Pandemic Flu Simulation And The Impact Of Ultraviolet Light On Reproduction Ratio

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Abstract

Influenza and similar viruses represent a threat to populations across the globe. So, it is important to study the behavior of these viruses and the impact of mitigation strategies their spread. Compartmental and stochastic models have been used to show that mitigation strategies like vaccination, prophylaxis antiviral agents, and travel restrictions can have some impact on or fully contain the spread of influenza. But, since there are many potential mitigation strategies, some have received less attention, such as ultraviolet (UV) radiation treament of air and surfaces. We examined the number of days of UV treatment required to sucessfully contain pandemic influenza in the United States of America with an initial reproduction ratio of $R_0 = 1.8$. During a 100 day simulation, beginning once 5% of the overall population has been infected, we determined that approximately 30 days of UV treatment would reduce the reproduction ratio of influenza to $R_0 \approx 1$, meaning that the spread of the virus is no longer in an outbreak status.

Introduction

Understanding the spread of infectious diseases, like the flu, is critical for advising policy making with respect to public health and wellness. For example, studying the behavior of virus transmission and recovery rates allows health professionals and policymakes to define the quantity of antiviral agents that should be readily available, regions and demographics that should be prioritized for vaccination, and other strategies intended to prevent a pandemic. Furthermore, being able to communicate the results of an infectious disease model/simulation is very important, as this will facilitate the adoption of containment measures.

Many researchers studying the spread of infectious diseases explicitly cite the 1918 influenza outbreak as a motivating factor for their work (Berkessel et al. 2021; Germann et al. 2006; Johnson and Mueller 2002; Valle, Mniszewski, and Hyman 2012). In the case of Johnson and Mueller (2002) and Patterson and Pyle (1991), the objective was to look back through previous records and data to verify morbitity of the 1918 pandemic. The authors made the observation that each time the statistics are reviewed, the total deaths from the pandemic seem to increase. In the 1920s, the record was approximately 21.5 million deaths; in 1991, Patterson and Pyle (1991) updated the estimate to 24.7-39.3 million; most recently, Johnson and Mueller (2002) estimated the death toll is on the order of 50 million. However, Johnson and Mueller (2002) do not make this claim conclusively. Instead, they allow for future speculation of estimates because there were many places affected by the 1918 influenza outbreak for which we do not have any data or the means of estimating today.

Clearly, the capacity for large-scale damage from infectious disease outbreaks is a very real threat. Hence, understanding how these things spread and the impact that different mitigation strategies have on the rate of spread and severity of illness is critical.

Literature Review

Infectious disease epidemic models have been the subject of study since the 1980s. It was Russian scientists that first began to implement models for estimating spread patterns of influenza and other viruses (Longini, Fine, and Thacker 1986). Much of that work is relatively inaccessible due to the fact that it is written in Russian. Nonetheless, eventually the work made its way into academia across the globe.

Generally, there are two approaches for modeling pandemic flu: deterministic or stochastic models. Early models were deterministic, and they described the movement of viruses using differential equations, and partitioned populations into a number of subgroups. These are referred to as SIR (susceptible-infected-recovered), SEIR (susceptible-exposed-infected-recovered), and other derivatives.

Initial reactions to these determinsitic models by academics were skeptical for a few reasons. First, geographic regions being studied were relatively isolated, hence the ability to apply these models for global study was uncertain (Longini, Fine, and Thacker 1986). Furthermore, for the time, the models were computationally expensive. Longini, Fine, and Thacker (1986) noted that over 90% of time spent studying influenza and virus spread was dedicated to running the algorithms themselves. However, this is less of an issue today because high-performance computing is readily available.

While relatively old, these determinstic models still have utility. Valle, Mniszewski, and Hyman (2012) used an SIR model to show that an individual's behavior will likely change in response to an outbreak; some individuals will adopt new behavior to protect themselves, thereby influencing the probability of transmission per contact.

More recently, stochastic models have become prevelant because they are able to capture more complex spreading patterns. Colizza et al. (2007), Cooper et al. (2006), Ferguson et al. (2005), Germann et al. (2006), Samsuzzoha, Singh, and Lucy (2013), and Tan et al. (2021) all used some stochastic process to model the spread of influenza or other infectious diseases, and analyze different mitigation strategies. Colizza et al. (2007) found that a large-scale application of prophylaxis antiviral agents could successfully contain a pandemic H5N1 influenza given a viral reproduction ratio of 1.9 or lower. Cooper et al. (2006) found that significant air travel restrictions could delay the spread of influenza, but not contain an epidemic altogether. The findings of Germann et al. (2006) determined that rapid and preferential vaccination of children could contain an outbreak when the reproduction ratio of influenza is at or below 1.9.

Others have explored the relationship between geographic variables (e.g., altitude and solar radiation) and incidence rates for COVID-19, as well as severity of illness (Arias-Reyes et al. 2021; Stephens, Chernyavskiy, and Bruns 2021). Arias-Reyes et al. (2021) concluded that above 1000 meters above sea level, incidence rates and severity for COVID-19 decline. Through analysis of public geographic and COVID-19 data, Stephens, Chernyavskiy, and Bruns (2021) determined that for increases of 495 meters in elevation above LA county, and for areas of equivalent population density, infection rates were 12.82%, 12.01%, and 11.72%. However, mortality rates were not statistically significantly different between high and low elevation areas. Stephens, Chernyavskiy, and Bruns (2021) note that other environmental variables such as increased solar radiation, larger swings of high/low temperatures throughout the day, and long-term exposure to altitude hypoxia could explain these observed differences.

Since influenza and similar viruses spread via aerosols, Sagripanti and Lytle (2007) proposed solar radiation as a contributing factor to the seasonality of influenza. Specifically, the authors calculated the expected inactivation of influenza by UV radiation in several cities and different times of the year. They estimated that a full day of sunlight exposure will reduce influenza by 99% in regions at a similar latitude to Mexico City, and by 90% in regions at a similar latitude to Miami. Jensen (1964) found that aerosol influenza A, when exposed to 0.03 watt-minutes per square foot (i.e., approximately 19.41286 Joules per square meter) of UV light, had an inactivation of greater than 99.9% at a flow rate 100 cubic feet per minute, and approximately 99.86% inactivation at 200 cubic feet per minute.

Therefore, higher altitude and higher solar radiation could theoretically influence the spread of influenza. The purpose of this paper was to simulate pandemic flu spread and identify critical thresholds for some of these covariates in order to minimize the risk of a severe outbreak.

Modeling Theory

As previously mentioned, there are two very general approaches to simulating pandemic virus spread. Here, we present the SIR model (Débarre, n.d.; "An Introduction to Deterministic Infectious Disease Models," n.d.) because it is relatively simple, and establishes a foundation for considering other approaches.