Estimation of Epidemiological Parameters for Historical Ship Outbreaks of Influenza

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Periodic Influenza epidemics are a cause of concern world-wide due to heavy burden of disease consequently leading to economic distress mortality. In modern era, rapid international travel between populations makes the impact of air-borne diseases like Influenza more dramatic, as observed in the last pandemic due to Swine origin Influenza A/H1N1 2009. Though transmission of Influenza in humans has been studied in various settings, studies on ship outbreaks are sparse. The current research aims to analyze the historical Influenza outbreaks on sailing ships. Study revealed the pattern of transmission in isolated population and estimates the epidemiological parameters viz. basic reproduction number ($R_0$), epidemic growth rate ($r$), transmission rate ($\beta$). High clustering lead to intense transmission with high value of basic reproductive number, $R_0$. Also, the study brought to light the limitations of analyzing historical data.

INTRODUCTION

Influenza, caused by Influenza viruses, have resulted in several pandemics over the last 100 years causing millions of deaths across the globe with the recent being due to the swine-origin Influenza A H1N1 in 2009. The “Spanish” influenza pandemic of 1918–1919 caused a mortality of approximately 50 million people. Further, Asian influenza epidemics reported in India during 1957 caused a death of 1098 out of 4.5 million cases (Jhung et al., 2011; Menon, 1959; Ortiz et al., 2012; Taubenberger and Morens, 2006). The most devastating Influenza pandemic was the Spanish flu of 1918–19, which occurred during the First world-war and movement of troops across continents played a vital role in the spread (Crosby, 2003; Johnson and Mueller, 2002; Jordan, 1927; Taubenberger, 2006). The focal point of the epidemic in terms of mortality was India, with an estimated death toll range of 10–20 million (Chandra and Kassens-
The modern age of global mobilization with rapid international transportation between populations makes the impact of air-borne diseases like Influenza even more dramatic. This was recognized in 2003 with the spread of Severe Acute Respiratory Syndrome (SARS), as the first major epidemic threat of the 21st century (Gumel et al., 2004), followed by pandemic due to swine-origin influenza A virus H1N1 in 2009 (Chan, 2009; Wessel et al., 2011), recent Ebola epidemics in African countries (2014–15) (Krauer et al., 2016) and the on-going Zika epidemics in the Americas (Mourya et al., 2016).

The pandemic caused by the novel Influenza A/H1N1 2009 and the recent Ebola epidemics have resulted in a renewed interest in mathematical modelling of (Chowell and Nishiura, 2014; Fraser et al., 2009; Lewnard et al., 2014). Considerable efforts have been made in understanding the transmission of viral diseases using mathematical modelling studies. Such analyses not only helps in understanding the dynamics of disease propagation in population, but also helps in estimating epidemiological parameters which cannot be determined by means of experimentation. Mathematical modelling can contribute in evaluating the effectiveness of control measures and effects of vaccinations (Shil, 2016). Modelling studies have been applied widely to describe the transmission of Influenza in human population in various settings including remote isolated villages, residential school populations, etc. (Boelle et al., 2009; Shil et al., 2011; Smith et al., 2009). However, there are hardly any mathematical epidemiology based analyses available about influenza outbreaks in isolated closed population such as on sailing ships or island fortresses.

Seafaring nations like India, operate large numbers of merchant ships as well as maintain strong naval forces with variety of warships, aircraft-carriers and submarines. Hence, outbreak of airborne viral diseases like Influenza, SARS, etc on-board sailing ships puts crew, troops and/or passengers at great risk. This necessitates studies to understand the transmission of such diseases on-board sailing ships. Hence, here we present epidemiological analyses of Influenza outbreaks on sailing ships based on available historical data.
Epidemiology of historical ship outbreaks of influenza

METHODS
Source of Data
Data for Influenza were obtained from Fluweb Historical Influenza Database (http://influenza.sph.unimelb.edu.au) hosted by the School of Population Health, University of Melbourne, Australia. It provides free access to a number of rare and valuable sources of data concerning past influenza outbreaks made available for researchers in medicine, population science and history (Mueller et al., 2012).

Estimation of Epidemics Growth Rate ($r$), Basic Reproduction Number ($R_0$) and Transmission Rate ($\beta$):
The growth rate of an epidemic ($r$) was calculated from the estimates of cumulative number of confirmed infections ($y$), the estimated start date and size of the outbreak ($t_0$ and $y_0$), and using the
\[
y = y_0 e^{r(t-t_0)}\]
..............................eqn. 1
Curve fitting of cumulative confirmed cases vs. time for recorded data was performed to determine $r$.

The basic reproduction number ($R_0$) is defined as the number of secondary cases generated by one infective person introduced into a totally susceptible population during the course of his/her infection. This was determined using the equation:
\[
R_0 = \frac{1+r}{1+r} \frac{1+r}{1+r} \tag{eqn. 2}
\]
with the mean infective period $1/\alpha$ and mean incubation period $1/\kappa$ (Shil, 2016; Shil et al., 2011). The $r$ was estimated from analyses of available data.

The transmission rate ($\beta$) was obtained from $R_0$ as: $\beta = a R_0/N$ .................eqn. 3
where, $N$ is the total population, and $1/\alpha = 1.5$ days is the incubation period for Influenza (Smith et al., 2009).

The doubling time for the outbreak (the time during which the outbreak size doubles) was estimated as $t_e = ln \left(\frac{2}{r}\right)$, where $r$ is the growth rate of the epidemic (Eqn. 1).

An excellent marker for transmission intensity for any disease is the force of Infection (FOI) (Marmara et al., 2014; Mueller et al., 2012). The Force of infection ($\lambda$) is defined as the per capita rate of acquisition of infection and was calculated as $\lambda = \beta I(t)$, where $\beta$ is per capita transmission rate and $I(t)$ represents the actual infectives at time $t$. Greater the force of infection, faster the spread of the disease through population.

Terminologies
By ‘Incidences’ we mean the number of confirmed cases reporting on a particular day. By actual ‘infectives’, $I(t)$ we mean...
the actual number of confirmed cases having symptoms at that point of time, \( t \). This is determined by considering each confirmed case to be infectious for 4 days.

It is assumed that the average duration of the infectious state is 4.0 days and the average incubation period (i.e., time period between acquiring the virus and onset of symptoms) is 1.5 days as standard for Influenza in humans (Shil et al., 2011).

**Study Design**

The purpose of the study is to estimate relevant epidemiological parameters for historical outbreaks of Influenza. Historical outbreaks data was downloaded from various sources and analysed. Two ship outbreaks data were considered based on details available. Incomplete data from other ships or defense installations were not considered.

Based on mathematical analyses, epidemiological parameters like growth rate, epidemic doubling time, Basic Reproduction number, etc. were determined. Plotting of graphs and mathematical calculations were performed in MATLAB\textsuperscript{®} analyses package and MS Excel.

**RESULTS**

**Case Study I: Outbreak of Influenza A (H3N2) On-board USS Arkansas in 1996**

**Outbreak descriptions**

The ship named USS Arkansas, was a nuclear powered, guided missile cruiser with a complement of 551 people onboard. An outbreak of influenza A (H3N2) occurred aboard this ship in February 1996, despite 95% of the crew’s having been appropriately vaccinated. Virus isolated from affected crew members was antigenically distinct from the vaccination strain. Outbreak occurred sometime after the Ship left the port and was sailing on high sea.

A total of 551 out of which 548 Navy crew members and 3 civilians were onboard between 1\textsuperscript{st} and 23\textsuperscript{rd} February 1996. A total of 232 USS Arkansas crew members were identified with an influenza-like illness during the outbreak (attack rate = 42%); 158 cases were identified by the medical department, 74 patients did not seek medical treatment but met the case definition criteria and were designated as ‘infectives’. An additional 63 crew members were (11%) reported having some influenza-like symptoms but did not meet the definite
case criteria. It should be noted that case definitions for Influenza in humans are provided by WHO guidelines and updated periodically.

**Estimation of epidemiological parameters**

Figure 1 shows the daily incidences that is the number of cases per day along with the estimated values of cumulative cases and actual infectives, $I(t)$ per day. With an attack rate of 42%, this outbreak demonstrates the potential for rapid spread of influenza in a confined population and the impact subsequent illness may have upon the workplace.

Based on the growth of cumulative confirmed cases for the first 7 days (Figure 2), the intrinsic exponential growth rate ($r$) was determined and the value was found to be 0.652 per day. Assuming the mean incubation period for Influenza as 1.5 days and mean infectious period (duration of symptomatic and infectious state) as 4.0 days, the basic reproduction number, $R_0$ was estimated to be 6.88. The transmission rate ($\beta$) was estimated as $3.12 \times 10^{-3}$ per day. The doubling time of the epidemic was found to be 1.12 days. The high value of $R_0$ indicated very intense and rapid transmission in the isolated population. Figure 3 shows the force of infection during the course of

**Figure 1:** Plot for Number of cases per day, actual infectives, $I(t)$, and daily cumulative confirmed cases daily vs Days, respectively for USS Arkansas.
outbreak. The force of infection increases rapidly and attains peak on 8th day of the outbreak, followed by a decrease.

Case Study 2: Influenza A H1N1

Outbreak on Boonah Ship, November 1919

Outbreak description
This vessel left Durban on 24th November 1919 with 164 crew and 931 troops, total of 1095. Initially few mild cases occurred, but the epidemic was first definitely recognized on 29th November, from which date the record begins. The course of epidemic was till the time of arrival at Fremantle. The total epidemic period was for 36 days only.

The epidemic lasted altogether from 29th November to 7th January, attacking a total of 435 cases out of a ship's company of 1095 (attack rate of 39%). The ship was assumed to be isolated vessel as no

Figure 2: Growth of the cumulative confirmed cases during the initial 7 days onboard USS Arkansas. The exponential growth rate $r = 0.652$ per day was obtained.

Figure 3: Force of infection (FOI) for the entire length of the outbreak of Influenza A/ H3N2 on USS Arkansas in February 1996.
other intruders and/or extruders were considered during this epidemic period. Figure 4 describes the daily incidences (confirmed cases), number of cumulative cases and actual infective per day.

**Estimation of epidemiological parameters:**

Based on the growth of cumulative confirmed cases for the first 6 days (Figure 5), the intrinsic exponential growth rate \( r \) was calculated and the value was found to be \( 0.745 \) per day. Assuming the mean incubation period as 1.5 days and mean infectious period (duration of symptomatic and infectious state) as 4 days, the basic reproduction number, \( R_0 \) was estimated to be 6.3. The transmission rate \( (\beta) \) was estimated as \( 1.42 \times 10^{-3} \), and the doubling time of the epidemic was found to be \( 0.98 \approx 1 \) day.

The force of infection (FOI) (Figure 6) was found to increase sharply with time for the initial 8 days and decrease thereafter. High value of \( R_0 \) accounts for the intense transmission especially in isolated clustered population on the ship.

**DISCUSSION**

In the present study, an epidemiological analysis has been performed on influenza outbreaks on board sailing ships. Based
on available historical records, two case studies were carried out.

The First case study on an outbreak of Influenza A/H3N2 in 1996 on-board USS Arkansas revealed a sharp increase in the incidences for the first six days. The highest number of confirmed cases was reported on 6th day. The number of actual infectives, $I(t)$ reached peak value $(i.e. 101)$ on 8th day (Figure 1) and then decreased. High value of $R_0$ indicated intense and rapid transmission in the clustered population. The overall attack rate was 28%. Major portion of the population was unaffected probably due to effects of control measures and modern age health care practices. It is known that the population was vaccinated but it is worth noting the outbreak was caused by a different strain of influenza A (H3N2). However, the available report does not emphasize on

Figure 5: Growth of the cumulative confirmed cases during the initial 6 days onboard Boonah Ship. The exponential growth rate $r = 0.745$ per day was obtained by curve fitting.

Figure 6: Force of infection for the entire length of the epidemic onboard Boonah Ship.
The study on Spanish flu outbreak on-board a ship named Boonah in 1919 revealed rapid increase in the number of cases during initial 7 days. The highest number of incidences (confirmed cases) was reported on 7th day. The number of actual infectives, \( I(t) \) that is the number of patients in infectious state at any time \( t \), reached peak value (\( i.e. 175 \)) on 8th day (Figure 4) and then decreased. The high value of \( R_0 = 6.3 \) indicated very intense transmission in the population. However, after the initial growth phase of 7 days, the number of cases per day decreased but outbreak continued till 36th day and the overall attack rate was only 39%. With the initial high value of \( R_0 \) and force of infection, we expected more number of people to be affected considering an isolated susceptible population with clustering. That a large section of the passengers on-board were left unaffected may be attributed to all or some of the following reasons: a) many individuals were asymptomatic and developed immunity without displaying any symptoms; b) there may have been some control measures and behavioural restrictions on the population aimed at reduced clustering and avoiding /reducing contacts with the infectives; and c) a substantial section of the population had immunity due to previous exposure (much before boarding); or d) possible discrepancy in clinical records as many individuals with mild symptoms may not have sought medical treatment and were thus not registered. The existing data does not reveal any of these details.

Correct estimation of epidemiological parameters of any disease depends on the nature of data and designing of a model that best describes the outbreak scenario. However, the major limitation with older records for ship outbreaks is the quality of data (both reliability and completeness). For the 1919 ship outbreak, sero-survey data is not expected as the technology did not exist. Hence, records cannot account for the number of asymptomatic individuals. There is no confirmation that all symptomatic individuals sought medical treatment. Thus, those with mild symptoms may have been left out from the records. This holds true for modern day ships as well. Ward et al., (2010) found that despite enhanced community awareness of the emerging pandemic (in 2010) due to Influenza A/H1N1 2009, a ship’s medical staff underestimated the case count by 13-fold. The number of
also revealed that an isolated population with high clustering results in an intense transmission of Influenza. Disease propagates rapidly with high value of Basic reproductive number until checked by interventions. However, the limitations of available data made it impossible to conduct a transmission dynamics modeling and evaluate the effects of interventions. Such studies can be taken up in future outbreaks. It is also suggested that for sea-faring nations maintaining large shipping business and navy, there is a need for guidelines for effective data collections, management and control of such outbreaks.

CONCLUSIONS
In the present study we have analyzed historical Influenza outbreaks on sailing ships and successfully demonstrated a method of estimating epidemiological parameters using principles of mathematical epidemiology. Our study also revealed that an isolated population with high clustering results in an intense transmission of Influenza. Disease propagates rapidly with high value of Basic reproductive number until checked by interventions. However, the limitations of available data made it impossible to conduct a transmission dynamics modeling and evaluate the effects of interventions. Such studies can be taken up in future outbreaks. It is also suggested that for sea-faring nations maintaining large shipping business and navy, there is a need for guidelines for effective data collections, management and control of such outbreaks.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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