SIR Model Parameter Fitting of SARS-CoV-2 Basic Reproduction Number in Venezuela and Ecuador Epidemic

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Abstract. A novel coronavirus, formerly called SARS-CoV-2 by the International Committee on Taxonomy of Viruses, caused an outbreak of atypical pneumonia in Wuhan, Hubei province by December of 2019 and then rapidly spread out in the whole China. In March 2020, the SARS-CoV-2 spread to Venezuela and Ecuador. The basic reproduction number ($R_0$) is a value that allows measuring the transmission rate of a virus. The SIR model is the simplest compartmental epidemiological model (Susceptible, Infectious, and Recovered). The SIR model can be used to estimate $R_0$ by fitting the curve of the infected compartment to the experimental curve of infected subjects per day. This work aims to study the projection of the $R_0$ of SARS-CoV-2 in Venezuela and Ecuador. For this purpose, five experiments took place by adjusting the SIR model curve of the infected compartment to experimental data at five-time intervals (the first 14, 28, 42, 56, and 178 days for Ecuador data and 165 days for Venezuela data). The $R_0$ fell from 6.923 to 1.003 (between experiments 2 and 3) for Venezuelan data, and from 3.622 to 1.022 (between experiments 1 and 2) for Ecuadorian data. These differences imply that $R_0$ depends on the preventive measures implemented to face the pandemic. On the other hand, the number of infections in Ecuador is higher compared to the infection numbers in Venezuela in each experiment. Venezuela is experiencing a complex economic crisis that limits the ability of its citizens to mobilize due to the lack of gasoline, monetary liquidity, and failures in basics services, suggesting that the economic activity of the countries will also influence the number of infections.
1 Introduction

A novel coronavirus caused an outbreak of atypical pneumonia in Wuhan, Hubei province in December of 2019, and then rapidly spread out in the whole of China [13,39]. The virus formerly called SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) by the International Committee on Taxonomy of Viruses. In February 13, 2020, there were over 60,000 reported cases (including more than 1,000 death report) in China [19]. Since January 2020, the central government of China implemented preventive measures to avert the spreading of SARS-CoV-2 [9,37]. Many cities in Hubei province applied a lockdown strategy, and many measures were implemented, such as tracing close contacts, quarantining infected cases, promoting social consensus on self-protection (wearing a face mask in a public area), and social distance [4,22].

Despite all the measures implemented by the Chinese government to contain the spread of SARS-CoV-2, by March 2020 the virus had spread to North America, Europe, and South America [8,24]. By the time of writing (October 9, 2020), the United States of America (with 7,863,045 of cases), India (with 6,964,074 of cases), and Brazil (with 5,035,744 of cases) are the countries with the highest number of infections in the world [36]. Besides, the latest findings have shown that SARS-CoV-2 is an inflammatory infection in which mortality may increase in certain types of populations, such as the elderly [18], patients with diabetes or associated metabolic diseases [7,28,31], patients with cancer [16], among others.

On March 13, 2020, Venezuela confirmed the first case of SARS-CoV-2, and by March 16, 2020, the Venezuelan government adopted measures of social distancing and preventive quarantine [20]. In Ecuador, the first registered case of SARS-CoV-2 was on February 29, 2020. As a consequence, on March 1, 2020, the Ecuadorian government suspended the celebration of massive events in the cities of Babahoyo and Guayaquil, since the first case of coronavirus confirmed in this region [25]. Both located in the southwest of the country. On March 12, 2020, the government of Ecuador decrees the suspension of classes, suspension of massive events, and the implementation of quarantine of international passengers to prevent the spread of SARS-CoV-2 [30].

Several epidemiological models can describe and predict the spread of disease. Among of these models is the SIR model [3,34]. The SIR model is a standard epidemiological compartmental model that assumes that individuals are in one of three possible compartments: Susceptible individuals (S), infected (I), or recovered (R) [23,35]. The basic reproduction number ($R_0$) is a measure that allows studying the propagation capacity of any contagious disease [10]. From the SIR model, the $R_0$ can be calculated from the parametric adjustment of the experimental curves of contagion per day and the curve of infected individuals given by the SIR model [12].

This work aims to study the different projections of the $R_0$ value of the SARS-CoV-2 in Venezuela and Ecuador. For this purpose, the SIR model has been
fitted to different periods of the existing data on infected cases. In the following section, the methodology developed in this research is explained. Results and discussion are presented in Sects. 3 and 4. Finally, conclusions and proposals for future work are presented in Sect. 5.

2 Methodology

2.1 Database

The database was collected from [36], the data used corresponds to the number of cases of SARS-CoV-2 infection per day. This database started reporting active cases since February 29 for Ecuador and March 13 for Venezuela. In both cases (Venezuela and Ecuador), the database cover from the day when the first case was reported [36].

2.2 SIR Model

The SIR (Susceptible-Infected-Recovered) model, developed by Ronald Ross, William Hamer, and others in the early 20th century, consists of a system of three coupled nonlinear ordinary differential equations, which does not possess an explicit formula solution [2]. The SIR model corresponds to the following three equations:

$$\frac{dS}{dt} = -\frac{\beta SI}{N}$$

$$\frac{dI}{dt} = \frac{\beta SI}{N} - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

where:

- $\beta$ is the infection rate (the rate of the population susceptible become infected).
- $\gamma$ is the removal rate (the rate of infected population recovering or dying), with the inverse of $\gamma$ being the recovery period of a susceptible subject since the moment infection begins until the negative diagnostic test result.
- $S$ is the susceptible population per day.
- $I$ is the infected population per day.
- $R$ is the recovered population per day.

The basic reproduction number is a theoretical parameter that provides some information about the speed with which a disease can spread in a given population. The $R_0$ can be calculated from the relation between $\beta$ and $\gamma$ from SIR model [2]:

$$R_0 = \frac{\beta}{\gamma}$$
2.3 Parameter Fitting

The fitting of $\gamma$ and $\beta$ parameters of the SIR model to the experimental data was performed following the procedure shown in Fig. 1 [26]. The vectors of $\gamma$ and $\beta$ were the inputs to the algorithm. In principle, these vectors were limited, taking as data the $R_0$ between 2 and 3.1 and the recovery time between 8 and 21 days, both reported in the literature [17,32]. However, these limitations prevented to achieve the minimization of the objective function, therefore very high and very low values of $\gamma$ and $\beta$ were established as limits, and their values were plotted as a function of the sum of absolute error to verify the minimum absolute error. Vectors were constructed with an equidistance of $10^{-4}$.

Combinations were made with each of the values of the vectors $\gamma$ and $\beta$. With each combination, the curve of infected subjects was found by solving the differential equation system of the SIR model using a six-stage of the fifth-order Runge-Kutta method. This curve was compared with the experimental curve of infected subjects found in [36] using the sum of absolute error as an objective function. Finally, the combination of $\gamma$ and $\beta$ that has the lowest sum of absolute error is the one chosen to find $R_0$.

In this study, five experiments were performed to look for the projection of the susceptible, infected, and recovered curves of the five-time intervals:

- Experiment 1: Active cases per day from the first day (February 29 for Ecuador and March 13 for Venezuela) to the fourteenth day were used for the projection.
- Experiment 2: Active cases per day from the first day (February 29 for Ecuador and March 13 for Venezuela) to the twenty-eighth day were used for the projection.
- Experiment 3: Active cases per day from the first day (February 29 for Ecuador and March 13 for Venezuela) to forty-second day were used for the projection.
- Experiment 4: Active cases per day from the first day (February 29 for Ecuador and March 13 for Venezuela) to fifty-sixth day were used for the projection.
- Experiment 5: Active cases per day from the first day (February 29 for Ecuador and March 13 for Venezuela) to two hundred and twenty-third day for Ecuador and two hundred and tenth day for Venezuela were used for the projection.

In each experiment, the procedure explained in Fig. 1 was performed for the curve of infected cases in Venezuela and Ecuador.

3 Results

Table 1 shows the projections for $R_0$, $\beta$, $\gamma$, and recovery period of the five experiments for Ecuador and Venezuela. In each case, the infected curve was fitted using the number of days of the experimental curve, for example, for the first
The vectors $\gamma$ and $\beta$ were defined:
\[
\gamma_1, \gamma_2, \gamma_3 \cdots \gamma_j \\
\beta_1, \beta_2, \beta_3 \cdots \beta_i
\]

Combinations of each of the values of vector $\alpha$ are made with each of the values of vector $\beta$:
\[
\gamma_1 \beta_1 \quad \gamma_1 \beta_2 \quad \gamma_1 \beta_3 \cdots \gamma_1 \beta_i \\
\gamma_2 \beta_1 \quad \gamma_2 \beta_2 \quad \gamma_2 \beta_3 \cdots \gamma_2 \beta_i \\
\gamma_3 \beta_1 \quad \gamma_3 \beta_2 \quad \gamma_3 \beta_3 \cdots \gamma_3 \beta_i \\
\vdots \quad \vdots \quad \vdots \quad \vdots \\
\gamma_j \beta_1 \quad \gamma_j \beta_2 \quad \gamma_j \beta_3 \cdots \gamma_j \beta_i
\]

With each combination $\gamma$ and $\beta$ ($\gamma_j \beta_i$), the curve of subjects infected by the SIR model is calculated (using Rungc-Kutta method) and compared with the real curve, using the absolute error.

The combination of $\gamma$ and $\beta$ that has the least absolute error is the one chosen to find $R_0$.

Fig. 1. Fitting of $\gamma$ and $\beta$ parameters of the SIR model to infected experimental curve.

experiment, the experimental curve was used from day one to fourteen. This was done in this way to observe how $R_0$ projection changes at different time points. Figure 2, 3, 4, 5, and 6 show the graphs of the fit of the SIR model curves for the Venezuelan data. Figure 7, 8, 9, 10, and 11 the SIR model curves for the Ecuadorian data. In the graphs (a) the SIR model curve fit graphs, the susceptible, infected, and recovered curves are shown on the left, and the infected curve is zoomed in on the right for more detail. On the other hand, in the graphs (b) the sum of the absolute error for the values of $\gamma$ and $\beta$ is showed.

4 Discussion

In the Table 1 the $R_0$ of experiments 1 and 2 of Venezuela data are reported between 5.833 and 6.923, this $R_0$ tendency changed in experiments 3, 4, and 5 where the $R_0$ fell to 1.003. Otherwise, the $R_0$ of experiment 1 for Ecuador data is 3.622 and since the experiment 2 to 5 this tendency changes and the $R_0$ fell
Table 1. Parameters projection to each experiment.

| Country | Parameters          | Exp.1 | Exp.2 | Exp.3 | Exp.4 | Exp.5 |
|---------|---------------------|-------|-------|-------|-------|-------|
| Ecuador | $R_0$               | 3.622 | 1.036 | 1.022 | 1.033 | 1.069 |
|         | $\gamma$            | 0.090 | 7.560 | 11.140| 6.340 | 1.310 |
|         | $\beta$             | 0.326 | 7.830 | 11.390| 6.550 | 1.400 |
|         | Recovery period [days] | 11.111| 0.132 | 0.090 | 0.158 | 0.763 |
|         | Sum of absolute error| 4.803 | 59.857| 265.286| 876.179| 8458.153|
| Venezuela| $R_0$              | 5.833 | 6.923 | 1.003 | 1.004 | 1.031 |
|         | $\gamma$            | 0.060 | 0.026 | 74.600| 23.900| 1.920 |
|         | $\beta$             | 0.350 | 0.180 | 74.800| 24.000| 1.980 |
|         | Recovery period [days] | 16.667| 38.462| 0.013 | 0.042 | 0.521 |
|         | Sum of absolute error| 17.481| 40.153| 38.769| 45.734| 1495.643|

Fig. 2. Venezuela experiment 1: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.

These findings suggest that social distancing, stipulated on March 12 for the Ecuador government and March 16 for the Venezuela government, had a significant impact on the decrease of $R_0$ [5].

It is important to note that SARS-CoV-2 has had a higher number of infections in Ecuador than in Venezuela, despite that the $R_0$ found in Ecuador data is lower. This could be due to the Venezuelan government implemented radical quarantine measures three days after the first case appeared, besides, the Venezuelan economic movement is very slowed down due to the lack of gasoline and the failure of basic services, all those conditions limit the movement of the
Fig. 3. Venezuela experiment 2: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.

Fig. 4. Venezuela experiment 3: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.
Fig. 5. Venezuela experiment 4: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.

Fig. 6. Venezuela experiment 5: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.
Fig. 7. Ecuador experiment 1: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.

Fig. 8. Ecuador experiment 2: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.
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Fig. 9. Ecuador experiment 3: (a) SIR model simulation and zoom-in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.

Fig. 10. Ecuador experiment 4: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.
population. Instead, the Ecuadorian government implemented social distance measures for twelve days before the quarantine, during those days the virus was able to spread.

On the other hand, the $R_0$ found with the data from Venezuela (experiments 1 and 2) doubles the $R_0$ found in Ecuador (experiment 1), besides, the $R_0$ found in Venezuela took 25 days to drop after the establishment of quarantine, while in the case of Ecuador the $R_0$ decreased after 13 days of the establishment of social distancing and two days of the establishment of quarantine. This could suggest they are two different strains of the virus [21,29], the strain that spread in Venezuela has similarities to the strain that spread in Spain, France, and Italy (more contagious and with a longer recovery time) [1]; and the strain that spread in Ecuador resembles the one that spread in China at the beginning of the pandemic that presented a $R_0$ between 2 and 3.1 [33,38]. In any case, it should be taken as a starting point that SARS-CoV-2 has an $R_0$ between 2 and 7 for future projections and preventive health measures.

In Venezuela and Ecuador data a directly proportional relationship was observed between $R_0$ and the projection of the maximum number of infected subjects and between $R_0$ and the duration of the epidemic [6]. In Fig. 2 and 3 the maximum number of active infected cases in Venezuela is $1.5 \times 10^7$ subjects approximately with a duration that ranged between 200 and 350 days; in Fig. 4, 5, and 6 the $R_0$ fell and the maximum number of active infected decreased between 100 and $1.5 \times 10^4$ subjects approximately with a duration between 60

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**Fig. 11.** Ecuador experiment 5: (a) SIR model simulation and zoom in on the experimental data interval. (b) $\beta$ and $\gamma$ vs. the sum of absolute error.
and 250 days. Likewise, the maximum number of active cases of infection in Ecuador (Fig. 7) is $6 \times 10^6$ subjects with a duration of 200 days approximately, after the $R_0$ decreased (Fig. 8, 9, 10, and 11) the maximum number ranged from $5 \times 10^3$ to $4 \times 10^4$ subjects and a duration between 60 and 200 days.

The sum of absolute error increases as the number of days studied increases in both data sets (Venezuela and Ecuador), this may be due to two reasons, the first reason is that when the experimental data has more days the error of the additional day is added to the sum of the absolute error values; and the second is that the model being used does not include certain aspects such as the amount of population varies every day by the number of people who naturally (not connected to SARS-CoV-2) died and were born, there is also a percentage of those recovered (14%) who could be re-infected by the disease [15], this type of population should be returned to the group of susceptible, and the disease has a latency period where the person has the virus without presenting symptoms this is not contemplated by the SIR model used in this research [11,15].

From the model, the average number of days a patient recovers can be calculated, as explained in the methodology section [14,27]. Table 1 shows that the recovery period ranged from 16.667 to 38.462 days in experiments 1 and 2 for the Venezuela data set, and 11.111 for Ecuador experiment 1. On the other hand, in experiments 3, 4, and 5 the recovery period ranged from 0.013 and 0.521 days for the Venezuela data set, and 0.090 and 0.763 days for the Ecuador data set. This could be due to that the probability of infection decreased as a consequence of establishing social distancing, and the dynamics of natural SARS-CoV-2 transmission are modified by the new conditions. It can also be verified that the recovery period found in the Venezuela dataset ($\approx 38$ days) is higher than that found in Ecuador and China (between 8 and 21 days) [17] this could suggest that the strain that spread in Ecuador is different of the one spread in Venezuela.

5 Conclusions

In this study the variations in $R_0$ were assessed, using five-time intervals as experimental values for the fitting of the infected curve. The decrease in $R_0$ was observed after the establishment of social distancing, suggesting that the distancing measures implemented in Venezuela and Ecuador were able to decrease the ability of the infection to spread. This makes distance measurements very important in flattening the infected curve and preventing the collapse of the health care system of the countries around the world.

The differences in $R_0$ values for the five experiments suggest that $R_0$ depends not only on the nature of the infection but also on the economic activity of the country and the preventive measures taken against the pandemic. Therefore, the $R_0$ could be different in each country. For future works, $R_0$ values will be calculated for other countries with different economic developments and with different cultures.

The SIR model used in this work did not contemplate some known characteristics of SARS-CoV-2, for example, there have been cases of reinfection, therefore
there is a percentage of recovered patients who return to the susceptible group, also the disease has a latency period where the person has the virus but does not suffer from it, however, they can transmit it, as is the case of the child population that can carry the virus without presenting symptoms. As future work, we will propose the inclusion of all these characteristics in the model to achieve a better fit with the experimental data in each country.

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