An age-structured epidemic model of rotavirus with vaccination

E. Shim · Z. Feng · M. Martcheva · C. Castillo-Chavez

Abstract  The recent approval of a rotavirus vaccine in Mexico motivates this study on the potential impact of the use of such a vaccine on rotavirus prevention and control. An age-structured model that describes the rotavirus transmission dynamics of infections is introduced. Conditions that guarantee the local and global stability analysis of the disease-free steady state distribution as well as the existence of an endemic steady state distribution are established. The impact of maternal antibodies on the implementation of vaccine is evaluated. Model results are used to identify optimal age-dependent vaccination strategies. A convergent numerical scheme for the model is introduced but not implemented. This paper is dedicated to Prof. K. P. Hadeler, who continues to push the frontier of knowledge in mathematical biology.

Keywords  Rotavirus · Age-structure · Vaccination

Mathematics Subject Classification (2000)  92D30 · 65N06 · 65N12

E. Shim (✉) · C. Castillo-Chavez
Department of Mathematics and Statistics, Arizona State University, P.O. Box 871804, Tempe, AZ 85287-1804, USA
e-mail: alicia@mathpost.asu.edu

Z. Feng
Department of Mathematics, Purdue University, 150 N. University Street, IN West Lafayette, 47907-2067, USA

M. Martcheva
Department of Mathematics, University of Florida, P.O. Box 118105, Gainesville, FL 32611-8105, USA
1 Introduction

The discovery of rotavirus ([3]) as the major etiologic agent of diarrhea in infants and young children has had a dramatic impact on public health policy programs geared towards the reductions of diarrhea morbidity and mortality over the last three decades. Ninety-five percent of children worldwide have experienced a rotavirus infection with most infections in the 3 – 5 year age-range [24]. The highest rate of infection occurs in infants between 6 and 24 months of age [18]. Mortality from rotavirus diarrhea is quite low but morbidity is still high. In the United States rotavirus infections affect approximately 2.7 million children under 5 years of age and result in the hospitalization of 55,000 children every year [24]. The direct costs on US medical care have been estimated to be around $274 million [24]. The overall cost associated with rotavirus infections has been estimated at more than $1 billion per year, in the United States alone [24]. Over 600,000 children die annually worldwide [7].

The primary mode of rotavirus transmission is fecal-oral [15]. Reported low titers of virus in respiratory tract secretions and other body fluids represent (less common) secondary transmission routes. Rotavirus can survive for months at room temperature and it is resistant to chloroform, ether, fluorocarbons, CsCl, non-ionic detergents and pH 4–9 [27]. Rotavirus can be passed from one person to another through a set of contaminated hands with the virus or by touching a contaminated surface or object. The virus enters the body through the mouth. Children can spread rotavirus before and after they develop symptoms [25].

Rotaviruses infect the mature absorptive villous epithelium of the upper two thirds of the small intestine and replicate in the cells that line the inside of the upper small intestine [24]. Infectious particles are released into the intestinal lumen and replicate more in the distal areas of the small intestine [24]. The replication rate decreases with the ability of the intestine to absorb salts and water [25]. Once infection occurs, the incubation period for rotavirus disease is about 2 days [21]. Most primary rotavirus infections are associated with acute diarrhea and may lead to dehydration and occasionally to death. Common symptoms involve vomiting and diarrhea for 3–8 days, frequent fever and abdominal pain. Immunity after infection is incomplete but recurrent infections tend to be less severe [3].

Many studies about rotavirus immunity have found that maternal antibodies protect younger infants [31]. Adults appear to be able to build up some level of immunity from recurrent infections [19]. Rotavirus disease is rare among infants younger than three months old as maternal antibodies protect them [24]. Newborns may be protected against infection for several months just from maternal antibodies [4]. Some studies suggest that long-lasting partial natural immunity may be possible [2]. In fact, some have shown that children who are infected more than once tend to have less severe symptoms in subsequent reinfections [34]. The highest rates of illness occur among infants and young children age 6 months – 2 years of age albeit adults can also be infected but their symptoms tend to be generally mild. Seropositive adults may develop diarrhea from