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Dynamics of a two-strain vaccination model for polio

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ABSTRACT

A new deterministic model for the transmission dynamics of two strains of polio, the vaccine-derived polio virus (VDPV) and the wild polio virus (WPV), in a population is designed and rigorously analysed. It is shown that Oral Polio Vaccine (OPV) reversion (leading to increased incidences of WPV and VDPV strains), together with the combined effect of vaccinating a fraction of the unvaccinated susceptible and missed susceptible children, could induce the phenomenon of backward bifurcation when the associated reproduction number of the model is less than unity. Furthermore, the model undergoes competitive exclusion, where the strain with the higher reproduction number (greater than unity) drives the other (with reproduction number less than unity) to extinction. In the absence of OPV reversions (leading to the co-existence of both strains in the population), it is shown that the disease-free equilibrium of the model is globally-asymptotically stable whenever the associated reproduction number is less than unity. Numerical simulations of the model suggest that the model undergoes the phenomenon of competitive exclusion, where the strain with the higher reproduction number (greater than unity) drives the other to extinction. Furthermore, co-existence of the two strains is feasible if their respective reproduction number are equal or approximately equal (and greater than unity).

1. Introduction

Polio, a highly-infectious viral disease caused by poliovirus [1,2], continues to exude significant public health burden in affected areas [3–5]. Although numerous concerted efforts to eradicate polio, such as the Global Polio Eradication Initiative (GPEI) supported by national governments and several international organizations like Rotary International, UNICEF and foundations like the Bill and Melinda Gates Foundation [5], have led to a dramatic decrease in polio cases globally (for instance, a 99% reduction in polio

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cases is achieved in 125 polio-endemic countries from 1988 to 2012 [6,5]; with only 223 cases remaining in 2012), polio eradication has not yet been achieved. In fact, polio remains endemic in at least three countries (Afghanistan, Nigeria and Pakistan) [5].

It is expected that until poliovirus transmission is effectively controlled (or eliminated) in the aforementioned polio-endemic countries, all remaining countries, especially those in West Africa to the Horn of Africa, remain at risk of re-emergence of polio [3]. Recently, the World Health Organization (WHO) reported that from January to April 2014 (months usually considered low-transmission season for polio), the virus has been exported to three countries in three major epidemiological zones, namely: Central Asia (from Pakistan to Afghanistan), in the Middle East (Syria to Iraq) and in Central Africa (Cameroon to Equatorial Guinea) [7]. Furthermore, Pakistan, Cameroon and Syria are countries exporting the wild poliovirus in 2014 while Afghanistan, Equatorial Guinea, Ethiopia, Iraq, Israel, Somalia and Nigeria are countries having wild poliovirus but have not transmitted it to another country in the low-transmission season in 2014 [7]. The recent report in [7] provides a clear signal that polio has re-emerged as a public health emergency with the virus affecting 10 countries worldwide [8]. For example, Pakistan has seen a rise in polio cases, with immunization campaigns often disrupted by Taliban militants [8]. The Pakistani government has recently announced a mandatory anti-polio immunization program at airports and border crossings to help stop its polio outbreak from spreading (as well as mandating residents into getting a dose of the polio vaccine) [8].

Polio invades the nervous system, and can cause a lifelong paralysis [5]. The virus lives in an infected person's throat and intestines [5]. It spreads through contact with the faeces (stool) of an infected person and through droplets from a sneeze or cough [5]. An infected person may spread the virus to others immediately before, and usually 1 to 2 weeks after, developing symptoms [9,5]. The virus can contaminate food and water [1,5]. Although most polio-infected people do not show any symptoms, some show recognizable symptoms, such as: fever, fatigue, headache and vomiting [2,5]. Furthermore, polio can affect an individual at any age (but it mainly affects children under five years of age [5]). Furthermore, 1 in 200 infections leads to irreversible paralysis [6,5]. About 5% to 10% of children who have paralysis from polio die (because the virus affects the muscles that help them breathe) [5].

Unfortunately, there is no cure for polio [10]. Hence, control efforts are preventive in nature. In particular, polio vaccines (given multiple times as part of a routine mass vaccination) can protect a child for life [5].

There are 3 serotypes of the virus, namely: Wild poliovirus type 1 (WPV1), Wild poliovirus type 3 (WPV3) and the circulating vaccine-derived poliovirus type 2 (cVDPV2). Type 1 is the commonest and most virulent while type 2 has not been detected globally since 1999 [10]. Two vaccines provide protection from polio: live oral poliovirus vaccine (OPV) and inactivated poliovirus vaccine (IPV) [10,11,5]. OPV is the vaccine of choice for global polio eradication because, amongst other reasons, it is cheap and easy to administer [3]. However, in some cases, the OPV can lead to the emergence of vaccine-derived polio viruses (VDPVs), notably the circulating-VDPVs (i.e., cVDPV2), and vaccine associated paralytic polio in populations with large number of susceptible children [3]. This is because the OPV contains a live, attenuated vaccine-virus (consisting of a mixture of live attenuated poliovirus strains of each of the three serotypes [5]). However, on rare occasion, if a population is seriously under-immunized, there are enough susceptible children for the excreted vaccine-derived polioviruses (from vaccinated children) to begin circulating in the community. Hence, the viruses are called circulating vaccine derived polioviruses (cVDPV) [3,10,11,5]. The longer the excreted vaccine-virus (from vaccinated children) is allowed to survive in the environment, the more genetic changes it undergoes [5]. In this case, the administered OPV results in polio infection due to a reversion of the vaccine strains to the more neurovirulent profile of wild poliovirus [11,5]. Vaccine associated paralytic polio occurs in both vaccines and their unimmunized contacts [10]. Note that OPV contains all three antigenic types, any of which may revert, to either the wild form or the circulating vaccine derived form of the polio virus [11].