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A Mechanism-Based Analysis of COVID-19 Transmission Using the SEIR Model: A Comparative Study of Wuhan and Italy

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Abstract

The COVID-19 pandemic has made it more important to be able to know the underlying mechanisms of the spread of infectious diseases beyond simple predictive modeling. The following study uses the SEIR (Susceptible exposed infectious recovered) model, which is a system of ordinary differential equations, to study the dynamics of an epidemic on a mechanism based approach. Based on a comparative case study of the Wuhan (China) and Italy at the initial phases of the outbreak, the study connects the main model parameters with real-world intervention actions and how the variables of the transmission rate, incubation period, and recovery rate affect the development of epidemics. The results indicate that changes in policy time and intervention intensity have a pronounced impact on transmission processes by changing key model parameters, especially the transmission rate and recovery rate. Wuhan had very early and strict measures, which led to a quick decrease in transmission and successful control of the epidemic, and Italy was characterized by delayed action, which increased the peak of the number of infected people and the duration of the outbreak. The findings reveal that the mathematical modeling framework of SEIR can reflect the dynamics of interaction between epidemiological mechanisms and the interventions of the population health. The study adds to the body of literature because it highlights the explanatory value of mathematical models in the study of epidemics and suggests that the linkage between theoretical modeling and the interpretation of policy is missing. The results are relevant to the practical use of enhancing the effectiveness of the interventions in the public health and increasing the preparedness to the occurrence of new epidemic events.

Keywords

SEIR model, COVID-19 transmission dynamics, mathematical modeling, epidemic mechanisms, public health interventions

1. Introduction

Since the onset of COVID-19 in 2019, global health systems have faced unprecedented challenges. A wide range of intervention measures has been implemented across countries, including large-scale testing, social distancing, vaccination, and digital contact tracing [1]. While these strategies have contributed to mitigating the spread of the pandemic, they have also exposed several critical issues, such as the uncertainty of transmission pathways, the time-lag effects of interventions, and heterogeneity in transmission across populations. In China, the rapid response and high organizational capacity have been used to define the pandemic control approach, but during the normalized prevention and control phase, it is a complicated decision to balance specific interventions with the socio-economic sustainability. Hence, an understanding of transmission of infectious diseases based on mechanisms is critical to enhancing the effectiveness and scientific foundation of health interventions by the populace [2].

The SEIR (Susceptible-Exposed-Infectious-Recovered) model is one of the epidemiological models that have been widely used because it is capable of capturing the incubation period of infectious diseases [3]. SEIR model gives us a methodical approach of explaining the dynamics of disease transmission by classifying the population into four compartments, which include the susceptible, exposed, infectious, and recovered. The SEIR model has a higher explanatory capacity of the latent transmission and delayed outbreak processes compared to the classical SIR model [4]. Nevertheless, the literature has hitherto given more emphasis on model prediction accuracy and parameter estimation and comparatively little emphasis has been given on its ability to explain transmission mechanisms in particular real-life scenarios.

To fill this gap, the paper uses the SEIR model as its central model of analysis and a case study methodology in analyzing the processes of transmission of infectious diseases in the real world. In particular, the paper will examine some of the transmission pathways and drivers at various levels of an outbreak. The proposed study will combine theoretical modelling with empirical instances of the study to maximize the explanatory power of the SEIR model and the gap between theory and practice. Theoretically, the research will be useful in a better understanding of the mechanisms of transmission of epidemics through analytical systematic study of the transmission pathways and the most significant factors that influence them within the framework of the SEIR model. Practically, the results offer insights on the use of the mechanisms to optimize prevention and control measures, hence offering useful references to the policy-making of the national health and risk management.

2. Literature Review and Theoretical Background

2.1 Development of Epidemic Models

Mathematical modeling has always been a critical instrument in the study of the dynamics of transmission of infectious diseases. The SIR (Susceptible Infectious Recovered) model is one of the simplest models used among others. It separates the population into three compartments: susceptible (S), infectious (I), and recovered (R) and defines the movement of individuals between these states with time. Although the SIR model is simple and interpretable, its primary assumption that people are infectious upon exposure thus restricts its use to diseases with a long incubation period [4].

To overcome this weakness, the SEIR (Susceptible-Exposed-Infectious-Recovered) model builds on the SIR paradigm by adding another compartment the exposed (E) one. This compartment symbolizes people who are infected but not yet infectious, thus includes the latent stage of disease development. Consequently, the SEIR model is more realistic in the dynamics of transmission of the majority of infectious diseases, including COVID-19 [5]. The SEIR model has over time been extended further to include other factors like age structure, spatial heterogeneity, vaccination and time-varying parameters to capture better real-world complexities.

There are a few important parameters in the SEIR framework that influence the dynamics of the epidemic. The transmission rate (β) determines how quickly the disease spreads through contact between susceptible and infectious individuals. The incubation rate (σ) governs the transition from the exposed to the infectious state, reflecting the duration of the latent period [6]. The recovery rate (γ) represents the rate at which infectious individuals recover or are removed from the transmission chain [6]. These parameters not only influence the speed and scale of an outbreak but also provide important insights into the effectiveness of intervention measures.

2.2 Current Research on Epidemic Transmission

Compartmental models have been used significantly in the literature to examine the transmission of infectious diseases in various countries and regions, especially using the SEIR framework [6]. The enhancement of model accuracy based on parameter estimations, data fitting, and prediction of future trends has remained the main concern of scholars in the international research field. A lot of research has included real-time information and sophisticated computational tools to improve predictive accuracy, in particular during the COVID-19 pandemic [4]. By contrast, the domestic research has tended to focus on the relevance of epidemic models in particular policy and governance settings. The effectiveness of intervention measures, including lockdowns, mobility restrictions, and mass testing on the dynamics of the transmission process have been studied. These articles bring to the fore the relevance of combining epidemiological modeling and the examination of public health policy. Nevertheless, even with such developments, a similar limitation is found in most of the available literature; they are more focused on prediction and modeling but less concerned about the mechanisms involved in the transmission. Specifically, research that would clearly connect model parameters with actual intervention measures and social settings is lacking.

3. Mechanism of Epidemic Transmission

This work is based on the SEIR framework and its parameters but, more importantly, it will look at the fundamental processes that govern epidemic transmission [7]. To begin with, the incubation period is important in determining the dynamics of transmission. Due to the fact that the exposed persons cannot be detected immediately, the existence of a latent phase creates a lag between infection and confirmation that may result in an underestimation of the actual spread in the early stages of an outbreak. Second, the transmission rate directly depends on the contact rate between persons. Close-range contacts in highly populated or socializing settings can facilitate the shift between the susceptible and the exposed groups, which boosts the overall rate of infections growth. On the other hand, the intervention strategies, including lockdowns and social distancing, are effective to decrease the contact rates and slow the transmission. Third, interventions in the public health are external regulatory forces that adjust the parameters of the models. As an illustration, the mobility limitations are the main factors influencing the transmission rate, whereas testing and isolation policies may reduce the infectious period and increase the rate of recovery in a functional sense. Besides these factors there are structural characteristics of the society which are as well important. The population density and the patterns of social networks are a part of the community structure, which influences the speed of the disease transmission within and between the groups. The population movement especially that between the regions also adds to the spatial spreading of the epidemic making localized outbreaks more of a widespread public health phenomenon.

4. Case Study

4.1 The SEIR Mathematical Model

In order to offer a rigorous basis to the case studies of Wuhan and Italy, this study applies the SEIR framework [5]. The interactions between these compartments of the population and their transitions are governed by the following system of ordinary differential equations:

$$\frac{dS}{dt} = -\frac{\beta SI}{N} \tag{1}$$

$$\frac{dE}{dt} = \frac{\beta SI}{N} - \sigma E \tag{2}$$

$$\frac{dI}{dt} = \sigma E - \gamma I \tag{3}$$

$$\frac{dR}{dt} = \gamma I \tag{4}$$

These equations explain the dynamics of movement between various epidemiological states of people over time. In particular, the former is the rate at which the susceptible individuals are exposed by being in contact with infectious individuals. The second equation describes the accumulation of exposed individuals and their movement into the infectious group following the incubation period. The third equation is a reflection of the change in the number of infectious individuals, which is calculated using new infections and recoveries, and the last equation is the rate of people getting out of the transmission process. Instead of viewing these equations as a mathematical expression, this paper views them as a depiction of the actual transmission in the real world.

A key indicator derived from the model is the basic reproduction number (R0), defined as:

$$R_0 = \frac{\beta}{\gamma} \tag{5}$$

This value indicates the average number of secondary infections generated by a single infectious individual in a fully susceptible population.

4.2 China Case: COVID-19 Outbreak in Wuhan (2019–2020)

4.2.1 Overview of Epidemic Transmission

The COVID-19 outbreak in Wuhan is one of the first and the most thoroughly researched epidemic events [8]. The transmission process can be generally divided into three phases: the first phase is the initial outbreak phase that is characterized by the undetected spread, the second phase is the rapid escalation phase which is characterized by the exponential increase in the number of confirmed cases, and the third phase is the containment phase that follows the strict intervention measures.

During the initial phase, the lack of awareness and the lack of testing capacity helped to propagate the virus silently. When the number of infections grew, the epidemic entered a fast development period, which placed a strain on the healthcare system. Afterwards, there was a relative reduction in new cases due to large scale interventions such as lockdown and mobility restrictions imposed on cities.

4.2.2 SEIR-Based Interpretation of Key Transmission Stages

In the light of the SEIR model, the initial outbreak in Wuhan can be viewed as the time when the number of exposed population (E) was vast, and it was not measured significantly because of the incubation period. This was a latent build up that caused a delayed yet rapid rise in the infectious population (I). In the exponential growth stage, the rate of transmission (β) was high due to the rampant social interaction and population mobility in the population, and, as a result, the transition rate between the susceptible (S) and exposed (E) populations was high. The model can be used to understand the reason behind the rapid spread of the epidemic even after containment was initially done. Following the implementation of strict interventions, the effective transmission rate (β) declined significantly, while the removal rate (γ) increased due to improved medical response and isolation measures. As a result, the growth of the infectious population slowed, eventually leading to epidemic control [8].

The Wuhan case illustrates how policy interventions directly influence SEIR model parameters. Lockdown measures and travel restrictions reduced contact rates, thereby lowering β. Mass testing and centralized quarantine enhanced early detection and shortened the infectious period, effectively increasing γ. These dynamic changes in parameters demonstrate the strong interaction between public health policies and epidemic transmission mechanisms.

4.3 International Case: Italy's Early COVID-19 Outbreak (2020)

4.3.1 Transmission Characteristics and Social Context

Italy also had one of the initial outbreaks of COVID-19 in Europe in large proportions. The Italian case had a high mortality rate and the rapid spread across the region as compared to Wuhan. There were a number of social and structural determinants to this trend and this was because the population was old, the generations were in close contact with each other and the level of social interaction was at a relatively high level [9]. As well, the response was rather slow, which gave the virus more time to spread throughout the region before harsh actions were taken. The outcome of this was a higher dispersed and less controlled pattern of transmission.

4.3.2 SEIR Interpretation of Infection Peaks and Trends

Within the SEIR framework, the Italian outbreak can be characterized by a rapid increase in the infectious population (I) following a relatively short transition from the exposed stage (E). High contact rates in community settings contributed to a sustained high transmission rate (β), leading to a sharp epidemic peak. The delay in implementing large-scale interventions meant that the reduction in β occurred later compared to the Wuhan case. Consequently, the model explains the higher peak and longer duration of the epidemic in Italy during the early phase.

Italy eventually adopted nationwide lockdown measures, which contributed to a gradual decline in transmission. However, compared to Wuhan, the timing and intensity of interventions differed, resulting in distinct parameter trajectories. The delayed reduction in β and slower increase in γ highlight the importance of early and decisive intervention in controlling epidemic spread.

5. Comparative Analysis

The relative analysis of the Wuhan and Italy cases highlights the functionality of the public health interventions as dynamical modulators of the SEIR differential equations.

In the Wuhan example, the lockdown and mobility measures were applied aggressively leading to a non-linear exponential decay in the effective transmission rate beta (β), which essentially starved the transfer of the Susceptible (S) to the Exposed (E) compartment. Simultaneously, the implementation of centralized quarantine and mass testing optimized the removal rate gamma (γ), shortening the infectious period and driving the basic reproduction number $R0 = \beta / \gamma$ below the critical threshold of 1 much faster.

The Italian pathway on the other hand featured a long-term high beta (β) because of a large initial contact rate and mathematical delay in the execution of policy. This postponed the inflection point of the infectious curve (I), leading to an increased stochastic peak and a more spread distribution of cases over time. The comparison of the two situations proves that the scale of the epidemic peak is hypersensitive to the speed of the change in parameters: a faster decrease in β and a coordinated growth in γ are mathematically optimal to avoid saturation of the healthcare system.

6. Conclusion

This paper uses the SEIR framework to discuss the processes of COVID-19 transmission using a comparative case study between Wuhan and Italy. The results can be interpreted as indicating that epidemic dynamics are not only biologically predetermined but extremely vulnerable to the alteration of the most important model parameters conditioned by the interventions in the sphere of the population health. Specifically, the rate of transmission (β) and removal (γ) is decisive in determining the magnitude and the duration of an outbreak. The comparison shows that both early and intensive interventions can quickly decrease β and enhance γ, and hence decrease the basic reproduction number and successfully restrain the epidemic growth. This demonstrates the importance of the SEIR model as a mechanism based analytical tool in connecting theoretical parameters to actual policy actions.

Nonetheless, there are a number of limitations in this study. The interpretation of the analysis is mostly qualitative understanding of the SEIR framework instead of strict parameter estimation or empirical calibration with large-scale data. Consequently, the study offers robust explanatory data but might not be able to adequately represent the quantitative intricacy and heterogeneity of epidemic dynamics in reality. This study can be improved in future studies by adding more comprehensive empirical evidence, as well as using time-varying parameter estimation techniques to increase the accuracy of the model. Moreover, analyzing more than one country or region would enable a more formal cross-contextual comparison, which would also enhance the applicability of mechanism-based lessons to the policy of the health of the populace.

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Conflicts of Interest

The authors declare no conflict of interest.

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