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The SARS-CoV-2 pandemic course in Saudi Arabia: A dynamic epidemiological model

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ABSTRACT

Objective: Saudi Arabia ranks second in the number of coronavirus disease 2019 (COVID-19) cases in the Eastern Mediterranean region. It houses the two most sacred religious places for Muslims: Mecca and Medina. It is important to know what the trend in case numbers will be in the next 4–6 months, especially during the Hajj pilgrimage season.

Methods: Epidemiological data on COVID-19 were obtained from the Saudi Arabian Ministry of Health. A susceptible-exposed-infectious-recovered (SEIR) prediction model was constructed to predict the trend in COVID-19 in Saudi Arabia in the next 6 months.

Findings: The model predicts that the number of active cases will peak by 22 May 2020. The cumulative infected cases are predicted to reach 70,321 at that time. The total number of infected individuals is estimated reach to 114,580 by the end of the pandemic.

Conclusion: Our estimates show that by the time the Hajj season commences in Saudi Arabia, the pandemic will be in the midst of its deceleration phase (phase 3). This information will likely be useful to policymakers in their management of the outbreak.

1. Introduction

Since late December 2019, the world has been experiencing a rapidly spreading, highly infectious virus, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The World Health Organization (WHO) declared this new disease a "Public Health Emergency of International Concern" on 30 January 2020 and then as a "Global Pandemic" 40 days later (World Health Organization, 2020b). Current knowledge suggests that respiratory droplets are the primary mode of transmission. Less than

Abbreviations: cfr, mortality proportion among the infected; COVID-19, coronavirus disease 2019; DCM, deterministic compartmental model; e.dur, duration of the exposed state; e.num, number of exposed; i.dur, duration of the infectious state; i.num, number of infected; MERS-CoV, Middle East respiratory syndrome coronavirus; p.num, number of protected; r.num, number of recovered; R0, basic reproduction number; s.num, number of susceptible; SARS-CoV 2, severe acute respiratory syndrome coronavirus 2; SEIR, susceptible, exposed, infectious and recovered infectious disease prediction model; SIR, susceptible, infectious and recovered infectious disease prediction model.

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50% of all active coronavirus disease 2019 (COVID-19) cases are asymptomatic, which is lower than that of influenza (56–80% asymptomatic) (Hsieh et al., 2014).

Within the Eastern Mediterranean region, the Kingdom of Saudi Arabia ranks second only to the Islamic Republic of Iran in total number of infected and active cases (World Health Organization, 2020a). Saudi Arabia has a population of 34 million, the majority (37%) of whom dwell in several major cities: Riyadh, Mecca, Jeddah, Dammam, and Medina (The General Authority for Statistics - Saudi Arabia, 2020). The majority of COVID-19 cases are concentrated within these cities. As of 28 May 2020, there were 80,185 total cases in Saudi Arabia, 54,553 recoveries and 441 deaths (Ministry of Health, 2020). The healthcare system of Saudi Arabia is no stranger to coronavirus outbreaks, having dealt before with local outbreaks of Middle East respiratory syndrome coronavirus (MERS-CoV) (Al-Dorzi et al., 2016).

The first COVID-19 case ($n = 1$) in Saudi Arabia was detected in the Eastern region (i.e., Qatif) on March 2nd; it was an individual who had traveled to the endemic region of Iran.

The Qatif area was put on lockdown within three days of the first case. The government took decisive measures to control potential outbreaks by cancelling festivals and events, suspending e-Visa entry, and halting all domestic travel by March 7th. The following day, all educational institutions were closed. Public gatherings and weddings were banned a week later. On March 15th, all arriving and departing international flights were cancelled, followed on March 17th by the prohibition of daily prayers in mosques, including the weekly Friday prayer. Transportation between cities was banned soon after on March 21st (Al-Tawfiq & Memish, 2020). To mitigate virus transmissions that occur from gatherings, Saudi authorities have enforced a 24-hour curfew in major cities (Riyadh, Medina, Jeddah, Mecca, and Dammam) since April 6th, while the rest of the country has been under limited curfew (from 3 pm to 6 am) since April 7th ("The Ministry of Interior: A 24-hour curfew in Riyadh, Dammam, Jeddah, and Tabuk," 2020). It announced a 5-day nationwide 24-hour curfew from May 23rd to May 27th to curb the tide of the epidemic (Saudi Arabia announces 24-hour curfew for Eid Al-Fitr holiday, 2020).

Saudi Arabia houses the two most sacred religious places for Muslims: Mecca and Medina. Muslims make pilgrimage to these cities either at a fixed time (i.e., Hajj) or at any time (i.e., Umrah) in a calendar year. During the current pandemic, Saudi authorities have stopped Umrah pilgrimage, effectively reducing imported SARS-CoV-2 cases (Ebrahim & Memish, 2020). Furthermore, decisions about Hajj were put on hold this year due to the overwhelming infection rate of SARS-CoV-2 (Batrawy & Gambrell, 2020). Since 2009, Saudi Arabia has faced multiple outbreaks during Hajj seasons, including the H1N1 pandemic (Ebrahim et al., 2009), multiple local MERS-CoV outbreaks (Al-Tawfiq, Zumla, & Memish, 2014), and Ebola and Zika viruses from African pilgrims (Ahmed, Kattan, & Memish, 2016; Memish & Al-Tawfiq, 2014). The literature has suggested Hajj pilgrims played a key role in the dispersion of the 1957 flu pandemic (Benkouiten, Al-Tawfiq, Memish, Albarrak, & Gautret, 2019).

Infectious disease prediction models are tools that use available data about the status and progress of an infectious outbreak to predict its future course (Keeling & Danon, 2009). In its most basic form, an infectious disease prediction model is constructed of three essential compartments: 1) susceptible (S), 2) infected (I), and 3) recovered (R), commonly abbreviated as the SIR model. The addition of a fourth compartment, i.e., exposed (E), increases the prediction capability of the resultant model (i.e., SEIR), which is now being widely used (Widyaningsih, Saputro, & Nugroho, 2014).

There are practical implications for predicting the epidemiological trajectory of COVID-19 in Saudi Arabia as the country is still in the midst of this outbreak. A prediction can inform the country's decisionmakers and help them make prudent decisions about the continued management of the outbreak. The Saudi healthcare system can also utilize this information to adapt to changing health needs. Meanwhile, we can hope to maintain a controlled situation until vaccines and treatments are deployed.

We name our prediction model KSA-CoV-19, and with it, aim to find the following: 1) the anticipated epidemic curve of SARS-CoV-2 in Saudi Arabia, 2) the peak, the end, and the number of COVID-19 cases associated with the curve, and 3) the timing of upcoming Hajj 2020 (July 28th –August 2nd) in relation to the anticipated epidemic curve.

2. Material and methods

2.1. Epidemiological data

The data used to generate our KSA-CoV-19 Model were obtained from the Saudi Arabian Ministry of Health (Ministry of Health, 2020), but the ministry did not provide daily updates in respect to the number of quarantined (i.e., exposed) cases. A recent report from the Centers for Disease Control and Prevention found that for 10 positive cases, 445 close-contact individuals were identified (Burke et al., 2020). We used this information to estimate the number of the exposed compartment in the model.

2.2. Epidemiological model compartments

A deterministic compartmental model (DCM) with a susceptible-exposed-infectious-recovered (SEIR) disease class was chosen to be implemented in the KSA-CoV-19 Model. For this model to work, a number of assumptions/variables needed to be inputted. Firstly, there were parameters that characterize the disease: 1) the basic reproduction number (R0), 2) the duration of the exposed state (e.dur), 3) the duration of the infectious state (i.dur), and 4) the case fatality rate (cfr). Secondly, the population parameters at the start of the modelling were also inputted: 1) number of susceptible (s.num), 2) the number of exposed (e.num), 3) the number of infected (i.num), and 4) the number of recovered (r.num). Building on the work of Peng, Yang, Zhang, Zhuge, and Hong (2020), a new compartment (P) was included in our model that conveyed the increased level of public health awareness, such as widespread use of face masks, strict social distancing, and the locking-down of cities. We assumed that the susceptible population (S) was declining at a steady rate as a result of a positive protection rate (α); the number of those protected (P compartment, p. num) is removed from the susceptible pool (s.num).

In this paper, we present four models: KSA-CoV-19 Model, two variants of KSA-CoV-19 Model, and a Natural Course model (Table 1). The parameters chosen for these four models are justified below.

R0: basic reproduction number; e. dur: duration of the exposed state; i. dur: duration of the infectious state; cfr: case fatality rate; α: protection rate; s. num: number of susceptible; e. num: number of exposed; i. num: number of infected; r. num: number of recovered; p. num: number of protected.

2.3. Parameter estimation

We assumed that our model is based on a closed system (i.e., S+P+E+I+R = 34 million, the total population of Saudi Arabia) (The General Authority for Statistics - Saudi Arabia, 2020; Prem et al., 2020), and that deaths in the population are solely due to COVID-19. In our model, we did not use parameters related to birth or death rates among the susceptible, exposed, infectious, or recovered, in line with the methodology used in similar studies (Prem et al., 2020).

We chose March 2nd, the day on which the first positive case (i.e., diagnosed) of COVID-19 was documented, to be the starting date of our prediction model. Burke et al. (2020) reported that 445 exposed people were tracked from 10 confirmed COVID-19 cases, thus we assumed that the first diagnosed case exposed an average 45 people.

In their report, Sanche et al. (2020) estimated the median R0 value of SARS-CoV-2 to be 5.7 (95% CI 3.8–8.9). Thus, the KSA-CoV-19 Model integrated an R0 value of 5.7. Furthermore, other reports found that the average incubation period of SARS-CoV-2 was 6.4 days (Backer, Klinkenberg, & Wallinga, 2020), which we have used as the e. dur in our model.

Woelfel et al. (2020) estimated an average duration of infection (i.dur) of 3 days or 7 days. Therefore, a conservative period of 7 days was inputted as the duration of the infected state (i.dur) in the KSA-CoV-19 Model (Table 1). We used a 3-day duration to generate another model (Model 3, Table 1). The aforementioned parameter estimates (i.e., e. dur, i. dur) have been previously used in other SEIR models (Prem et al., 2020).

In regards to the death rate among those infected, although the WHO states that the global mortality rate of COVID-19 is approximately 3.4% (World Health Organization, 2020c), in Saudi Arabia, a rate of 0.86% was calculated by averaging the death rate from when the first death case was recorded until 9 April 2020. We used this rate (0.86%) in all four models that we present.

After trial and error, we chose an α (protection rate) value of 0.023 for our model. This value produced a prediction line that most closely fit the observed cases in Saudi Arabia so far. As a sensitivity measure, we used values reported by other studies that have utilized a similar methodology. For example, in their original report, Peng et al. (2020) used a value of 0.18, so we used that to generate another model (Model 2, Table 1).

Finally, we generated a model that simulated the natural course or “free fall” of the SARS-CoV-2 virus in Saudi Arabia. This model assumes that people were mixing at random and that no preventive measures were taken to halt the progression of the infection (Natural Course Model, Table 1).

2.4. Statistical software

The analytic component of this paper was carried out using the EpiModel (Jenness, Goodreau, & Morris, 2018) package in the R statistical programming language, version 3.6.3 (R Foundation for Statistical Computing). Microsoft Excel 2016 was used for data storage and management.

Table 1
Different parameters used to generate the epidemiological models of COVID-19.

Parameters	Natural Course Model	KSA-CoV-19 Model	Model 2	Model 3
R0	5.7	5.7	5.7	5.7
e.dur	6.4 days	6.4 days	6.4 days	6.4 days
i.dur	7 days	7 days	7 days	3 days
cfr	0.86%	0.86%	0.86%	0.86%
α	0	0.023	0.18	0.023
s.num	33,999,954			
e.num	45			
i.num	1			
r.num	0			
p.num	0			

3. Results

In this paper, we generated four different models that provided an estimation for the COVID-19 course in Saudi Arabia. A summary of the models is shown in Fig. 1.

The Natural Course Model shows a hypothetical worst-case scenario in which no preventive measures are taken. The ascending phase (phase 2) would start on April 21st, and the peak would be reached by May 16th. At the peak, the cumulative case count would be 22, 791, 741 (67% of the total population). The descending phase (phase 3) would conclude approximately by July 17th. A total of 33,593,849 would be infected by that time. It is important to note that this model does not take into account herd immunity, which is achieved when 82.45% of the population gets infected (Fine, Eames, & Heymann, 2011).

Out of all the models generated, the KSA-CoV-19 Model most closely fit the observed data. This model takes into account the preventive measures that are to be implemented to halt the progression of the disease, introduced into the model as a factor of α. In this model, the second (acceleration) phase lasts a period of 56 days from March 27th till the peak on May 22nd. The number of cumulative cases at the peak is 70,321 cases. The third (deceleration) phase will finish by August 20th, with a total of 114,547 infected individuals by that time. The 2020 Hajj season will coincide with the deceleration leg of this pandemic curve. The total number of infected individuals is estimated to reach 114,580 by the end of the pandemic. Fig. 2 shows the predicted number of active COVID-19 cases for the KSA-CoV-19 Model.

Using an α (protection rate) value of 0.18, similar to that used in the model constructed by Peng et al., resulted in a quick resolution of the pandemic in Model 2, which predicted a peak on March 17th and a total of 102 infected individuals by that time. The deceleration (third) phase finishes by April 29th, with the number of infected people not exceeding 136 individuals. The curve of this model was omitted from Fig. 1 due to its minuteness.

Model 3 implemented the same parameters used in the KSA-CoV-19 Model, changing only the duration of the infected state (i.dur) from 7 days to 3 days. This model closely resembles the Natural Course model, albeit with lower magnitude. A peak is reached by May 14th, with 1,243,581 total infections. The end of the third phase is reached by July 15th, and the number of infected is projected to reach 2,173,676.

4. Discussion

The rapid evolution of the COVID-19 situation worldwide and in Saudi Arabia makes it extremely challenging for healthcare systems to adapt. This paper predicts the course of the pandemic in the coming months in Saudi Arabia. We predict that the effects of the COVID-19 will have peaked during the third week of May 2020.

Availability of epidemiological modelling of the novel coronavirus in the Middle East is scarce. Indian researchers recently predicted that COVID-19 cases would peak between the third and fourth weeks of April 2020 in India, when they would reach 68,978 confirmed cases (Tiwari, Kumar, & Guleria, 2020). Recent reports have stated that the current forecasts project a continuing increase with large uncertainty (Petropoulos & Makridakis, 2020).

A major strength of our mathematical model is that it incorporated a susceptible-exposed-infectious-recovered (SEIR) mathematical model, which is more favorable than a susceptible-infectious-recovered (SIR) one.

On the other hand, one limitation of this study is that the accuracy of the predictions only lasts for a few weeks to months due to the erratic behavior of the current coronavirus. Similarly, the accuracy of this prediction is highly correlated with how accurately and effectively new cases are recorded; it is vital to note that the number of identified infected cases will largely

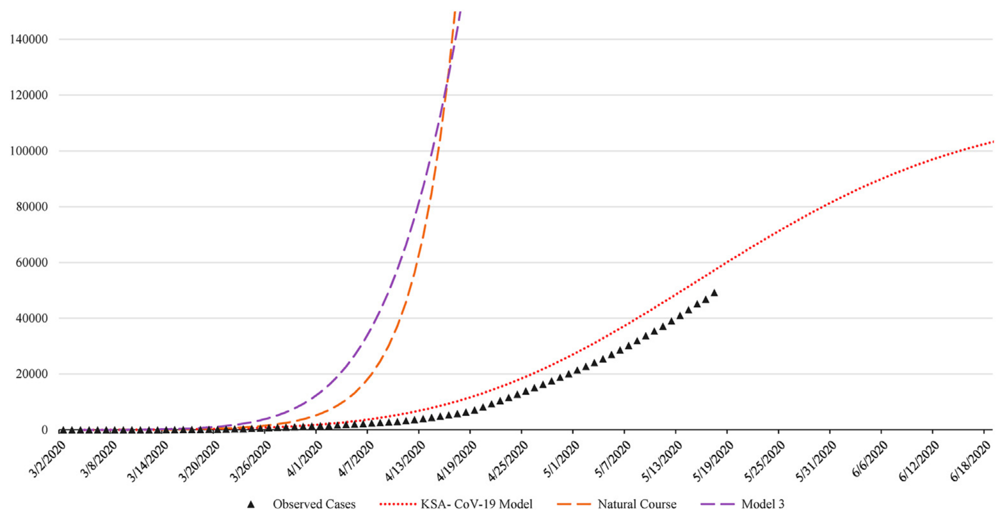

Fig. 1. The trend of COVID-19 in Saudi Arabia. Three different models are plotted to predict the growth of cases.

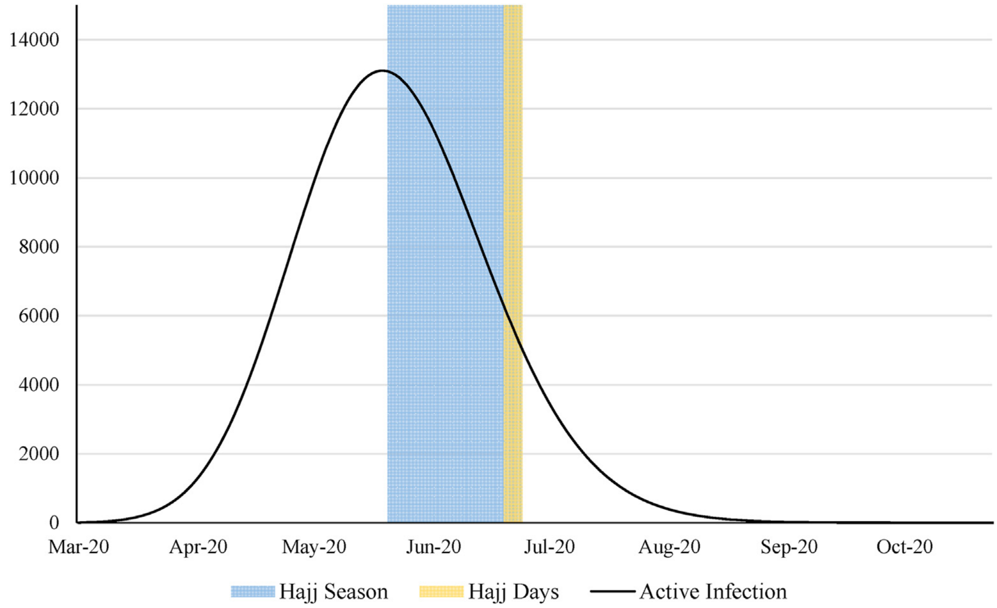

Fig. 2. The predicted number of actively infected cases in Saudi Arabia according to the KSA-CoV-19 Model. The duration of the Hajj Season is shown in blue.

depend on the implemented testing strategy (i.e., how many tests are done in the population). As of May 28th, Saudi Arabia had done 770,696 tests, which is equal to approximately one test per 45 people (Ministry of Health, 2020). Additionally, our KSA-CoV-19 Model overestimates the number of recovered cases, but the number of recovered cases in Saudi Arabia has been increasing rapidly. For instance, in a period between 5 May and 15 May 2020, the number of recoveries increased 4-fold, and by May 28th, the number of recovered cases had surpassed the number of active cases by a large margin (Ministry of Health, 2020). Although we utilized previously published estimates for the average incubation period (e.dur) and average infection duration (i.dur), the model still undershoots the amount of active infection due to the rapid flow from the infected (I) compartment to the recovered (R) compartment of the SEIR model. Finally, despite the important insight that a prediction model provides, intensive care unit admission, hospitalization, and mortality rate remain the three best parameters for estimating the true burden of the COVID-19 pandemic (Miller, Becker, Grenfell, & Metcalf, 2020).

5. Conclusion

In conclusion, this KSA-CoV-19 Model is one of the few and early prediction models in Saudi Arabia and the Middle East. Our estimates show that by the time the Hajj season commences in Saudi Arabia, the pandemic will be in the midst of its deceleration phase (phase 3), during which the danger of the pandemic will be declining, but exceptional care should be taken to avoid a resurgence. Strict adherence to the current control measures is essential for maintaining the predicted pattern, and caution should be taken when easing these measures because deviation may adversely alter the predicted course.

6. Follow-up

In the end, the Saudi government chose not to cancel the Hajj season altogether in 2020. However, to address the extraordinary circumstances caused by COVID-19, it did take an unprecedented approach and managed social distancing during the pilgrimage by limiting attendance to just 10,000 pilgrims, a fraction of the usual 3 million pilgrims anticipated each year (Coronavirus, 2020).

Declaration of competing interestCOI

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Abdullah Murhaf Al-Khani: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Mohamed Abdelghafour Khalifa:** Writing - original draft. **Abdulrahman Almazrou:** Formal analysis, Writing - review & editing. **Nazmus Saquib:** Formal analysis, Writing - review & editing.

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