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Application of control strategies to a seasonal model of chikungunya disease

Xinzhi Liu *, Peter Stechlinski

Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

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ABSTRACT

This paper analyzes a new model of the vector-borne disease chikungunya by considering time-varying parameters and impulsive control. In particular, the birth rate of the mosquito population varies between rainy season and dry season, and the contact rate between mosquito and human changes in time. Mechanical control of breeding sites and reduced contact rate strategies are studied. Motivated by a potential commercial vaccine in the future, pulse vaccination with vaccine failure is considered. Sufficient conditions are established which guarantee disease eradication or persistence of the disease in the endemic case.

1. Introduction

The chikungunya virus is an arthropod-borne viral disease (arbovirus), transmitted primarily by mosquitoes of the Aedes genus: *Aedes aegypti* and *Aedes albopictus* [1,2]. A chikungunya infection is an acute illness generally described by the sudden onset of fever and incapacitating arthralgia (which distinguishes chikungunya from dengue), often accompanied by headache, rash, and myalgia. Less frequent symptoms include nausea, vomiting, and hemorrhagic symptoms [1,3]. The first isolated cases of chikungunya virus occurred in Tanzania in 1953. Since then there have been reported cases of the virus in rural areas of tropical Africa and urban areas of Asia [3]. In the past decade, a series of outbreaks have occurred over a geographic area including African islands in the Indian Ocean and the Indian subcontinent: the first outbreak occurred in Kenya in 2004, followed by outbreaks on the Comoros Islands in early 2005, and by a large outbreak in India in 2005–06 where the World Health Organization reported an estimated 1.3 million cases [1,3–5].

Réunion is a French island located in the Indian Ocean, east of Madagascar. A confirmed case of chikungunya virus was reported in Réunion on April 29, 2005, imported from Grande-Comore. This led to an outbreak of chikungunya virus in Réunion in 2005 and 2006, which consisted of two epidemic waves. The first wave occurred in May 2005 with 450 reported cases. The second wave began in December 2005 with an exponential growth in the number of weekly cases, peaking in January and February 2006 with more than 47,000 estimated cases [3]. In total, there were 244,000 estimated cases during the outbreak [3,6], approximately one third of the island population [7]. The main focus of this report is studying the outbreak in Réunion.

* Corresponding author. Tel.: +1 519 8884567; fax: +1 519 746 4319.
E-mail addresses: xzliu@uwaterloo.ca (X. Liu), pstechli@uwaterloo.ca (P. Stechlinski).

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The spread of chikungunya is influenced by a number of factors, including the behavior of the human population and mosquito population, as well as the environment in which it spreads [6]. Seasonal fluctuations in the environment play an important role in the spread of vector-borne diseases. For example, the transmission of dengue disease (transmitted by *Aedes aegypti*) is high when the temperature is high, during wet and humid periods, and the transmission is low when the temperature is low [3,8]. In Réunion, the 2005 outbreak appeared between March and June, which is the beginning of the winter season and end of the hot season (when the mosquito population is at a maximum) [9]. Another factor that played an important role in the spread of chikungunya in Réunion is that two strains of the virus were isolated during the outbreaks: the first strain (05.115) was isolated in May 2005 during the first outbreak. The second strain (06.21), isolated in November 2005, had a higher rate of transmission from human to mosquito. It was shown that the probability of a mosquito contracting the infection by biting an infected human increased from 37% for the first strain to 95% for the second strain [7].

Currently the main methods for preventing chikungunya outbreaks involve the control of the mosquito population or the interruption of contact between humans and vectors (such as individual protection against mosquito bites) [2]. Measures to control the *Aedes albopictus* vector population were used in Réunion when the DRASS (an agency of the French government for disease prevention and vector control) conducted several interventions [7]: localized treatment of a chemical larvicide Bti (Bacillus thuringiensis israelensis); massive spraying of Deltamethrin (a chemical adulticide); and the mechanical destruction of breeding sites by eliminating standing water in rain gutters, buckets, plastic covers, tires, tree holes, or any other potential breeding site for mosquitoes. Dumont and Chiroleu noted in [7] that larvicide treatments do not have a relatively large impact on a chikungunya epidemic, compared to adulticide. The authors gave a potential explanation that this may be due to the fact that only breeding sites are treated with the larvicide, which can be very localized. On the other hand, the use of adulticides, such as Deltamethrin and Fenitrothion, can cause harm to the environment [2,3,7], and, in some areas, Aedes have rapidly developed resistances to the chemical Deltamethrin in up to 60% of the population [2]. Mechanical control requires the cooperation of the local population but is relatively cheap, sustainable, and can be effective depending on the duration and time of application [7]. Recently, a new technique called sterile insect technique (SIT) has been proposed and studied where sterile male insects are periodically released into the wild to control the vector population [10,11].

One strategy not listed above is pulse vaccination, which involves applying a vaccination to a fraction of the susceptible population in a relatively short time period (with respect to the time scale of the disease spread). Real world examples of a successful pulse vaccination strategy include preventing rabies and hepatitis B [12], controlling poliomyelitis and measles in Central and South America [13], and achieving a mean coverage of 92% for measles and rubella in children aged five to 16 in the UK [13]. The most prominent example is the World Health Organization's initiative against smallpox beginning in 1967, when there were approximately 15 million cases per year, which eventually led to worldwide eradication by 1977 [14]. First analyzed mathematically by Shulgin et al. in [15], this strategy has been studied in the literature for numerous epidemic models of different diseases (for example, see [12,13,16–23]).

There are some candidate vaccines for chikungunya disease that have been tested in human beings and appear to be safe, but there is currently no commercially available vaccine [1]. Beginning with trials conducted by the US Army Medical Research Institute, neutralizing antibody titres were obtained that persisted in 85% of cases after one year, and satisfactory seroconversion rates of 95% on day 28 were obtained [24]. However, due to the emergence of potential terrorist biological weapons threats in 2003, the French National Institute of Health and Medical Research assumed control of the trials, with plans for a phase III trial of the candidate vaccine [1]. Recently there has been increased interest in the development of a vaccine. For example, there are several vaccine candidates in the preclinical and clinical stages of development (see Table 1 in [25]). However, it should be stressed that no commercial vaccine is currently available.

Since it is possible for chikungunya virus to re-emerge after years or even decades of absence [3], and motivated by the outbreaks in the last decade, there has been an increased interest recently in studying chikungunya. In [9], Dumont et al. were the first to analyze a model based on the chikungunya outbreak in Réunion. The authors computed the basic reproduction number of the disease, proved a necessary condition for eradication of the disease, and presented a stable numerical scheme with several simulations of the outbreak in different cities on the island. Dumont and Chiroleu [7] were the first authors to consider vector control for the outbreak in Réunion by analyzing and comparing the use of larvicide, adulticide, and mechanical control. Dumont and Tchuenche [10] analyzed the use of sterile insects to help prevent the spread of chikungunya disease by controlling the vector population. More recently, Dufourd and Dumont [11] investigated the effects of periodic parameters on the temporal and spatio-temporal evolution of a vector population under the sterile insect technique. In [6], Moulay et al. studied a chikungunya model for the outbreak in Réunion with an embryonic, larvae, and adult stage for the vector population and susceptible, infected, and recovered compartments for the human population. These authors proved stability using Lyapunov functions and the theory of competitive systems. Moulay et al. [2] studied optimal control of the chikungunya disease by considering reducing the number of vector-host contacts, treatment of individuals (such as by isolating infected patients in hospitals), and vector control (using larvicide, larvivore fish, and water traps). The authors Bowong et al. [26] investigated a multi-city model for chikungunya-like diseases with humans travelling between the cities.

In [27], Bacaër studied a periodic model of chikungunya disease to model the Réunion outbreak of 2005–2006. In particular, Bacaër developed numerical methods to approximate the basic reproduction number of vector-borne diseases with periodic vector population. As noted by Bacaër, many chikungunya models in the literature make the inappropriate assumption that the vector population is constant in time, but seasonality plays an important role in the spread of the disease [27]. From