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BRIEF REPORT

Predicting the evolution and control of the COVID-19 pandemic in Portugal [version 1; peer review: 2 approved with reservations]

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Abstract

Coronavirus disease 2019 (COVID-19) is a worldwide pandemic that has been affecting Portugal since 2 March 2020. The Portuguese government has been making efforts to contradict the exponential growth through social isolation measures. We have developed a mathematical model to predict the impact of such measures in the number of infected cases and peak of infection. We estimate the peak to be around 2 million infected cases by the beginning of May if no additional measures are taken. The model shows that current measures effectively isolated 25-30% of the population, contributing to some reduction on the infection peak. Importantly, our simulations show that the infection burden can be further reduced with higher isolation degree, providing information for a second intervention.

Keywords

COVID-19, Pandemic Control, Predictive modeling, Simulation, Social Isolation, Mathematical model

This article is included in the **Pathogens** gateway.

This article is included in the **Emerging Diseases and Outbreaks** gateway.

Open Peer Review

Approval Status

	1	2
version 2 (update) 09 Sep 2020	view	view
version 1 23 Apr 2020	view	view

1. **Elves Heleno Duarte** , University of Cambridge, Cambridge, UK

2. **Kamal Shah** , University of Malakand, Chakdara, Chakdara, Pakistan

Any reports and responses or comments on the article can be found at the end of the article.

This article is included in the **Coronavirus** collection.

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Author roles: Pais RJ: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing – Original Draft Preparation; Taveira N: Conceptualization, Data Curation, Investigation, Methodology, Supervision, Validation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The author(s) declared that no grants were involved in supporting this work.

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Introduction

Coronavirus disease 2019 (COVID-19) is already considered a world pandemic which is starting to have dramatic effects in Europe, where, as of 27 of March, 265,421 cases have been reported^{1,2}. COVID-19 infection in Portugal has been growing exponentially with an average rate of $34 \pm 13\%$ new cases per day from 2 March and is far from reaching the peak by the end of March. As of March 27, 4268 infection cases and 76 deaths have been reported². The highest infection burden is found in Porto (317 cases, 7.4%) and in Lisbon (284 cases, 6.7%) but the disease is present throughout the entire country. As in other countries, infection occurs mostly in individuals' with ≥ 40 years of age (71.9% males; 69.3% females). Death occurs mostly in males (64.5%) all with ≥ 50 years of age.

Predictive models estimate that the peak of COVID-19 infection globally will be between mid-April and May, with an estimated total of 48 million people infected³. As with most other countries, the Portuguese national health care system cannot deal with the increasing demand of care due to limited ventilators and care units³. Therefore, the Portuguese government together with the National Health Directorate (DGS) declared a state of emergency and adopted interventional populational measures (IM) on 18 March 2020 in an attempt to drop the peak of infections even if at the cost of prolonging the infection time. These measures are based on the isolation of people at home, social distancing and adopting protective antiseptic policies. Most forecasting models are based on the number of cases reported and do not take into account the effects of these government-imposed measures and behavioral change. Thus, how these measures impact the evolution of the COVID-19 infection and can prevent the expansion of the epidemic is unknown. Recently published mathematical modelling studies of COVID-19 transmission have already provided useful insights that can be used to guide public health measures and resource allocation to better control this pandemic^{4,5}. However, most parameters of statistical models have been estimated with high degree of uncertainty, resulting in predictions with wide intervals of confidence⁴. Compartmental models such as susceptible, infected and resistant (SIR) models are deterministic approaches that have been successful in describing the dynamics of virus infection in populations, including COVID-19^{5,6}. Here, we provide a simple SI model that describe the dynamics of transition of COVID-19 in Portugal during the first 21 days and predicts the impact of isolation measures towards the expected peak of infection.

Methods

Basic transmission dynamics of COVID-19 was modelled using a simple mathematical model based on a system of two ordinary differential equations (ODE) developed specifically for this purpose (Equation 1 and Equation 2). The equations reflect the number of people infected (I) and susceptible (S) to infection per unit of time (dI/dt and dS/dt). In this model, we accounted for the reported average time of duration of infection (τ) of 14 days^{4,7}. The model was calibrated by adjusting

the rate constant (k) to approximate the total infection value reported by the DGS at 17 March. No further fitting was performed in this model. The effect of isolating different fractions of the population was modelled through the variation of parameter α in Equation 1 and Equation 2. We assumed that protective measures were 99% effective, accounted through model parameter β . The ODEs were encoded and solved using PLAS software version 1.2.0.120, where a series of simulations were carried scanning various values of the α parameter⁸. Simulations were carried with the initial two cases reported by the DGS and considering only the population of the grand Lisbon and Porto areas (total of 6.5×10^6) since they represent most of the susceptible population (see Figure 2). Further analysis, computations and plots were conducted using Python 3 in the Jupiter Notebook ipython 7.8.0 programming environment under Anaconda distribution version 4.7.12. Data regarding the daily evolution of number of total infected in Portugal by COVID-19 was collected from the DGS web site (<https://covid19.min-saude.pt/ponto-de-situacao-atual-em-portugal/>) from 2 to 27 March 2020 (see Source data, Table S1)⁹. The model is available as Extended data⁹.

$$\frac{dI}{dt} = k(1 - \alpha)SI + \alpha k \beta SI - \frac{1}{\gamma} I \quad (\text{Equation 1})$$

$$\frac{dS}{dt} = -k(1 - \alpha)SI - \alpha k \beta SI \quad (\text{Equation 2})$$

Results and discussion

Simulation of the first 18 days with our model was able to describe the exponential increase of the number of confirmed cases reported by the DGS between 2 and 18 March 2020 (Figure 1). The predicted peak time for this scenario was 49 days which would be by the 21 of April. This is within the estimated range predicted by statistical modelling of US, Italy and Korea scenarios³. Further, the predicted numbers of cases for the end of March if no measures were taken would be around 42,000. This is also in agreement with the number released by the DGS to the social media based on statistical modelling. Thus, the model presented here is consistent with the forecasting made by conventional models, reinforcing the confidence on our model capacity to generate predictions. Importantly, our results show that the isolation measures had an immediate impact on diminishing the exponential increase of the number of infected cases and this depends on the percentage of the population that is isolated (Figure 2). This is evident by the increasing deviation of the reported number of cases relative to the unperturbed simulation (0%) with time. The evolution of the number of cases reported by DGS between 18 and 25 March fit between the simulation curves corresponding to 20% and 30% population isolation. This suggests that the estimated percentage of the population that have been effectively isolated is between these percentages. Interestingly, the results shows a slight gradual shift of the obedience towards isolation with time, starting from a predicted 20% isolation and reaching 30% isolation at March 27. From simulations, we identify other intervals (e.g. 50–60% and

Figure 1. COVID-19 spreading on Portuguese population up to 19 of March. Left, the distribution of confirmed cases on 19 March are depicted in the map. Right, evolution of the cases between 2 and 19 of March. Lines indicate simulation using the mathematical model and blue dots correspond to the confirmed cases reported by DGS.

70–75%) that suggest further isolation percentages may be more effective and still within a plausible of pandemic time. Based on the fraction of hospitalized and mortality reported by the DGS on 27 March 2020, together with our model predictions, we computed several infection indicators for these intervals (Table 1).

Our model analysis indicates that current government-mandated measures may shift the expected peak of infections towards the beginning of May and can cause a substantial reduction in the infection numbers (Figure 2, Table 1). Thus, the predicted peak in the number of cases without any isolation measures would be around 2 million, whereas the intervention measures have decreased it to around one half of the cases (Table 1). In addition, the estimated reduction of hospitalized patients and death cases on peak would be predicted around 59,000 and 12,000 people, respectively. Our simulations also indicate that the peak of infection can be further reduced by ~3.5-fold with a delay to November if 70% of the population were isolated at home and follows the government recommendations. For higher percentages of isolation (>75%), our model predicts a substantial reduction in the number of infections and delay of peaks, stopping the COVID-19 epidemic. These solutions would result in much less total mortality and hospitalization requirements on peak in comparison to the current trend (Table 1, Figure 2. Meanwhile, this comes with the burden of prolonging the time of pandemic to almost a year, which can be

economically unbearable. In alternative, further isolation to 50–60% of the population may be also a solution that substantially reduce most pandemic indicators and shifts the ending of the pandemic to September, with the peak between June and July. The results obtained during simulations are available as *Extended data*, Table S2⁹.

Although our model precisely described the exponential curve and explains the shift in the temporal evolution of DGS data, it has limitations that may compromise the exact values of predictions. The fact that we only assume two compartments (susceptible and infected) considering the main populated cities (Lisbon and Porto) as one is huge approximation that neglects regional dynamics. Thus, the model is just an approximation that reflects an average trend and may fail to explain regional observations. In this model we also neglected many important parameters of infection transmission such as age groups, types of social interactions, contact dependent probability, and viral load dependent probability¹⁰. The inclusion of these parameters would definitely make the model more realistic. However, this data is not available for the Portuguese case and these models require accurate processing of data curation for suitable validation. We have bypassed these limitations by aggregating all of these parameters into one constant, which was fitted to the available data. Overall, the predictions shown here should be taken as semi-quantitative estimates within an upper and lower case-scenarios.

Figure 2. Simulation of the dynamics of COVID-19 spreading on Portuguese population with different percentages of social isolation. Above, predicted total infected population in the month of March. The starting of the isolation measure is depicted by IM and the arrow indicates the time of change. Below, Predicted peak of infection.

Table 1. Predicted ranges (upper and lower values) for several COVID-19 infection indicators.

Indicators	Current control (25–30% isolation)	Mild control (50–60% isolation)	Optimal control (70–75% isolation)
Total Infected	4,648,087 – 4,791,783	3,295,201 – 3,910,457	1,354,146 – 2,202,358
Total death	41,594 – 44,421	18,141 – 27,406	2,723 – 7,623
Infected (on peak)	2,335,835 – 2,494,627	1,018,771 – 1,539,093	152,938 – 428,124
Hospitalized (on peak)	193,740 – 206,911	84,499 – 127,656	12,685 – 35,509
Expected peak occurrence	1–10 May 2020	6 Jun – 8 Jul 2020	Oct 2020 – Jan 2021

Conclusions

In this work we demonstrate the potential of modelling COVID-19 dynamics of infection as a useful support tool for predicting the impact of corrective measures. Government-mandated measures to isolate the Portuguese population at home effectively prevented COVID-19 from reaching dramatic numbers in Portugal but still can be substantially improved to reduce the infection peak. Our estimates may help guiding additional measures to control the COVID-19 epidemic in Portugal.

Data availability

Source data

Figshare: Modelling COVID-19 evolution and control in Portugal: Code and data from 2 to 27 of March 2020. <https://doi.org/10.6084/m9.figshare.12136446.v1>⁹.

This project contains the following source data used in the present study:

- Table S1 (CSV). (The number of confirmed cases in Portugal officially reported by the DGS.)

Extended data

Figshare: Modelling COVID-19 evolution and control in Portugal: Code and data from 2 to 27 of March 2020. <https://doi.org/10.6084/m9.figshare.12136446.v1>⁹.

This project contains the following extended data:

- model_code (TXT). (Code used for the model.)
- Table S2 (CSV). (Results obtained during simulation.)
- Python-code (MD). (Python code used with this model.)

Data are available under the terms of the [Creative Commons Attribution 4.0 International license](#) (CC-BY 4.0).

Acknowledgments

Eng. Pedro Fernandes for the critical discussions' and advices on the modelling approach. The CiiEM (Egas Moniz) for hosting institution and supporting publication fees.

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Open Peer Review

Current Peer Review Status: ? ?

Version 1

Reviewer Report 09 July 2020

<https://doi.org/10.5256/f1000research.25829.r64347>

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Kamal Shah

Department of Mathematics, University of Malakand, Chakdara, Chakdara, Pakistan

Coronavirus disease 2019 (COVID-19) is a worldwide pandemic that has been affecting Portugal since 2 March 2020. The Portuguese government has been making efforts to contradict the exponential growth through social isolation measures. In this regard, the authors have developed a mathematical model to predict the impact of such measures in the number of infected cases and peak of infection. They have estimated the peak to be around 2 million infected cases by the beginning of May if no additional measures are taken. The model shows that current measures effectively isolated 25-30% of the population, contributing to some reduction in the infection peak. Importantly, their simulations showed that the infection burden can be further reduced with a higher isolation degree, providing information for a second intervention. The considered study is interesting in this regard and has the potential to give some sound information about COVID-19.

The work is good but there are some issues to be addressed:

1. Provide the existence of the model.
2. What is the feasible region for the considered model?
3. Also, simulate the model for a long time that is months, 40 days, etc.
4. What techniques for numerical simulation have been used?
5. Some relevant and recent work in this regard also must be included. Please see these examples of recent work:
On a comprehensive model of the novel coronavirus (COVID-19) under Mittag-Lefer Chaos, Solitons and Fractals xxx (xxxx) 109867¹
Qualitative Analysis of a Mathematical Model in the Time of COVID-19 , BioMed Research International 2020, Article ID 5098598, 11 pages²
Statistical analysis of forecasting COVID-19 for upcoming month in Pakistan, Chaos, Solitons and Fractals 138 (2020) 109926³
Study of Transmission Dynamics of Novel COVID-19 by Using Mathematical Model." (2020).

Archive.⁴

I recommend its publication in this journal strongly.

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Applied mathematics, Numerical solutions. Mathematical modeling and analysis.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 25 Aug 2020

Ricardo Pais, Instituto Universitário Egas Moniz, Caparica, Portugal

We would like to acknowledge the reviewer for the relevant comments and suggestions. We have considered them all and have revised the manuscript accordingly.

Comment 1

"According to the authors, the model 'predicts the impact of isolation measures towards the expected peak of infection'. I am not convinced this is accurate. I believed the authors used the model to estimate the strength of the measures (i.e. percentage lockdown) and not to estimate the impact of the measures on the spread of SARS-Cov-2"

Reply 1

We agree with the suggestion and have changed the manuscript to convey the idea of estimating the strength of measures, which include the percentage of lockdown, social isolation and usage of masks (see revised version).

Comment 2

"the consistently wrote 'transmission dynamics of COVID-19' and not the correct form 'transmission dynamics of SARS-CoV-2'"

Reply 2

We agree with the suggestion and have changed the manuscript replacing COVID-19 with SARS-CoV-2 (see revised version).

Comment 3

"The authors predicted 2 million cases, which I find surprisingly high. Using the optimal isolation percentage (70-75%), the model still predicted over 150,000 cases which are approximately 5-fold higher than the current number of cases in Portugal (~35,000)"

Reply 3

Indeed, our predictions are higher than the reported values. This is because only a small fraction of SARS-COV-2- infected individuals are tested for the virus has only a few patients show symptoms. However, our results are in agreement with the recent serologic study conducted by the National Institute of Health (INSA) from Portugal that found that a total of 300.000 people were exposed to the virus, 6-fold higher than the number of reported cases. By the time we conducted the model calibration and analysis, these results were not known, resulting in the deviation between predictions and reported values. Thus, we have corrected the model accounting for the asymptomatic fraction not tested and other recent data. This resulted in novel results which were compared with new data up to August and presented in the revised manuscript.

Comment 4

"I would like to see the model's prediction using even higher percentages of isolation. This

should be also discussed."

Reply 4

We have simulated the model with higher percentages and discuss the results (see revised manuscript).

Competing Interests: No competing interests to disclosure.

Author Response 25 Aug 2020

Ricardo Pais, Instituto Universitário Egas Moniz, Caparica, Portugal

We would like to acknowledge the reviewer for the relevant comments and suggestions. We have considered them all and have revised the manuscript accordingly.

Comment 1

"Provide the existence of the model"

Reply 1

According to F1000 Research rules for supplementary data, we included the model code, data and the analysis code in python as extended on figshare (see revised version references).

Comment 2

"What is the feasible region for the considered model?"

Reply 2

The recommended feasible region for this model is $10^8 > (S+I) > 10^4$ where initial $S + I =$ city population.

Comment 3

"Also, simulate the model for a long time that is months, 40 days, etc."

Reply 3

We have performed simulations for 500 days for predictions and 17 days for model calibrations. By the time we submitted the paper no more than 27 days of data was available. Indeed, we only used a 17 days simulation for model calibration to estimate a rate constant in the absence of control. Unfortunately, it is not possible to use more data for model calibration since an uncontrolled lockdown was implemented in Portugal immediately after these 17 days of infection. Using more data would actually result in wrong estimates since many people follow the DGS recommendations but others do not. This is why we have simulated a total of 500 days with multiple % of lockdown scenarios towards estimating how much % of lockdown during the evolution of COVID pandemic.

However, we now include relevant reported DGS data (up to August) for contrasting with model simulations and predictions (see revised version).

Comment 4

"What techniques for numerical simulation have been used?"

Reply 4

The numerical solver was based on the Adams/BDF method, implemented in the LSODA routine of PLAS software. This is a general-purpose stiff, variable-step and variable-order solver. We add this information in the methods section (see revised version).

Comment 5

"Some relevant and recent work in this regard also must be included. Please see these examples of recent work"

Reply 5

We have read your suggestions of new modelling work which are quite relevant and innovative for citing as examples of similar modelling approaches applied in the forecasting of SARS-CoV-2 infection dynamics in Pakistan and Wuhan. Thus, we have included these in the new revised version and other recent work as well.

Competing Interests: No competing interests to disclose.

Reviewer Report 09 June 2020

<https://doi.org/10.5256/f1000research.25829.r63480>

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Elves Heleno Duarte

Department of Genetics, University of Cambridge, Cambridge, UK

The work presented by Pais & Taveira is entitled Predicting the evolution and control of the COVID-19 pandemic in Portugal and it aims to describe the spread of SARS-CoV-2 during the first 21 days. The authors used a simple mathematical model assuming 14 days infection period.

According to the authors, the model 'predicts the impact of isolation measures towards the expected peak of infection'. I am not convinced this is accurate. I believed the authors used the model to estimate the strength of the measures (i.e. percentage lockdown) and not to estimate the impact of the measures on the spread of SARS-Cov-2. This would imply a more elaborated study (e.g. case-control study). Indeed the consistently wrote 'transmission dynamics of COVID-19' and not the correct form 'transmission dynamics of SARS-CoV-2'.

The authors predicted 2 million cases, which I find surprisingly high. Using the optimal isolation percentage (70-75%), the model still predicted over 150,000 cases which are approximately 5-fold higher than the current number of cases in Portugal (~35,000). I would like to see the model's prediction using even higher percentages of isolation. This should be also discussed.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

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Partly

Are sufficient details of methods and analysis provided to allow replication by others?

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If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Genetics, bioinformatics, epidemiology, medical entomology, Wolbachia, and host-microorganism interactions

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Competing Interests: No competing interests to disclosure

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