When vaccines are imperfect: What math can tell us about their effects on disease propagation

November 20 2014

The control of certain childhood diseases is difficult, despite high vaccination coverage in many countries. One of the possible reasons for this is "imperfect vaccines," that is, vaccines that fail either due to "leakiness," lack of effectiveness on certain individuals in a population, or shorter duration of potency.

In a paper publishing today in the *SIAM Journal on Applied Mathematics*, authors Felicia Magpantay, Maria Riolo, Matthieu Domenech de Celles, Aaron King, and Pejman Rohani use a mathematical model to determine the consequences of vaccine failure and resulting disease dynamics.

"We examined the effects of individual-level vaccine failure on the propagation of a disease through a population," says author Felicia Magpantay. "Specifically, we took into account different ways in which vaccines may fail. We distinguished between vaccine-induced immunity that is 'leaky', whereby vaccination reduces the probability of infection upon exposure but does not eliminate it; 'all-or-nothing', which leads to perfect protection in some individuals, but none in others; and 'waning', which reflects transient protection—or some combination of all three."

While leakiness, degree and duration of coverage have direct effects at the individual level, the protection from imperfect vaccines and reduced disease transmission at the population level is not easy to determine. "By carefully ensuring a like-with-like comparison of the differences in the mechanism of vaccine failure, we identified distinct epidemiological signatures at the population-level and explored their implications for disease control," Magpantay explains.

The group of professional applied mathematicians considers a systematic analysis based on the "susceptible-infectious-recovered" model used in epidemiological studies. This model allows one to calculate the number of susceptible, infectious and recovered individuals in a population, factoring in infection and recovery rates as well as contact between susceptible and infected individuals. The authors adapt this model with an added vaccine component to compare the dynamics of the three aforementioned types of imperfect vaccines.

The critical proportion of the model population that needs to be vaccinated in order to drive the disease to extinction is seen to be the same in all three cases. When vaccination coverage is maintained below the critical ratio, the disease remains endemic in the population at a higher level for leaky vaccines, compared to the other two imperfect vaccines. "Among vaccines that exhibit the same level of individual-level effectiveness, the purely leaky vaccine always leads to the highest prevalence of infection in the long run. The purely all-or-nothing and purely waning vaccines lead to the same levels of prevalence," Magpantay elaborates.

The authors then extend their ordinary differential equation model to account for age distribution in the population using a system of partial differential equations for age-specific transmission. "The age distribution of the infected class depends on the type of vaccine failure, the age-specific contact rates and the vaccine coverage. In the cases that we have considered, the waning vaccine leads to the highest mean age of first infection," Magpantay says.

The authors also show that the three imperfect vaccines have distinct transient dynamics following the initiation of vaccination in a population. "Numerical simulations suggest that vaccination with leaky and waning vaccines can bring about a long honeymoon period: a temporary period of low disease prevalence after the onset of mass vaccination," Magpantay explains. "This provides an alternative explanation for the observed resurgence of some diseases like pertussis in regions that maintain high vaccination coverage." All-or-nothing vaccines appear to show a more stable transition.

More information: Epidemiological Consequences of Imperfect Vaccines for Immunizing Infections, *SIAM Journal on Applied Mathematics*, 74 (6), 1810-1830. November 20, 2014

Provided by Society for Industrial and Applied Mathematics