Original Article

Emergency department treatment process planning: a field research, case analysis, and simulation approach

Xiaoyan Huang[1,2#], Shuai Zhou[3#], Xudong Ma[4#], Zhitao Yang[3], Yuanyuan Xu[5], Xiaoxiao Shen[6], Zengni Zhang[6], Guang Ning[7], Erzhen Chen[2,8], Na Li[6], Yong Lu[1,2,3]

[1]Department of Director's Office, Ruijin Hospital, Luwan Branch, Shanghai Jiao Tong University School of Medicine, Shanghai, China; [2]Shanghai Venous Thromboembolism Alliance, Shanghai, China; [3]Division of Medical Affairs, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, Shanghai, China; [4]Department of Medical Administration, National Health Commission of the People's Republic of China, Beijing, China; [5]General Office, Shanghai Hospital Association, Shanghai, China; [6]Department of Industrial Engineering and Management, School of Mechanical and Engineering, Shanghai Jiao Tong University, Shanghai, China. [7]Department of Endocrinology and Metabolism, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, Shanghai, China; [8]Department of Emergency Intensive Care Unit, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, Shanghai, China

Contributions: (I) Conception and design: X Huang, Y Lu; (II) Administrative support: E Chen, G Ning, Y Lu; (III) Provision of study materials or patients: Y Lu, Z Yang; (IV) Collection and assembly of data: S Zhou, Z Yang; (V) Data analysis and interpretation: X Huang, N Li; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.
[#]These authors contributed equally to this work.

Correspondence to: Yong Lu. Ruijin Hospital, Luwan Branch, Shanghai Jiao Tong University School of Medicine, No. 149, South Chongqing Road, Shanghai 200020, China. Email: 18917762053@163.com; Na Li. School of Mechanical and Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China. Email: na-li03@sjtu.edu.cn; Erzhen Chen, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, No. 197 Ruijin 2nd Road, Shanghai 200025, China. Email: erzhenchen1963@sina.com.

Background: The coronavirus disease 2019 (COVID-19) has forced accelerated optimization of Emergency Department (ED) process, and simulation tools offer an alternative approach to strategic assessment and selection.

Methods: Field research and case analysis methods were used to obtain the treatment process and medical records information from the ED of a general hospital. Minitab was used for analysis of the measurement system, and Arena was applied for simulation modelling. We established a framework for the triage protocol of ordinary and quarantined patients, analysed bottlenecks in the treatment time of the hospital's ED, and proposed an optimised management strategy.

Results: The computed tomography (CT) pre-scheduling strategy simulation results demonstrated that longer CT room preparation times for quarantined people before their arrival (T_p) resulted in reduced CT scan and waiting times for quarantined patients, but these times were longer for ordinary patients. The nucleic acid priority strategy simulation results demonstrated that when the average daily number of ordinary patients (λ_c) was relatively stable, the hospital could guide ordinary patients to perform nucleic acid testing first followed by CT testing. However, when λ_c fluctuated greatly, the hospital could appropriately reduce the proportion of preferential nucleic acid testing. Furthermore, when λ_c was overloaded, the nucleic acid priority strategy showed no advantages. The joint analysis results demonstrated that the optimal strategy selection was significantly affected by the severity of the epidemic. The nucleic acid detection sample size optimisation strategy demonstrated that optimizing the sample size of each batch according to the number of patients could effectively reduce the waiting times for nucleic acid testing (T_n).

Conclusions: Simulation tools are an alternative method for strategic evaluation and selection that do not require external factors.

Keywords: Simulation; emergency department (ED); nucleic acid detection test; CT testing; coronavirus disease 2019 (COVID-19) epidemic

Introduction

The coronavirus disease 2019 (COVID-19) pandemic has been the most widespread and difficult to prevent/control of any major public health emergency (1,2), has placed an unprecedented burden on health care systems and economies around the globe (3-5). Most countries have adopted the strategy of strict social distancing guidelines, particularly to protect and strengthen health care systems (6). Global dramatic changes have also taken place in medical practices including the introduction of temporary screening and assessment areas outside the footprint of the main hospital structures (7), Which is highlighting gaps around the world in the design and workflow of Emergency Departments (EDs) (8). The EDs, the hospital's primary outpost in the fight against COVID-19, triage ordinary as well as febrile patients, identify suspected COVID-19 cases early, and implement isolation to control the source of infection and avoid further spread of infectious diseases (9). Failure to recognise the cases and delays in management of an outbreak can pose global health risks (10) and risks to the health of medical staff (11). Due to the vulnerability of the ED environment, the treatment process design and risk mitigation measures are extremely important before the outbreak of infectious diseases (12). Further study is needed to optimise the emergency treatment protocols, in order to reduce contact between patients with suspected or confirmed COVID-19 infection and ordinary patients, and to achieve more effective infection protection.

In severe epidemic situations, process optimisation has always been one of the key tasks for ensuring the continuous improvement of medical quality and safety. Some researchers have proposed the concept of peripheral defence (13), that is, forming a conceptual through the ED design and workflow to segregate potentially infected patients from other nonsuspect cases. Other researchers proposed to separate the ED into physically independent areas, introduce outpatient COVID-19 testing to enhanced surveillance, and reorganize the medical manpower into modular teams (14). There is no denying the effectiveness of these methods, but verifying the effect requires a lot of personal protective equipment, medical personnel, sanitation workers and isolation space, resulting in a heavy burden on hospitals.

Realistically, hospitals need to maintain adequate resources during hospital outbreaks or community pandemics. Herein, we present an alternative approach to address both the tactical and strategic needs of a hospital system by using discrete event simulation and simulation-based optimisation methods (15). Virtual reality technology can be created and designed without the necessity for samples, venues, time, personnel, funding, etc., and can provide managers with ideal decision-making options while reducing costs and promoting major economic and social benefits. Virtual reality technology, most of which are mastered by third-party professional technicians, has been applied to develop medical processes such as clinical operations, optimal staffing, virtual reality surgery simulations for training, and digital hospital medical simulations, etc. (16-19).

This is the first study to use data modelling and simulation experiments to optimise the treatment process for ordinary patients and quarantined people who visit the ED, while minimising manpower, material, financial, and other costs. Simultaneously, our study proposes that simulation tools are an alternative method that does not require external factors, which can assist hospitals or other institutions in strategic evaluation and selection. We present the following article in accordance with the MDAR reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-1944/rc).

Methods

Study design

The present study adopted a combination of theory, field investigation, case analysis, and simulation in its research framework design. We reviewed the literature to understand the application of simulation models in the process optimisation of medical systems. Field investigations were used to disclose the treatment process and obtain medical records information from our hospital's ED.

Based on the findings of the above groundwork, we designed a simulation model and formed its assumptions. The final strategy was obtained through simulation optimisation (*Figure 1*). The study was conducted in accordance with the Declaration of Helsinki (as revised in
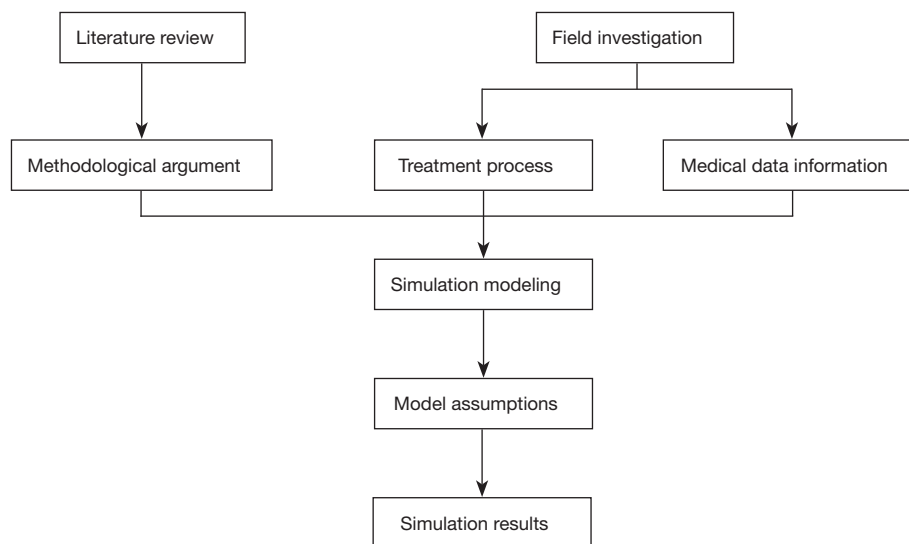
Figure 1 Study design flow chart.

2013). Informed consent was taken from all the participants.

Flow chart of the treatment process of ordinary patients and quarantined people

Our researchers and staff, roleplaying as both ordinary patients and quarantined people, visited the hospital's ED and underwent the entire treatment process. Together with interviews from doctors and nurses, we were able to optimize the treatment process for the hospital's ordinary patients and quarantined people coming in for testing (*Figures 2,3*).

Medical records information

We reviewed 6,364 records from September to November 2020 to determine the nature of patient flow. We found that the arrival times of ordinary patients were unevenly distributed at various times throughout the day. There were two obvious peaks from 9:00 to 11:00 and 19:00 to 21:00, as well as a small peak from 13:00 to 15:00 (*Figure 4*). The arrival times of quarantined people exhibited a high degree of variability, and data analysis did not reveal any discernible pattern in the frequency distributions. The number of arrivals per day was less than five, and the average daily arrival was 0.8.

We also analysed and fitted data of the time interval between nucleic acid testing and computed tomography (CT) scanning during triage from September to November 2020. We found that the number of priority patients for nucleic acid testing was 74.7% of the number of people who needed both CT and nucleic acid testing, and the number of priority patients for CT testing was 25.3%. Simultaneously, with regard to the time interval from CT examination to report delivery, the Minitab fitting result was distributed in accordance with the lognormal distribution LOGN (3.803, 0.760) (*Figure 5*). The time interval between initiation of the polymerase chain reaction (PCR) nucleic acid detection equipment and delivery of the nucleic acid test report conformed to the lognormal distribution LOGN (4.983, 0.410) (*Figure 6*).

Simulation modelling

A simulation model was built based on the treatment process and the treatment records information, and the relevant parameters, attributes, and variables were set according to the real application situations.

Patient attributes and settings are shown in Table S1.

Resources and process time settings are shown in Table S2.

The statistical variables in the simulation model are shown in Table S3.

Model assumptions

Considering the availability of data and the operability of the ED, this study was designed to investigate the following five hypothetical scenarios: (I) CT pre-scheduling strategy; (II) nucleic acid testing priority strategy; (III) nucleic acid
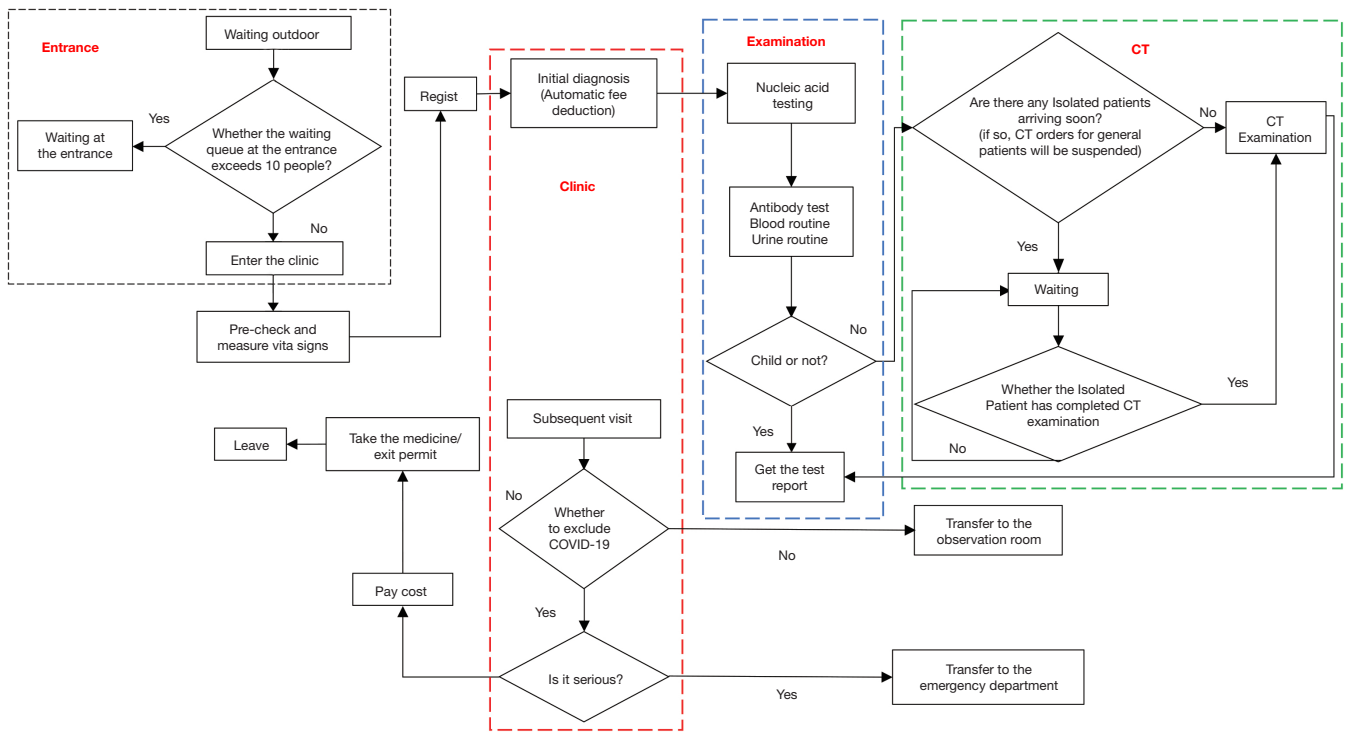
Page 4 of 15

Huang et al. Emergency department treatment process optimization

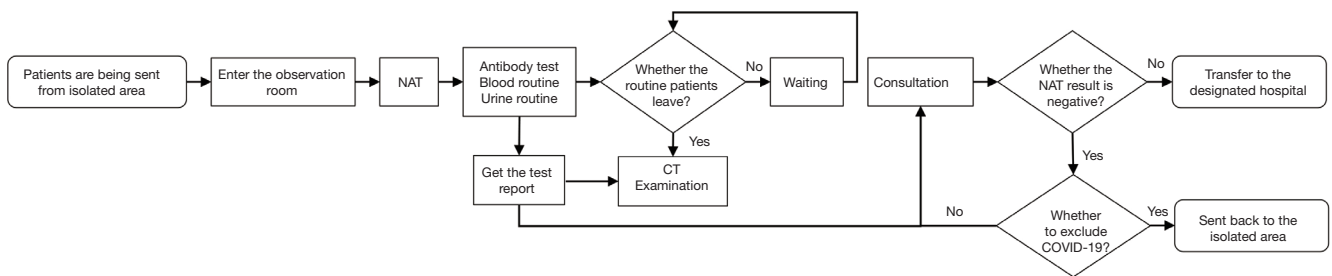**Figure 2** Treatment flow chart for ordinary patients. CT, computed tomography.

Figure 3 Treatment flow chart for quarantined people. NAT, nucleic acid testing; CT, computed tomography.

detection sample size optimisation strategy; (IV) CT pre-scheduling and nucleic acid priority strategy joint analysis; and (V) nucleic acid priority strategy and test sample size optimisation joint analysis. We simulated the total process time that the patient spends in these five hypothetical scenarios to evaluate the population capacity and risk of cross-infection in the ED.

Evaluation index

In our hospital, the completion time of blood sampling and

antibody testing was significantly shorter than the total time needed for nucleic acid testing, and the short transfer time of patients between stations had little effect on the total process time. Thus, these parameters were not specifically analysed in the model. We selected the following evaluation index:

Average total process time for patients (T): the total process time refers to the total time required from the beginning of the pre-check to completion of the return visit. According to the results of the medical records information, the average maximum patient endurance time for the overall
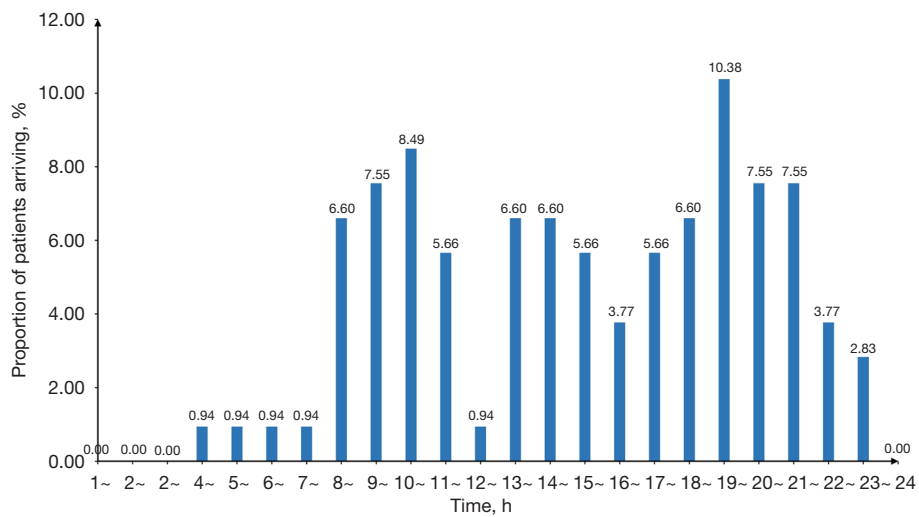
Figure 4 Arrival time distributions of ordinary patients in the emergency clinic.
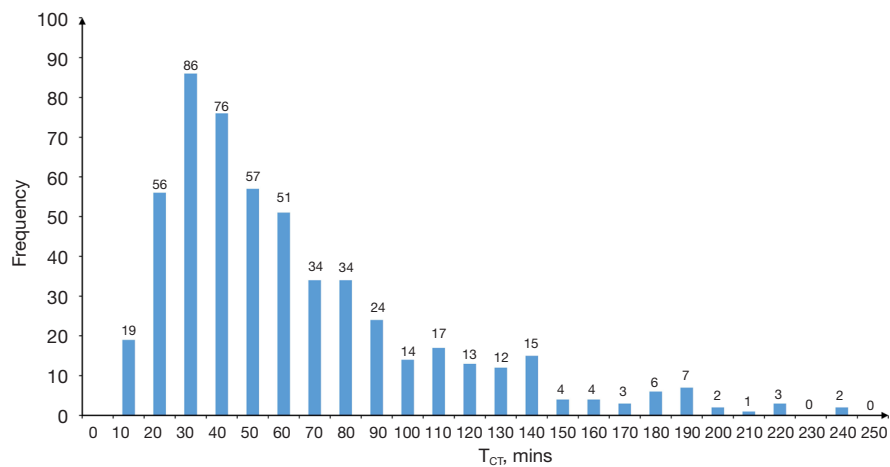

Figure 5 Time distribution of CT testing process. T_{CT}, CT scan and waiting time; CT, computed tomography.

process was 257 minutes.

Crowd density (w, person/m², w ≤1): real-time crowd density refers to the total number of patients waiting for a certain process (including those waiting for consultation rooms, examination, and reports)/total waiting area.

Resource utilisation: the utilisation rate of nucleic acid sample inspection machines (u_n) ≤95%, and the utilisation rate of the CT room (including routine and ultraviolet disinfection time) (u_c) ≤95%.

The times of CT room cross-use (a, times/day): cross-use refers to the use of the CT room by an ordinary patient

followed by a quarantined person.

Statistical analysis

The data distribution of continuous variables was presented as average values [± standard deviation (SD)], and categorical variables were presented as frequencies (%). The intervals between CT examinations and nucleic acid sampling were examined with a normal distribution. The average daily arrivals of ordinary and quarantined people were investigated using the Poisson test. Statistical software,
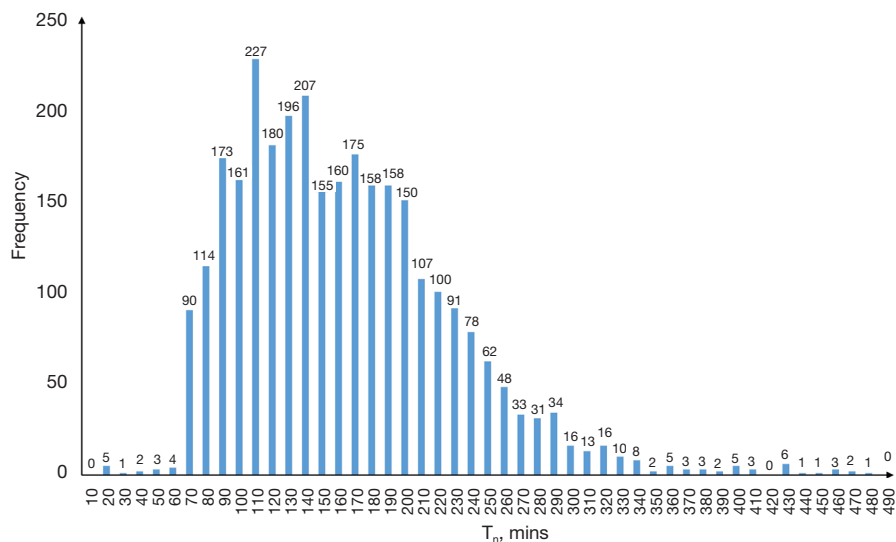
Page 6 of 15

Huang et al. Emergency department treatment process optimization

Figure 6 Time distribution of the nucleic acid detection process. T_n, Waiting time for nucleic acid testing report after sampling.

including Minitab16 and Arena14, was used for statistical analysis, simulation modelling, and drawing.

Results

Simulation of CT scheduling strategy to reduce the risk of cross-infection

The CT pre-scheduling strategy set up scenarios with different proportions of ordinary and quarantined patients, and simulated the influence of different preparation times in the CT room prior to the arrival of quarantined patients (T_p) on the average total process time (T).

The original strategy was to temporarily suspend the billing of ordinary patients in the system who required CT at triangular distribution (TRIA) {30, 45, 60} before the arrival of the quarantined people until all of the quarantined people in the system had completed their CT testing, and then reopen to ordinary patients. In the CT scheduling strategy, for different epidemic severities ($\lambda_o=3$; $\lambda_o=5$) and different carrying capacities [$\lambda_c \in$ {30, 80}], when the original strategy and the CT preparation time changed to TRIA {0, 15, 30}, the mean changes of T, T_{CT}, u_c, u_n, a, and N_t were recorded to evaluate the impact of the CT scheduling strategy on reducing the risk of cross-infection. Arena software was employed to perform simulations and was repeated 10 times in 5 days.

The simulation results demonstrated that shortening the preparation time by a TRIA of {0, 15, 30} decreased both the T and T_{CT}. When $\lambda_o=3$, $\lambda_c \geq 50$ or $\lambda_o=5$, $\lambda_c \geq 60$, as the

preparation time was shortened, T_{CT} and T both decreased. When λ_c was small, the preparation time TRIA, T_{CT} decreased, and T appeared to increase slightly (*Table 1*).

Simulation of the nucleic acid priority strategy to reduce the risk of cross-infection

In the nucleic acid testing priority strategy, $\lambda_c=60$, 80, 100, and $\lambda_o=1$ represented the following three scenarios: patients were free to choose the priority order of examination (74.7% of patients preferred nucleic acid testing), the patient's 100% priority nucleic acid detection, and the patient's 100% priority CT examination. The mean changes in T, T_{CT}, u_c, u_n, a, and N_t were used to evaluate the impact of different strategies on reducing the risk of cross-infection. Arena software was applied to perform simulations and was repeated 20 times in 5 days.

The simulation results demonstrated that when $60 \leq \lambda_c \leq 80$, and $\lambda_o=1$, the patient's 100% priority was nucleic acid detection, which effectively shortened T and reduced N_t. Compared to when the patient's 100% priority was CT examination, N_t was shortened by 26 min ($\lambda_c=60$, $\lambda_o=1$) and 38 min ($\lambda_c=80$, $\lambda_o=1$). When the load capacity was not exceeded ($\lambda_c=80$), larger λ_c represented a more obvious optimisation effect of the nucleic acid priority strategy on reducing the risk of infection. When $\lambda_c=100$ and $\lambda_o=1$, the patient's 100% priority nucleic acid detection was better than that of CT examination, but was similar to the patient's free choice of examination order (*Table 2*).

Table 1 CT pre-scheduling strategy simulation results

No.	T_p (min)	λ_c	λ_o	T (min)	T_{CT} (min)	u_c (%)	u_n (%)	a	N_t
1	TRIA {30, 45, 60}	30	3	264.01	61.67	58.17	24.95	3	7
2		40	3	260.36	70.65	67.23	31.99	3	10
3		50	3	266.59	77.42	76.83	42.51	3	12
4		60	3	253.02	85.42	84.01	46.33	3	14
5		70	3	312.55	208.87	93.7	55.18	3	21
6		80	3	430.60	418.71	95.23	55.21	3	34
7		30	5	274.12	84.06	74.53	26.83	4.88	8
8		40	5	250.43	97.28	84.73	31.14	4.92	9
9		50	5	285.60	164	94.77	39.02	4.96	13
10		60	5	410.31	367.89	97.79	45.65	5	24
11	TRIA {0, 15, 30}	40	3	262.04	49.65	68.32	34.4	3	10
12		50	3	252.46	63.57	79.63	40.11	3.04	12
13		60	3	253.79	81.43	88.05	47.31	3.04	14
14		70	3	278.02	158.59	96.05	52.21	3	19
15		80	3	425.38	390.28	94.75	63.51	3.04	34
16		40	5	263.85	73.3	85.32	35.24	4.92	10
17		50	5	299.81	171.06	94.52	39.69	5.04	14
18		60	5	378.19	333.08	97.75	44.94	4.96	22

T_p, CT room preparation time for quarantined people before their arrival; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people; T, total process time for patients; T_{CT}, CT scan and waiting time; u_c, CT utilisation; u_n, PCR utilisation; a, average number of cross-uses of CT; N_t, average number of waiting patients.

Nucleic acid detection sample size optimisation strategy to shorten the processing time

Rapid nucleic acid tests can detect multiple samples at the same time and reduce testing times. However, when the number of consultations was small, time was incurred in waiting to reach the minimum number of samples required to run the test. The experiment explored optimisation of the nucleic acid detection sample size (S_n) in different visits to reduce the waiting times for nucleic acid detection results. This study designed three sets of experiments with λ_o =1, λ_c=60, 80, 90, $S_n \in \{3, 5\}$, and conducted simulation experiments that were repeated 20 times in 5 days. The researchers simultaneously recorded the mean changes in T, T_{CT}, T_n, u_c, u_n, a, and N_t for each experiment.

The simulation results demonstrated that when $S_n \in \{3, 5\}$, as S_n increased, T and N_t exhibited a trend of initially decreasing and then increasing. When S_n=4, T was the

shortest and N_t was the smallest, which implied that four samples at a time were ideal for optimising the process in our hospital (*Table 3*).

Joint analysis of CT pre-scheduling and nucleic acid priority strategies

Since λ_o was primarily affected by the CT pre-scheduling and nucleic acid priority strategies, we conducted a joint analysis of the CT pre-scheduling strategy and the nucleic acid priority strategy, especially considering the urgency of the quarantined cases.

For different arrival rates λ_o =1, 3 and λ_c = 60, 80, the experiment altered the CT scheduling strategy ($T_p$max =60 min, $T_p$min =0 min)* and nucleic acid priority strategy. The mean changes in T_c, T_{CT}, T_o, N_t, etc. were simultaneously recorded (*considering that the quarantined people treated in the hospital only had a 60-minute drive)

Page 8 of 15

Huang et al. Emergency department treatment process optimization

Table 2 The nucleic acid priority strategy simulation results

No.	P_o (%)	λ_c	λ_o	T (min)	T_{CT} (min)	u_c (%)	u_n (%)	a	N_t
1	74.7	60	1	236.88	46.06	68.46	42.48	1	14
2	100%	60	1	234.11	47.10	69.07	45.18	1	22
3	0	60	1	262.17	48.86	69.14	44.69	1	13
4	74.7	80	1	256.87	87.89	88.83	61.45	1	13
5	100	80	1	248.32	93.62	88.10	62.19	1	15
6	0	80	1	294.43	98.94	88.41	59.51	1	19
7	74.7	100	1	416.74	375.33	93.99	76.46	1	18
8	100	100	1	420.80	417.68	94.35	73.39	1	22
9	0	100	1	636.70	448.49	94.20	67.53	1	41

P_o, proportion of preferential nucleic acid testing; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people; T, average total process time for patients; T_{CT}, CT scan and waiting time; u_c, CT utilisation; u_n, PCR utilisation; a, average number of cross-uses of CT; N_t, average number of waiting patients.

Table 3 Simulation results of the nucleic acid detection sample size optimisation strategy

No.	S_n	λ_c	λ_o	T (min)	T_{CT} (min)	T_n (min)	u_c (%)	u_n (%)	a	N_t
1	3	60	1	238.02	45.84	227.38	68	61.94	1	13
2	4	60	1	231.50	44.71	221.72	68.46	42.48	1	13
3	5	60	1	255.24	46.55	242.82	68.51	36.87	1	14
4	3	80	1	255.79	99.74	255.79	74.87	78.65	1	19
5	4	80	1	264.71	100.38	223.92	90.81	62.35	1	20
6	5	80	1	278.02	113.29	235.78	88.95	50.54	1	21
7	3	90	1	372.62	269.99	254.58	93.37	88.01	1	33
8	4	90	1	296.35	177.40	206.16	93.41	64.23	1	25
9	5	90	1	316.77	212.81	215.47	94.12	54.15	1	27

S_n, sample size; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people; T, average total process time for patients; T_{CT}, CT scan and waiting time; T_n, waiting time for nucleic acid testing report after sampling; u_c, CT utilisation; u_n, PCR utilisation; a, average number of cross-uses of CT; N_t, average number of waiting patients.

using Arena software to perform simulations that were repeated 10 times in 3 days, and a weight system was established to evaluate and select optimisation strategies.

The simulation results demonstrated that with an increase in the number of quarantined people, reducing T_p would have a greater impact on shortening T_c, and with an increase in the number of ordinary patients, increasing T_p appropriately would shorten T_o (*Table 4*).

Considering that T_p and the nucleic acid/CT priority strategies jointly affected the time for nucleic acid samples to reach the laboratory and the effects of their interaction had a non-linear relationship with the results, the experiment used a weighting method [$W_c = U_c * \lambda_c / (U_c * \lambda_c + U_o * \lambda_o)$, $W_o = U_o * \lambda_o / (U_c * \lambda_c + U_o * \lambda_o)$] to evaluate the combined impact of CT pre-scheduling and nucleic acid priority strategies on T_p. According to the experimental hypothesis, the weighted results showed that T_p met the optimal time queue {60, 30, 0} when $U_c=1$ and $U_o=25$, at different visits ($\lambda_c=60, 80, \lambda_o=1, 3$), and nucleic acid priority strategies were applied ($P_o=100\%, 75\%, 50\%, 25\%, 0\%$) (*Figure 7*).

Within the load capacity of the medical system, the

Table 4 The simulation results of joint analysis of CT pre-scheduling and nucleic acid priority strategies

No.	P_o (%)	T_p (min)	λ_c	λ_o	Ordinary patient		Quarantined people			N_t
					T_c (min)	T_{CT} (min)	T_o (min)	T_a (min)	T_{CT} (min)	
1	100	60	60	1	234.68	50.68	247.95	218.22	12.58	13
2		30	60	1	232.97	42.36	204.53	162.98	21.6	13
3		0	60	1	231.64	40.10	206.35	154.4	32.92	13
4		60	60	3	255.04	127.99	220.07	185.83	18.23	14
5		30	60	3	242.51	94.39	194.96	161.97	16.46	13
6		0	60	3	239.29	76.26	220.92	185	18.05	13
7	75	60	60	1	247.42	46.70	275.57	244.06	14.8	14
8		30	60	1	237.13	38.72	246.20	208.77	21.74	13
9		0	60	1	240.18	44.39	237.79	184.9	31.35	13
10		60	60	3	258.52	101.79	238.98	207.86	14.58	14
11		30	60	3	257.62	86.05	238.96	204.56	18.75	14
12		0	60	3	249.50	65.02	222.34	185.75	16.74	14
13	50	60	60	1	254.92	51.63	232.02	203.02	14.47	14
14		30	60	1	248.51	46.92	240.48	201.54	24	14
15		0	60	1	248.74	42.59	215.66	165.3	33.5	14
16		60	60	3	265.61	110.53	215.55	183.78	16.43	15
17		30	60	3	265.13	87.63	244.10	209.75	17.59	15
18		0	60	3	249.92	63.78	229.65	190.91	19.91	14
19	25	60	60	1	258.96	46.55	229.14	202.17	13.31	14
20		30	60	1	254.23	45.43	261.78	221.96	25.03	14
21		0	60	1	254.54	42.69	277.76	224.41	34.16	14
22		60	60	3	291.26	112.21	223.98	190.93	16.51	16
23		30	60	3	267.80	77.06	220.85	187.36	15.36	15
24		0	60	3	269.70	77.37	258.59	218.82	19.35	15
25	0	60	60	1	258.50	47.45	233.72	204.77	14.26	14
26		30	60	1	254.16	43.22	252.53	212.55	23.26	14
27		0	60	1	256.41	43.66	299.29	249.03	31.3	14
28		60	60	3	301.64	112.38	253.14	219.69	15.99	17
29		30	60	3	289.35	89.64	247.39	210.76	20.04	16
30		0	60	3	268.08	67.24	229.82	193.73	18.6	15
31	100	60	80	1	237.80	99.60	190.93	159.94	14.78	18
32		30	80	1	230.75	82.56	174.52	131.29	22.27	17
33		0	80	1	244.08	82.12	272.51	217.17	30.21	18

Table 4 (*continued*)

Page 10 of 15

Huang et al. Emergency department treatment process optimization

Table 4 (*continued*)

No.	P_o (%)	T_p (min)	λ_c	λ_o	Ordinary patient		Quarantined people			N_t
					T_c (min)	T_{CT} (min)	T_o (min)	T_a (min)	T_{CT} (min)	
34	75	60	80	1	251.61	98.70	186.12	152.97	14.76	19
35		30	80	1	254.61	96.23	192.15	154.42	21.35	19
36		0	80	1	250.89	83.15	228.13	176.75	31.68	18
37	50	60	80	1	267.3	91.48	232.89	203.15	14.33	20
38		30	80	1	264.17	89.72	221.86	179.30	24.12	19
39		0	80	1	268.15	96.30	266.73	207.66	33.39	20
40	25	60	80	1	279.38	92.86	238.86	208.28	15.06	21
41		30	80	1	265.64	72.14	271.79	230.41	22	20
42		0	80	1	269.3	74.47	248.29	194.52	30.49	20
43	0	60	80	1	288.91	88.40	246.84	215.00	14.67	21
44		30	80	1	291.63	103.14	241.78	200.34	22.95	22
45		0	80	1	273.45	78.19	249.16	191.32	31.69	20

P_o, proportion of preferential nucleic acid testing; T_p, CT room preparation time for quarantined people before their arrival; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people; T_c, total process time for ordinary patients; T_{CT}, CT scan and waiting time; T_o, total process time of quarantined people; T_a, time from CT test to getting both reports; N_t, average number of waiting patients.
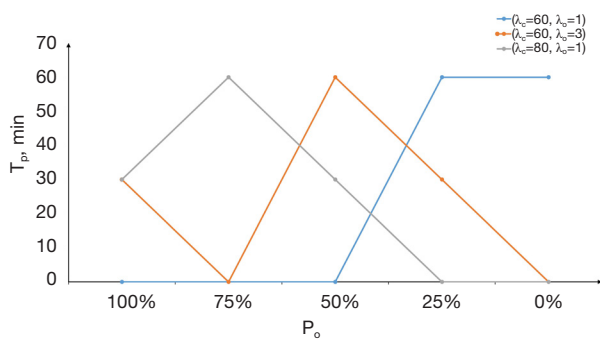

Figure 7 The optimal choice of TP in different visits and nucleic acid priority strategies. T_p, CT room preparation time for quarantined people before their arrival; P_o, proportion of preferential nucleic acid testing; λ_c, average daily visits for ordinary patients.

experiment compared the impact of the nucleic acid priority and the CT pre-scheduling strategies on T_w in different medical visits. When the number of visits remained the same, the nucleic acid priority strategy always reduced the total process time and the reduction was greater than that

achieved with the CT pre-scheduling strategy. When the system adopted the nucleic acid priority strategy, a more obvious impact of T_p on T was observed with increased patient frequency (*Figure 8*).

At the same time, the experiment considered the severity of the epidemic and attempted to design an optimal strategy for when U_c:U_o=1:25, 1:10, and 1:1. The choice of optimal strategy was greatly affected by the severity of the epidemic. When U_o was lower, shortening T_p was conducive to shortening T (*Figure 9*).

Joint analysis of the nucleic acid priority strategy and test sample size optimisation

Based on the above results, we conducted a joint analysis of two variables that influence T_n, i.e., nucleic acid priority strategy (P_o) and the average test S_n. Considering the peak visit hours and the long duration of patient visits, this study selected all patient visits from 7:00 p.m. to 11:00 p.m. from the above experimental data and performed 20 repeated experiments. This experiment was performed based on the following: (I) under the premise that all ordinary
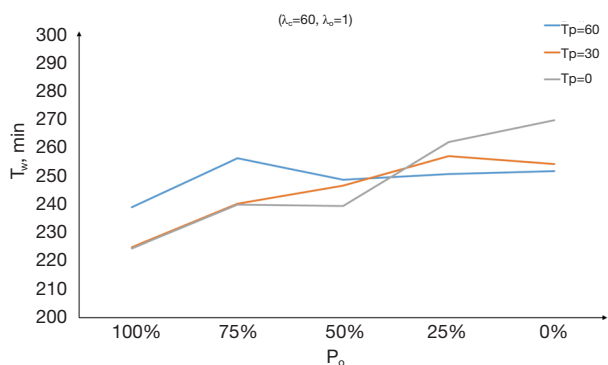
Figure 8 Comparison of the influence of the nucleic acid priority and CT pre-schedule strategies on T_w in different visits. T_w, patient weighted process time; T_p, CT room preparation time for quarantined people before their arrival; P_o, proportion of preferential nucleic acid testing; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people.

Figure 9 Optimal strategy selection under different epidemic severities. T_p, CT room preparation time for quarantined people before their arrival; P_o, Proportion of preferential nucleic acid testing; λ_c, average daily visits for ordinary patients; λ_o, average daily visits of quarantined people; U_c, urgency of ordinary patient; U_o, urgency of quarantined people.

patients chose the nucleic acid priority strategy, the experiment established $S_n \in \{2, 6\}$ and conducted five sets of experiments to record T_c, T_n, and T_{CT}, in order to compare the optimal detection S_n. (II) In the combined analysis of the nucleic acid priority strategy and average sample size, the experiment set $S_n \in \{2, 6\}$, P_o=90%, 70%, and eight sets of experiments recorded T_c, T_n, and T_{CT} to compare the optimal strategies (*Table 5*).

According to the simulation results, when P_o=100%, as S_n increased, T_c exhibited a trend of initially decreasing and then increasing. The optimal average sample detection volume under the current peak of visits was four (S_n=4). Although S_n=6, T_c was the lowest because the total process time of most ordinary patients was increased and not included in the system. Furthermore, as the results of the previous groups of experimental data tended to be more obvious, this study did not consider S_n=6. At the same time, when $S_n \in \{2, 5\}$, P_o dropped to 90%, T_c decreased significantly, but when it dropped to 70%, the downward trend was less obvious. It may be that during peak hours, the excessive accumulation of nucleic acid samples increased the invalid waiting times. Therefore, a moderately small reduction in P_o could optimise the allocation of resources, while a large reduction in P_o would make the time stacking effect caused first by the patient's CT and then by the
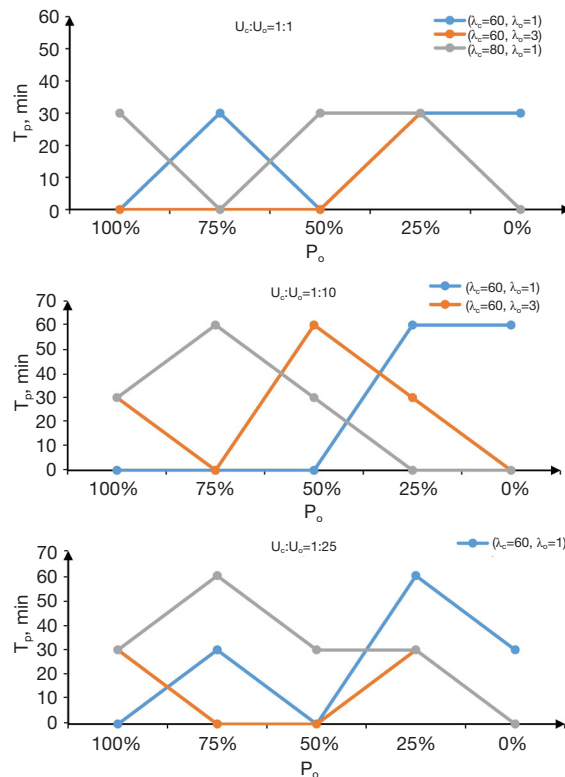
nucleic acid testing more obvious.

Discussion

Strategies for entry personnel to control and prevent infection

Previous study has shown that controlling the density of personnel can reduce the risk of cross-infection (20). The ED could play a role in active surveillance; however, the costs, benefits, and implications of hospital-based surveillance have yet to be studied (21). A quick assessment area could be set up at the entrance of the ED to reduce access and contact opportunities for non-essential patients

Page 12 of 15

Huang et al. Emergency department treatment process optimization

Table 5 Simulation results of strategy optimisation during peak hours

S_n	P_o (%)	T (min)	T_{CT} (min)	T_n (min)
2	100	343.10	123.64	388.29
3		243.43	117.43	232.30
4		226.79	142.76	65.08
5		244.39	110.53	183.73
6		227.07	111.58	204.01
2	90	287.35	97.15	344.54
2	70	341.58	112.10	402.58
3	90	218.80	101.69	213.53
3	70	235.85	91.31	200.08
4	90	203.53	108.92	173.14
4	70	226.47	108.02	175.30
5	90	211.76	94.85	171.10
5	70	226.77	98.85	185.62

S_n, sample size; P_o, proportion of preferential nucleic acid testing; T, average total process time for patients; T_{CT}, CT scan and waiting time; T_n, waiting time for nucleic acid testing report after sampling.

and staff (22). For example, by installing monitoring devices, the system dynamically recognises the number of people entering, and when the density of patients exceeds the threshold, it sends an early warning to the staff to restrict patients from entering the outpatient and the ED, and also alerts those waiting outside the entrance.

Optimise the information system to automatically initiate the CT pre-scheduling strategy

The above results showed that the longer the preparation time before the arrival of quarantined people, the longer the waiting time for ordinary patients and the shorter the waiting time for quarantined people. At the same time, simulation tools can assist in evaluating the results of different strategies and in making strategic choices based on the hospital's preferences. Our study findings suggest that it is necessary to establish effective communication channels between the ED and the administrative, clinical, and medical technical departments. For example, the administrative department should relay the arrival times of quarantined people in advance, whereby the hospital information system algorithm can determine the time when ordinary patients should stop using the CT room and quarantined people may start to use the CT room

independently. This will help to improve the efficiency of CT use and reduce patient waiting times, while at the same time preventing cross-use.

Nucleic acid priority strategy to reduce the risk of cross-infection

The nucleic acid priority strategy results demonstrated that when $60 \leq \lambda_c \leq 80$ and $\lambda_o = 1$, the patient's 100% priority nucleic acid detection effectively shortened T and reduced N_t. Owing to the long time it takes to complete the nucleic acid sampling and deliver the report for review, CT detection can be completed during this time; hence, the nucleic acid priority strategy was beneficial to increase the time coincidence of T_n and T_{CT}, thereby shortening T. When $\lambda_c = 100$, the patient's 100% priority nucleic acid detection was superior to that of the CT examination, but was less dissimilar to the patient's free choice of examination order. It may be that when the number of visits increased, T_{CT} increased rapidly, which reduced the degree of coincidence with T_n. However, when $\lambda_c > 100$, the advantage of the nucleic acid priority strategy was not prevalent because of the rapid growth of T_{CT}. Therefore, when the number of consultations is relatively stable, the hospital can guide ordinary patients to perform nucleic acid testing

first followed by CT testing, which is more conducive to shortening T. However, when the number of visits fluctuates greatly, the system can appropriately reduce P_o; for example, 90% of patients prioritise nucleic acid testing and 10% of patients prioritise CT testing. Furthermore, this study also found that when the number of visits remained the same, shortening the processing time for a single patient was also conducive to reducing the density of people in the system and reducing the risk of cross-infection. Hospitals can select the optimal strategy according to the actual scenario.

Sample sizes per batch testing optimisation process

According to the sample size analysis results, based on an actual scenario in our hospital, four samples per batch were found to be beneficial for optimising the process and reducing the risk of infection. However, the sample size of each batch is not uniform; it is very common for 10 samples to be tested in the whole population and five samples to be tested in a large group in China. Other health institutions can also use simulation methods to determine the optimal sample size for nucleic acid testing according to the severity of the epidemic and the need of nucleic acid testing, thereby saving time and budget costs.

Efficient review strategy for nucleic acid test results

Research and data analysis showed that after completing nucleic acid testing, issuing test reports took 2–3 hours in some cases, causing patients to remain in the outpatient clinic and thus increasing the risk of cross-infection. We propose the use of automatic prompts (23), such as SMS and WeChat, to alert doctors to speed up the review, and use adherence to this practice as one of the criteria for the evaluation of a doctor's performance.

Refined patient classification, precise prevention, and control

As a precaution during the epidemic, medical institutions should formulate a clear classification of emergency patients (especially those with fever), determine a targeted treatment process for grading patients, and optimize the ED according to this scheme.

Conclusions

The simulation tool is a viable and effective approach

for identifying workflow inefficiencies, which can assist in evaluating the results of various strategies according to different needs. This will facilitate the discovery and validation of options for improvement through what-if scenario testing, as hospitals can choose strategies based on their own needs and obtain the most benefits with the least cost. This method is worthy of replication and promotion by similar hospitals or fields.

For the ED of our hospital, when the number of consultations was relatively stable, the hospital was able to guide ordinary patients to undergo nucleic acid testing first followed by CT testing, which was more conducive to shortening T. In cases where the number of visits fluctuated greatly, the system could appropriately reduce the proportion of priority nucleic acid testing (P_o), and four samples per batch were beneficial for optimising this process. However, regardless of the strategy adopted, it was adjusted according to the actual scenario observed in the ED. According to the national public health emergency response level, decision makers can predict the risk level and difficult challenges of infectious diseases, and carry out the simulation design of emergency plan according to the actual situation of the hospital to customize the workflow optimization strategy.

Acknowledgments

Footnote

Reporting Checklist: The authors have completed the MDAR reporting checklist. Available at https://atm.amegroups.com/article/view/10.21037/atm-22-1944/rc

Data Sharing Statement: Available at https://atm.amegroups.com/article/view/10.21037/atm-22-1944/dss

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://atm.amegroups.com/article/view/10.21037/atm-22-1944/coif).

Page 14 of 15

Huang et al. Emergency department treatment process optimization

The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). Informed consent was taken from all the participants.

Open Access Statement: This is an Open Access article distributed in accordance with the Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International License (CC BY-NC-ND 4.0), which permits the non-commercial replication and distribution of the article with the strict proviso that no changes or edits are made and the original work is properly cited (including links to both the formal publication through the relevant DOI and the license). See: https://creativecommons.org/licenses/by-nc-nd/4.0/.

References

1. Shen J, He Q, Shen T, et al. "An integrated system, three separated responsibilities", a new fever clinic management model, in prevention and control of novel coronavirus pneumonia. World J Clin Cases 2021;9:9050-8.
2. Ates AA, Alomari T, Bhardwaj A, et al. Differences in endodontic emergency management by endodontists and general dental practitioners in COVID-19 times. Braz Oral Res 2020;34:e122.
3. Rodriguez HC, Gupta M, Cavazos-Escobar E, et al. Umbilical cord: an allogenic tissue for potential treatment of COVID-19. Hum Cell 2021;34:1-13.
4. Campanella S, Arikan K, Babiloni C, et al. Special Report on the Impact of the COVID-19 Pandemic on Clinical EEG and Research and Consensus Recommendations for the Safe Use of EEG. Clin EEG Neurosci 2021;52:3-28.
5. Bhowmick NA, Oft J, Dorff T, et al. COVID-19 and androgen-targeted therapy for prostate cancer patients. Endocr Relat Cancer 2020;27:R281-92.
6. Khan M, Adil SF, Alkhathlan HZ, et al. COVID-19: A Global Challenge with Old History, Epidemiology and Progress So Far. Molecules 2020;26:39.
7. Miller NM, Jones I, Russ S, et al. A model for rapid emergency department expansion for the COVID-19 pandemic. Am J Emerg Med 2020;38:2065-9.
8. Nadarajan GD, Omar E, Abella BS, et al. A conceptual framework for Emergency department design in

a pandemic. Scand J Trauma Resusc Emerg Med 2020;28:118.
9. Hu X, Liu S, Wang B, et al. Management practices of emergency departments in general hospitals based on blockage of chain of infection during a COVID-19 epidemic. Intern Emerg Med 2020;15:1545-52.
10. The Neglected Dimension of Global Security. The Neglected Dimension of Global Security. National Academy of Sciences; 2016.
11. Wilder-Smith A, Low JG. Risk of respiratory infections in health care workers: lessons on infection control emerge from the SARS outbreak. Southeast Asian J Trop Med Public Health 2005;36:481-8.
12. Ong ME. War on SARS: a Singapore experience. CJEM 2004;6:31-7. Erratum in: CJEM 2004;6:79.
13. Cliff A, Smallman-Raynor M. Oxford Textbook of Infectious Disease Control.Oxford Textbook Infect Dis Control. 2013:1-69.
14. Tan RMR, Ong GY, Chong SL, et al. Dynamic adaptation to COVID-19 in a Singapore paediatric emergency department. Emerg Med J 2020;37:252-4.
15. Tellis R, Starobinets O, Prokle M, et al. Identifying Areas for Operational Improvement and Growth in IR Workflow Using Workflow Modeling, Simulation, and Optimization Techniques. J Digit Imaging 2021;34:75-84.
16. O'Hara S. Planning intensive care unit design using computer simulation modeling: optimizing integration of clinical, operational, and architectural requirements. Crit Care Nurs Q 2014;37:67-82.
17. Shim SJ, Kumar A, Jiao R. Using computer simulation for optimal staffing: A case for the patient registration process of a hospital. Technol Health Care 2017;25:385-90.
18. Holford N, Ma SC, Ploeger BA. Clinical trial simulation: a review. Clin Pharmacol Ther 2010;88:166-82.
19. Li B, Wang H, Li G, et al. A patient-specific modelling method of blood circulatory system for the numerical simulation of enhanced external counterpulsation. J Biomech 2020;111:110002.
20. Gilligan P, Quirke M, Winder S, et al. Impact of admission screening for methicillin-resistant Staphylococcus aureus on the length of stay in an emergency department. J Hosp Infect 2010;75:99-102.
21. Liang SY, Theodoro DL, Schuur JD, et al. Infection prevention in the emergency department. Ann Emerg Med 2014;64:299-313.
22. Sangal RB, Scofi JE, Parwani V, et al. Less social emergency departments: implementation of workplace contact reduction during COVID-19. Emerg Med J

2020;37:463-6.

23. Zhou S, Ma X, Jiang S, et al. A retrospective study on the effectiveness of Artificial Intelligence-based Clinical Decision Support System (AI-CDSS) to improve the incidence of hospital-related venous thromboembolism (VTE). Ann Transl Med 2021;9:491.

(English Language Editor: A. Kassem)

Table S1 Patient attributes and settings

Attributes	Settings
Ordinary patients or quarantined people	Ordinary patients-1, quarantined people-2
Adult or child	70.3% adults, 29.7% children, discrete distribution (0.703, 1, 1.0, 2)
Inspection Sequence	74.7% of patients were prioritised for nucleic acid testing, and 25.3% of patients were prioritised for CT examination, discrete distribution (0.747, 1, 1, 2)

Table S2 Resources and process duration settings.

Area	Key information	Settings	Resource
Entrance	Limit number of people	≤10	
	Preparation time before the arrival of the quarantined people	TRIA (30, 45, 60)	
	Ordinary patient pre-screening	TRIA (0.5, 1, 1.5)	1 nurse
	Registration window	TRIA (0.5, 1, 1.5)	1 registrar
	Payment window	TRIA (0.5, 1, 1.5)	1 clerk
	Medicine window	TRIA (0.5, 1, 1.5)	1 pharmacy assistant
General consultation room	First visit time	TRIA (2, 2.5, 3)	2 doctors for adults and 1 doctor for children. Three people were responsible for consultation of quarantined people at the same time, and they need to leave the general consulting room to go to the observation room during work.
	Follow-up time	TRIA (6, 10, 16)	
Nucleic acid testing	Time to obtain sample	TRIA (0.5, 1, 1.5)	1 nurse
	Sample inspection strategy	4 samples per batch, 1 PCR nucleic acid detection equipment	
	Detection time	LOGN (4.983, 0.410)	6 PCR nucleic acid detection equipments
CT examination	CT scan	TRIA (6, 10, 13)	1 CT machine
	CT result analysis and review	LOGN (3.803, 0.760)	
CT room disinfection	Ultraviolet disinfection	three times a day at 8 am, 4 pm, and 10 pm	Following use by ordinary patients, the CT room was disinfected for 2 min. Following use by quarantined people, the CT room was disinfected with ultraviolet light for 1 h
	Surface disinfection	Every 2 h 10 min interval	
Observing room	Pre-check	TRIA (0.5, 1, 1.5)	1 nurse
	Nucleic acid sampling	TRIA (0.5, 1, 1.5)	

TRIA, triangular distribution; PCR, polymerase chain reaction; CT, computed tomography; LOGN, lognormal distribution.

Table S3 Statistical variables in the simulation model

Variable	Definition
λ	Average daily visits
λ_c	Average daily visits for ordinary patients
λ_o	Average daily visits of quarantined people
T	Average total process time for patients
T_c	Total process time for ordinary patients
T_o	Total process time of quarantined people
T_{CT}	CT scan and waiting time
$T_{CT\text{-}c}$	CT scan and waiting time of ordinary patients
$T_{CT\text{-}o}$	CT scan and waiting time of quarantined people
T_w	Patient weighted process time
t_a	Time from CT test to getting both reports
T_n	Waiting time for nucleic acid testing report after sampling
u_c	CT utilisation
u_n	PCR utilisation
a	Average number of cross-uses of CT
A	Upper limit of cross-use times of CT room
N_t	Average number of waiting patients
S	Area of the fever clinic system
w	Crowd density
k	Maximum total process time the patient can tolerate
T_p	CT room preparation time for quarantined people before their arrival
U_c	Urgency of ordinary patient
U_o	Urgency of quarantined people
W_c	Ordinary patient weight
W_o	Quarantined person weight
T_w	Patient weighted total process time
P_0	Proportion of preferential nucleic acid testing

PCR, polymerase chain reaction; CT, computed tomography.