AN EPIDEMIOLOGICAL MODEL TO AID DECISION-MAKING
FOR COVID-19 CONTROL IN SRI LANKA

Dileepa Ediriweera¹, Nilanthi de Silva¹, Neelika Malavige², Janaka de Silva¹

¹ Faculty of Medicine, University of Kelaniya, Sri Lanka
² Faculty of Medical Sciences, University of Sri Jayewardenepura, Sri Lanka

Correspondence
Dileepa Ediriweera email: dileepa@kln.ac.lk

Abstract

Background: Sri Lanka diagnosed the first local case of COVID-19 on 11 March 2020. The government acted swiftly to contain transmission, with very stringent measures for social distancing: complete island-wide lockdown, contact tracing and isolation, and quarantine of all inbound passengers were all adopted by 20 March. In the first 30 days, Sri Lanka has had 197 cases with 7 deaths, and is now considering a staged relaxing of the lockdown. This paper proposes a theoretical basis for estimating the limits within which the reproduction number should be constrained, in order to ensure that the COVID-19 case load remains within the capacity of Sri Lanka’s health system, while the infection spreads slowly.
Methods: We used publicly available data and adopted a Susceptible, Infected, Recovered (SIR) model to explore the number of new infections and estimate ICU bed requirement at different levels of $R_0$ values after a lockout period. We considered the entire population of the country exposed, with a 14-day period of infection. We assumed 50% of the infected are symptomatic, of which 5% would require critical care, and that the maximum national capacity for treatment of such patients would be 300 beds in Intensive Care Units. We developed a web-based application to demonstrate the epidemic curves and obtain expected cases under different scenarios.

Results: The cumulative case load increased exponentially during the first 8 days of the epidemic and started flattening out from day 9 in the country. In a lockout situation, if the number of infected doubles every 50 days ($R=1.2$), the ICU bed capacity is not likely to exceed 300 by the end of 180 days. If the number of infected doubles every 20 days ($R=1.5$), at least 300 ICU beds are likely to be required by the end of 100 days. If the number infected doubles every 14 days ($R=1.7$), the ICU bed capacity is likely to be exceeded in 70 days. This period is reduced to 50 days if infected cases double every 10 days ($R=2.0$). Our web-based application can be accessed via ‘bit.ly/COVID19_ICU’.

Conclusion: Our model suggests that the desired level of control post-lockout to ensure that the case load remains within the assumed capacity of health system lies below $R=1.2$. This model can be refined to suit other low and middle income countries which may contemplate lockout, but have similar health resource constraints.
Main Text

Introduction

COVID-19 is the disease caused by a new coronavirus (SARS CoV-2) that emerged in China in December 2019. Although it causes an asymptomatic or mild infection in most instances, it can cause severe respiratory illness or even death. Transmission is mainly via droplets released into the air when an infected person coughs or sneezes. However, aerosol and fomite transmission of SARS-CoV-2 is also possible, since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days, depending on the inoculum shed (van Doremalen et al, 2020). There is no vaccine at present, nor is there any antiviral agent of proven efficacy; the principle preventative measures relate to social distancing and personal hygiene.

The basic reproduction number ($R_0$) is a central concept in infectious disease epidemiology, representing the average number of new infections generated by an infectious person in a completely susceptible population. For COVID-19, $R_0$ has been estimated by the WHO to be 1.4 – 2.5. Others have placed it higher, at a median of 2.79 with an interquartile (IQR) range of 1.16 (Liu et al 2020). For comparison, seasonal flu has a reported median $R_0$ of 1.28 (IQR, 1.19–1.37), while measles has an $R_0$ of 12–18 (Lake, 2020).

Situation in Sri Lanka

The 1st case of COVID-19 was diagnosed in Sri Lanka on 28 January, who was a tourist from China. The 2nd case was detected nearly 6 weeks later, on 11 March, who was a tour guide, who probably contracted the infection from a group of Italian tourists. Since then, the spread of infection has been relatively slow, and mostly confined to returnees from countries with high transmission, and their contacts. However, it must be noted that in four of the 190 cases diagnosed in the 30 days from 11 March to 9 April 2020, it was not possible to identify the
source of infection. It took nearly a week for the caseload to double from 50 (on 19 March) to 100 on (25 March). It had not yet doubled again as of 11th April, when the count was 197 cases.

The government of Sri Lanka acted swiftly to contain transmission, with very stringent measures for social distancing: complete island-wide lockdown, contact tracing and isolation, and quarantine of all inbound passengers were all adopted almost simultaneously. The airport has been closed for inbound passengers since 19 March. The national policy with regard to testing was that all symptomatic individuals clinically suspected of infection with SARS-CoV-2, should be tested in one of seven designated laboratories, using PCR as a diagnostic tool. All positive individuals (regardless of severity of illness) are managed in one of twelve state hospitals, designated for management of COVID-19. These hospitals are also equipped with intensive care units and ventilators for management of the critically ill.

However, these control measures have imposed a very heavy social and economic cost, and Sri Lanka now needs to determine a sensible exit strategy. Even if current local transmission is driven down to zero or near zero during the course of April, for economic and social reasons, the government will be forced to re-open Sri Lanka’s borders in the near future, while the pandemic is still going on elsewhere. Given that a commercially available vaccine is thought to be at least 12 – 18 months away, it is necessary that the population should be allowed to develop natural immunity under strictly controlled levels of transmission.

**Potential impact of COVID-19**

It has been suggested that most people infected with SAR-CoV-2 show no symptoms but are still able to infect others. Blanket testing of an isolated village of about 3000 individuals in northern Italy found that 50 – 75% of infected individuals were asymptomatic (Day, 2020). Analysis of the outbreak in China found that 81% of symptomatic individuals had mild
illness, whereas 14% developed severe illness (i.e., dyspnea, respiratory frequency ≥30/min, blood oxygen saturation ≤93%, partial pressure of arterial oxygen to fraction of inspired oxygen ratio <300, and/or lung infiltrates >50% within 24 to 48 h) and another 5% became critically ill with respiratory failure, septic shock, and/or multiple organ dysfunction or failure (Wu et al 2020). It is the provision of effective care for this last group of patients, who may require ventilation for 2 – 3 weeks, that is the crucial limiting factor in any health system.

The global numbers as of 10 April were 1,617,204 cases, 364,686 recovered, and 97,039 deaths, which suggests a case fatality rate of 5.5% (Johns Hopkins University & Medicine, Coronavirus Resource Centre). Of the first 140 patients treated for COVID-19 at the Infectious Disease Hospital in Sri Lanka, nine (6.4%) have required intensive care; a similar proportion to that reported from Wuhan. Of the 190 patients reported to date (9 April) in Sri Lanka, 54 have recovered and seven have died, a case fatality rate of 3.7%.

If the spread of infection is not controlled, the R₀ of SARS-CoV-2 is such that it will sweep swiftly through the susceptible population, resulting in a large number of very ill persons within a short period of time, which overloads the health system and causes it to collapse. However, it is clearly possible to slow down transmission through social and physical distancing, as has been demonstrated in Sri Lanka. If the infection is allowed to spread slowly, a large proportion of infected persons will recover without requiring hospital care (or not even fall ill at all), some will require hospitalization, and a few, especially the elderly and others with co-morbidities, will die. The availability of beds and ventilators in hospital intensive care units (ICU), to care for critically ill patients is a major constraining factor, and Sri Lanka will need to closely monitor and control the rate of spread of infection so that the requirement for ICU beds and ventilators remains within the available capacity.

This paper proposes a theoretical basis for estimating the limit within which the reproduction number should be constrained, in order to ensure that the infection spreads
slowly, and the COVID-19 case load remains within the capacity of Sri Lanka’s health system.
Methods

The cumulative case load for the period 11 March to 9 April was plotted as shown in Figure 1. These numbers are based on a policy of screening all symptomatic individuals clinically suspected of infection with SARS-CoV-2, using PCR as a diagnostic tool, as recorded in the daily situation reports released by the Epidemiology Unit of the Ministry of Health. It should be noted that an exception to this policy was made on 31 March, when screening was extended to contacts, and 10 of the 21 cases reported on 1 April were asymptomatic positives.

Figure 1: Cumulative case load over 30 days commencing 9 March 2020

Figure 2. Fitted models for the first 8 days and after 8 days
According to the data and figure 1, the cumulative case load increased exponentially during the first 8 days of the epidemic and started flattening out from day 9. The flattening out of the case load could be attributed to the strict social distancing and lockdown of cities in the country. Figure 2 illustrates the behavior of the caseload in these 2 phases using a log linear model with (with an exponential function of time) for the period to day 8, and after day 8 using a linear model (with a linear function of time). Therefore, we assumed that the first 8 days represented the natural epidemic curve of the country and used the initial data pertaining to the first 8 days to calculate the reproduction number (we call this ‘R1’).

We used moving averages of 3 days to calculate R1 (Figure 3). We used R0 package in R programming language to estimate R1 using maximum likelihood method for this period. This resulted in a R1 value of 3.05 [95%CI: 1.70 - 4.98] for the initial 8 days (Figure 4).

![Figure 3. Reported new cases (solid line) and moving average of 3 days (red dashed line)](image-url)
We used the Susceptible, Infected, Recovered (SIR) model to explore the number of new infections and estimated ICU bed requirements at different levels of $R_0$ values after lockout. These $R_0$ values were selected to represent the range within which transmission may be constrained (Table 1).

**Table 1: $R_0$ values and doubling time of infections**

| $R_0$ | Doubling time of active infections |
|-------|-----------------------------------|
| 1.2   | 50 days                           |
| 1.5   | 20 days                           |
| 1.7   | 14 days                           |
| 2.0   | 10 days                           |
These SIR models were then run for a period of 18 months using the parameters listed below to estimate the epidemiological curves from 6th of April 2020, assuming a complete lockout situation.

1. Population at risk = 22 million (entire population of Sri Lanka)
2. Infectious period = 14 days
3. Infected number on Day 0 = 348 (174 diagnosed cases on 5 April x 2, assuming that 50% of infections are asymptomatic)
4. Proportion of symptomatic infections that need ICU care = 5%
5. Average duration of ICU stay = 2 weeks
6. Maximum critical care capacity = 300 ICU beds and ventilators (at present, the state hospitals in Sri Lanka have a total of about 670 functional ICU beds with ventilators. While retaining capacity for management of patients with other illnesses, we assumed that up to 300 of these ICU beds may be made available for management of COVID-19 patients at the peak of the epidemic).

We developed a web-based application to demonstrate the epidemic curves and obtain expected cases under different scenarios.
Results

Figure 5 shows the possible course of the epidemic if transmission remained at the initial level seen during the first 8 days (R=3.05). This model suggests that the epidemic would have peaked in about 3 months, with more than 5,000,000 affected individuals at the very peak.

![Figure 5. Natural progression of COVID-19 epidemic when R=3.05](image)

Figure 6 shows how the spread of infection could progress through Sri Lanka’s population at varying levels of transmission. Although the same number of individuals are infected in the long run (up to 18 months), it can be seen that as the value of $R_0$ decreases, the curve becomes flatter: the peak arrives progressively later, and affects a smaller number at any one time.
Figure 6. The epidemic curve over time at different values of R

Table 2 shows the scenarios that emerge at different values of R, in terms of active infections and ICU requirements after 1 month and after 2 months. If R=1.2, the total cases (symptomatic + asymptomatic) would rise to 534 (from a base of 348) after 1 month, and to 821 after 2 months. If R=1.5, the total cases would be 1,017 after one month, and 2,974 after 2 months. If R=1.7, the number of total cases would rise to 1,563 after 1 month, and 7,008 after 2 months. If R=2.0, the number of total cases would rise to 2,974 after 1 month, and 25,326 after 2 months.
Table 2. Predicted active infections and ICU bed requirements at different values of R

| R   | Active infections after 1 month | ICU requirement after 1 month | Active infections after 2 months | ICU requirement after 2 months |
|-----|---------------------------------|------------------------------|---------------------------------|------------------------------|
| 1.2 | 534                             | 13                           | 821                             | 21                           |
| 1.5 | 1,017                           | 25                           | 2,973                           | 74                           |
| 1.7 | 1,563                           | 39                           | 7,008                           | 175                          |
| 2.0 | 2,974                           | 74                           | 25,326                          | 633                          |

Figure 7 shows the scenarios that emerge with different values of R over a period of 180 days.

Figure 7. Total infections with time with different values of R
Figure 8 shows the ICU bed requirements in these same scenarios. When R=1.2, the ICU bed requirement will rise slowly, and would not exceed 300 even after 180 days, whereas if R=1.5, the ICU bed requirement will start to rise rapidly much earlier, and 300 beds would be required by day 99. If R=1.7, this will be in 71 days and if R=2.0, this will be in 50 days.

Table 3 presents the expected number of infections and cases on day 7, day 14, day 30 and day 60 if epidemic continues under the same values of R in a lockout situation. Under R=1.7, we can expect 34 new infections or 17 new cases on day 14 and 76 new infections or 38 cases on day 30. Higher number of infections or cases than this situation will indicate an
emerging epidemic with R value of 2 or higher and risk of exceeding the 300-bed ICU capacity before 50 days in the country.

Table 3. Expected new infections and cases up to day 60, with different values of R

| R  | New infections (new cases) on day 7 | New infections (new cases) on day 14 | New infections (new cases) on day 30 | New infections (new cases) on day 60 |
|----|-----------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1.2| 5 (2.5)                           | 6 (3.0)                             | 8 (4.0)                             | 12 (6.0)                            |
| 1.5| 16 (8.0)                          | 20 (10.0)                           | 36 (18.0)                           | 104 (52.0)                          |
| 1.7| 24 (12.0)                         | 34 (17.0)                           | 76 (38.0)                           | 342 (171.0)                         |
| 2.0| 40 (20.0)                         | 65 (32.5)                           | 205 (102.5)                         | 1741 (720.5)                        |

We have developed a web-based application to obtain these results which can be accessed via ‘bit.ly/COVID19_ICU’.

Discussion

These findings suggest that the stringent social distancing measures imposed by the government are completely justified because the caseload that would have resulted from continued transmission at that initial level (R=3.05) would have almost certainly overwhelmed Sri Lanka’s health system within a month, peaking in about 3 months, with well over 5 million active infections at that point.

The first of the 4 scenarios presented above suggests that the ICU bed requirement would not exceed 300 over a 6-month period if R is kept at 1.2. In this scenario, the number of new infections would rise very slowly at a level below that seen at present, with extremely stringent measures to enforce social distancing.
The second scenario (R=1.5) envisages a situation where the number of new infections rise more rapidly from 16 on Day 7, to 20 on Day 14, 36 on Day 30 and 104 on Day 60 (the number of symptomatic cases would be half these values). At this level of transmission, which may be considered analogous to the present situation, at least 300 ICU beds are likely to be required for treatment of critically ill patients by the end of the 3\(^{rd}\) month. In the third scenario, when R=1.7, the number of infections rises more rapidly and the requirement of ICU beds is likely to exceed 300 early in the 3\(^{rd}\) month. In the 4\(^{th}\) scenario, when R=2.0, the assumed ICU bed capacity of 300 is likely to be exceeded before the end of the second month.

Thus this model suggests that the desired level of control for Sri Lanka after lockout would lie somewhere below R=1.2, where the number of new infections would be 5 on Day 7, 6 on Day 14 and 8 on day 30.

The parameters used to set this model can be refined further as more data becomes available. The model can also be used to visualize the impact of varying levels of control in different settings, such as comparison of the 6 high risk districts with the other 19 districts categorized as of lower risk. The model may also be appropriate for other low and middle income countries that may consider lockout after having employed stringent social distancing measures to contain the epidemic, but have similar resource constraints for ICU care.

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Conflict of Interest Statement

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