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Time-dependent modified SEIR model development for investigating COVID-19 transmission pattern at Salt Lake County

Introduction

From several decades, there has been much of research about SEIR model to predict pattern of epidemic curve and the spread of pandemics over time (Gao et al. 1998; Liu and Makholm 1999; Brown et al. 2010; Biagini et al. 2020; Chen et al. 2020). However, the traditional SEIR model has two limitations: it cannot capture the latent contact or time spent in each compartment, and the reproduction number is not reflected complex reality only with several parameters such as infectious rate, latent time, and cure rate. Hence many researchers have tried to improve SEIR model by using matrix model to reflect individual’s time spent (Frisell 2020), dynamic network model to capture individual contacts (Shu et al. 2012; Panamalige et al. 2012; Lee et al. 2020), or time dependent parameters (Mangoni and Pontil 2020; Peng et al. 2020; Xiong and Yan 2020). Despite those efforts, however, SEIR model has two challenging issues due to the structural limitations.

1) Since the SEIR model has a bell-shaped curve of infected population that has one peak point, it would not represent curve shape in the real world that might have more than one peak. As shown in Fig. 1, to make this model useful in early stage since the outbreak of disease with lack of data, which cause under or overestimation of peak infected population point and period with pandemic.

2) Although the contact between individuals that emerges in spatiotemporal context, much research estimated contact rate based on socio-demographic data or dynamic network model excluding ‘spatiotemporal’ concept since it is extremely hard to reflect contact rate precisely in real world. The study has shown that the contact rate has been underestimated spatiotemporal contact rate, it still depends on assumptions or probability for estimating initial value of contact rate (Zhu et al. 2020; Hernandez-Flores et al. 2020; Mao and Bao 2020).

To address issues above, this research is to suggest prediction and surveillance strategy by dividing the period of pandemic into early, middle, and late stages. As a first step, we made modified SEIR model by employing time-dependent parameters to see the potential to make it fit the real infectious pattern. The stage-based approach and spatiotemporal contact pattern consideration will be dealt in future study.

Modified SEIR model

The yellow highlighted part is a generalized classical SEIR model (Hoffman 2020; Lubalho and Bong 2020; Mangoni and Pontil 2020; Tang et al. 2020) to replace the 1st (time) variables. The variables (\(S(t), E(t), I(t), R(t), F(t), D(t)\)) represent the population which are susceptible, exposed, infected, quarantined, recovered, dead, and no time-space at the time \(t\). For example, \(S(t)\) is the number of people who are at the exposed individual with probability if she/he contacts with an infected individual (Xiong and Yan 2020).

Each coefficient \(a(t), b(t), d(t), e(t)\) indicates the Protection Rate, average latent time, average quarantine time, cure rate, and mortality rate, separately (Peng et al. 2020). Widespread use of protective devices like face masks can cause protection to Mangoni and Pontil (2020) and decrease of \(a(t)\) and \(b(t)\). And short period of latent time can cause quick change to infectious phase (\(I(t)\) from exposed compartment (\(E(t)\)). Coefficients \(e(t), d(t)\) are the time-dependent parameters that can be acquired by actual data.

Each of (\(I(t), E(t), S(t)\)) means contact rate, protection rate, and quarantine rate which are considered in this research. Contact rate \(e(t)\) indicates the chance of actual contact in person over time.

In this study, we hypothesized all people are susceptible to virus thus we regard protection rate as 1 at a rate of population conducting self-protection such as wearing in their house, social distancing, and wearing mask. In June 20, Salt Lake county health department announced ‘public health order’ that urges people to comply social distancing and makes wearing mask mandatory. Based on Fig. 2, the number of patients began to decrease after 2 weeks later, since July 09 peaked at 409 infected case a day. Therefore, we could regard as time dependent variables \(e(t)\) along with phases of fast growth around June 20.

Li et al. (2020) suggested 14-day medical observation period or quarantine for exposed person. In this study, quarantine time \(d(t)\) regards a certain period from symptom appearance to recovery or death.

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\begin{align*}
\sum_{k=1}^{n} (\lambda_k - \rho_k d(t)) (\tau_k + \rho_k d(t))
\end{align*}
\]

\(1)\) and \(2)\) are the number of people who are in infectious phase and quarantine phase-separated time. As a result, the estimation minimum can be defined as quarantin time because all infected people must be recovered or death phase \(d(t)\) during quarantine time. In this study, we try to divide \(d(t)\) to 3 stages. To estimate cure and mortality rate, we used GAM model to fit real data (Fig. 4) and applied to SEIR. Linear regression model was conducted using the data from 150 to 191, when cure and mortality rate started to be multiplied.

As shown in Fig. 8, the infected pattern does not always appear as bell shape. It shows the need of time-dependent parameters of SEIR. Therefore, we modified traditional SEIR model by applying time-dependent parameters. If this time-dependent parameter based SEIR model is used for estimation of contagion disease in early stage for prediction, as well as for surveillance by changing parameters continuously with real-time data, we can make more feasible decision on going health policy.

The future study is to suggest prediction and surveillance strategy by dividing the period of pandemic into early, middle, and late stages. Each stage will have different scenarios and strategy to reduce infection rates, which helps in reducing under or overestimated peak of infected population and the period of pandemics. For constructing spatiotemporal contact pattern, clustering analyses will be used to find our suitable parameters that represent real contact rate. The methodology and the results of this research would give a more useful and easy way to cope with any kinds of pandemic we would be facing now, as well as Covid-19.

Fig. 2. Number of patients in Salt Lake County

Table 1. Coefficients

Table 2. Quarantine time equation result

Fig. 3. Cure and Mortality rate with GAM model

Fig. 4. Protection and contact rate scenarios (114 days)

Fig. 5. Top 5 scenarios that fit the real Covid-19 cases

Fig. 6. Covid-19 dashboard in Salt Lake County

Future Study

Unlike the traditional SEIR model, Fig. 8 is not a simple bell-shaped pattern but shows more similar pattern as Fig. 7 which is real infected population graphs in Salt Lake County. To sum up the whole situation, these results imply that we should consider the time-dependent parameters to build suitable SEIR model reflecting the real world.

Fig. 9 shows future work, to predict and conduct surveillance of contagion disease at an early, middle, and late stage of pandemic. Since there is a lack of data issue at the early stage, it would be essential to the SEIR model with spatiotemporal or time-dependent initial parameters including contact, quarantine, latent time, or cure probability. Also, judging from this fact that the infection rate started to decrease after the announcement of ‘public health order’ in Salt Lake county, it would be reasonable to predict infected population curve until first peak. Based on the scenario about government announcement ordering ‘social distancing’ and ‘wearing mask’. Because we cannot assume the data of vaccine development or whether it naturally decreases at the early stage, we need the strategy to let people fulfill self-protection after setting minimum possible measures through the scenario stated above.

In the middle stage, the study will focus on the surveillance as well as prediction of infected population curve. For that, we can monitor current contact rate in space thereby we would know which regions would be susceptible to the transmission. Also, the gap between contact rate and infected populations curve in SEIR model enables us to estimate self-protection rate consistently. Prediction will be conducted as a short-term period prediction (interval of latent time) and long-term prediction (by public holiday or lock down scenarios).

Lastly, in the late stage, we need to predict based or scenario of vaccine development a change in spatiotemporal contact rate, and self-protection rate. Through this, we can anticipate the minimum and maximum period to propose the strategy to reduce spread of pandemics.

The results of the research are expected in two ways:

1) Predicting SEIR curve (Exposed, Infected, recovered population, and etc.) and suggesting transmission reducing strategy at each early, middle and late stage based on reasonable scenarios.

2) Spatiotemporal surveillance strategy, in reducing the spread of Covid-19 in Salt Lake County, applying spatiotemporal change of contact rate to SEIR model in Fig. 4.

Fig. 7. Covid-19 dashboard in Salt Lake County

Fig. 8. Covid-19 epidemiological simulation of 2019 novel coronavirus disease (COVID-19) in Salt Lake County

Fig. 9. Future work of SEIR model

Fig. 10. Spatiotemporal contact cluster and the SEIR model result

Conclusion

Reference

As shown in Fig. 8, the infected pattern does not always appear as bell shape. It shows the need of time-dependent parameters of SEIR. Therefore, we modified traditional SEIR model by applying time-dependent parameters. If this time-dependent parameter based SEIR model is used for estimation of contagion disease in early stage for prediction, as well as for surveillance by changing parameters continuously with real-time data, we can make more feasible decision on going health policy.

The future study is to suggest prediction and surveillance strategy by dividing the period of pandemic into early, middle, and late stages. Each stage will have different scenarios and strategy to reduce infection rates, which helps in reducing under or overestimated peak of infected population and the period of pandemics. For constructing spatiotemporal contact pattern, clustering analyses will be used to find our suitable parameters that represent real contact rate. The methodology and the results of this research would give a more useful and easy way to cope with any kinds of pandemic we would be facing now, as well as Covid-19.

Fig. 11. Time-dependent modified SEIR model

Fig. 12. Future work of SEIR model