^2)\gamma_p P_t - \sigma_t IS_t & (e)\\
\frac{dR_t}{dt} &= \sigma_t I_t + \sigma_t IS_t & (f)
\end{aligned}
\tag{1}
$$

Where β_t is the transmission rate weighted by the time-variant mobility intensity m_t; *q* is the relative ratio for transmissibility of the presymptomatic infections than the symptomatic infections; γ_e is the inverse of duration from exposed to presymptomatic; γ_p is the inverse of duration from presymptomatic to symptomatic, that is, the presymptomatic infectious period; α_t^1 and α_t^2 are the proportions of the new symptomatic infections discovered through close-contact tracing and community-based NAT, respectively; σ_t is the inverse of duration from symptom onset to be removed. The details of parameter calculation could be found in online supplemental text 2 and online supplemental table S3. We calibrated our model by the Metropolis-Hastings Markov chain Monte Carlo (MCMC) algorithm and assessed the convergence by the trace plot and the Gelman-Rubin diagnostic (online supplemental

text 2).[12 13] The initial settings of model parameters are summarised in online supplemental table S4.

Scenario settings

Three dynamic parameters, that is, m_t, α^1_t and α^2_t, were introduced in our model to assess the effects of three NPIs, that is, localised lockdown, close-contact tracing and community-based NAT, respectively. We designed three types of scenarios, involving (1) none NPIs implemented, (2) only one of the NPIs implemented and (3) only one NPI not implemented (ie, implementing two of the NPIs), to evaluate the effectiveness of these NPIs in containing the epidemic. The scenario simulation was based on the assumptions that: (1) the public health resources, including the resources for isolation, close-contact tracing and the ability to diagnose infected individuals, are enough even when the cases surged; and (2) the effects of NPIs would not be impacted by the start/stop of other NPIs. For all scenarios, we adjusted the dynamic parameters concerning the settings. We repeated the simulations based on the parameter values estimated by the 10 million MCMC iterations (online supplemental text 2) to construct the 95% CI of the epidemic curve. The simulation results were presented as mean values and 95% CI for both daily and cumulative incidence. All analyses were based on Python software (V.3.6.0) and the PyMC package (V.2.3.8).[14]

Sensitivity analyses

We designed six sensitivity analyses to test the robustness of our simulation results. For each of the sensitivity analyses, we fixed parameters and initial states to be the same as the main analysis except for those mentioned below. (S1) Assume the initial number of exposed individuals E(0)=35, which is 10% less than the observed value. (S2) Assume the initial number of exposed individuals E(0)=43, which is 10% more than the observed value. (S3) Assume the initialisation of transmission rate β_0=0.45, which is 50% of the value in the main analysis. (S4) Assume the initialisation of transmission rate β_0=1.35, which is 150% of the value in the main analysis. (S5) Assume the incubation period fixed to 4.1 days, which is the lower 95% CI from reference.[3] Correspondingly, the presymptomatic infectious period is fixed to 1.1 days, according to the previous study.[15 16] (S6) Assume the incubation period fixed to 7.0 days, which is the upper 95% CI from reference.[3] Correspondingly, the presymptomatic infectious period is fixed to 3.0 days, according to the previous study.[15 16] We compared the simulation results under those models with the main analysis.

Statistical analyses

Attack rate (AR) with 95% CI was computed using the population estimate of the National Statistical Yearbook 2019 (National Bureau of Statistics of China), and presented as number of cases per million persons. Skewed data were expressed as median (IQR or range). The categorical variables were reported as frequency (n)

and proportion (%). To estimate the differences between groups, Student's t-test or Wilcoxon rank-sum test was used for a continuous variable where appropriate, and the χ^2 test was used for a categorical variable. Spearman's correlation analysis was used to measure the correlations between number of cases at different districts and commuting distance, goods flow volume and visitor flow volume. Root mean square error was used as a standard to measure the prediction results of model. All the analyses were conducted using R software, V.3.6.1, and Python software, V.3.6.0. A two-tailed p value <0.05 was considered to be statistically significant.

Patient and public involvement

Patients and the public were not involved in the design or conduct of the study.

RESULTS

As of 5 July 2020, a total of 335 laboratory confirmed cases had been reported in Beijing, of which 55.8% were males (table 1), significantly higher than proportion of males in Wuhan (47.7%, p=0.003). During this outbreak, SARS-CoV-2 was more likely to infect young adults, with median age of 43 years (IQR 31–52), while the virus tended to infect older people in Wuhan (median age: 53, IQR 40–64) and Beijing (median age: 45, IQR 34–60) before March 2020 (online supplemental figure S2A and S2B). Over half of the cases in this outbreak were people working in Xinfadi Wholesale Market, and there were 20 (6.0%) purchasing agents and 59 (17.6%) customers infected in the market. About a quarter of cases were close contacts to infected people or contaminated goods or environment. We estimated a median incubation period of 5 days (range 0–16) (online supplemental text 3, online supplemental figure S3). The median durations from symptom onset to hospital admission and reporting were 1 day (range −10–17) and 2 days (range 0–18), respectively. Most identified cases (97.9%) were mild to moderate, and no one died.

The recent outbreak has affected 47 (14.2%) subdistricts in 11 districts (figure 1A), with an AR of 24.3 (IQR 13.9–57.8) per million persons (figure 1B). All cases were epidemiologically linked to Xinfadi Wholesale Market, which has a high daily population activity density before suspension (13 June), especially in fresh meat and beef and mutton markets (figure 1C, online supplemental figure S4). The outbreak started on 4 June. The majority of cases were exposed to Xinfadi Wholesale Market between 7 June and 11 June, and experienced symptoms about 5 days later. The index case was reported on 11 June, and the epidemic peaked around 13 June (figure 1D). After the NPIs conducted, the growth of new cases slowed down and the epidemic was brought under control. The bottom part of the distance-date-case matrix, corresponding to people living close to Xinfadi Wholesale Market, was where the largest number of cases had

Table 1 Characteristics of COVID-19 cases in Beijing from 11 June 2020

Characteristics	COVID-19 cases in Beijing
Date of report	11 June 2020–5 July 2020
Number of cases	335
Male (%)	187 (55.8)
Age: median (IQR)	43 (31–52)
Type of cases*	
Working population/ vendors (%)	175 (52.2)
Purchasing agents (%)	20 (6.0)
Customers (%)	59 (17.6)
Close contacts (%)	81 (24.2)
Incubation period: median (range)	5 (0–16)
Days from symptom onset to hospital admission: median (range)	1 (–10–17)
Days from symptom onset to reporting: median (range)	2 (0–18)
Clinical classification	
Mild	57 (17.0%)
Moderate	271 (80.9%)
Severe	4 (1.2%)
Critical	3 (0.9%)

*Classified by the exposure history to Xinfadi Wholesale Market. Working population/Vendors, people working in the market; purchasing agents, people purchasing at the market for smaller wholesale markets, restaurants, supermarket chains, stalls and online shopping platforms; customers, people buying at the market for individuals; close contacts, people contacting with infected persons or contaminated goods from Xinfadi Wholesale Market.

been recorded (figure 1E), especially within 10 km from the market (72.5%) (online supplemental figure S5A–C).

Figure 2A indicates that no significant correlation was found between number of cases and goods flow volume (p=0.184). The agricultural products from Xinfadi Wholesale Market are mainly supplied to the northern districts, including Chaoyang, Haidian Districts and the surrounding Fengtai, Xicheng and Dongcheng Districts. In contrast, the population flow was mainly between Xinfadi Wholesale Market and the southern areas, especially Fengtai and Daxing Districts (figure 2A). Traffic volume between the market and subdistricts is shown in figure 2B, which indicates that cases are mainly distributed in subdistrict with higher traffic volume from the market, especially in the southern areas. Huaxiang Town and Xincun Residential District, Xinhongmen Town and Huangcun Town had the highest traffic volume with the top three number of cases. Generally speaking, the shorter the commuting distance (p=0.019) and the larger visitor flow volume (p=0.021) of an area to Xinfadi

Wholesale Market, the higher risk of people being infected (figure 2C). However, Huangcun Town and Yongdinglu Residential District, farther from Xinfadi Wholesale Market, also had a large number of cases, which was mainly due to the clusters of PepsiCo's factory and East Yuquan Market, respectively. The findings suggest that SARS-CoV-2 was mainly transmitted through person-to-person, rather than through contaminated products.

Taking COVID-19 containment as the most pressing priority, various public health measures had been implemented in Beijing (online supplemental figure S1). The effective reproduction number R_t was up to 6.6 with a wide CI at the very beginning of the outbreak, when the virus silently occurred and transmitted in Xinfadi Wholesale Market (figure 3A). Then, R_t dramatically dropped to the level of 3.0 on 13 June, when Xinfadi Wholesale Market was suspended and the surrounding communities were closed and disinfected. After that, the relative traffic volume in all subdistricts dropped significantly by 20% (figure 3B), and the decrement rate of high-risk, median-risk and low-risk areas were 50%, 35% and 20%, respectively. Compared with >80% traffic volume reduction in the first wave of COVID-19 outbreak in China, this Xinfadi outbreak has less impact on urban traffic.[17] Since the first case was reported on 11 June, blanket screening has been conducted to find out people who had been to Xinfadi Wholesale Market. As of 2 July, a total of 8500 close contacts have been traced and quarantined (figure 3C). From 14 June onwards, the authorities tested all purchasers, people working at Xinfadi Wholesale Market and residents living in the high-risk and medium-risk area. The intervention action is called 'Testing Everyone Who Should be Tested'. During this week, the proportion of positive tests was relatively high, although the daily amount of NAT was quite small. Since 20 June, any individuals who are willing to have a NAT can go to the medical institutions. This policy is called 'Testing Everyone Who Wants to be Tested'. In this phase, the amount of NAT in Beijing increased significantly; however, the positive number decreased to a low level. As of 5 July 2020, over 10 million people have been tested (figure 3D). On 16 June, Beijing authorities raised their public health emergency response from the level 3 to level 2. R_t maintained downward trend and finally decreased to below 1 on 18 June, 2 weeks after the first case occurred (figure 3A). Cases of COVID-19 were basically identified through the three approaches. First, active medical treatment (patients go to medical institutions for diagnosis actively), which includes 93 cases (27.8%). Second, close-contact tracing, which includes 92 cases (27.5%). The third is by community-based NAT, including 150 cases and occupying 44.8%. The proportion of cases screened by close-contact tracing and NAT increased during the outbreak (figure 3E).

Figure 4 shows the results of model simulations. We first fitted the modified SEIR model (online supplemental figure S6) to daily incidence from 4 June 2020 to 5 July 2020, and simulated the spread of epidemic under several
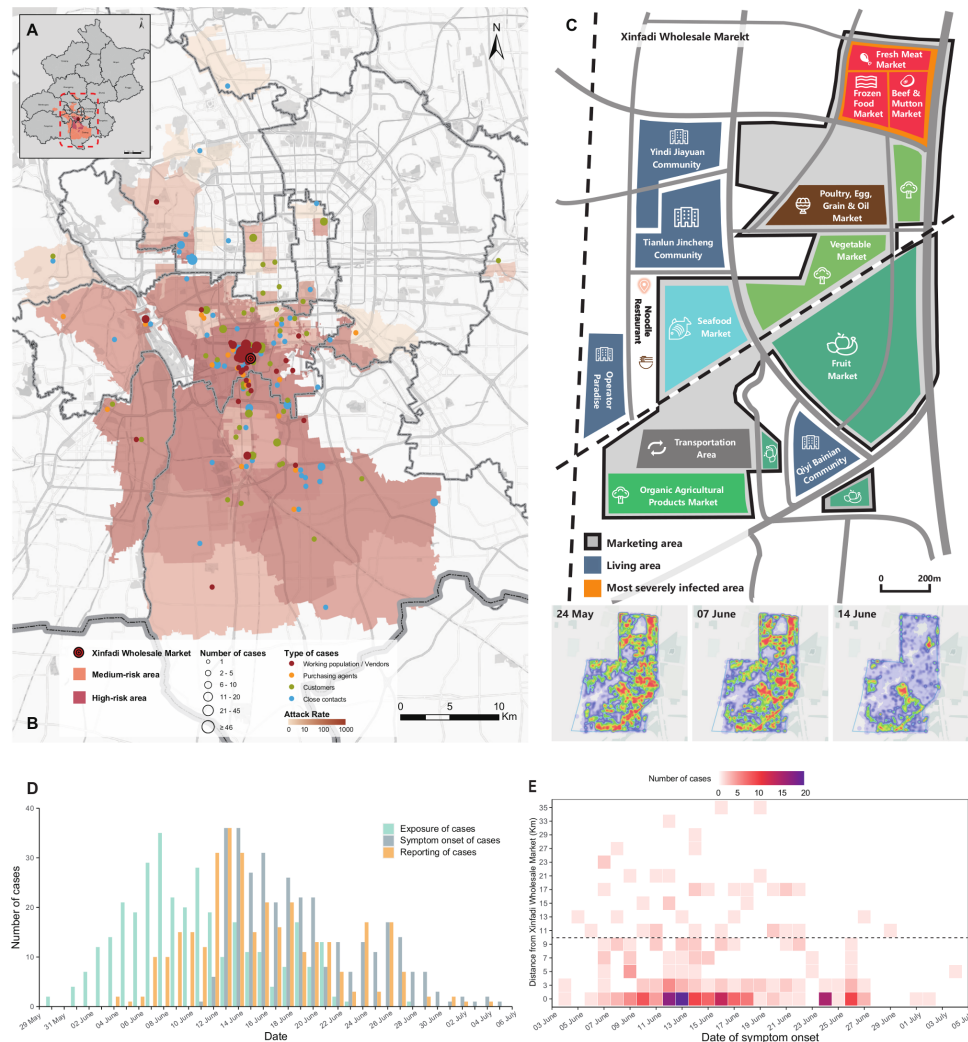
Figure 1 Spatiotemporal characteristics of COVID-19 outbreak linked to Xinfadi Wholesale Market in Beijing in June 2020. (A) The distribution of medium-risk and high-risk areas during the outbreak. (B) The subdistrict-level attack rate of COVID-19 in Beijing. Communities or subdistricts with confirmed cases are marked on the map based on the number and type of cases. (C) The layout and daily visitor flow volume of Xinfadi Wholesale Market. (D) Epidemic curve (exposure, symptom onset and reporting date) of cases. (E) Shows the matrix between the number of cases and the date of symptom onset and distance to the market.

scenarios with different combinations of NPIs. Figure 4A provides a general description of the results, which plots the number of cumulative cases under all scenarios by 5 July, 1 month after the first case of this outbreak developed symptoms. Under the scenario that all NPIs we investigate (localised lockdown, close-contact tracing and community-based NAT) are absent, there would be a total of 25 708 COVID-19 cases (95% CI 13 657 to 40 625) in Beijing, which is an 76.7-fold increase compared with the actual scenario (online supplemental figure S7A). Figure 4B plots the individual impacts of the NPIs. For the scenario with only localised lockdown, close-contact tracing or community-based NAT is conducted, there would be 2175 (95% CI 1368 to 2990), 2651 (95% CI 2006 to 3417) or 1291 (95% CI 1039 to 1602) cases as of 5 July, which are 6.5-fold, 7.9-fold or 3.9-fold increase, respectively. Among them, the scenario with only community-based NAT produces the least cumulative cases. We also

simulated the effects of paired NPIs, that is, only one of the NPIs lacks. For the scenario without localised lockdown intervention, without close-contact tracing or without community-based NAT, the total COVID-19 cases in Beijing by 5 July could be up to 472 (95% CI 410 to 564), 573 (95% CI 477 to 682) or 1107 (95% CI 828 to 1387), which are 1.4-fold, 1.7-fold or 3.3-fold increase compared with the actual scenario, respectively (online supplemental figure S7B). In order to evaluate the effectiveness of the targeted test policy, we estimated a scenario without NAT after 20 June, which would be a total of 398 (95% CI 352 to 450) cases by 5 July, with only 63 more cases than the actual scenario. Therefore, the targeted test policy in the early stage of the outbreak has a significant effect on containing infections. Overall, among all NPIs we investigated, community-based NAT was the most effective intervention under single NPI scenarios. In contrast, close-contact tracing, combined
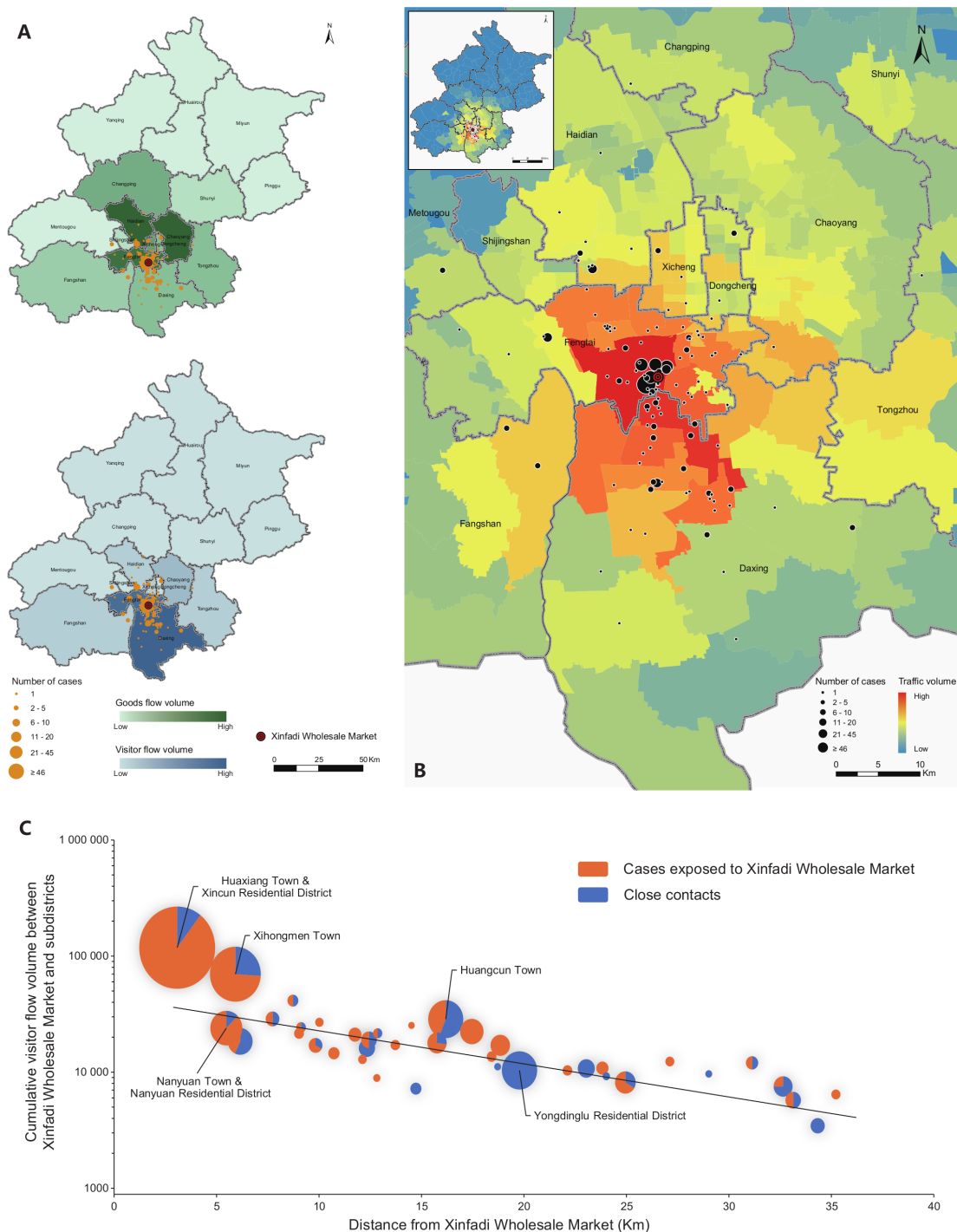
Figure 2 The correlation of human mobility and goods transportation from Xinfadi Wholesale Market with the COVID-19 outbreak in Beijing. (A) Spatial distribution and flow volume of goods and visitors from Xinfadi Wholesale Market. (B) Traffic volume of all subdistricts from the market based on data of an online ride-hailing platform. (C) The distance-visitor flow volume scatter plot, and pie plots represent proportions of different exposure cases.

with community-based NAT performed the best among paired NPIs scenarios. Moreover, the effects of combined interventions were more significant compared with single or partial interventions (online supplemental table S5 for the main analysis and online supplemental figure S6–S11 for sensitivity analyses). Performance of models in the main and sensitivity analyses are summarised in online supplemental table S12, figure S8A and S8B. Trace plots

were used for judging the convergence of model fitting (online supplemental figure S9).

DISCUSSION

The resurgent COVID-19 outbreak in Beijing highlights a new challenge for the pandemic control. The origin of this outbreak is still unknown. One possible origin was
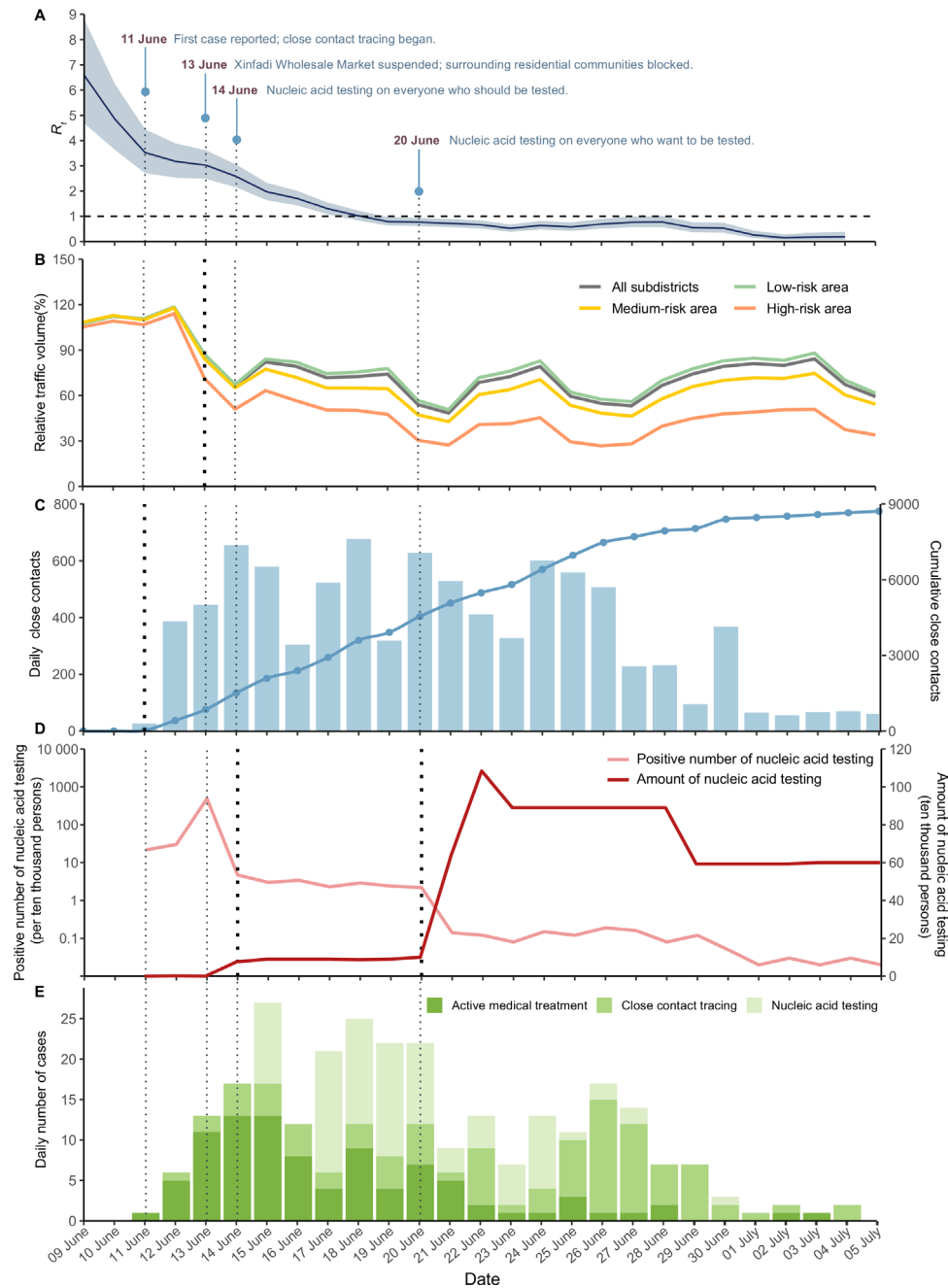
Figure 3 The efficacy of containment measures implemented in Beijing. (A) Average R_t and 95% CI. The critical value of R_t=1 is marked with a horizontal dash line. The moment of important events and public health control measures are marked by date. Each dot line in bold corresponds to the observation that this measure affect. (B)–(D) Observations (relative traffic volume, close contacts and nucleic acid testing) change during the outbreak. (E) The daily number of cases confirmed by three approaches, that is, active medical treatment, close contact tracing and nucleic acid testing. R_t=effective reproduction number.

the contaminated frozen products, in which the longer stability of the virus could be expected under cold condition.[18–22] Another possible origin was the presymptomatic or asymptomatic people working in the market infected with the virus. No matter its origin, Xinfadi Wholesale Market has been a potential 'virus amplifier' where uncontainable spread inside and outside the market facilitated. Xinfadi Wholesale Market is the largest wholesale market in Asia, occupying 1680 acres with the highest sales volume.[23] The market has the trade volume as high

as 1749 million tons in 2019, and supplied around 90% of total supplies of fruit and vegetable, and 15%–20% of beef and mutton in Beijing. The transport volume of the market is around 60 000 people per day and 30 000 vehicles per day. The market was roughly divided into nine areas based on commodity category. The COVID-19 infections were detected from all areas and the areas for frozen seafood and beef and mutton were most severely infected both in cases and environmental samples.[24] The areas for storage, processing and sale of frozen goods or products
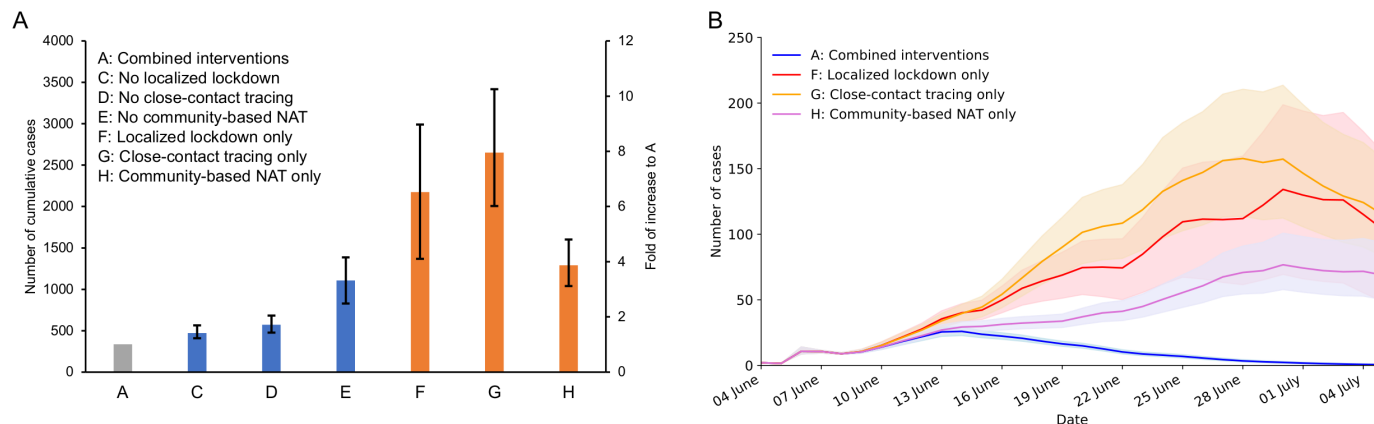
Figure 4 The results of simulations under different combinations of NPIs. (A) Cumulative cases by 5 July under scenario from (A)–(H) and increase of fold for scenario (C)–(H) compared with (A). We exclude the plotting of scenario (B) in (A) because of its large value. (B) The solid colour line segment represents the median of replicated experiments, and the shadow represents 95% CI of the replicates. During the experiments, we ran the Metropolis-Hastings Markov chain Monte Carlo simulation for 10 million iterations and sampled at every 1000th step. NAT, nucleic acid testing; NPIs, non-pharmaceutical interventions.

are at a high risk of maintaining and disseminating the virus. During the ongoing global pandemic, great attention and control measures focusing on big wholesale markets should be taken.

In this study, we suggested that exposed population rather than contaminated sales was the principal reason for the spread of the virus in Beijing. People working in Xinfadi Wholesale Market who had constant exposures to the contaminated environment have the highest infection rate. It may also explain the relatively higher proportion of male and younger median age of Beijing cases than the overall country cases.[25] Occupational health guideline or legislation on COVID-19 prevention and control for employers in wholesale market, or wet market should be strengthened. We identified that the exposed human not contaminated goods have mainly transmitted the virus. The special humidity and temperature or even particular processing activities occurred in the market might favour the virus containment, however, the infectivity of the virus contained in the products seemed to be dramatically decreased after a long trip of transportation. Our observation that most cases distributed around 10 km distance to Xinfadi Wholesale Market also supported this hypothesis.

Beijing authorities downgraded the emergency response to COVID-19 to level 3 on 6 June, and masks were no longer mandatory. Facing the hard-won adjustment of the response level and unbearable heat in early June, some citizens in Beijing did not wear masks when they were outdoors. Xinfadi Wholesale Market is a place with high people mobility and density, where people have more chances to contact others closely, which has facilitated the quick transmission from person to person.

Learning from the experience and lessons from the first epidemic wave in Wuhan, rapid and targeted control measures were implemented in Beijing (online supplemental figure S1). Almost at the same time as the epidemic started, Beijing authorities have responded quickly to shut down Xinfadi Wholesale Market (on 13

June) and enhanced its emergency response to level 2 (on 16 June) again. During the outbreak, authorities only locked down streets and communities in high-risk areas, rather than confining everyone in Beijing to their homes. All people working or living in these areas, or having exposed to Xinfadi Wholesale Market were required to take nucleic acid tests and self-quarantine for further observation. Considering thousands of people might be exposed to the market, the authorities used big data and artificial intelligence technologies to track individuals' movements and identify those who had visited Xinfadi Wholesale Market.[26] By those combined NPIs, Beijing epidemic was promptly controlled and only self-sustained for around 2 weeks.

Because most of cases were mild and easy to be misdiagnosed and under-reported, we evaluated a scenario in which the disease was unnoticed and no intervention was conducted. From 4 June to 5 July, there would be around 25 000 COVID-19 cases in Beijing without any intervention. Before the travel restrictions and strict interventions implemented on 23 January in Wuhan city, a total of 830 COVID-19 cases was documented,[27] although some mathematical model suggested a substantial undocumented infection before the lockdown of Wuhan city.[28] To some extent, our model indicated that the precise identification of Xinfadi Wholesale Market as the epicentre and the decisive conduction of public health interventions in Beijing has avoided a similar severe epidemic as in Wuhan. Our improved model could be used to evaluate effects of the different strategies on active case finding and management, compared with previous modelling on COVID-19 control.[29–31] We showed that NAT is the most important way to identify the cases; furthermore, the NAT targeted on Xinfadi-exposed population contributed to around 91.8% effect of NAT on the disease control. The city has at first tested nearly all the people who have exposure history to Xinfadi Wholesale Market and related cases, then the testing was enlarged to the residents living in the high-risk and medium-risk areas and employees in

key industries, such as catering, supermarkets, express delivery, social welfare institutions, medical and health institutions, bank counter staff, transportation and beauty salons. As to combat against COVID-19, the increase in NAT capability by adopting high-technique equipment and high-throughput technology is essential in the future.

Our research provides a constructive framework to analyse the transmission dynamics of the emergent cluster of COVID-19 from two perspectives, including (i) detailed spatiotemporal analysis based on individual recordings on laboratory-confirmed COVID-19 case data and mobility data of both visitors and products; (ii) modified epidemiological modelling with time-variant parameters inferred from data for in-depth analysis on the effects of NPIs. However, we do acknowledge several limitations. In our simulations, we assumed that the medical resources were unlimited and the efficiency of all the NPIs would not decrease even when the infected population grows in a short period. In reality, as the epidemic develops unnoticeably, medical resources (eg, testing reagents) would become strained and even shortage, and the difficulty of conducting epidemiological investigations would increase as well, which may reduce the efficiency of NPIs. Besides, some of the NPIs implemented in Beijing, like wearing masks or disinfection of public places, were not considered in this study. Finally, our approach for model calibration may not be applicable to all countries or regions. Specifically, we only used the reported infections to calibrate our model, which may lead to errors for areas with the issue of under-reporting. However, due to the large-scale testing in China, this problem can be avoided in our study.

CONCLUSION

Although the origin of Beijing outbreak is still a mystery and requires further tracing, we highlight that big market-related outbreak is a significant event and may lead to severe epidemic without proper control measures. The key to tackling is to target the market-exposed people. Enlarged NAT and big data contact tracing are efficient approaches to be implemented.

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Competing interests None declared.

Patient consent for publication Not required.

Ethics approval As this study constituted public health surveillance rather than research in human beings, ethical approval from institutional review boards was not required. All information on individual persons had been anonymised.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available. The data set used to support the findings of this study are not publicly available as proprietary or confidential information was included.

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