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Renaissance model of an epidemic with quarantine

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HIGHLIGHTS

- ► A susceptible-infected-recovered (SIR) model with inclusion of quarantine.
- ► We examine an epidemic of syphilis in Europe during the 16th century.
- ► The carrying capacity of quarantine facility can be used to control the epidemic.
- ► False positives can present an impediment for success of quarantine strategies.
- ► Imbalance in the sex ratios can alter success of quarantine strategies.

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ABSTRACT

Quarantine is one possible solution to limit the propagation of an emerging infectious disease. Typically, infected individuals are removed from the population by avoiding physical contact with healthy individuals. A key factor for the success of a quarantine strategy is the carrying capacity of the facility. This is often a known parameter, while other parameters such as those defining the population structure are more difficult to assess. Here we develop a model where we explicitly introduce the carrying capacity of the quarantine facility into a susceptible–infected–recovered (SIR) framework. We show how the model can address the propagation and control of contact and sexually transmitted infections. We illustrate this by a case study of the city of Zurich during the 16th century, when it had to face an epidemic of syphilis. After Swiss mercenaries came back from a war in Naples in 1495, the authorities of the city addressed subsequent epidemics by, among others, placing infected members of the population in quarantine. Our results suggest that a modestly sized quarantine facility can successfully prevent or reduce an epidemic. However, false detection can present a real impediment for this solution. Indiscriminate quarantine of individuals can lead to the overfilling of the facility, and prevent the intake of infected individuals. This results in the failure of the quarantine policy. Hence, improving the rate of true over false detection becomes the key factor for quarantine strategies. Moreover, in the case of sexually transmitted infections, asymmetries in the male to female ratio, and the force of infection pertaining to each sex and class of sexual encounter can alter the effectiveness of quarantine measures. For example, a heterosexually transmitted disease that mainly affects one sex is harder to control in a population with more individuals of the opposite sex. Hence an imbalance in the sex ratios as seen in situations such as mining colonies, or populations at war, can present impediments for the success of quarantine policies.

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1. Introduction

Although syphilis can be effectively treated with the use of antibiotics since the 1940s, the disease still remains a public health problem worldwide (Hook and Peeling, 2004; Hvistendahl, 2012). For instance, the social and economic changes that took place in China in the 1980s were followed by an increase of syphilis cases of about 30% per year by the late 1990s (Hvistendahl, 2012). The rate of infections in Europe have also risen in the last decade (Robert Koch-Institut, 2010). In the 16th century, the city of Zurich faced an epidemic of syphilis (Gall et al., 2012). It started when Swiss mercenaries, several among them ill with syphilis, came back from a war in Naples in 1495. At first, the city council tried to contain the epidemic by preventing outside access to the city, and by advising sick people to stay at home and avoid public places like churches or markets. Moreover, sex workers were sent away from the city. Later, those who were diagnosed with syphilis, or with similar symptoms, were brought

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by order of the authorities into a specialized facility. The facility was run by nuns and called the *Blatternhaus*: a word derived from the German *Böse Blattern* (evil pox), which was the description for syphilis at the time. Individuals placed in the *Blatternhaus* were benefiting from special treatments developed for curing people diagnosed with syphilis, or syphilis-like symptoms. Besides the medication itself, the treatment included regular meals with meat and beverage, shelter against the weather, and regular examinations by doctors.

Quarantine strategies have been investigated in the past, as isolation remains a potentially effective means to prevent epidemics (Day et al., 2006; Feng and Thieme, 1995; Hethcote et al., 2002; Hyman and Li, 1998; Sattenspiel and Herring, 2003; Fraser et al., 2004). For instance, in a study based on the phenomenon of recurrent outbreaks of childhood diseases (Feng and Thieme, 1995), the authors have shown how isolation can make the endemic equilibrium less stable and lead to oscillations (see also Hethcote et al., 2002). However, when the size of a population is larger than its census size, which is the case of cities with many visitors, it has been proposed that quarantine can increase the transmission of the disease by holding infected individuals in that city (Sattenspiel and Herring, 2003).

Previous studies have not explored the effectiveness of quarantine strategies in relation to the carrying capacity of the facility. Here we cover this aspect by showing how the effectiveness of quarantine may depend on this factor. We also wish to understand the potential effectiveness of the decision by the authorities in Zurich to quarantine infected individuals inside the *Blatternhaus*. The answer to these questions can shape future quarantine policies.

In order to quantitatively evaluate the efficiency of quarantine, we developed a model that incorporates the *Blatternhaus* as quarantine facility, and where the rate at which individuals are quarantined is proportional to the amount of spare room inside the quarantine facility. We used the classical SIR approach (Kermack and McKendrick, 1927) and extended it with two new states that correspond to individuals isolated from the population. One state or compartment contains susceptible individuals and the second state, infected ones. We ask whether our model supports the decision of the city council towards reducing or stopping the epidemic.

For our analysis of Zurich during the 16th century, we estimated the size of the population to be 4000 individuals. Based on the 17th century sketches of the buildings, we also estimated the upper bound of the carrying capacity of the *Blatternhaus* as 100 individuals. Syphilis is caused by both venereal and non-venereal contacts. Instead of starting directly with a sexually transmitted disease (STD), we first considered a contact disease (CD) model. By doing so, we were interested to assess the question whether the same legislation can be efficiently implemented in the case of a CD. The STD model appears then as a direct extension of the CD model by taking genders into account. We show that in both the CD and STD models, the presence of a quarantine facility in the form of the *Blatternhaus* can efficiently reduce or even stop the epidemic, but the effectiveness of quarantine is dependent on the carrying capacity of the *Blatternhaus*, the force of infection, the removal rate, and the effective quarantine rates. We show that without having sophisticated treatment methods nor a complete knowledge of the etiology of the disease, the authorities of the city of Zurich were in the position to find effective measures to reduce the epidemic.

2. Contact disease with quarantine

2.1. Description of the model

One of the earliest epidemic models is that of Kermack and McKendrick (1927). The model in its simplest form assumes the existence of three individual states that are translated into a compartmental approach: susceptible (S), infected (I) and recovered or removed (R). Susceptible and infected individuals are in contact within a homogeneous population. The force of infection is the rate at which susceptible individuals become infected. In our case, the force of infection is a combination of the probability of encounter per capita between susceptible and infected individuals, and the probability to transmit the infection. The rate of recovery defines the time after which the person is not infectious anymore. The SIR approach is characterized by two key parameters: ρ, sometimes called the *relative removal rate*, and R_0, the *basic reproduction rate* (Murray, 1993; Diekmann et al., 1990; Hyman and Li, 2000). The value R_0, which is also the reciprocal of the relative removal rate ρ, indicates the number of secondary infections produced by one primary infection in an entire population of susceptible individuals. Given a per capita force of infection k_1 and a recovery rate k_2, meaning that the infectious period is $1/k_2$, then $R_0 = k_1 S_0/k_2$, where S_0 is the entire population of susceptible individuals at the time $t=0$: the moment when a single infected individual is introduced. If $R_0 > 1$ an epidemic will ensue, while if $R_0 \leq 1$ the disease will die out and no epidemic will occur since on average every infected person will at most replace itself (Keeling and Rohani, 2008; Anderson and May, 1979; Hethcote, 2000).

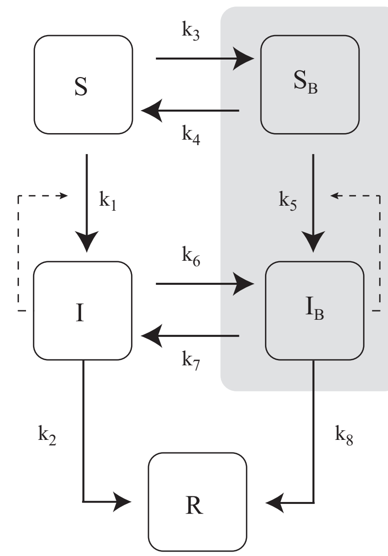

Fig. 1. Flow diagram of the SIR-based contact model showing the two classes of individuals in quarantine: S_B and I_B. The parameters k_3 and k_6 in the model are the rates at which individuals are quarantined. The model assumes that the effective rates of quarantine depend on the carrying capacity C of the *Blatternhaus*, which is proportional to $C-S_B-I_B$. At the same time, individuals can be excluded from the quarantine facility, and sent back at a given rate (which is here k_4 and k_7) into the population without recovery, independently from the effective rates of quarantine. For k_3, k_4, k_5, k_6 and k_7 equal to zero, the model reverts to a basic SIR approach.

Here, the CD model is extended by adding two quarantine states to the standard SIR approach: susceptible (S_B) and infected (I_B) individuals. The subscript B stands for *Blatternhaus*. Fig. 1 shows the flow diagram of our CD model with all the five states: S, S_B, I, I_B, and R. The relative rates and their direction are indicated by arrows. The dashed-line arrows display the potential interaction between susceptible and infected individuals. For S_B and I_B, we take into account the possibility to have a reverse rate for individuals excluded from the quarantine facility.

Only primary and secondary syphilis are considered contagious (http://www.cdc.gov/std/syphilis/stdfact-syphilis.htm,http://www.merckmanuals.com/professional/index.html). Transmission is usually by sexual contact, but it may occur by skin contact as

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