Early in the pandemic of coronavirus disease 2019 (COVID-19), face masks were used extensively by the general public in several Asian countries. The lower transmission rate of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in Asian countries compared with Western countries suggested that the wider community use of face masks has the potential to decrease transmission of SARS-CoV-2. A risk assessment model named Susceptible, Exposed, Infectious, Recovered (SEIR) model is used to quantitatively evaluate the potential impact of community face masks on SARS-CoV-2 reproduction number ($R_0$) and peak number of infectious persons. For a simulated population of one million, the model showed a reduction in $R_0$ of 49% and 50% when 60% and 80% of the population wore masks, respectively. Moreover, we present a modified model that considers the effect of mask-wearing after community vaccination. Interestingly mask-wearing still provided a considerable benefit in lowering the number of infectious individuals. The results of this research are expected to help public health officials in making prompt decisions involving resource allocation and crafting legislation.

**KEYWORDS**
coronavirus, infectious disease, $R_0$, risk assessment, SEIR

### 1 | INTRODUCTION

In December 2019, an outbreak of pneumonia of unknown etiology was detected in Wuhan, China (Zhu et al., 2020). Chinese health authorities later identified the cause of pneumonia to be the novel coronavirus severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (World Health Organization, 2020d). SARS-CoV-2 exhibited efficient person-to-person transmission of the illness that became known as coronavirus disease 2019 (COVID-19), quickly causing a global outbreak. As a result, on March 11, 2020, the World Health Organization (WHO) declared COVID-19 a pandemic (World Health Organization, 2020a). As of June 26, 2020, more than 9,200,000 cases of COVID-19 have been reported, leading to more than 475,000 deaths (World Health Organization, 2020c).

When vaccines are not available, alternative strategies are required to decrease SARS-CoV-2 transmission. Behavior of the population and government regulations, such as hand hygiene, quarantine of exposed persons, isolation of symptomatic persons, and travel restriction, play an essential role in decreasing respiratory virus transmission (Shaw et al., 2020). Another countermeasure that has been a subject of discussion is the use of face masks, which are inexpensive, easy to use, and historically have been available in countries with limited supplies of antiviral drugs and vaccines (Trach et al., 2010). For example, persons in China who wore masks in public had a significantly lower risk of acquiring 2003 SARS-CoV compared to persons who did not wear masks (Wu et al., 2004). In Hong Kong, 76% of the residents reported using masks during the 2003 SARS epidemic, which was one of several community hygienic measures that may
have decreased incidence of acute respiratory virus infections (Lo et al., 2005). An early study by Wang et al. (2020) showed that mask use could be effective in the prevention of household transmission of SARS-CoV-2.

To interrupt SARS-CoV-2 transmission, several Asian countries employed early use of face masks in the community, including use by asymptomatic persons (Feng et al., 2020). In Hong Kong, the department of health advised people to wear surgical masks when taking public transport or staying in crowded places (Hong Kong Department of Health, 2020). Japan announced on April 1, 2020, that each household would receive two reusable cloth masks for prevention of COVID-19 (Jozuka & Ogura, 2020). In addition, the ministry of health in Singapore urged people with respiratory symptoms to wear masks (Ministry of Health in Singapore, 2020).

The widespread use of face masks among the general public in some parts of Asia, including South Korea, Japan, Hong Kong, and Singapore, was correlated with lower incidence of SARS-CoV-2 infections compared to Western countries where community use of face masks was less prevalent early in the pandemic (Cheng et al., 2020). The correlation between public face mask use and lower COVID-19 incidence rates has raised important questions regarding the potential effectiveness of face masks in preventing the spread of COVID-19. However, little research has been published to date to quantify the potential impact of face masks on COVID-19 transmission. Hence, this study aims to introduce a risk assessment model to explore the impact of the surgical masks on controlling the spread of COVID-19.

2  |  MASK EFFECTIVENESS AGAINST CORONAVIRUS AND INFLUENZA-LIKE ILLNESS

Person-to-person spread of COVID-19 is thought to occur primarily via respiratory droplets, and asymptomatic transmission may occur (Bai et al., 2020; World Health Organization, 2020e). In order to evaluate the possible influence of different strategies of interventions on coronavirus and Influenza-Like Illness (ILI), various risk assessment models have been implemented (Beauchemin & Handel, 2011; Canini & Carrat, 2011; Guo et al., 2015). Deterministic models such as Susceptible, Infectious, Recovered (SIR), Susceptible, Exposed, Infectious, Recovered (SEIR), and carrier state models have been commonly used to model transmission of respiratory disease (Goscé et al., 2020). Face masks can capture respiratory droplets, but the effectiveness of face masks in preventing transmission of COVID-19 is not known. Furthermore, the relative effectiveness of face masks when worn by an infected person, susceptible person, or both is also unknown. Several recent studies suggested that face masks could decrease COVID-19 transmission. Matuschek et al. (2020) performed an extensive query of the most recent publications addressing the prevention of viral infections, including community use of face masks. They concluded that simple masks covering the mouth and nose could be useful when the recommended minimum distance of 1.5 m is not feasible. Goscé et al. (2020) used a risk assessment model to predict the epidemiological impact of lifting the lockdown in London, UK. They investigated the impact of multiple nonpharmaceutical interventions and concluded that the best strategy to lift lockdown was a combination of weekly universal testing, contact tracing, and the use of facemasks. Cheng et al. (2020) compared the incidence of COVID-19 per million in Hong Kong with community-wide masking to that of non-mask-wearing countries comparable to Hong Kong in terms of population density, healthcare system, BCG vaccination, and social distancing measures. The authors suggested that community-wide mask-wearing may control COVID-19 by reducing the amount of emission of infected saliva and respiratory droplets from individuals with subclinical or mild COVID-19. Leung et al. (2020) compared the efficiency of surgical masks for source control of seasonal coronavirus, influenza, and rhinovirus. The study was conducted on 10 participants and revealed that masks were effective at blocking coronavirus droplets of all sizes for every subject. The authors concluded that face masks might have a substantial role in source control of the COVID-19 outbreak. Liang et al. (2020) presented a systematic review and meta-analysis of the 21 studies. They showed that face masks could reduce the risk of the transmission of respiratory viral infections, including SARS-CoV-2. However, they concluded that more evidence is required to clarify the effectiveness of masking in various situations.

Yan et al. (2019) used a SIR model to estimate the effectiveness of different types of face masks in reducing the infection rate in an influenza outbreak. Each mask studied was associated with at least a 50% decrease in the risk of acquiring influenza. Moreover, the study showed that the model could be helpful to public health officials making decisions involving resource allocation or education strategies. Guha et al. (2015) tested three brands of face masks designed for pediatric patients and evaluated the penetration of submicron size particles at different flow rates. They found that penetration varied from 15 to 50% among brands at the highest flow rates. Finally, MacIntyre and Chughtai (2015) evaluated several clinical trials on use of mixed interventions to prevent respiratory illness and found that the combination of face masks and hand hygiene may be beneficial in community settings.

3  |  METHODS

Deterministic models such as SEIR model are usually adopted to estimate $R_0$ and associated descriptors, which are essential for studying and tracking an epidemic (Currie et al., 2020). The ability of such models to estimate $R_0$ supports decisionmakers in evaluating the effectiveness of intervention and mitigation strategies such as physical distancing (Tuite et al., 2020), lockdowns (Alrashed et al., 2020), school closure, and voluntary event cancellation (Kurita et al., 2020).
TABLE 1 Variable used in the proposed SEIR model for COVID-19

| Class | Variable | Definition                                                                 |
|-------|----------|-----------------------------------------------------------------------------|
| I     | S        | Count of susceptible individuals not wearing a mask                         |
|       | S_m     | Count of Susceptible individuals wearing a mask                              |
| II    | E        | Count of exposed individuals not wearing a mask                              |
|       | E_m     | Count of exposed individuals wearing a mask                                  |
| III   | I        | Count of infected individuals not wearing a mask                             |
|       | I_m     | Count of infected individuals wearing a mask                                 |
| IV    | R        | Count of recovered individuals                                              |
| V     | D        | Count of dead individuals                                                    |

This study uses SEIR model to assess the impact of the community use of surgical masks on the risk of COVID-19 transmission rather than making actual predictions. This model can be helpful in understanding and predicting the prospective course of an outbreak, given a set of underlying assumptions. Several papers in the literature have addressed how coronavirus and ILI transmission can be modeled using the SEIR model (Chu et al., 2020; Gardner et al., 2014; Nicolaides et al., 2020). However, little research has been published to quantify the effect of global community use of face masks on COVID-19 transmission. Lesser research has been carried out on the effect of the same intervention after vaccination on the spread of COVID-19. Hence, this study introduces a risk assessment model to investigate the impact of the surgical masks on controlling the spread of COVID-19 before and after vaccination.

3.1 Proposed SEIR model without vaccination

We estimated the required parameters of the model based on real data and calculated the effect of mask-wearing on reducing the reproduction number ($R_0$) in various scenarios, including a simulated population of size 1 million. In addition, we used this model to simulate the possible benefits of mask-wearing in decreasing the number of active infections in five western countries: France, Germany, Italy, Spain, and the United States. Individuals of a population were split into mask-wearing (variable with $m$ subscript) and nonmask wearing groups. The variables used in the SEIR model are illustrated in Table 1.

We assumed five classes to describe the epidemiological status, and the variables in each class were defined as follows: susceptible, denoted by $S$ and $S_m$ (i.e., people who are not infected and not immune to the virus), exposed, denoted by $E$ and $E_m$ (i.e., people who are exposed but not yet infected or contagious), and infectious individuals, $I$ and $I_m$ (i.e., people with active infections who are contagious), while $R$ and $D$ denoted recovered and dead individuals, respectively. The eight epidemiological variables are defined and summarized in Table 1, and the possible transitions are shown diagrammatically in Figure 1. Because we evaluated the effectiveness of masks in a single time period, we used a closed system with no migration in or out. In addition, births and natural deaths were excluded from the model.

The transfer rate of individuals from class II (exposed), $E$ and $E_m$, to the class III (infectious), $I$ and $I_m$, are $\varepsilon E$ and $\varepsilon E_m$, where $\varepsilon$ is the transfer rate from the exposed class. Infectious individuals can move to either class IV (recovered) or V (dead), with a rate $\gamma I$ and $\gamma I_m$, and $\mu I$ and $\mu I_m$, respectively, where $\gamma$ is the recovery rate and $\mu$ is the mortality rate.

In this model, we assumed that the number of contact activity levels remained the same as before the epidemic. Without loss of generality of the model, we assumed that individuals change their attitudes towards wearing or not wearing masks based on the number of individuals infected with SARS-CoV-2. The transfer rate in the same class from not wearing to wearing a mask is defined as

$$\varphi_i = \frac{b_i - a_i}{1 + e^{-10(i + I_m - \tau)}} + a_i$$  (1)

where $\varphi_i$ is a sigmoid function for $i = S, E, I, S_m, E_m, I_m$, and $\tau$ is the threshold such that if $I + I_m > \tau$, then the transfer rate in the same class is $b_i$. On the other hand, if $0 \leq I + I_m \leq \tau$, then $a_i$ is the transfer rate in the class. We defined $\varphi_{S_m}, \varphi_{E_m}$, and $\varphi_{I_m}$ to be the transfer rates at each class from the $S, E$, and $I$ to the $S_m, E_m$, and $I_m$, respectively. Similarly, $\varphi_S, \varphi_E$, and $\varphi_I$ are the transfer rates from the $S_m, E_m$, and $I_m$ to the $S, E$, and $I$, respectively.

Using the transfer diagrams in Figure 1, the following system of differential equations can be obtained:

$$\frac{dS}{dt} = -(\varphi_{S_m} + \lambda) S + \varphi_S S_m$$
$$\frac{dE}{dt} = -(\varphi_{E_m} + \varepsilon) E + \varphi_E E_m + \lambda S$$
$$\frac{dI}{dt} = -(\varphi_{I_m} + \gamma + \mu) I + \varphi_I I_m + \varepsilon E$$
$$\frac{dS_m}{dt} = -(\varphi_S + \lambda_m) S_m + \varphi_{S_m} S$$  (2)
$$\frac{dE_m}{dt} = -(\varphi_E + \varepsilon) E_m + \varphi_{E_m} E + \lambda_m S_m$$
$$\frac{dI_m}{dt} = -(\varphi_I + \gamma + \mu) I_m + \varphi_{I_m} I + \varepsilon E_m$$
$$\frac{dR}{dt} = \gamma (I + I_m)$$
\[ \frac{dD}{dt} = \mu (I + I_m) \]

\( \lambda \) (nonmask group) and \( \lambda_m \) (mask group) are the forces of infection (i.e., the transfer rates from the susceptible class, \( S \) and \( S_m \), to the exposed class, \( E \) and \( E_m \)) and are given by

\[ \lambda = \frac{\beta}{N} \left[ I + (1 - \eta_s) I_m \right] \]  

(3)

\[ \lambda_m = \frac{\beta}{N} \left( 1 - \eta_s \right) \left[ I + (1 - \eta_i) I_m \right] \]  

(4)

In Equation 3 and 4, \( N \) is the population size. The infection rates, \( \lambda \) and \( \lambda_m \), incorporate the probability of \( \eta_s \) and \( \eta_i \), which accounts for the effectiveness of the mask in reducing susceptibility and infectivity, respectively, in addition to the transmissibility \( \beta \). \( \beta \) is actually the probability of disease transmission multiplied by the average number of contacts an individual had per day (Chowell et al., 2006) and can be calculated by \( \beta = (\mu + \gamma) \times R_0 \).

The “next-generation operator” approach (Van den Driessche & Watmough, 2002) was used to find an expression for the reproduction number when individuals wear masks \( R_0 \). The computation was done by linearizing the system of Equation 2 around the disease-free equilibrium (DFE).

The DFE has \( E, E_m, I, \) and \( I_m \) initially equal to zero with \( S_0, S_{m0} \) positive. \( R \) is also equal to zero since there is no immunity from previous infection or vaccination. The four-dimensional linearized system is of the form \( \frac{dX}{dt} = (F - V)X \) where

\[ F = \frac{1}{N} \begin{bmatrix} 0 & 0 & S_0 \beta & S_0 \beta (1 - \eta_i) \\ 0 & 0 & S_{m0} \beta (1 - \eta_s) & S_{m0} \beta (1 - \eta_i) (1 - \eta_s) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \]

\[ V = \begin{bmatrix} \varphi_{E_m} + \varepsilon & -\varphi_E & 0 & 0 \\ -\varphi_{E_m} & \varphi_E + \varepsilon & 0 & 0 \\ -\varepsilon & 0 & \varphi_{I_m} + \gamma + \mu & -\varphi_I \\ 0 & -\varepsilon & -\varphi_{I_m} & \varphi_I + \gamma + \mu \end{bmatrix} \]

The new reproduction number \( R_0^\dagger \) can be obtained as \( R_0^\dagger = \rho(FV^{-1}) \) where \( \rho(A) \) is the spectral radius of square matrix \( A \).

3.2 Proposed SEIR model under vaccination

We modify the proposed SEIR model to consider the impact of mask-wearing under vaccination on the COVID-19 spread. As shown in Figure 2, a new class \( V \) denoting the number of vaccinated cases is added. The class is formulated as a portion of the susceptible population with a rate of \( \alpha \). The disease transmission flow of the proposed model is sketched in Figure 2. Since a class of vaccinated individuals is added, vaccine inefficiency \( (0 < \sigma < 1) \) should also be considered in our model. If \( \sigma = 0 \), the vaccine offers 100% protection against the disease where vaccine efficacy can be estimated as \( 1 - \sigma \). In the model, a rate of \( \sigma \) is transferred to E class while the remaining stays at the V class.

\[ \frac{dS}{dt} = - (\varphi_{S_m} + \lambda) S + \varphi_S S_m - \alpha S \]

\[ \frac{dE}{dt} = - (\varphi_{Em} + \varepsilon) E + \varphi_E E_m + \lambda S + \omega \sigma V \]

\[ \frac{dI}{dt} = - (\varphi_{Im} + \gamma + \mu) I + \varphi_I I_m + \varepsilon E \]

\[ \frac{dS_m}{dt} = - (\varphi_S + \lambda_m) S_m + \varphi_{S_m} S - \alpha S_m \]  

(6)
SEIR MODEL TO ADDRESS THE IMPACT OF FACE MASKS

**FIGURE 2** Schematic relationship between different classes of COVID-19 under vaccination

\[
\begin{align*}
\frac{dE_m}{dt} &= -(\varphi_E + \varepsilon)E_m + \varphi_{Em}E_m + \lambda_P S_m + \omega \sigma V \\
\frac{dI_m}{dt} &= -(\varphi_I + \gamma + \mu)I_m + \varphi_{Im}I_m + \varepsilon E_m \\
\frac{dR}{dt} &= \gamma (I + I_m) \\
\frac{dD}{dt} &= \mu (I + I_m) \\
\frac{dV}{dt} &= \alpha (S + S_m) - \sigma V
\end{align*}
\]

where \( \omega \) here represents the ratio of vaccinated individuals wearing masks.

3.3 Estimation of parameters

Conclusive data on rates of COVID-19 transmission, recovery, and mortality are not yet known. The parameter values shown in Table 2 were chosen based on the best available data. The median incubation period for COVID-19 was reported to be approximately 4.5 days (Guan et al., 2020; Lauer et al., 2020), making the transfer rate to the infectious class, \( I \) and \( I_m \), constant with \( \varepsilon = \frac{1}{4.5} \). The mortality rate for our model \( \mu \) ranges from 3 to 4% (3.5% on average) (World Health Organization, 2020b). The infectious (i.e., contagious) period is believed to have a median of 10.5 days (Chang et al., 2020). Consequently, the baseline value for the recovery rate is constant at \( \gamma = \frac{1}{10.5} - \mu = 0.0602 \). The current estimate of the transmission of COVID-19 is that one infected person may typically infect two to four people (Liu et al., 2020). The susceptibility of the population is set to one, and the number of contacts an individual has per day is assumed to be \( r = 16 \) (Tracht et al., 2010). The infectivity can be determined by \( R_0/(\mu + \gamma) \). Liu et al. (2020) reviewed the estimates of \( R_0 \) of COVID-19 in 12 studies from China and overseas and reported a mean of \( R_0 = 3.28 \), hence, \( \beta = 0.895 \).

We estimated mask efficiency based on several published studies that evaluated the performance of surgical masks in a variety of contexts (Grinshpun et al., 2009; Lai et al., 2012; Oberg & Brosseau, 2008; Rengasamy et al., 2014; Wang et al., 2020; Willeke et al., 1996). Based on these data, we set the baseline values for the effectiveness of surgical masks when worn by uninfected persons to be \( \eta_S = 0.35 \) (i.e., decrease in susceptibility when a susceptible person wore a surgical mask). Efficiency of masks as source control (i.e., the ability of the masks to decrease the infectivity of a sick individual) was estimated to be greater than efficiency in decreasing susceptibility because masks worn by an infected person have the potential to decrease both direct spread of respiratory droplets, as well as indirect spread from surfaces and other fomites (Tang et al., 2009). Based on available data, we set the baseline value for the effectiveness of surgical masks for infectious persons to be \( \eta_I = 0.45 \). Although sick individuals may change their behavior when they develop symptoms (Del Valle et al., 2005), we assume that their behavior remains the same, and they continue to have the same number of daily contacts as a healthy individual.

\( R_0 \) varies notably for different countries. One method to estimate \( R_0 \) of a country is to use the exponential growth rate during an outbreak for the country of interest (Wallinga & Lipsitch, 2007). The exponential growth rate, denoted by \( r_g \), is defined by the per capita change in number of new cases per unit of time and can be estimated from real data. The reproduction number is computed as \( R_0 = \frac{1}{M(-r_g)} \) where
TABLE 2 Summary of parameters used and corresponding values

| Description                       | Parameter | Value   | Reference                                      |
|-----------------------------------|-----------|---------|------------------------------------------------|
| Recovery relative rate            | $\gamma$  | 0.0602  | (World Health Organization, 2020b)             |
| Mortality rate                    | $\mu$     | 3.5%    | (Liu et al., 2020)                             |
| Reproduction number               | $R_0$     | 3.28    |                                                 |
| Transmissibility                  | $\beta$   | 0.312   |                                                 |
| (SM) Decrease in susceptibility   | $\eta_s$  | 0.35    | (Grinshpun et al., 2009; Lai et al., 2012; Oberg & Brosseau, 2008; Patel et al., 2016; Rengasamy et al., 2014; Willeke et al., 1996) |
| (SM) Decrease in infectivity      | $\eta_i$  | 0.45    |                                                 |

TABLE 3 Countries’ populations and estimated $R_0$

| Country   | Population (million) | Estimated $R_0$ |
|-----------|----------------------|-----------------|
| France    | 66.99                | 6.32            |
| Germany   | 83.02                | 6.07            |
| Italy     | 60.36                | 3.27            |
| Spain     | 46.94                | 5.08            |
| USA       | 328.2                | 4.02            |

$M$ is the moment generating function of the distribution that best fits the data. Table 3 shows the estimated $R_0$ for France, Germany, Italy, Spain and the United States, using the exponential growth rate method at March 2020 (Gunzler & Sehgal, 2020; Yuan et al., 2020).

The SEIR model will be first implemented under a generic case in which the population size was assumed to be 1 million and then using real population data for the five different countries listed in Table 3. All persons are initially in the susceptible class $S$. The initial number of infected individuals is given by $I = 50$. We assumed that individuals begin wearing masks after 100 individuals are infected.

4 | RESULTS

4.1 | Proposed SEIR model without vaccination

We analyzed two scenarios, assuming 60% and then 80% of susceptible and exposed individuals wore surgical masks when in public areas. The estimated effect of wearing masks on the $R_0$ of COVID-19 is shown in Table 4. In the generic case with a simulated population of 1 million people, when 60% of the population wore masks, the value of $R_0$ decreased from 3.28 to 1.67, a reduction of 49%. Similarly, when using real population data and estimated $R_0$ for France, Germany, Italy, Spain, and the United States, the value of $R_0$ decreased from 6.32, 6.07, 3.27, 5.08, and 4.02 to 3.23, 3.10, 1.67, 2.59, and 2.05, respectively. When 80% of the population wore masks, the value of $R_0$ decreased to 1.64 for the generic case of 1 million people, a reduction of 50%, and to 3.17, 3.04, 1.64, 2.54 and 2.01 for France, Italy, Germany, Spain and the United States, respectively.

A sensitivity analysis of the joint effect of $\eta_i$ and $\eta_s$ on $R_0 = 3.28$ when 60% of the population wore masks is shown in Figure 3. Lower mask effectiveness was associated with less reduction of $R_0$, but even very low mask effectiveness led to notably lower $R_0$ compared to scenarios without mask use.

Furthermore, we provide a sensitivity analysis for all other parameters used in the proposed model. As it can be seen in Figure 4(A,B), both $\gamma$ and $\mu$ have a negative exponential effect on $R_0$. This can be interpreted in the way that if the recovery rate of COVID-19 increases, $R_0$ decreases where it gets drastically lower after the value of 0.2. Similarly, if the mortality rate increases, $R_0$ decreases since dead people cannot transfer the virus. In comparison, $\beta$ has a direct linear effect on $R_0$, as indicated in Figure 4(C).

Figure 5(A–D) show the long-term dynamics of the SEIR model for the simulated population of 1 million when different percentages (0%, 60%, and 80%) of susceptible and exposed individuals wore masks. As shown in Figure 5(A), the number of confirmed cases initially was very low, and most of the population was in a susceptible state. For the scenario with no community mask use, exponential growth was exhibited in the number of exposed and infectious individuals, reaching a peak of approximately 70,000 and 140,000 after 105 and 110 days, respectively, as shown in Figure 5(B and C). Subsequently, there was a monotonic decrease in the number of susceptible individuals until approximately 200 days. Contrariwise, the number of recovered personnel monotonically increased until 200 days, as in Figure 5(D).

The SEIR curves that model when 60% or 80% of the population wore masks were substantially different from those that model a population not wearing masks. When masks were worn, the number of exposed individuals peaked at approximately 20,000 and 17,000 after 320 and 360 days for 60% and 80% of the population wore masks, respectively (Figure 5B), and the number of infectious individuals peaked at approximately 10,000 and 9000 after 340 and 370 days for 60%, and 80% of the population wore masks, respectively (Figure 5C), while the number of susceptible and recovered individuals saturated after 500 and 600 days, respectively (Figure 5A and D).
### Table 4  Effect of wearing a mask on $R_0$

| Country     | Population (million) | Estimated $R_0$ | $R_0$ (60% wearing mask) | $R_0$ (80% wearing mask) |
|-------------|----------------------|----------------|--------------------------|--------------------------|
| Generic case| 1.00                 | 3.28           | 1.67                     | 1.64                     |
| France      | 66.99                | 6.32           | 3.23                     | 3.17                     |
| Germany     | 83.02                | 6.07           | 3.10                     | 3.04                     |
| Italy       | 60.36                | 3.27           | 1.67                     | 1.64                     |
| Spain       | 46.94                | 5.08           | 2.59                     | 2.54                     |
| USA         | 328.2                | 4.02           | 2.05                     | 2.01                     |

**Figure 3**  Sensitivity analysis of the joint effect of $\eta_i$ and $\eta_s$ on $R_0$ when 60% of the population wear masks.

We also investigated the effect of wearing masks on the number of infectious individuals for France, Italy, Germany, Spain, and the United States, and the results are depicted in Figure 6. We used real population data and estimated $R_0$ listed in Table 3. For France, in the absence of mask use, the simulated number of infectious cases peaked at 19.8 million after 80 days. When 60% of the population wore masks, the peak number of infectious cases was lower, at 10.8 million, and occurred later, after 170 days. When the percentage of individuals wearing masks was 80%, the peak number of infected cases was slightly lower at 10.3 million cases and occurred after 175 days. Likewise, after 85 days, the maximum count of infectious cases in Germany reached 23.7 million cases, in contrast to peaks of 12.5 and 12.0 million active cases after 175 and 180 days, respectively, when 60% and 80% of the population wore masks. Similarly, for Italy, the simulated count of infectious cases peaked at 6.4 million after 180 days, compared to peaks of approximately 1 million infectious persons after more than 500 days for the two scenarios with mask use. For Spain, the simulated number of infectious cases reached 11.5 million after 100 days, and it was mitigated after 215 and 225 days to 5.0 and 4.7 million, respectively, when 60% and 80% of the population wore masks. Finally, for the United States, without public mask use, the maximum number of infected individuals reached 58.9 million after 150 days. When 60% and 80% of the population wore masks, the maximum number of infectious individuals was lower, at 18.2 and 16.6 million, respectively, and these mitigated peaks occurred more than 380 days after outbreak onset. Therefore, for each country analyzed, 60% mask use decreased the peak number of infectious cases by at least 45%.

### 4.2 Proposed SEIR model under vaccination

In order to investigate the effect of mask-wearing on the number of infectious individuals under vaccination, we estimate
FIGURE 4  Sensitivity analysis of the effect of $\gamma$, $\mu$, and $\beta$ on $R_0$ if 60% of the population wears masks

the number of infectious and recovered individuals over a period of 250 days. Due to the possibility of various mutants of the COVID-19 and the uncertainty of the vaccine’s efficiency, we provide the estimates under different values of $\alpha$ ranging from 0.01 to 1% and $\sigma$ from 0 to 0.3 while all other parameters are the same as those in Table 2 with a population of one million. In general, it can be seen in Figures 7 and 8 that the number of infectious individuals is lowered as the vaccination inefficiency decreases. Similarly, in Figures 9 and 10, the number of recovered individuals increases as the vaccination inefficiency decreases. The effect of face masks on lowering the number of infectious individuals is shown in Figure 7(A, B) using $\alpha = 0.01$, and Figure 8(A, B) using $\alpha = 0.001$. The difference in the number of infectious individuals is more significant when the vaccination rate is lower. Likewise, the effect of face masks on increasing the number of recovered individuals is shown in Figure 9(A, B) using $\alpha = 0.01$, and Figure 10(A, B) using $\alpha = 0.001$.

5  |  COMPARATIVE STUDY

In this section, we compare the proposed SEIR model with the SIR model recently developed by Yan et al. (2019) for modeling the effectiveness of different types of face masks in mitigating influenza outbreaks. The main difference between the SEIR model and the SIR model is that the SEIR model takes the exposed group into consideration, while the SIR model does not. The exposed group is a transition between the susceptible and infectious groups. The strength of the SEIR model is that it includes individuals who have been exposed to the infection but are not yet infectious. Consequently, the SEIR model is more realistic than the SIR model. The exposed group is an essential element of any model that evaluates the impact of respiratory protective devices on the reproduction number because the exposed individuals to COVID-19 do not immediately become infectious.

In order to provide a comparison of these model types, we compared the estimated number of infectious individuals of
both SEIR and SIR models to the actual number of SARS-CoV-2 infectious individuals in a country that employed universal masking—Hong Kong. We selected Hong Kong due to the availability of the data required for this comparison, as well as the high compliance of face mask usage by the Hong Kong general public, which has ranged from 95.7 to 97.2% (Cheng et al., 2020).

The actual number of active cases is obtained from the department of health of the government of Hong Kong (Hong Kong Department of Health, 2021). The same parameters ($\eta_s$, $\eta_i$, $\gamma$, $\mu$, $\beta$) presented in Section 3.1 are used. The population of Hong Kong is approximately 7.5 million.

The first wave started in February is depicted in Figure 11(A). The proposed SEIR model was more accurate than the SIR model for both $\eta_s = 0.45$ and $\eta_i = 0.35$, and $\eta_s = 0.35$ and $\eta_i = 0.25$. The peak of the actual number of infectious individuals was 695, closely approximated by the maximum estimated number of infectious individuals obtained by the SEIR model which is 784 and 613 when $\eta_s = 0.45$ and $\eta_i = 0.35$, and $\eta_s = 0.35$ and $\eta_i = 0.25$, respectively. On the other hand, the maximum estimated number of infectious individuals resulted from the SIR model is 973 (when $\eta_s = 0.45$ and $\eta_i = 0.35$) and 831 (when $\eta_s = 0.35$ and $\eta_i = 0.25$) was higher than the actual case counts. In addition, the SEIR model predicted the time of the peak number of cases more accurately than the SIR model. Similarly, for the second wave started in May, as presented in Figure 11(B), the proposed SEIR model was more accurate than the SIR model for both $\eta_s = 0.45$ and $\eta_i = 0.35$, and $\eta_s = 0.35$ and $\eta_i = 0.25$.

On the other hand, in order to show the performance of the modified SEIR model, we defined the interval from the first given vaccination dose in February 2021 till July 2021. The vaccination rate used in the model is estimated by dividing the total number of vaccinated personnel over the vaccination period which is found to be 0.2%. This implicitly means that the used rate is assumed to be constant over the modeling period. Since the government of Hong Kong provides two types of vaccines to the public, vaccine inefficacy is estimated as a weighted average of the inefficacy of the two vaccine types. We used inefficacies of 5% (Polack et al., 2020) and 17% (McMenamin & Cowling, 2021), and weights of 60.2% and 39.8% (Hong Kong - Center of Health Protection, 2022).

As shown in Figure 12, the proposed model still has more accurate results than the SIR model compared with the actual values.

6 | DISCUSSION

At the beginning of respiratory virus outbreaks, mitigation strategies such as vaccines and antivirals may not be readily available. Face masks are often recommended as a means of source control for persons who are symptomatic in order to decrease the spread of droplets produced by coughing or sneezing. Furthermore, for the current pandemic of COVID-19, increasing evidence suggests that persons with mild or no symptoms at the early stages of infection can
contribute to the transmission of SARS-CoV-2 (Li et al., 2020; Rothe et al., 2020; Wei, 2020). Therefore, to combat the spread of COVID-19, several countries, particularly in Asia, have endorsed widespread community use of face masks, including use among asymptomatic persons.

In the current study, we employed a risk assessment model to investigate the potential impact of community use of surgical masks in Western countries on reducing the spread of the pandemic COVID-19. Using conservative estimates of the effectiveness of surgical masks in this setting, our model showed potential for surgical mask use by the general public to have a significant impact on decreasing the transmission of SARS-CoV-2. We first analyzed a general case, evaluating a population of size 1 million with estimated $R_0 = 3.28$. The model predicted that the use of surgical masks would be able to reduce $R_0$ to 1.67 and 1.64 when 60% and 80% of the population wore masks, respectively. The results of the model implied that if the $R_0$ is less than 2, mask usage would be more likely to make $R_0$ less than 1, which is an indication that the disease would eventually die out. We then analyzed real population data for France, Italy, Germany, Spain, and the United States. In this more specific model, the peak number of infections for each country decreased by at least 45% for each community masking scenario. These trends emphasized that surgical masks may effectively “flatten the curve” and hence reduce the burden of COVID-19 by decreasing the peak of hospitalizations and related resource utilization.

On the other hand, as more and more people become fully vaccinated, it is ambiguous whether mask-wearing could still be beneficial. Vaccines are a robust layer of protection, yet they do not provide 100% protection. There is no way to tell who does not respond to the vaccine and will still be at risk.
FIGURE 7  Number of infectious individuals under vaccination rate of 0.01

FIGURE 8  Number of infectious individuals under vaccination rate of 0.001

FIGURE 9  Number of recovered individuals under vaccination rate of 0.01
for COVID-19. In addition, vaccines prevent illness, but more research is needed to determine if the vaccines also prevent transmission, hence vaccinated individuals might be asymptomatic spreaders. Thus, we model the case when people continue to wear masks after getting vaccinated. The results of the model implied that face masks are still beneficial even after vaccination, especially when vaccination rates are low.

These results also had important implications for COVID-19 infection prevention strategies and related public health policies. Our models showed that community surgical mask use has the potential to substantially decrease transmission of SARS-CoV-2, especially when coupled with other strategies, such as hand hygiene, social distancing, isolation of symptomatic persons, and travel restrictions. In the short-term, widespread surgical mask use in public areas may decrease the frequency and severity of new clusters of COVID-19 occurred when many governments relax social distancing orders and businesses reopen. Longer-term strategies could include the periodic reintroduction of community face mask use for selected regions in response to acute increases in COVID-19 incidence rates.

Results from this study also highlighted several areas where further research on use of face masks is needed. Worldwide shortages of surgical masks have occurred during the COVID-19 pandemic, and more data are needed on the relative efficacy of various types of facemasks in decreasing the transmission of SARS-CoV-2. For example, in many settings, surgical masks may only be available to healthcare personnel, but cloth and other home-made masks may be more widely available to the public (Rengasamy et al., 2010; van der Sande et al., 2008). Finally, more data on disinfection and reuse of face masks are needed (Centers for Disease Control...
SEIR MODEL TO ADDRESS THE IMPACT OF FACE MASKS

7 | CONCLUSIONS

SEIR model is employed as a risk assessment tool to estimate the effectiveness of community use of surgical face masks before and after vaccination. In the case when vaccines are not available, it was found that the use of face masks has the potential to reduce $R_0$ by at least 49% and, as a result, decrease the community spread of COVID-19. In addition, the same model revealed that masking could decrease the estimated peak number of infectious cases of SARS-CoV-2 by at least 45% in France, Germany, Italy, Spain, and the United States. In the case when vaccines are available, face masks are still found to be beneficial in lowering the number of infectious individuals. Finally, this model can aid public health officials and policymakers in developing masking policies and allocating resources.

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (71971181 and 72032005) and by Research Grant Council of Hong Kong (11203519, 11200621). It is also funded by Hong Kong Innovation and Technology Commission (InnoHK Project CIMDI) and Hong Kong Institute of Data Science (Project 9360163).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Ahmed Maged  
https://orcid.org/0000-0002-5071-5253

REFERENCES

Alrashed, S., Min-Allah, N., Saxena, A., Ali, I., & Mehmood, R. (2020). Impact of lockdowns on the spread of COVID-19 in Saudi Arabia. Informatics in Medicine Unlocked, 20, 100420. https://doi.org/10.1016/j.imu.2020.100420

Bai, Y., Yao, L., Wei, T., Tian, F., Jin, D.-Y., Chen, L., & Wang, M. (2020). Presumed asymptomatic carrier transmission of COVID-19. JAMA, 323(14), 1406–1407.

Beauchemin, C. A. A., & Handel, A. (2011). A review of mathematical models of influenza A infections within a host or cell culture: Lessons learned and challenges ahead. Bmc Public Health [Electronic Resource], 11(1), S7. https://doi.org/10.1186/1471-2458-11-S1-S7

Canini, L., & Carrat, F. (2011). Population modeling of influenza A/H1N1 virus kinetics and symptom dynamics. Journal of Virology, 85(6), 2764. https://doi.org/10.1128/JVI.01318-10

Centers for Disease Control Prevention. (2020). Decontamination and reuse of filtering facepiece respirators. https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html

Chang, D., Mo, G., Yuan, X., Tao, Y., Peng, X., Wang, F.-S., Xie, L., Sharma, L., Cruz, C. S. D., & Qin, E. (2020). time kinetics of viral clearance and resolution of symptoms in novel coronavirus infection. American Journal of Respiratory and Critical Care Medicine, 201(9), 1150–1152. https://doi.org/10.1164/ajrccm.2020-03-0524LE

Cheng, V. C.-C., Wong, S.-C., Chuang, V. W.-M., So, S. Y.-C., Chen, J. H.-K., Sridhar, S., To, K. K.-W., Chan, J. F.-W. C., Hung, I. F.-N., Ho, R.-L., & Yuen, K.-Y. (2020). The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. Journal of Infection, 81(1), 107–114. https://doi.org/10.1016/j.jinf.2020.04.024

Chowell, G., Ammon, C., Hengartner, N., & Hyman, J. (2006). Transmission dynamics of the great influenza pandemic of 1918 in Geneva, Switzerland: Assessing the effects of hypothetical interventions. Journal of Theoretical Biology, 241(2), 193–204.

Chu, D. K., Akl, E. A., Duda, S., Solo, K., Yacoob, S., Schünemann, H. J., & Schünemann, H. J. (2020). Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: A systematic review and meta-analysis. The Lancet, 395(10242), 1973–1987. https://doi.org/10.1016/S0140-6736(20)31142-9

FIGURE 12 Estimated and actuals number of infectious individuals in Hong Kong after 96% mask usage and vaccination.
Currie, C. S. M., Fowler, J. W., Kottadis, K., Monks, T., Onggo, B. S., Robertson, D. A., & Tako, A. A. (2020). How simulation modelling can help reduce the impact of COVID-19. *Journal of Simulation*, 14(2), 83–97. https://doi.org/10.1080/17477778.2020.1751570

Del Valle, S., Hethcote, H., Hyman, J. M., & Castillo-Chavez, C. (2005). Effects of behavioral changes in a smallpox attack model. *Mathematical Biosciences*, 195(2), 228–251.

European Center for Disease Prevention and Control. (2020). Using face masks in the community. https://www.ecdc.europa.eu/sites/default/files/documents/COVID-19-use-face-masks-community.pdf

Feng, S., Shen, C., Xia, N., Song, W., Fan, M., & Cowling, B. J. (2020). Rational use of face masks in the COVID-19 pandemic. *The Lancet Respiratory Medicine*, 8(5), 434–436.

Gardner, L. M., Rey, D., Heywood, A. E., Toms, R., Wood, J., Travis Waller, S., & Rina MacIntyre, C. (2014). A scenario-based evaluation of the middle east respiratory syndrome coronavirus and the hajj. *Risk Analysis*, 34(8), 1391–1400. https://doi.org/10.1111/risa.12253

Goscel, L., Phillips, A., Spinola, P., Gupta, R. K., & Abubakar, I. (2020). Modelling SARS-CoV2 spread in London: Approaches to lift the lockdown. *Journal of Infection*, 81(2), 260–265.

Grinshpun, S. A., Haruta, H., Eninger, R. M., Reponen, T., McKay, R. T., & Lee, S.-A. (2009). Performance of an N95 filtering facepiece particulate respirator and a surgical mask during human breathing: Two pathways for particle penetration. *Journal of Occupational and Environmental Hygiene*, 6(10), 593–603.

Guo, D., Li, K. C., Peters, T. R., Snively, B. M., Poehling, K. A., & Zhou, X. (2015). Multi-scale modeling for the transmission of influenza and the evaluation of interventions toward it. *Scientific Reports*, 5(1), 8980. https://doi.org/10.1038/srep08980

Gritzner, D., & Seghal, A. R. (2020). Time-Varying COVID-19 reproduction number in the United States. *MedRiv*. https://doi.org/10.20006/medriv.10043

Guo, D., Li, K. C., Peters, T. R., Snively, B. M., Pechling, K. A., & Zhou, X. (2015). Multi-scale modeling for the transmission of influenza and the evaluation of interventions toward it. *Scientific Reports*, 5(1), 8980. https://doi.org/10.1038/srep08980

Hong Kong - Center of Health Protection. (2022). *Hong Kong vaccination dashboard*. https://www.coronavirus.gov.hk/en/dashboard

Hong Kong Department of Health. (2020). Guidelines on prevention of coronavirus disease 2019 (COVID-19) for the general public. https://www.chp.gov.hk/files/pdf/936_guideline_general_public_en.pdf

Hong Kong department of health. (2021). *Data in coronavirus disease (COVID-19)*. https://data.gov.hk/en-data/dataset/hk-dh-chpsebcddr

Jozuka, E., & Ogura, J. (2020). Anger as Japanese Prime Minister offers school closure and voluntary event cancellation as COVID-19 countermeasures in Japan. *Journal of Infection and Chemotherapy*, 26(5), 676–680.

Li, R., Pei, S., Chen, B., Song, Y., Zhang, T., Yang, W., & Shaman, J. (2020). Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV2). *Science*, 368(6490), 489–493.

Liang, M., Gao, L., Cheng, C., Zhou, Q., Uy, J. P., Heiner, K., & Sun, C. (2020). Efficacy of face mask in preventing respiratory virus transmission: A systematic review and meta-analysis. *Travel Medicine and Infectious Disease*, 36, 101751. https://doi.org/10.1016/j.tmaid.2020.101751

Liu, Y., Gayle, A. A., Wilder-Smith, A., & Rocklöv, J. (2020). The reproductive number of COVID-19 is higher compared to SARS coronavirus. *Journal of Travel Medicine*, 27(2), taao21. https://doi.org/10.1093/jtm/taao21

Lo, J.-Y., Tsang, T. H., Leung, Y. H., Yeung, E. Y., Wu, T., & Lim, W. W. (2005). Respiratory infections during SARS outbreak, Hong Kong. 2003. *Emerging Infectious Diseases*, 11(11), 1738.

Machtyre, C. R., & Chughtai, A. A. (2015). Facemasks for the prevention of infection in healthcare and community settings. *BJM*, 350, h694.

Matuschek, C., Moll, F., Fangerau, H., Fischer, J. C., Zänker, K., van Griensven, M., Schneider, M., Kindgen-Milles, D., Knoefel, W. T., Lichtenberg, A., Tamaskovics, B., Dijepmo-Njangan, F. J., Budach, W., Corradini, S., Häussinger, D., Felt, T., Jensen, B., Pelka, R., Orth, K., & Haussmann, J. (2020). Face masks: Benefits and risks during the COVID-19 crisis. *European Journal of Medical Research*, 25(1), 32. https://doi.org/10.1186/s40001-020-00430-5

McMenamin, M. E., & Cowling, B. J. T. L. (2021). CoronaVac efficacy data from Turkey. *Lancet*, 398(10131), 1873–1874.

Ministry of Health in Singapore. (2020). *Updates on Covid-19 (coronavirus disease 2019) local situation*. https://www.moh.gov.sg/covid-19

Mourad, A., Turner, N. A., Baker, A. W., Okeke, N. L., Narayanasamy, S., Rolfe, R., Engemann, J. H., Cox, G. M., & Stout, J. E. (2020). Social disadvantage, politics, and SARS-CoV-2 trends: A county-level analysis of United States data. *Clinical Infectious Diseases*, https://doi.org/10.1093/cid/ciaa1374

Nicolaides, C., Avraam, D., Cueto-Felgueroso, L., Gonzalez, M. C., & Juanes, R. (2020). Hand-hygiene mitigation strategies against global disease spreading through the air transportation network. *Risk Analysis*, 40(4), 723–740. https://doi.org/10.1111/risa.13438

Oberg, T., & Brosseau, L. M. (2008). Surgical mask filter and fit performance. *American Journal of Infection Control*, 36(4), 276–282.

Patel, R. B., Skaria, S. D., Mansour, M. M., & Smaldone, G. C. (2016). Respiratory source control using a surgical mask: An in vitro study. *Journal of Occupational and Environmental Hygiene*, 13(7), 569–576. https://doi.org/10.1089/01455692.2015.1043050

Polack, F. P., Thomas, S. J., Kitchin, N., Abosalon, J., Gurtman, A., Lockhart, S., Perez, J. L., Perez Marc, G., Moreira, E. D., Zerbini, C., Bailey, R., Swanson, K. A., Roychoudhury, S., Koury, K., Li, P., Kalina, W. V., Cooper, D., French, R. W., Jr, Hammitt, L. L., Türci, O., … C4591001 Clinical Trial Group. (2020). Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. *The New England Journal of Medicine*, 383(27), 2603–2615.

Rengasamy, S., Eimer, B., & Shaffer, R. E. (2010). Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Annals of Occupational Hygiene*, 54(7), 789–798.

Rengasamy, S., Eimer, B. C., & Szalajda, J. (2014). A quantitative assessment of the total inward leakage of NaCl aerosol representing submicron-size bioaerosol through N95 filtering facepiece respirators and surgical masks. *Journal of Occupational and Environmental Hygiene*, 11(6), 388–396.

Röthe, C., Schunk, M., Sothmann, P., Bretzel, G., Froeschl, G., Wraa, C., Zimmer, T., Thiel, V., Janke, C., Guggemos, W., Seilmair, M., Drosten, C., Vollmar, P., Zwiglmairer, K., Zange, S., Wölfel, R., & Guggemos, W. (2020). Transmission of 2019-nCoV infection from an asymptomatic contact in Germany. *New England Journal of Medicine*, 382(10), 970–971.
Shaw, R., Kim, Y.-k., & Hua, J. (2020). Governance, technology and citizen behavior in pandemic: Lessons from COVID-19 in East Asia. Progress in Disaster Science, 6, 100090.

Tang, J. W., Liebner, T. J., Craven, B. A., & Settles, G. S. (2009). A schlieren optical study of the human cough with and without wearing masks for aerosol infection control. Journal of the Royal Society Interface, 6(6), S727–S736.

Tracht, S. M., Del Valle, S. Y., & Hyman, J. M. (2010). Mathematical modeling of the effectiveness of facemasks in reducing the spread of novel influenza A (H1N1). PLoS One, 5(2), e9018.

Tuite, A. R., Fisman, D. N., & Greer, A. L. J. C. (2020). Mathematical modelling of COVID-19 transmission and mitigation strategies in the population of Ontario. Canada, 192(19), E497–E505.

Van den Driessche, P., & Watmough, J. (2002). Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. Mathematical Biosciences, 180(1–2), 29–48.

van der Sande, M., Teunis, P., & Sabel, R. (2008). Professional and home-made face masks reduce exposure to respiratory infections among the general population. PLoS One, 3(7), e2618. https://doi.org/10.1371/journal.pone.0002618

Wallinga, J., & Lipsitch, M. (2007). How generation intervals shape the relationship between growth rates and reproductive numbers. Proceedings of the Royal Society B. Biological Sciences, 274(1609), 599–604. https://doi.org/10.1098/rspb.2006.3754

Wu, J., Xu, F., Zhou, W., Feikin, D. R., Lin, C.-Y., He, X., Zhu, Z., Liang, W., Chin, D. P., & Schuchat, A. (2004). Risk factors for SARS among persons without known contact with SARS patients, Beijing, China. Emerging Infectious Diseases, 10(2), 210.

Yuan, J., Li, M., Lv, G., & Lu, Z. K. (2020). Monitoring transmissibility and mortality of COVID-19 in Europe. International Journal of Infectious Diseases, 95, 311–315.

Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., Niu, P., Zhan, F., Ma, X., Wang, D., Xu, W., Wu, G., Gao, G. F., & Tan, W., China Novel Coronavirus Investigating and Research Team. (2020). A novel coronavirus from patients with pneumonia in China, 2019. New England Journal of Medicine, 382(8), 727–733.

World Health Organization. (2020a). Coronavirus disease 2019 (COVID-19) situation report –46. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200306-sitrep-46-covid-19.pdf?sfvrsn=96b64adff_4

World Health Organization. (2020b). Coronavirus disease 2019 (COVID-19) situation report –114. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200513-covid-19-sitrep-114.pdf?sfvrsn=17ebbb4_4

World Health Organization. (2020c). Coronavirus disease (COVID-19) outbreak. https://www.who.int/westernpacific/emergencies/covid-19

World Health Organization. (2020d). Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations: Scientific brief, 27 March 2020. https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

How to cite this article: Maged, A., Ahmed, A., Haridy, S., Baker, A. W., & Xie, M. (2023). SEIR model to address the impact of face masks amid COVID-19 Pandemic. Risk Analysis, 43, 129–143. https://doi.org/10.1111/risa.13958