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**Original Article**

# The Dynamic Effective Reproductive Number of COVID-19 during the Epidemic in Iran

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**Abstract**

**Background:** We aimed to determine the generation time, the best model for estimating reproduction number (R), and to estimate the basic reproduction number ($R_0$) and effective reproduction number ($R_t$) for COVID-19 in Iran.

**Methods:** We used the daily incidence cases of COVID-19, hospitalized due to a probable diagnosis of COVID-19 from 19 February 2020 to 17 November 2020 in Iran. Four models, including maximum likelihood (ML), exponential growth (EG), time-dependent (TD), sequential Bayesian (SB) were evaluated. The weekly reproduction number with a 95% confidence interval (CI) was calculated.

**Results:** TD model shows the best fit compared to other models for estimating reproduction number in Iran. The $R_0$ in Iran in the first week of the epidemic, leading up to 21 February 2020 was 7.19, 95% CI: 5.56, 9.00. The lowest value for the $R_t$ was equal to 0.77 between 3 to 10 March 2020 and 4 to 11 December 2020. From 11 June 2020 up to13 August 2020, the $R_t$ was more than one but after then to 24 September 2021 was less than one.

**Conclusion:** TD model was the best fit for estimating the R in Iran. The worst situation of the epidemic in Iran was related to the weeks leading up to 26 February 2020 and 28 October 2020, and better status was related to the weeks leading up to 10 March 2020 and 11 December 2020.

**Keywords:** COVID-19; Basic reproduction number; Effective reproduction number; Iran

## Introduction

The measurement of the speed of spreading of the disease is necessary using reproduction number (R) of the diseases. Basic reproductive number ($R_0$) is the average number of people infected

by an infected person in a completely susceptible population without any intervention. The effective reproductive number ($R_t$) is the average number of people infected by an infected person if preventive measures are performed (1). The variability in the value of $R_0$ in different countries was from 2.28 to 7.8 (2-4). In addition, the effective reproductive number of the disease was reported in these studies.

There are different methods for estimating R such as maximum likelihood (ML), exponential growth (EG), time-dependent (TD), sequential Bayesian (SB), and Susceptible-Infected Removed dynamic (5-7). Published studies used these methods but there are differences among the estimated R using different methods (8). The required parameters for estimating the R by the mentioned models are the daily incidence and generation time of the disease. These parameters are different in the countries so the estimated R in a country may not be applicable for other countries.

We aimed to determine the generation time of COVID-19, the best model for estimating the R, and to estimate the $R_0$ and $R_t$ for COVID-19 in Iran.

## Methods

The proposal for this study was approved by the Ethical Committee of Hamadan University of Medical Sciences, Hamadan, Iran (IR.UMSHA.REC.1399.193).

### *Data*

We used the daily incidence cases of COVID-19, hospitalized due to a probable diagnosis of COVID-19 from 19 February 2020 to 17 November 2020 in Iran. The daily incidence data were collected by the National COVID-19 Epidemiology Committee across provinces of Iran. In addition, we used the total daily incidence cases of COVID-19 reported by the Iranian Ministry of Health each day from 15 February 2020 to 23 September 2021.

### *Generation time*

Generation time (GT) is the average duration between the time of infection of primary cases and the time of infection of its secondary cases (1). We estimated the GT of COVID-19 in Hamadan Province, in the west of Iran. We followed the secondary cases who contact with confirmed cases of COVID-19 and asked them the time between onsets of symptoms with onsets of symptoms in confirmed primary cases.

A sample (29 secondary cases) was asked. Considering that the rapid transmissibility and pathogenicity features of the virus is not dependent to the geographic area (9). It seems the estimated GT in Hamadan might be applied for the whole country. A function ("est.GT") from the $R_0$ package was used to estimate the GT. The best distribution of GT in our sample was determined and the mean and standard deviation of the GT was calculated.

### *Models*

Four models, including ML, EG, TD, and SB were evaluated. In the first step, we fitted the incidence data for Iran and each province for the mentioned models. In addition, the weighted mean square error (MSE) and R square for each fitted model were calculated. A model with the best fit with the daily incidence data was selected as the best model (5). A model with a larger R square and lower weighted MSE was selected as the best model for estimating $R_t$. In addition, the fit of predicted incidence with the mentioned models and daily reported incidence of the disease was evaluated visually. The weekly reproduction number was reported. Because in February 2020 all Iranian populations were susceptible, in the first week of the epidemic we calculated the $R_0$, and during the epidemic because of conducting interventions such as social distancing, using the facemask, we calculated the $R_t$.

The statistical analysis was performed using R version 3.6.3, and $R_0$ packages version 1.2-6 (2015-05-21).

## Results

The best-fitted distribution for the GT was lognormal with a mean of 5.98 and a standard deviation of 3.74. The TD model showed the best fit compared to ML, EG, and SB for estimating R in Iran (Table 1) and 31 provinces in Iran. The weekly estimated reproduction number in Iran from COVID-19 from 19 February 2020 to 21 September 2021 is shown in Table 2.

**Table 1:** Comparison of the model fit using R square and weighted MSE

| *Index* | *ML* | *EG* | *TD* | *SB* |
|---|---|---|---|---|
| R squared | 0.81 | 0.36 | 0.91 | 0.35 |
| Weighted MSE | 81.63 | 264.57 | 35.64 | 1772887.50 |

**Table 2:** The weekly dynamic reproduction number of COVID-19 in Iran

| *Week leading up to* | *Rt* | *95% CI* | *Week leading up to* | *Rt* | *95% CI* | *Week leading up to* | *Rt* | *95% CI* |
|---|---|---|---|---|---|---|---|---|
| 21-Feb-20 | 7.19 | (5.56, 9.00) | 04-Sep-20 | 1.07 | (1.02, 1.11) | 19-Mar-21 | 0.99 | (0.97, 1.01) |
| 28-Feb-20 | 5.03 | (4.52, 5.54) | 11-Sep-20 | 1.15 | (1.11, 1.20) | 26-Mar-21 | 1.18 | (1.16, 1.21) |
| 06-Mar-20 | 1.79 | (1.70, 1.88) | 18-Sep-20 | 1.21 | (1.17, 1.25) | 02-Apr-21 | 1.41 | (1.39, 1.44) |
| 13-Mar-20 | 1.28 | (1.21, 1.35) | 25-Sep-20 | 1.09 | (1.06, 1.13) | 09-Apr-21 | 1.35 | (1.33, 1.36) |
| 20-Mar-20 | 1.30 | (1.24, 1.36) | 02-Oct-20 | 1.08 | (1.05, 1.11) | 16-Apr-21 | 1.06 | (1.05, 1.07) |
| 27-Mar-20 | 1.48 | (1.42, 1.53) | 09-Oct-20 | 1.08 | (1.05, 1.11) | 23-Apr-21 | 0.92 | (0.91, 0.93) |
| 03-Apr-20 | 0.91 | (0.88, 0.95) | 15-Oct-20 | 1.12 | (1.09, 1.15) | 30-Apr-21 | 0.91 | (0.89, 0.92) |
| 10-Apr-20 | 0.77 | (0.74, 0.81) | 23-Oct-20 | 1.26 | (1.23, 1.29) | 07-May-21 | 0.86 | (0.85, 0.88) |
| 17-Apr-20 | 0.81 | (0.77, 0.85) | 30-Oct-20 | 1.22 | (1.20, 1.25) | 14-May-21 | 0.82 | (0.80, 0.83) |
| 24-Apr-20 | 0.86 | (0.81, 0.91) | 06-Nov-20 | 1.19 | (1.16, 1.21) | 21-May-21 | 0.87 | (0.85, 0.88) |
| 01-May-20 | 1.06 | (1.01, 1.12) | 13-Nov-20 | 1.18 | (1.16, 1.20) | 28-May-21 | 0.93 | (0.91, 0.94) |
| 08-May-20 | 1.24 | (1.19, 1.30) | 20-Nov-20 | 1.06 | (1.05, 1.08) | 04-Jun-21 | 0.91 | (0.89, 0.93) |
| 15-May-20 | 1.20 | (1.15, 1.25) | 27-Nov-20 | 1.00 | (0.99, 1.02) | 11-Jun-21 | 1.08 | (1.06, 1.10) |
| 22-May-20 | 1.08 | (1.04, 1.12) | 04-Dec-20 | 0.88 | (0.86, 0.89) | 18-Jun-21 | 1.04 | (1.03, 1.06) |
| 29-May-20 | 1.17 | (1.12, 1.21) | 11-Dec-20 | 0.77 | (0.76, 0.79) | 25-Jun-21 | 1.12 | (1.10, 1.14) |
| 05-Jun-20 | 0.95 | (0.92, 0.99) | 18-Dec-20 | 0.82 | (0.80, 0.84) | 02-Jul-21 | 1.24 | (1.22, 1.25) |
| 12-Jun-20 | 1.00 | (0.96, 1.04) | 25-Dec-20 | 0.92 | (0.90, 0.95) | 09-Jul-21 | 1.24 | (1.22, 1.25) |
| 19-Jun-20 | 1.02 | (0.98, 1.06) | 01-Jan-21 | 1.00 | (0.98, 1.03) | 16-Jul-21 | 1.16 | (1.15, 1.18) |
| 26-Jun-20 | 1.01 | (0.97, 1.05) | 08-Jan-21 | 1.01 | (0.98, 1.03) | 23-Jul-21 | 1.17 | (1.16, 1.18) |
| 03-Jul-20 | 1.00 | (0.96, 1.03) | 15-Jan-21 | 1.00 | (0.97, 1.02) | 30-Jul-21 | 1.15 | (1.14, 1.17) |
| 10-Jul-20 | 0.96 | (0.92, 1.00) | 22-Jan-21 | 1.02 | (1.00, 1.04) | 06-Aug-21 | 1.10 | (1.09, 1.11) |
| 17-Jul-20 | 1.01 | (0.97, 1.05) | 29-Jan-21 | 1.05 | (1.02, 1.07) | 13-Aug-21 | 1.02 | (1.01, 1.03) |
| 24-Jul-20 | 1.03 | (0.99, 1.07) | 05-Feb-21 | 1.07 | (1.05, 1.09) | 20-Aug-21 | 0.94 | (0.93, 0.95) |
| 31-Jul-20 | 1.02 | (0.98, 1.06) | 12-Feb-21 | 1.05 | (1.03, 1.07) | 27-Aug-21 | 0.91 | (0.91, 0.92) |
| 07-Aug-20 | 0.94 | (0.90, 0.97) | 19-Feb-21 | 1.05 | (1.02, 1.07) | 03-Sep-21 | 0.85 | (0.84, 0.86) |
| 14-Aug-20 | 0.98 | (0.94, 1.02) | 26-Feb-21 | 1.02 | (1.00, 1.04) | 10-Sep-21 | 0.82 | (0.81, 0.83) |
| 21-Aug-20 | 0.95 | (0.91, 0.99) | 05-Mar-21 | 1.00 | (0.98, 1.02) | 17-Sep-21 | 0.83 | (0.81, 0.84) |
| 28-Aug-20 | 0.92 | (0.88, 0.96) | 12-Mar-21 | 0.97 | (0.95, 0.99) | 24-Sep-21 | 0.93 | (0.89, 0.98) |

The weekly estimated reproduction number for all provinces of Iran from COVID-19 from 19 February 2020 to 17 November 2020 is shown in Table 3.

Overall, the lower value of $R_t$ in most provinces of Iran was related to the week leading up to 4 December 2020. The fluctuation of $R_t$ in the provinces was different (Table 3).

**Table 3:** The weekly dynamic reproduction number of COVID-19 for provinces of Iran

| | 21-Feb-20 | 28-Feb-20 | 6-Mar-20 | 13-Mar-20 | 20-Mar-20 | 27-Mar-20 | 3-Apr-20 | 10-Apr-20 | 17-Apr-20 | 24-Apr-20 | 1-May-20 | 8-May-20 | 15-May-20 | 22-May-20 | 29-May-20 | 5-Jun-20 | 12-Jun-20 | 19-Jun-20 | 26-Jun-20 | 3-Jul-20 | 10-Jul-20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| East ,Azerbaijan | 5.62 | 2.27 | 1.43 | 1.17 | 1.03 | 1.01 | 1.05 | 0.99 | 0.91 | 0.92 | 0.93 | 1.03 | 0.95 | 0.99 | 1.07 | 1.16 | 1.10 | 1.07 | 1.10 | 1.02 | 1.00 |
| West ,Azerbaijan | 6.80 | 2.01 | 1.40 | 1.27 | 1.09 | 1.08 | 1.09 | 0.90 | 0.84 | 0.92 | 1.00 | 0.96 | 0.93 | 1.11 | 1.23 | 1.27 | 1.28 | 1.10 | 1.03 | 0.96 | 0.92 |
| Ardabil | 5.27 | 1.79 | 1.63 | 1.13 | 0.96 | 1.16 | 0.91 | 0.89 | 0.92 | 0.80 | 0.91 | 0.92 | 0.86 | 0.86 | 1.02 | 1.01 | 0.93 | 1.16 | 1.25 | 1.42 | 1.22 |
| Isfahan | 5.85 | 1.95 | 1.25 | 1.00 | 0.93 | 0.91 | 0.94 | 0.90 | 0.94 | 0.89 | 0.91 | 0.88 | 0.93 | 0.93 | 1.03 | 1.11 | 1.07 | 1.04 | 1.12 | 1.10 | 1.09 |
| Alborz | 4.60 | 2.26 | 1.38 | 1.05 | 0.97 | 0.96 | 0.89 | 0.85 | 0.95 | 0.93 | 0.94 | 0.89 | 0.86 | 0.92 | 1.10 | 1.10 | 1.16 | 1.17 | 1.23 | 1.17 | 1.08 |
| Ilam | 5.09 | 1.93 | 1.53 | 1.16 | 0.95 | 0.98 | 1.09 | 0.99 | 0.81 | 0.80 | 1.11 | 1.25 | 0.88 | 0.86 | 1.28 | 1.20 | 1.15 | 1.17 | 1.13 | 0.96 | 0.82 |
| Bushehr | 7.48 | 1.90 | 1.11 | 0.81 | 0.78 | 1.08 | 0.95 | 0.94 | 0.99 | 1.02 | 0.80 | 1.01 | 1.26 | 1.01 | 1.21 | 1.28 | 1.23 | 1.10 | 1.09 | 1.03 | 1.06 |
| Tehran | 4.95 | 1.91 | 1.33 | 1.12 | 0.97 | 0.93 | 0.93 | 0.84 | 0.90 | 0.88 | 0.83 | 0.84 | 0.84 | 0.95 | 0.99 | 1.09 | 1.14 | 1.19 | 1.23 | 1.14 | 1.12 |
| Chaharmahal and Bakhtiari | 5.38 | 1.49 | 1.21 | 0.99 | 1.12 | 1.24 | 1.02 | 0.90 | 0.95 | 0.98 | 0.98 | 0.92 | 0.90 | 0.99 | 1.13 | 1.14 | 1.10 | 1.12 | 1.10 | 1.05 | 1.01 |
| South ,Khorasan | 6.66 | 1.88 | 1.07 | 1.19 | 1.10 | 0.93 | 1.00 | 0.97 | 1.01 | 1.00 | 0.90 | 0.90 | 0.93 | 1.05 | 1.12 | 1.20 | 1.08 | 1.10 | 1.08 | 0.95 | 0.99 |
| Razavi ,Khorasan | 3.52 | 1.50 | 1.22 | 1.06 | 0.95 | 1.02 | 0.99 | 0.88 | 0.96 | 0.98 | 0.91 | 0.95 | 0.94 | 0.94 | 1.03 | 1.15 | 1.10 | 1.13 | 1.18 | 1.18 | 1.11 |
| North ,Khorasan | 4.76 | 1.41 | 1.38 | 1.24 | 0.94 | 1.00 | 0.89 | 0.97 | 1.03 | 1.08 | 1.23 | 0.99 | 0.91 | 0.85 | 0.96 | 0.93 | 0.97 | 1.13 | 1.16 | 1.24 | 1.23 |
| Khuzestan | 4.4 | 1.59 | 1.13 | 1.05 | 1.03 | 1.03 | 1.06 | 0.99 | 1.05 | 1.17 | 1.16 | 1.21 | 1.13 | 1.02 | 1.07 | 1.09 | 1.07 | 1.00 | 0.93 | 0.87 | 0.82 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zanjan | 6 8.15 | 1.96 | 1.17 | 1.16 | 1.03 | 1.00 | 0.98 | 0.94 | 0.93 | 0.93 | 0.89 | 0.90 | 0.98 | 1.02 | 1.16 | 1.09 | 1.18 | 1.27 | 1.29 | 1.08 | 1.02 |
| | Qom | 5 5.35 | 1.86 | 1.40 | 0.90 | 0.75 | 0.82 | 0.80 | 0.81 | 0.88 | 0.92 | 0.88 | 1.04 | 1.03 | 0.81 | 1.11 | 0.88 | 1.05 | 1.21 | 1.20 | 1.16 | 1.26 |
| | Qazvin | 7 7.10 | 1.45 | 0.92 | 1.03 | 0.94 | 0.99 | 1.00 | 1.09 | 0.95 | 0.94 | 1.01 | 1.06 | 1.07 | 1.11 | 1.19 | 1.16 | 1.03 | 1.14 | 1.08 | 0.91 | 0.94 |
| | Fars | 3 3.10 | 1.10 | 0.86 | 1.11 | 1.03 | 1.01 | 1.10 | 1.01 | 0.97 | 0.96 | 0.88 | 1.03 | 0.92 | 0.98 | 1.08 | 1.16 | 1.17 | 1.32 | 1.08 | 1.03 | 1.04 |
| | Semnan | 5 2.03 | 2.27 | 1.30 | 0.94 | 0.84 | 0.85 | 0.90 | 0.88 | 1.00 | 0.95 | 0.93 | 0.95 | 0.93 | 0.94 | 1.05 | 1.03 | 1.10 | 1.08 | 1.02 | 1.04 | 1.12 |
| and | Baluchestan Sistan | 3 3.21 | 1.58 | 1.03 | 0.88 | 0.70 | 0.74 | 0.85 | 0.99 | 0.94 | 0.86 | 0.68 | 0.86 | 0.87 | 0.88 | 0.98 | 0.97 | 0.98 | 1.24 | 1.22 | 1.06 | 1.08 |
| | Kurdistan | 4 4.98 | 1.60 | 1.38 | 1.13 | 0.94 | 0.97 | 0.96 | 1.01 | 0.88 | 1.03 | 1.01 | 1.00 | 1.11 | 1.26 | 1.20 | 1.38 | 1.26 | 1.08 | 0.88 | 0.75 | 0.77 |
| | Kerman | 4 4.88 | 1.61 | 1.14 | 0.97 | 1.01 | 0.99 | 1.23 | 0.98 | 0.99 | 1.01 | 1.00 | 1.00 | 1.05 | 1.06 | 1.03 | 1.15 | 1.08 | 1.17 | 1.18 | 1.11 | 1.00 |
| | Kermanshah | 7 7.44 | 1.46 | 1.14 | 1.18 | 0.96 | 1.07 | 1.08 | 1.01 | 0.97 | 1.04 | 1.02 | 1.03 | 1.10 | 1.09 | 1.32 | 1.18 | 1.11 | 0.99 | 0.97 | 0.89 | 0.81 |
| and | Kohgiluyeh Boyer-Ahmad | 6 6.21 | 1.47 | 1.25 | 1.42 | 1.07 | 0.82 | 1.11 | 0.99 | 0.93 | 0.86 | 0.99 | 0.99 | 0.77 | 1.00 | 1.16 | 1.15 | 1.24 | 1.24 | 1.12 | 1.06 | 1.16 |
| | Golestan | 5 5.14 | 1.97 | 1.23 | 0.78 | 0.60 | 0.71 | 0.86 | 0.93 | 0.91 | 1.04 | 1.01 | 1.02 | 0.90 | 0.90 | 1.02 | 1.31 | 1.26 | 1.24 | 1.18 | 1.06 | 0.99 |
| | Gilan | 3 3.61 | 1.77 | 1.05 | 0.74 | 0.56 | 0.67 | 0.88 | 0.97 | 1.00 | 0.98 | 0.94 | 0.96 | 0.91 | 0.84 | 0.98 | 1.07 | 1.03 | 1.00 | 1.12 | 1.16 | 1.05 |
| | Lorestan | 5 5.71 | 1.87 | 1.37 | 1.04 | 0.98 | 1.02 | 1.13 | 0.96 | 0.83 | 0.88 | 0.99 | 1.03 | 1.01 | 0.96 | 1.11 | 1.16 | 1.05 | 1.13 | 1.08 | 1.04 | 1.01 |
| | Mazandaran | 5 5.62 | 2.69 | 1.52 | 1.04 | 0.76 | 0.68 | 0.75 | 0.83 | 0.88 | 0.88 | 0.90 | 0.92 | 0.88 | 0.92 | 1.06 | 0.98 | 0.99 | 1.11 | 1.22 | 1.48 | 1.56 |
| | Markazi | 5 5.50 | 1.86 | 1.23 | 0.90 | 0.85 | 1.08 | 1.04 | 0.75 | 0.86 | 0.92 | 0.88 | 0.97 | 0.94 | 0.96 | 1.06 | 1.08 | 1.02 | 1.12 | 1.22 | 1.08 | 1.07 |
| | Hormozgan | 7 | 1. | 1. | 0. | 0. | 1. | 1. | 0. | 0. | 1. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 0. |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | .554 | 56 | 01 | 92 | 90 | 20 | 19 | 94 | 84 | 02 | 98 | 08 | 14 | 10 | 37 | 24 | 20 | 09 | 99 | 94 | 87 |
| Hamadan | 4.195 | 1.88 | 1.41 | 1.17 | 1.05 | 0.99 | 1.01 | 0.98 | 0.98 | 0.95 | 0.86 | 0.92 | 0.91 | 1.05 | 1.10 | 1.16 | 1.26 | 1.23 | 1.15 | 1.09 | 1.00 |
| Yazd | 5.86 | 2.40 | 1.41 | 1.18 | 0.89 | 0.80 | 0.93 | 0.85 | 0.93 | 0.91 | 0.92 | 0.78 | 0.79 | 0.96 | 1.01 | 1.16 | 1.09 | 1.21 | 1.22 | 1.07 | 1.08 |

**Table 3:** Continue

| | *17-Jul-20* | *24-Jul-20* | *31-Jul-20* | *7-Aug-20* | *14-Aug-20* | *21-Aug-20* | *28-Aug-20* | *4-Sep-20* | *11-Sep-20* | *18-Sep-20* | *25-Sep-20* | *2-Oct-20* | *9-Oct-20* | *15-Oct-20* | *23-Oct-20* | *30-Oct-20* | *6-Nov-20* | *13-Nov-20* | *20-Nov-20* | *27-Nov-20* | *4-Dec-20* | *11-Dec-20* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ,Azerbaijan East | 0.91 | 0.91 | 0.89 | 0.96 | 1.00 | 1.04 | 1.08 | 1.12 | 1.07 | 1.06 | 1.02 | 1.01 | 1.11 | 1.11 | 1.02 | 1.05 | 1.03 | 0.94 | 1.02 | 1.04 | 0.89 | 1.19 |
| ,Azerbaijan West | 0.84 | 0.86 | 0.85 | 0.86 | 0.99 | 0.99 | 1.08 | 1.20 | 1.18 | 1.19 | 1.13 | 1.13 | 1.17 | 1.14 | 1.11 | 1.06 | 1.00 | 0.92 | 0.90 | 1.05 | 0.87 | 1.23 |
| Ardabil | 1.18 | 1.02 | 0.89 | 0.83 | 0.92 | 0.90 | 0.99 | 1.02 | 1.00 | 1.05 | 0.94 | 1.05 | 1.13 | 1.17 | 1.15 | 1.15 | 1.13 | 1.01 | 0.96 | 1.04 | 0.75 | 1.37 |
| Isfahan | 1.04 | 1.04 | 0.98 | 0.99 | 1.02 | 1.06 | 1.01 | 1.05 | 1.10 | 1.11 | 1.05 | 1.05 | 1.03 | 1.06 | 1.10 | 1.09 | 1.04 | 0.97 | 1.01 | 1.04 | 0.91 | 1.18 |
| Alborz | 0.99 | 0.92 | 0.91 | 0.97 | 0.94 | 0.90 | 0.98 | 1.07 | 1.15 | 1.13 | 1.06 | 1.10 | 1.08 | 1.07 | 1.05 | 1.05 | 1.98 | 0.97 | 0.96 | 1.04 | 0.84 | 1.24 |
| Ilam | 0.89 | 0.86 | 0.87 | 0.99 | 1.02 | 0.85 | 0.95 | 1.01 | 0.93 | 1.09 | 1.19 | 0.99 | 1.30 | 1.28 | 1.17 | 1.04 | 1.03 | 1.00 | 1.06 | 1.04 | 0.68 | 1.45 |
| Bushehr | 0.95 | 0.92 | 1.00 | 0.99 | 0.99 | 0.90 | 1.01 | 1.07 | 0.97 | 1.05 | 0.98 | 1.02 | 1.04 | 1.03 | 0.89 | 0.92 | 0.95 | 0.94 | 0.81 | 1.02 | 0.74 | 1.32 |
| Tehran | 1.02 | 0.93 | 0.89 | 0.90 | 0.93 | 0.92 | 0.97 | 1.16 | 1.18 | 1.12 | 1.03 | 1.08 | 1.06 | 1.05 | 1.05 | 0.99 | 0.96 | 0.94 | 0.98 | 1.03 | 0.95 | 1.11 |
| Chaharmahal and Bakhtiari | 1.06 | 1.03 | 1.06 | 1.03 | 1.01 | 1.08 | 0.98 | 1.02 | 1.02 | 1.09 | 1.04 | 1.05 | 1.06 | 1.09 | 1.06 | 1.08 | 1.07 | 0.99 | 0.94 | 1.05 | 0.73 | 1.41 |
| ,Khorasan South | 0.98 | 0.93 | 0.86 | 0.96 | 1.07 | 1.02 | 0.95 | 1.04 | 1.15 | 1.09 | 1.17 | 1.17 | 1.04 | 1.24 | 1.24 | 1.17 | 1.08 | 0.97 | 1.06 | 1.06 | 0.75 | 1.40 |
| ,Khorasan Razavi | 1.01 | 0.87 | 0.85 | 0.88 | 0.87 | 0.92 | 0.92 | 1.08 | 1.07 | 1.07 | 1.07 | 1.12 | 1.15 | 1.20 | 1.15 | 1.15 | 1.07 | 1.00 | 1.01 | 1.05 | 0.91 | 1.19 |
| ,Khorasan North | 1.14 | 1.09 | 0.84 | 0.84 | 0.88 | 0.96 | 0.96 | 1.09 | 1.05 | 1.02 | 1.12 | 1.01 | 1.03 | 1.08 | 1.15 | 1.12 | 1.06 | 1.03 | 1.17 | 1.05 | 0.73 | 1.40 |
| Khuzestan | 0.84 | 0.85 | 0.86 | 0.93 | 0.99 | 0.95 | 1.07 | 1.13 | 1.09 | 1.03 | 1.01 | 1.08 | 1.05 | 1.05 | 1.01 | 1.02 | 1.04 | 0.97 | 1.01 | 1.02 | 0.89 | 1.17 |
| Zanjan | 0.88 | 0.85 | 0.85 | 0.84 | 0.93 | 1.01 | 1.00 | 1.04 | 1.10 | 1.06 | 1.01 | 1.05 | 1.07 | 1.12 | 1.19 | 1.12 | 1.03 | 1.02 | 1.10 | 1.05 | 0.79 | 1.31 |
| Qom | 1.15 | 0.95 | 0.89 | 0.95 | 0.95 | 1.06 | 1.00 | 1.06 | 1.09 | 1.08 | 1.04 | 1.10 | 1.07 | 1.22 | 1.23 | 1.24 | 1.05 | 0.94 | 1.90 | 1.05 | 0.77 | 1.37 |
| Qazvin | 0.86 | 0.94 | 0.88 | 0.85 | 0.98 | 0.99 | 0.98 | 1.94 | 1.01 | 0.97 | 1.09 | 1.00 | 1.01 | 1.09 | 1.14 | 1.21 | 1.10 | 1.13 | 1.31 | 1.05 | 0.75 | 1.37 |
| Fars | 0.97 | 0.91 | 0.93 | 0.90 | 0.97 | 0.93 | 0.96 | 1.04 | 1.03 | 0.98 | 1.09 | 1.15 | 1.05 | 1.11 | 1.20 | 1.24 | 1.17 | 1.03 | 1.95 | 1.06 | 0.90 | 1.22 |
| Semnan | 1.01 | 1.00 | 1.01 | 0.97 | 0.98 | 0.99 | 1.06 | 1.06 | 1.05 | 0.94 | 1.02 | 1.01 | 1.12 | 1.12 | 1.18 | 1.12 | 1.03 | 1.03 | 1.23 | 1.05 | 0.77 | 1.35 |
| and Sistan Baluchestan | 1.08 | 1.07 | 1.07 | 1.08 | 1.02 | 1.98 | 1.96 | 1.23 | 1.32 | 1.20 | 1.07 | 1.98 | 1.92 | 1.90 | 1.97 | 1.99 | 1.96 | 1.94 | 1.93 | 1.02 | 1.81 | 1.25 |
| Kurdistan | 0.83 | 0.85 | 0.83 | 0.84 | 1.03 | 1.90 | 1.00 | 1.19 | 1.23 | 1.19 | 1.25 | 1.27 | 1.23 | 1.22 | 1.17 | 1.07 | 1.00 | 1.91 | 1.88 | 1.05 | 1.81 | 1.31 |
| Kerman | 1.05 | 0.96 | 1.01 | 0.89 | 0.92 | 0.94 | 0.88 | 0.96 | 0.06 | 0.01 | 0.15 | 0.15 | 0.16 | 0.14 | 0.14 | 0.14 | 0.07 | 0.99 | 0.97 | 1.05 | 0.88 | 1.24 |
| Kermanshah | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 1. | 0. | 1. |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 91 | 91 | 87 | 91 | 00 | 00 | 00 | 20 | 18 | 19 | 16 | 12 | 12 | 18 | 15 | 17 | 03 | 80 | 76 | 04 | 83 | 27 |
| Kohgiluyeh | 1. | 1. | 0. | 0. | 1. | 1. | 1. | 0. | 1. | 1. | 1. | 1. | 0. | 1. | 1. | 1. | 0. | 1. | 0. | 1. | 0. | 1. |
| and Boyer- | 00 | 01 | 85 | 98 | 09 | 02 | 11 | 94 | 05 | 04 | 02 | 01 | 98 | 07 | 20 | 23 | 97 | 06 | 97 | 05 | 61 | 55 |
| Ahmad | | | | | | | | | | | | | | | | | | | | | | |
| Golestan | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 1. | 0. | 1. |
| | 98 | 87 | 85 | 90 | 95 | 87 | 90 | 99 | 92 | 93 | 98 | 09 | 03 | 10 | 24 | 13 | 21 | 05 | 98 | 03 | 80 | 27 |
| Gilan | 1. | 1. | 1. | 1. | 0. | 0. | 1. | 1. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 0. | 1. | 1. | 1. | 0. | 1. |
| | 06 | 07 | 01 | 03 | 96 | 96 | 04 | 03 | 93 | 89 | 99 | 07 | 07 | 09 | 06 | 02 | 98 | 07 | 06 | 02 | 83 | 23 |
| Lorestan | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 1. | 0. | 1. |
| | 95 | 88 | 88 | 91 | 97 | 99 | 06 | 10 | 09 | 08 | 08 | 08 | 13 | 12 | 11 | 11 | 04 | 96 | 97 | 05 | 84 | 26 |
| Mazandaran | 1. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 0. | 1. | 0. | 1. |
| | 26 | 99 | 89 | 81 | 80 | 81 | 86 | 96 | 90 | 91 | 97 | 02 | 12 | 13 | 16 | 07 | 99 | 92 | 90 | 02 | 87 | 17 |
| Markazi | 1. | 0. | 1. | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 1. | 1. | 0. | 1. |
| | 03 | 97 | 03 | 99 | 99 | 97 | 97 | 05 | 15 | 09 | 12 | 07 | 06 | 12 | 10 | 08 | 96 | 92 | 14 | 04 | 82 | 29 |
| Hormozgan | 0. | 0. | 0. | 0. | 1. | 0. | 0. | 1. | 0. | 0. | 0. | 1. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 1. |
| | 86 | 86 | 90 | 94 | 00 | 99 | 96 | 00 | 97 | 94 | 95 | 00 | 95 | 05 | 03 | 10 | 12 | 02 | 27 | 03 | 77 | 31 |
| Hamadan | 0. | 0. | 0. | 0. | 0. | 1. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 0. | 1. | 0. | 1. |
| | 92 | 91 | 85 | 87 | 94 | 00 | 99 | 14 | 18 | 13 | 07 | 14 | 07 | 11 | 07 | 08 | 99 | 91 | 91 | 04 | 82 | 27 |
| Yazd | 1. | 1. | 0. | 0. | 0. | 0. | 0. | 0. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 1. | 0. | 0. | 1. | 0. | 1. |
| | 07 | 01 | 93 | 97 | 92 | 87 | 90 | 99 | 08 | 18 | 22 | 14 | 18 | 31 | 28 | 19 | 07 | 86 | 80 | 05 | 83 | 29 |

## Discussion

TD method was a better fit than other models for estimating R in Iran. TD and SB models could show the effect of interventions for the control of epidemic during the time. In addition, compared with ML and EG models, the TD model can produce $R_t$ in different periods, and we can see the trend of $R_t$ during the time. In China, the EG method had the best fit for data (10), which is not in the line with the results of our study in Iran.

The estimated GT in our study was 5.98 days that is the same as the results of another study in the west of Iran. The mean and standard deviation of GT in the mentioned study was 5.71 and 3.89 days respectively (11).

The first estimate of R in the first week of the epidemic can be considered as $R_0$, because in February 2020 nearly all-Iranian population was susceptible to COVID-19. Then in the next weeks, the intervention measures were conducted so the estimated reproduction number is the $R_t$.

During the study period, there were fluctuations in the value of $R_t$ in Iran. The value of $R_t$ from 7.19 on 21-Feb-20 reached 1.48 on 27-Mar-20. From 20-Aug-21 up to 24-Sep-21, the $R_t$ was lower than one in Iran. The decrease in the value of $R_t$ may be due to a comprehensive vaccination program in Iran.

In the first week of the epidemic, the minimum and maximum values of $R_0$ in the provinces of Iran were 3.10 and 8.15 respectively that indicating high infectiousness of the disease. In Qom, Gilan, and Tehran provinces, as provinces that the first epidemic was observed in, the $R_0$ were 4.35, 3.61, and 4.95 respectively. Overall, this value for Iran was 4.41. In China, the estimated $R_0$ was 3.49 and after taking preventive measures this value reached 2.95 (10).

During the last week of February and March 2020, preventive measures such as lockdowns, closing universities and schools, using masks, and prohibiting travels were conducted (12), consequently, the value of $R_t$ in Iran was reduced. However, the $R_t$ was more than one which showed the progress of the epidemic in all provinces of Iran. From mid-March, the $R_t$ in many provinces decreased and reached one or lower than one in some provinces. However, it is necessary to mention that the $R_t$ merely indicates the status of the epidemic, and it is not indicating the epidemic severity. In other words, the value of $R_t$ may be one, but the epidemic status is in a stable status and can be at a severe level and vice versa.

The week leading up to 26 February 2020, Iran was in the initial phase of the epidemic and we expected the $R_t$ to be more than one. However, in the late spring and early summer of 2020, the $R_t$ increased in most provinces of Iran. This in-

crease in the value of $R_t$ and incidence of the disease in Iran may be due to the reopening of many jobs and decreased compliance with health protocols. After a decrease in the value of $R_t$ in the last two months of summer in many provinces, again at fall $R_t$ increased in all provinces of Iran. One of the main reasons for this increase in the fall may be due to a lack of proper ventilation due to cold weather. The population density in closed places is one of the main risk factors for the spread of the virus (13). R is a function of the contact rate and the probability of transmission per contact (1). Population density, especially in closed places increases the contact rate between patients and susceptible people, so we expect an increase in the incidence of the disease. In addition, Iran faced some challenges in the management of epidemics. Iran is a vast country with many variations in cultures, climate, and socioeconomic status. These variations need different approaches for the management of epidemics in each region of the country. The economic problems, exacerbated by sanctions, lead to the reopening of many jobs and consequently an increase in the incidence of disease (14).

A major limitation of this study was related to the daily incidence of cases of the disease. Because we had no access to the daily incidence of both hospitalized and outpatients' cases we used only hospitalized cases. Part of our analysis was based on the daily incidence cases of hospitalized patients, while many patients are outpatients and many people have asymptomatic infection (15), so there was an underreporting in the incidence data and the estimated R0 based on the hospitalized patients has a delay in detecting the changes of transmission during the epidemic. The underreporting in the daily incidence cases cannot affect the estimated $R_t$, because $R_t$ would be constant if a fixed fraction of the numbers of subjects to be used in the computation. However, we think the estimated $R_t$ during the epidemic can be a useful index for the monitoring and better management of the epidemic.

## Conclusion

TD model was the best fit for estimating the R in Iran. The worst situation of the epidemic in Iran was related to the weeks leading up to 26 February 2020 and 28 October 2020, and better status was related to the week leading up to 26 April 2020.

## Journalism Ethics considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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## Conflict of interest

Aliakbar Haghdoost and Ehsan Mostafavi were managers and members of the Advisory Epidemiologic Committee of COVID-19 in MoHME. The rest of the authors have no conflict of interest.

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