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Analysis and Prediction of the COVID-19 Pandemic in Senegal Using the SIR Model

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Abstract

In this study, the mathematical SIR model (Susceptible-Infected-Recovered (cured and deceased)) was applied to the case of Senegal during the first two waves of the COVID-19 pandemic. During this period, from March 1, 2020, to March 30, 2021, the transmission and recovery rates as well as the number of reproduction were calculated and analyzed for the impact of the decisions taken by the Senegalese government. In both waves, the variation of the basic reproduction number as a function of time, with values below one towards the end of each study period, confirms the success of the Senegalese government in controlling the epidemic. The results show that the solution of mandatory mask-wearing is the best decision to counter the spread of the disease. Indeed, the mean number of reproduction is 2.11 in the first wave, and the second wave has a lower mean value of 1.23, while the decisions are less restrictive during this latter wave. Also, a short-term prediction model (about 4 months) was validated on the second wave. The validation criteria of this model reveal a good match between the results of the simulated model and the COVID-19 data reported via the Ministry of Health, Solidarity, and Social Action of Senegal.

Keywords

COVID-19, Senegal, Basic Reproduction Number, SIR Model

1. Introduction

The COVID-19 pandemic, discovered in December 2019 in the Chinese city of Wuhan [1], is currently affecting almost all countries around the world and with several forms of mutations [2] [3]. Consequently, it does not seem to be over, and it does not spare any country either. Indeed, the first investigations have shown that the disease is caused by a new coronavirus named coronavirus 2019 (COVID-19). Since January 30, 2020, when the World Health Organization

(WHO) declared this disease a public health emergency of global concern (https://www.who.int/), every country or economic area has been affected by the disease.

In Senegal, the first case was discovered on March 1, 2020, and as of March 30, 2021 (end of the second wave), the total number of cumulative active cases reported in Senegal amounted to 38,618 for 1049 deceased persons as illustrated in **Figure 1** showing the cumulative number of cases of infected persons reported.

To protect itself from possible external contamination, each country has taken decisions that it considers appropriate. The first decision of the government of Senegal was taken two weeks after the first case, *i.e.* on March 14, 2020. Among the decisions taken to curb the pandemic, we can mention the one that consists in restricting the movement of people, either continuously or intermittently. This is the containment or curfew under certain conditions. We also have the wearing of masks, which is the most used solution in the world. Another alternative to limit the progression of this epidemic is vaccination with several types of vaccines and different efficiencies.

This study is limited to the first two waves of the epidemic, from March 1, 2020, to September 15, 2020, and from December 1, 2020, to March 30, 2021, in Senegal as shown in **Figure 2**. A series of binding decisions have been taken to contain this epidemic:

- March 14, 2020: the ban on public events and gatherings.
- March 16, 2020: closure of schools (high schools, universities, etc.).
- March 20, 2020: closure of air borders.

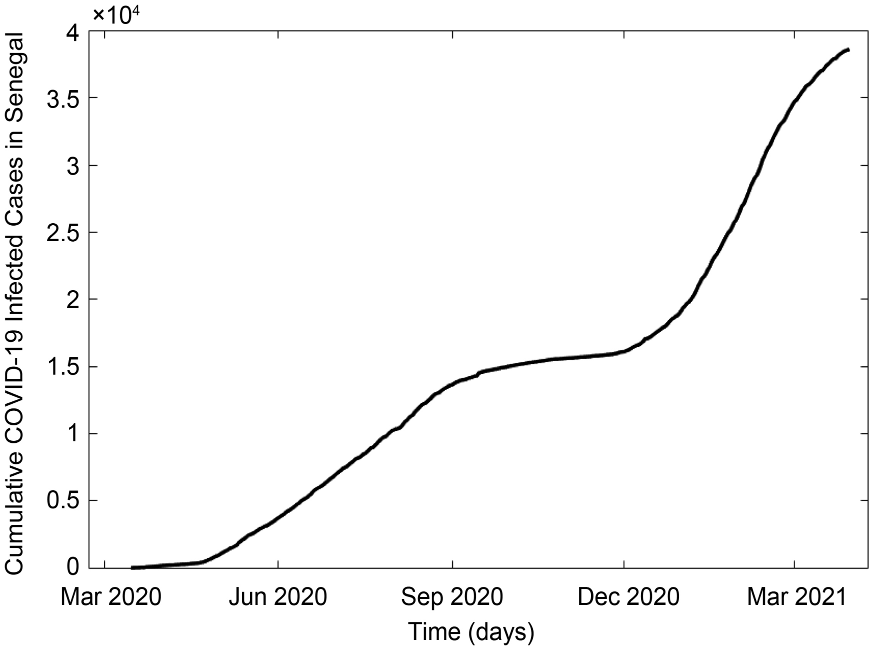

Figure 1. Cumulative COVID-19 cases in Senegal during the first two waves of contamination.

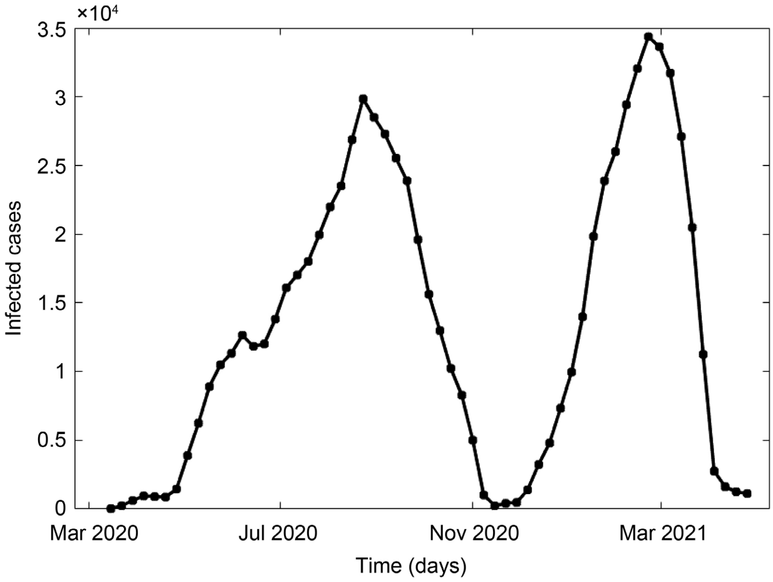

Figure 2. New daily active infective cases in Senegal during the first two waves of contamination.

- March 24, 2020: declaration of a state of emergency with a curfew from 8 p.m. to 6 a.m. Intercity transportation is prohibited.
- April 20, 2020: the mandatory wearing of masks in public places.

The relaxation measures took place as follows:

- May 11, 2020: reduction of curfew time from 9 p.m. to 5 a.m.
- June 7, 2020: the reopening of intercity transportation.
- June 30, 2020: End of curfew.
- July 15, 2020: Opening of air borders.

Knowing that the epidemic progresses seasonally [4], the use of mathematical models (SIR, SEIR) is an essential tool in the prediction and concrete evaluation of the effectiveness of the measures taken to eradicate the COVID-19 pandemic.

The purpose of this study is to:

- Calculate the key parameters of the SIR model daily, which are the cure rate, the infection rate, and the number of reproduction.
- Examine the impact of decisions taken by the Senegalese authorities in the management of the COVID-19 pandemic.
- Build a robust model capable of predicting the number of individuals infected by the coronavirus.

To achieve these objectives, the key parameters listed above will be calculated daily on the first two waves using the finite difference method. The predictive model will be validated by comparing the results of the observation with those of the model on the second wave only and by setting a validity criterion.

2. Materials and Methods

2.1. SIR Epidemiological Model

First postulated by Kermack and McKendrick in 1927 [5] [6], the SIR model has been the basis for most models of infectious disease [7] [8] [9]. This model divides a homogeneous population into three groups. The infected and still infectious individuals are noted as $I(t)$, the potentially infected or susceptible individuals as $S(t)$, and those recovered from the infection (cured or dead) as $R(t)$. This model, therefore, describes the transmission dynamics of diseases with natural immunity by infection. In this model, we consider that a recovered or cured person will not be re-infected because he/she develops immunity.

This choice is explained by the fact that it is a reliable model, easy to use, and therefore the input parameters are easily accessible. The SIR model is given by three coupled ordinary differential equations (ODE) that describe the temporal evolution of the three groups:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\frac{\alpha}{N} S(t) I(t) \tag{1}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = -\frac{\alpha}{N} S(t) I(t) - \beta I(t) \tag{2}$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = -\beta I(t) \tag{3}$$

In these equations, t represents the time (in days), α is the transmission (or contamination) rate which represents the number of people contracting the infection per unit of time. The parameter β is the cure rate. The ratio between α and β is the reproduction number R_0.

If $R_0 < 1$, the infection dies out and does not spread in the population. If $R_0 > 1$, the infection spreads in the population. This parameter, which is important in assessing disease, changes with vaccination and other mitigation measures such as the mandatory wearing of a mask and curfew.

The three groups of the population will sum up to give the total number of the population:

$$S(t) + I(t) + R(t) = N \tag{4}$$

The classical SIR model, therefore, assumes a constant population where the sensitive population decreases monotonically toward zero.

With data provided daily, the Equations (1), (2), and (3) of the SIR model, are discretized using an implicit Euler scheme [10] and we obtain:

$$\frac{S_{i+1} - S_i}{t_{i+1} - t_i} = -\frac{\alpha_{i+1}}{N} S_{i+1} I_{i+1} \tag{5}$$

$$\frac{I_{i+1} - I_i}{t_{i+1} - t_i} = -\frac{\alpha_{i+1}}{N} S_{i+1} I_{i+1} - \beta_{i+1} I_{i+1} \tag{6}$$

$$\frac{R_{i+1} - R_i}{t_{i+1} - t_i} = -\beta_{i+1} I_{i+1} \tag{7}$$

With M representing the number of days of the study.

From Equations (5) and (7), the parameters of the SIR model are determined by the following expressions:

$$\alpha_{i+1} = -\frac{N\left(S_{i+1} - S_i\right)}{S_{i+1} I_{i+1} \Delta_{i+1}} \tag{8}$$

$$\beta_{i+1} = \frac{R_{i+1} - R_i}{I_{i+1} \Delta_{i+1}} \tag{9}$$

With $\Delta_{i+1} = t_{i+1} - t_i$

The numerical model based on the finite difference method, allowing us to predict the evolution of the pandemic, is described from Equations (5), (6), and (7). These discretized equations are the following:

$$S_{i+1} = S_i - \Delta_{i+1} \frac{\alpha_{i+1}}{N} S_{i+1} I_{i+1} \tag{10}$$

$$I_{i+1} = I_i + \Delta_{i+1} \left(\frac{\alpha_{i+1}}{N} S_{i+1} I_{i+1} - \beta_{i+1} I_{i+1} \right) \tag{11}$$

$$R_{i+1} = R_i + \Delta_{i+1} \beta_{i+1} I_{i+1} \tag{12}$$

The input parameters of this model, which are the cure and contamination rates, are determined only during the second wave and according to the approach [11]. Studies in the literature have shown that the cure rate appears to be constant while the contamination rate follows a decreasing exponential function:

$$\alpha(t) = \alpha_1 \mathrm{e}^{-\alpha_2 t} \tag{13}$$

$$\beta(t) = \beta \tag{14}$$

The constants α_1, α_2 and β are calculated from the real measured data and by an inverse method.

2.2. Real COVID-19 Data

Senegal is located in West Africa. It is bordered on the west by the Atlantic Ocean, on the east by Mali, on the north by Mauritania, and on the south by Guinea-Bissau and Guinea Conakry. Its population at the last census is 17,215,433 extended over an area of 144,500 km^2. Its strategic position makes it an international hub of world air transport, and therefore exposed it strongly during the COVID-19 epidemic.

The results that will be used for comparison and validation are available on the website of the Ministry of Health, Solidarity and Social Action of Senegal (https://www.sante.gouv.sn/). These values are recorded daily by this ministry, which is the only institution authorized in the national territory to coordinate and manage the fight against the pandemic.

The study period is from March 01, 2020, to March 30, 2021, and corresponds to the first two waves of the coronavirus pandemic as shown in **Figure 2**. These data, centralized by this ministry, allow us to know every day the number of infected cases, the number of cured cases and the number of death cases in Senegal in this study period. The evaluation of the measures taken by the Senegalese government will be done on both waves. Validation of the predictive model will be done only on the second wave.

To smooth out the sudden jumps in the COVID-19 data and to have smooth sequential data, a 7-day moving average was used in this study.

3. Results and Discussions

Figure 3 presents the infection rate of COVID-19 in Senegal during the first two waves of the pandemic. This figure can be divided into two main parts. The first, from March 2020 to September 2020, clearly shows an exponential decrease in the infection rate. The oscillating behavior of the contamination rate at the beginning of the first wave is explained by the various successive restrictions (ban on gatherings, curfew, wearing of masks, etc.). The behavior of the contamination rate during the second wave, which runs from December 2020 to March 2021, seems more stable but still decreasing. Contamination seems to be higher in the second wave than in the first.

Figure 4 shows the recovery rate during the two waves. It can be seen that, despite the instability at the beginning of the first wave, this parameter varies little during this wave. Therefore, it can be considered a constant. The average value during the first wave is estimated at 0.08. In the second wave, the average rate was 0.06. The improvement in the cure rate between the two waves is partly explained by the improvement in health care. Indeed, there was a better understanding of the disease and therefore the treatments became more effective. It should also be noted that at the end of the second wave (February 23, 2021), the vaccination campaign, although timid since it represented less than 2% of the Senegalese population, began in the national territory.

We also see peaks in **Figure 3** and **Figure 4**. This occurs especially at the

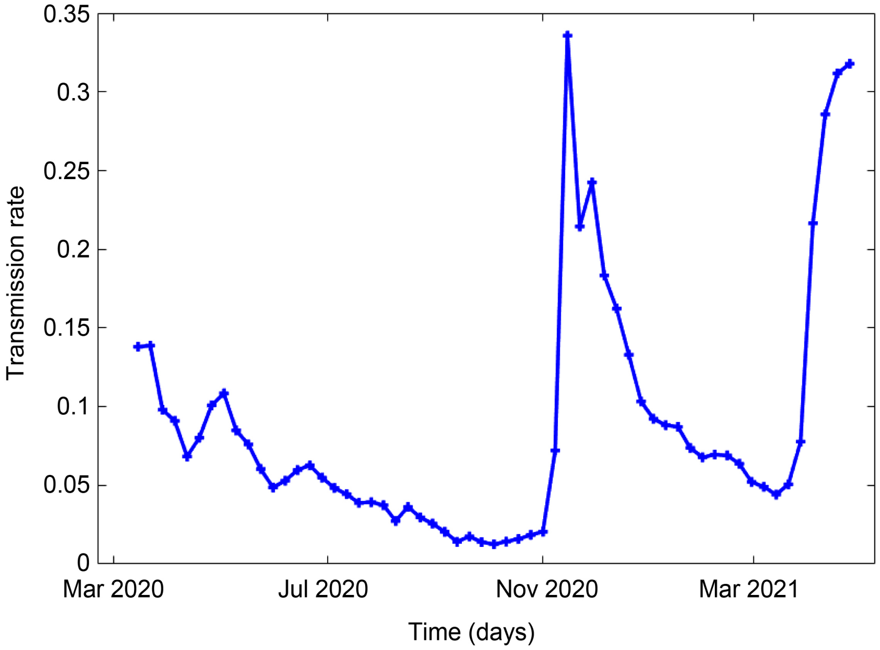

Figure 3. Transmission rate vs time (in day) in Senegal during the first two waves of contamination.

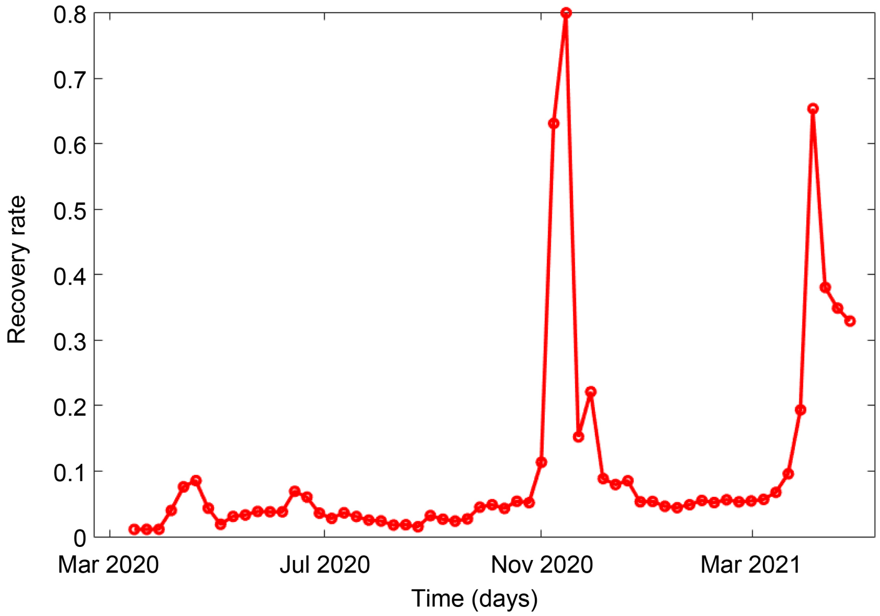

Figure 4. Recovery rate vs time (in day) in Senegal during the first two waves of contamination.

beginning of each wave. In this transition period, the number of infected individuals is not significant, and the cure tests are not yet effective.

The number of reproduction is shown in **Figure 5**. During the first wave, the average number was 2.11 despite the various restrictive measures taken by the Senegalese authorities. Indeed, during the first three months, a curfew was enforced from 8:00 p.m. to 6:00 a.m. as well as the closure of schools and public places. Inter-city travel was also prohibited during these months. The mandatory wearing of masks was implemented only on April 20, 2020, in Senegal and seems to have been accepted by the population.

During the second wave, the average value of the number of reproduction was 1.23. This decrease is noted despite the relaxation of the measures, since only the mandatory wearing of the mask was required.

This confirms that wearing a mask seems to be the most efficient solution to fight against the transmission of the disease. This measure is undoubtedly the most adapted to the sociocultural realities

From Equations (8) and (9), the contamination and cure rates are calculated using the data of the observation during the second wave of the pandemic. The values found for the constants α_1, α_1 and β are 0.25, 0.01, and 0.11, respectively. By inserting these values into Equations (10), (11), and (12), it is possible to predict the number of susceptible, infected, and recovered (cured and dead) individuals in the future. **Figure 6** shows the confrontation of the results of the observation, those of the MSAS, with those obtained numerically by the predictive model on the second wave of the pandemic. The results show a good approximation of the SIR model over about four months, which is still a long period of prediction.

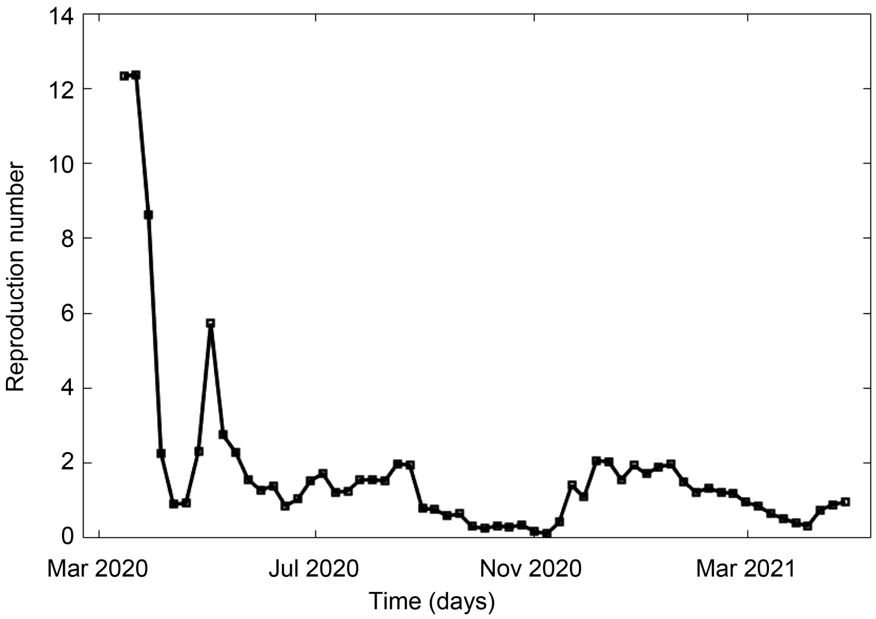

Figure 5. Reproduction number vs time (in day) in Senegal during the first two waves of contamination.

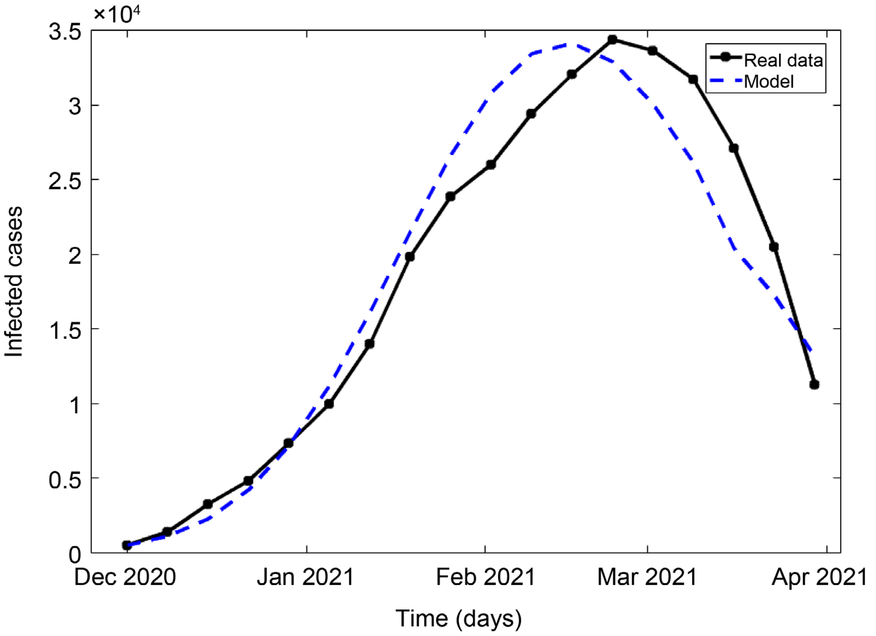

Figure 6. Comparison of model predictions and real data for active infected cases in Senegal during only the second wave of contamination.

The accuracy and reliability of the model, in this study, were evaluated via the RMSE and its correlation coefficient [12] [13]. The value of the RMSE error is 0.13 while the calculated correlation coefficient is 0.94. This illustrates the robustness of the SIR model applied in this study.

Control interventions (e.g. school closures, curfew, market closures, border closures) were effective during the first wave because the modes of disease transmission were not well known. The results of this study also show that behavioral changes (e.g. regular hand washing, wearing masks, social distancing) are the most effective in curbing disease transmission rates.

From February 23, 2021, the start date of the vaccination campaign, to March 31, 2021, the end date of the second wave in Senegal, there were 274,942 individuals who had been vaccinated. This low proportion of immunized people, about 1.6% of the overall population of Senegal, is low enough to explain the improvement in the reproduction number.

It should be noted that there are infected cases, which have recorded only mild or no symptoms of the virus and therefore do not appear in government statistics. This under-reporting of the total number of active cases of COVID-19 inevitably distorts the epidemiological reality, especially in the case of a small population like that of Senegal. Moreover, the SIR model assumes a homogeneous and closed population set. This may slightly impact the results with the opening of borders and new births.

4. Conclusions

The modeling and prediction of the COVID-19 pandemic in Senegal were presented using the SIR model throughout the first two waves. The finite difference method was used to know the daily progression of key parameters such as the cure rate, the infection rate, and the number of reproduction. By confronting them with the various decisions of the Senegalese government to fight against this pandemic, it was proven that wearing a mask is the most effective and least restrictive measure during these waves of contamination.

The validation of the SIR model was done by confronting the numerical results with those of the observation on only the second wave, which extends over four months. The RMAE error, being 0.13 and its correlation coefficient of 0.94, confirms the robustness of the SIR model. While this research cannot predict when a wave is emerging, it does predict the size and severity of illness in the following days. The results of this study also show the beginning of a third wave and the beginning of the vaccination campaign initiated by the Senegalese government. Finally, as the model does not consider the effect of vaccination on the transmission of the disease, a more in-depth study would make it possible to study the effect of this measure on transmission and even on the appearance of future waves.

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Declaration of Interests

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.

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