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The first year of the SARS-CoV-2 pandemic in Maringá-PR: real-time surveillance and evaluation with a second derivative model

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Abstract: *This study investigates the dynamics of the Covid-19 pandemic in Maringá, Brazil, during its first year and explores the utility of mathematical models for decision-making. Originating in Wuhan, China, Covid-19 rapidly evolved into a global pandemic, reaching Brazil in February 2020. Daily cumulative case data from April 2020 to April 2021 is analyzed, revealing temporal heterogeneity characterized by distinct waves of Covid-19 cases. Mathematical models, particularly exponential models, are employed to predict pandemic trends, and their accuracy is assessed. The results emphasize the effectiveness of interventions such as curfews and mask mandates in shaping transmission dynamics. Analysis of infection speed and acceleration demonstrates the impact of holidays and interventions on the spread of the virus. A parameter, Pi, is introduced to evaluate model fitness, indicating good agreement with real-world data for most of the study period. This research underscores the crucial role of mathematical modeling in pandemic management and provides valuable insights for decision-makers and stakeholders in mitigating the impact of outbreaks like Covid-19. Understanding the temporal dynamics of pandemics is essential for implementing effective interventions and safeguarding public health. Overall, this study contributes to our knowledge of pandemic control strategies and their application in future outbreaks.*

Keywords: *Covid-19, Exponential model, Linear regression.*

O primeiro ano da pandemia de SARS-CoV-2 em Maringá-PR: vigilância e avaliação em tempo real com um modelo de segunda derivada

Resumo: *Este estudo investiga a dinâmica da pandemia de Covid-19 em Maringá, Brasil, durante seu primeiro ano e explora a utilidade de modelos matemáticos para a tomada de decisões. Originária de Wuhan, na China, a Covid-19 evoluiu rapidamente para uma pandemia global, chegando ao Brasil em fevereiro de 2020. Dados diários cumulativos de casos de abril de 2020 a abril de 2021 são analisados, revelando heterogeneidade temporal caracterizada por ondas distintas de casos de Covid-19. Modelos matemáticos, particularmente modelos exponenciais, são empregados para prever as tendências da pandemia, e sua precisão é avaliada. Os resultados sublinham a eficácia de intervenções como o recolher obrigatório e a imposição de máscaras para moldar a dinâmica da transmissão. A análise da velocidade e da aceleração da infeção demonstra o impacto dos feriados e das intervenções na propagação do vírus. É introduzido um parâmetro, Pi, para avaliar a adequação do modelo, indicando uma boa concordância com os dados do mundo real durante a maior parte do período de estudo. Esta investigação sublinha o papel crucial da modelação matemática na gestão da pandemia e fornece informações valiosas aos decisores e às partes interessadas para atenuar o impacto de surtos como o da Covid-19. Compreender a dinâmica temporal das pandemias é essencial para implementar intervenções eficazes e salvaguardar a saúde pública. Globalmente, este estudo contribui para o nosso conhecimento das estratégias de controle da pandemia e da sua aplicação em futuros surtos.*

Palavras-chave: *Covid-19, Modelo exponencial, Regressão linear.*

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Introduction

The SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2, Covid-19) was first detected in Wuhan, China. It belongs to the same family as the MERSCoV (Middle East Respiratory Syndrome) and SARSCoV (Severe Acute Respiratory Syndrome).

The first case of COVID-19 was reported in December 8, 2019 in the city of Wuhan. Then, the epidemy became a pandemic that reach Brazil in February 26, 2020 with the first infection case in São Paulo state (UNISUS, 2020). During this period, happened the holiday of Brazilian Carnival between February 21-29, 2020 (G1, 2020a). The World Health Organization (WHO) officially declared the Covid-19 as a pandemic on March 11, 2020 when 118.000 cases in 114 countries were confirmed.

Immediately following the declaration of WHO, massive actions were taken the next day to reduce the virus transmission: On March 16, 2020 face-to-face municipal classes became optional; March 18,2020 the first case was reported in Maringá (the third most populated city in the Paraná state, Brazil) (PREFEITURA DE MARINGÁ, 2020b).

On March 18, 2020 the sector of business was closed and just essential services were kept (G1, 2020b); cultural public spaces were closed. On March 19, 2020 the second cased of Covid-19 was confirmed pulling airport and bus station to increase security protocol (PREFEITURA DE MARINGÁ, 2020a).

The mandatory face mask just was established on April 18, 2020. The number of people infected, suspected of being infected, those undergoing treatment and deaths were announced to the public on a daily basis. On April 27, 2020, the Health Department mapped confirmed cases of coronavirus in Maringá to help with strategies to combat and prevent the disease (PREFEITURA DE MARINGÁ, 2020a).

On the early period of the pandemic there was little information about the few infection cases. The dissemination of the disease follows a nonlinear process. Soma studies find the exponential function is a good model for Maringá infection cases (DA SILVA; DA SILVA; DE ALBUQUERQUE; DO NASCIMENTO JUNIOR *et al.*, 2021). But these studies lack a parameter for daily assess rate of the model to the real data (CHEN; YU, 2020). The mathematical models might be useful to predict the growing rate an outbreak epidemy or a pandemic and help to stakeholders to make correct decision about what to do.

The aim of this study is to provide a simple prediction model that might be used for stakeholders and researchers for the first year of an outbreak similar to covid-19 in 2020.

Methods

Daily detected and confirmed cases

The data for this study were daily cumulative cases with Covid-19 infection from Maringá-PR for the first 12 months (365 days) of the epidemic from April 01, 2020 to April 01, 2021. These data were collected from Municipal Health Department to monitor the dynamic of Covid-19 on a daily basis to: 1) assess an exponential model is suitable for Covid-19; 2) inform the future trend of the pandemic for Maringá (SAÚDE, 2020).

In theory, it is impossible to determine the exact number of individuals infected with Covid-19, regardless of our efforts to detect it. In practical terms, among the cases of infection reported daily, there are those who have already passed the virus's latency period, during which it becomes detectable. These patients can then be detected if: a) They have access to detection services. b) All those potentially infected have access to the services and are tested. c) The test method is sensitive, valid and reliable.

Model daily change in the pandemic

We started our modeling analysis using daily data on the cumulative count of diagnosed Covid-19 infections. Where x_i represents the number of newly diagnosed cases on day *i*, where *i* = (1, 2, 3, ..., n). *F(x)* is the cumulative number of newly diagnosed cases and can be described mathematically as below:

$$F(x) = \int_{i=1}^{n} x_i = \sum_{i=1}^{n} x_i \tag{1}$$

The derivative results of *F(x)* can be used to improve the applicability of financial resources in order to achieve target prevention and treatment. However, the surveillance can be done by first order derivative as an indicator for sensitive changes in pandemic scenario:

$$F'(x) = \int_{i=1}^{(n+1)} x_i - \int_{i=1}^{n} x_i = \sum_{i=1}^{n+1} x_i - \sum_{i=1}^{n} x_i \tag{2}$$

The first derivative describes the speed of *F(x)*, while the second order derivative indicates its acceleration. We thus used the second derivative $F'(x)$:

$$F''(x) = F'(x_{i+1}) - F'(x_i) \tag{3}$$

Mathematically, $F'(x)$ measures infection/day and $F'(x)$ measures infections/(day)^2. Therefore, $F'(x) \approx 0$ is an indication of infection stabilization; $F'(x) > 0$ means that there is an acceleration in the infection cases; while $F'(x) < 0$ is a previous indication of deceleration.

Modeling the pandemic with assumption of no intervention

The dynamic of transmission of coronavirus is a well-known exponential growth of new infections in the beginning of the outbreak (CHANG; KAPLAN, 2023). By fitting the observed daily cumulative cases to an exponential curve, we then went on to estimate the potential number of new instances that may be found each day over the timeframe. Considering the number of confirmed cases and the continuous spread of the virus it is possible to model the coronavirus news infections (PAVLYUTIN; SAMOYAVCHEVA; KOCHKAROV; PLESHAKOVA *et al.*, 2022):

$$y = y_0 + \alpha e^{\beta t} \tag{4}$$

Setting $y_0 = k\alpha e^{\beta t}$, we applied the natural logarithm in both sides of the equation:

$$\ln(y - y_0) = \ln(\alpha e^{\beta t}) \tag{5}$$

We used the logarithm property to simply:

$$\ln(\Delta y) = \ln(\alpha) + \beta t \tag{6}$$

Setting $Y = \ln(\Delta y)$ and $\theta = \ln(\alpha)$. The linear regression is a simple model used to represent the relationship between two variables. The linear model attempt to model the observations as a straight line described by the following equation:

$$Y = \theta + \beta t \tag{7}$$

To estimate the parameter θ, β e y_0 parameters of the linear model we used the least-square method in the software Origin Student version.

$$\theta = \frac{\left(\sum_{i=1}^{n} Y_i\right)\left(\sum_{i=1}^{n} t_i^2\right) - \left(\sum_{i=1}^{n} t_i\right)\left(\sum_{i=1}^{n} t_i \cdot Y_i\right)}{n \cdot \left(\sum_{i=1}^{n} t_i^2\right) - \left(\sum_{i=1}^{n} t_i\right)^2} \tag{8}$$

$$\beta = \frac{n \cdot \left(\sum_{i=1}^{n} t_i \cdot Y_i\right) - \left(\sum_{i=1}^{n} t_i\right)\left(\sum_{i=1}^{n} Y_i\right)}{n \cdot \left(\sum_{i=1}^{n} t_i^2\right) - \left(\sum_{i=1}^{n} t_i\right)^2} \tag{9}$$

Fit rate for daily cases

To assess the fitness the estimated cases to respect to real daily confirmed new cases we used the equation proposed by Chen and Yu (2020) to obtain a time series of $F'(x)$ divided by the first derivative y' to predict the model detection rate P_i for day *i* as:

$$P_i = \frac{F'(t_i)}{y'} \tag{10}$$

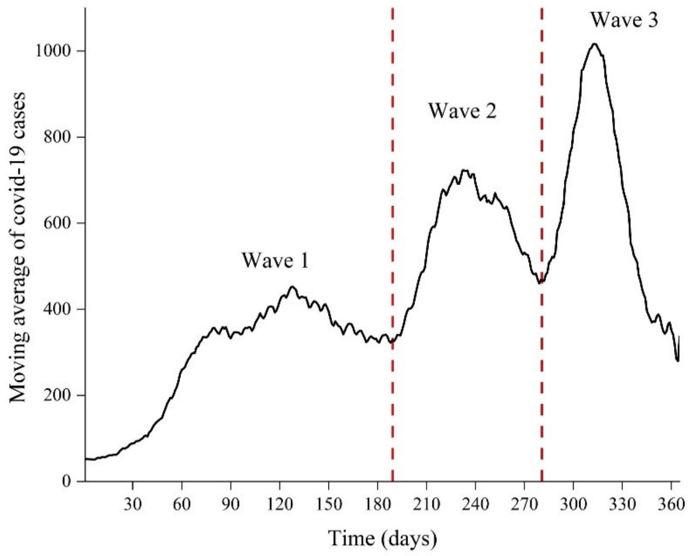
The values of P_i can indicate three different situations: 1) $P_i > 1$ indicate detecting more cases than it was expected; 2) $P_i = 1$ the model is predicting exactly the same values as the confirmed cases; 3) $Pi < 1$ indicate detected less cases than it was expected.

Results and discussion

Temporal heterogeneity and waves of cases

The complete evolution of Covid-19 cases in Maringá was analyzed by thirty-day moving average as illustrated in Fig. 1. Even though there is no concern about to define a covid-19 wave, some authors recommend a period of rise and fall (SUNAHARA; PESSA; PERC; RIBEIRO, 2023). The wave 1 was less intese and well distributed by the time reaching about 400 cases/day; wave 2 and wave 3 were massive reaching about 600 and 1000 cases/day. The wave 3 had a high frequency of cases in a short period in comparison to the wave 1.

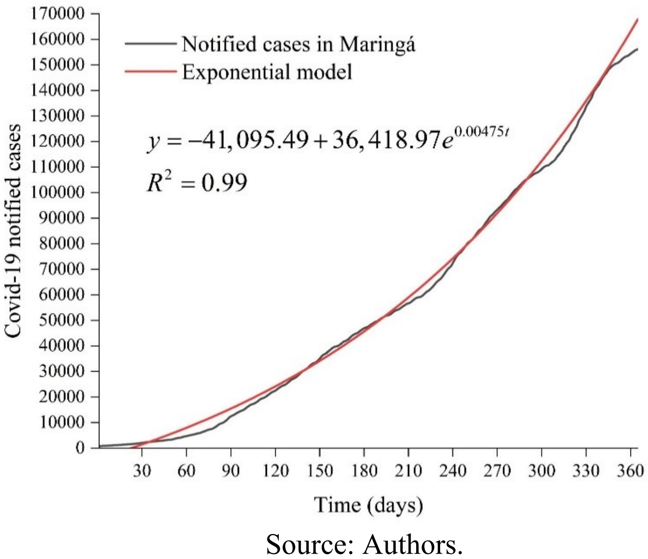
Figure 1. The thirty-day of moving average covid-19 cases 2020-2021



Source: Authors.

The Fig. 2 shows the cumulative notified case of covid-19 and exponential model for Maringá. The linear regression allowed determine the determination coefficient equal to 0.99 for the period indicating a great fit of the model to the data.

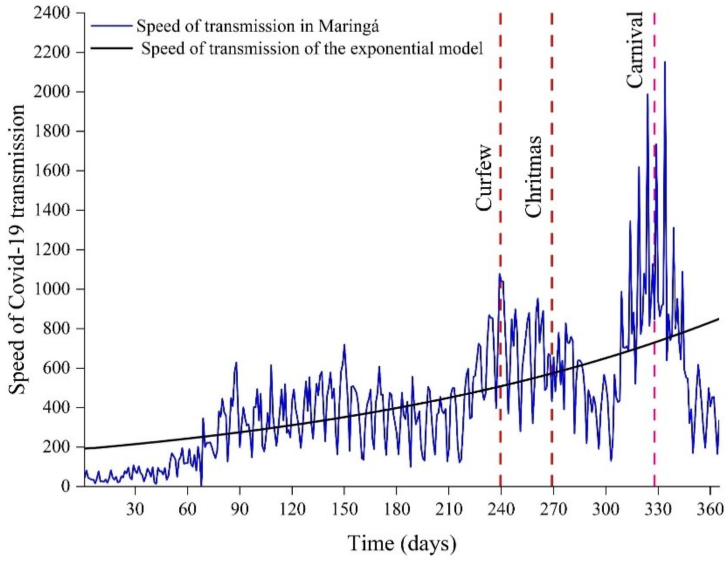
Figure 2 – Exponential model for cumulative covid-19 cases in Maringá 2020-2021.



Source: Authors.

The derivative of covid-19 is similar to the moving average of Fig. 1. The Fig. 3 the derivative of the data and the exponential model (DOS REIS; SEGALA; BELOTO,). The real data had an oscillatory behavior every week. After the day 240 some regulatory established curfew to contain the dissemination of the virus. The decrease was intensified after the Christmas, but it became higher in the period of carnival due relaxed mask wearing and social gatherings (QUEIROZ; PEREIRA; DE OLIVEIRA; MATTA *et al.*, 2021).

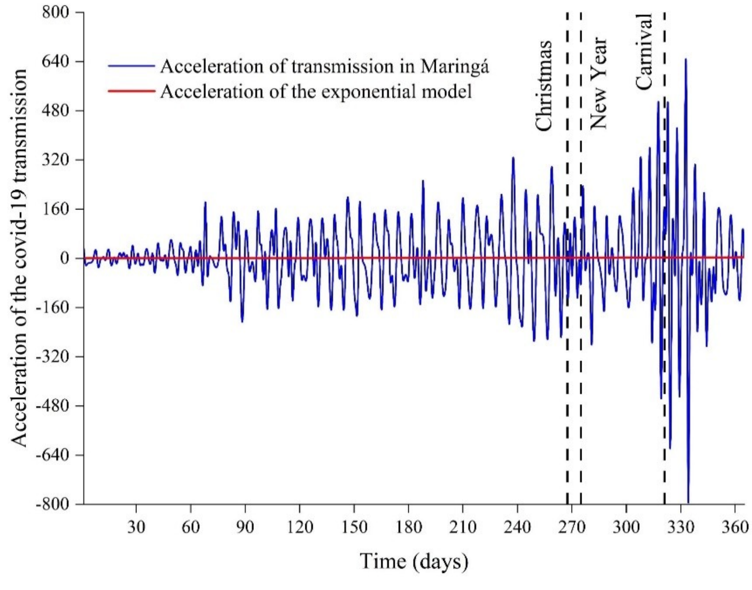
Figure 3 – Speed of covid-19 transmission in Maringá 2020-2021.



Source: Authors.

The acceleration of covid-19 is shown in the Fig. 4. The restrictions near the Christmas and New Year holidays made the frequency of the acceleration to decrease (MOURA; NASCIMENTO; FERREIRA, 2021). Although we can affirm the social gatherings in Carnival holiday may have a significative effect on the increase of the case (PEDROSO; PIRES; MALIK; PEREIRA, 2021).

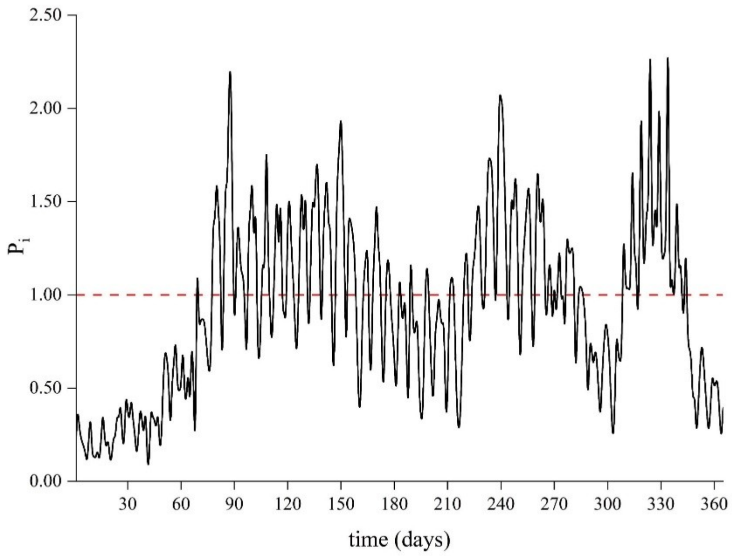
Figure 4 – Acceleration of the covid-19 transmission cases for Maringá 2020-2021.



Source: Authors.

The P_i is a parameter that allows to assess the fitness of the model to the data (RIBEIRO; SUNAHARA; SUTTON; PERC *et al.*, 2020). For Maringá in the first 60 days the model was overestimating the expecting cases. It is important to notice that in the most of the time the P_i stayed below 2.5, indicating that the model has a good adjust to the cumulative function. The majority of the $P_i = 1$ is an indicative that the parameter of the model was appropriate.

Figure 5 – Estimated daily detection rate P_i for the notified covid-19 cases in Maringá.



Source: Authors.

Conclusion

This study provides a comprehensive analysis of the Covid-19 pandemic's dynamics in Maringá during its first year, emphasizing the utility of mathematical models for decision-making and intervention planning. The findings underscore the effectiveness of measures like curfews and mask mandates in slowing virus transmission and reveal the importance of understanding the temporal heterogeneity of outbreaks. Overall, this research contributes valuable insights for managing similar outbreaks in the future.

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