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Caitlyn Cardetti
Minnesota State University, Mankato

Katie Groskreutz
Minnesota State University, Mankato

Melissa Zins
Minnesota State University, Mankato

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Herd Immunity and the Necessity of Vaccinations:
Modeling the Effects of MMR Vaccinations

Caitlyn Cardetti, Katie Groskreutz, and Melissa Zins (Mathematics and Biology)
Dr. Namyong Lee, Faculty Mentor (Mathematics) and Dr. Anne-Marie Hoskinson, Faculty Mentor (Biology)

The MMR vaccination is a two dose vaccine given to children between the ages of $12 - 15$ months and the second dose between the ages of $4 - 6$ years to prevent measles, mumps, and rubella. The objective was to mathematically model the effects of the MMR vaccinations in a hypothetical school through multiple compartment and spatial models. These models were based on each disease individually with their respective vaccine effectiveness and disease infection rates. These models demonstrated the limits of herd immunity. Herd immunity occurs when a high enough percentage of the population is immune or vaccinated to prevent the spread of diseases to those who are susceptible. Once herd immunity was determined, the necessity of the vaccinations became evident. This model demonstrated the effects of not vaccinating a child and how it affected not only the individual but the whole population; by weakening the herd immunity of the whole population (Szabo 2010). Through this, parents, educators, and public health officials can be educated on the importance of getting children vaccinated.

Introduction

The MMR vaccine is a two dose vaccine for measles, mumps, and rubella. The first dose is given to children at 12-15 months. The second dose is given to children at 4-6 years. According to the CDC, currently 96% of preschool children in the U.S. have received the MMR vaccine. Common symptoms for measles, mumps, and rubella mimic the flu; however, there can be serious complications such as hearing loss, brain damage, and death (CDC 2008).

Herd immunity occurs when a high enough percentage of the population is immune (or vaccinated; varies depending on disease) to prevent the spread of disease to those who are susceptible. Due to the fact that the MMR vaccine is modified live, many people cannot receive the vaccine and are dependent on herd immunity. A modified live vaccine is when the virus is still active in just a weakened state; healthy individuals' immune systems would properly fight off the disease but is not recommended for those with compromised immune systems. A few examples are those with suppressed immune systems or cancer (CDC 2008).

Methods and Materials

Initially a compartment model was constructed to show the progression of the MMR diseases, see Figure 1.

Fig.1. Generic compartment model for measles, mumps, and rubella. Models the progression of the diseases in a large population.

The compartment model showed the whole population divided into four categories: susceptible, infected asymptomatic, infected symptomatic, and recovered. The first category, susceptible, encased anyone who was capable of contracting the disease from an infected individual; this

included everyone in the population who had not been vaccinated, was not currently infected, and had never had the disease. The second category was the infected asymptomatic. Asymptomatic are individuals who have contracted the disease but do not display any symptoms; therefore they are more likely to spread the disease due to being unaware of being ill. Next was the infected symptomatic, these individuals were less likely to spread the disease than the infected asymptomatic because they were now aware of their illness and limited their interactions with others by staying home from work or school. Finally, there was the recovered category which included those who had recovered and gained lifetime immunity and those who had been vaccinated. This compartment model (Fig. 1.) explained the progression of all three of the diseases and showed the importance of vaccinations; because in the case of measles, mumps, or rubella becoming vaccinated automatically puts an individual in the recovered category. The recovered category as previously stated was those with lifetime immunity without the need to experience the disease and its detrimental effects due to being vaccinated.

Following the compartment model, a spatial model was developed in an Excel document to show a population of 361 preschool aged children interacting and how a disease would spread based on their interactions in one moment. The model assumed no movement due to the complexity of factoring in each individual's pattern of movement; there were just too many factors to be considered. The model only displayed one brief moment in time, an individual was only in contact with the eight other individuals who surrounded them (due to the set up in Excel). There was an equal amount of contact between the individual and its eight neighbors. So the probability of infection was solely based on whether the number randomly generated was within the range of the individual to be infected. Also it was assumed that there was only one initial source of infection.

The model on Excel was composed of three main sections: the susceptibility map, the infected map, and the working area. All the maps were composed of a square grid (19 by 19 cells) to form a total of 361 cells or individuals. In each cell of the susceptibility map there was a number between 0 and 1.

This number represented the probability of the individual being susceptible, the lower the number the lower the chance of becoming infected.

Table 1. MMR vaccine effectiveness for each disease at one and two doses (CDC 2010).

Vaccine Effectiveness	Measles	Mumps	Rubella
1 dose	95-98%	80%	95%
2 doses	99%	84%	95.25%

These numbers were generated based off of the effectiveness of the vaccine, whether an individual received the vaccine, and whether the individual received one or two doses of the vaccine (Table 1). The percent who only received one dose of the vaccine could not be determined through research since there was no available data.   The Center for Disease Control was contacted and they stated all of their data was based off the assumption that each individual received two doses and that there was no data available for individuals who only received one dose of a series. It was assumed that only 1% of the total population received one dose of the vaccine because it was highly unlikely that an individual would get only one of the two doses of the vaccine according to the CDC. In real life, a population is not homogenously mixed, so placement for each individual and their probability of susceptibility were randomly generated for each simulation.

The next portion of the model was the infected map whose cells contained a value of zero represented no infection. The infection map was where the initial source of infection was started by changing one of the cells values from zero to one. Having only one initial source was an assumption determined after various testing with multiple sources (Table 3).

Table 2. Shows the values for percent infected and their ranges for each of the different percent of the population vaccinated.

Percent Vaccinated	Percent Infected (One source)	Percent Infected (Two Sources)	Times higher than one source	Percent Infected (Four Sources)	Times higher than one source
50	41.5	48.10	0.15	49.83	0.20
70	3.70	5.74	0.55	16.20	3.38
80	1.00	3.68	2.68	4.72	3.72
90	0.26	0.62	2.03	1.32	3.9

Testing showed that the number of initial sources only made a significant difference when 70% or 80 % of the total population vaccinated. Mainly, the difference was associated with the presence of four initial sources which was over 1% of the total population being initially infected; thus, being very unlikely. When the percent vaccinated was below 70% or above 90%, the number of initial sources had little effect on the percent of the population becoming infected. The next step was to gather data from the working area.

Each of the cells in the working area was coded to read its eight surrounding neighboring cells to see if any of them were infected. If none of them were infected, the cell in question, or middle cell was incapable of becoming infected. If one of the eight neighboring cells were infected, there was now a chance of the middle cell to become infected; however this infection was not guaranteed. This middle cell now referred back to its value given in the infection map to see its probability of contracting the disease. A random number was then generated; if the random number was less than the value of susceptibility, the cell then became infected. If the random number was greater than the value of its cell on the susceptibility map, the cell did not become infected.

The spatial model was then tested with four different scenarios; each scenario represented a different percentage of the population being vaccinated: 50%, 75%, 96%, and 100. Fifty simulations were run for each scenario.

Results

Table 3. Shows the values for percent infected and their ranges for each of the different percent of the population vaccinated.

Percent Vaccinated	Measles		Mumps		Rubella	
	Avg. Percent Infected	Ranges of Percent Infected	Avg. Percent Infected	Ranges of Percent Infected	Avg. Percent Infected	Ranges of Percent Infected
100%	.06%	0-1.10%	.03	0-1.11%	.03%	0-.83%
96%	.18%	0-1.10%	.14	0-2.22%	.1%	0-.83%
75%	3.01%	0-13.85%	2.4	0-13.29%	2.4%	0-10.25%
50%	41.50%	.83-56.50%	41.8	0.28-71.47	41.8%	20.50-56.50%

In the case of measles, when 75% of the population was vaccinated, the average percentage of children who became infected was 3.01%, and when 50% were vaccinated, over 41% became infected. However, at both 96% and 100% vaccinated less than 1% became infected.

Using the model to run simulations for mumps, it was found that on average about 169 children became infected or 46.91% of the population became infected when only 50% of the population was vaccinated. At 75% of the population being vaccinated, 14 children or 3.89% of the population became infected. For both 96% and 100% of the population being vaccinated, less than 1% of the population other than the initial source became infected. For rubella, at 50% of the population vaccinated, on average 151 children became infected, or approximately 42% of a population of 361 children. At 75% vaccinated, an average of 8.8 children were infected, or approximately 2.4% of the total population. At 96% and 100% of the population vaccinated, less than 1% of the population became infected other than the initial source.

Figure 2 displays how measles, mumps, and rubella all had the similar resulting trends. The percentage of people who were infected from one initial source increased exponentially as the percentage of people vaccinated lowered.
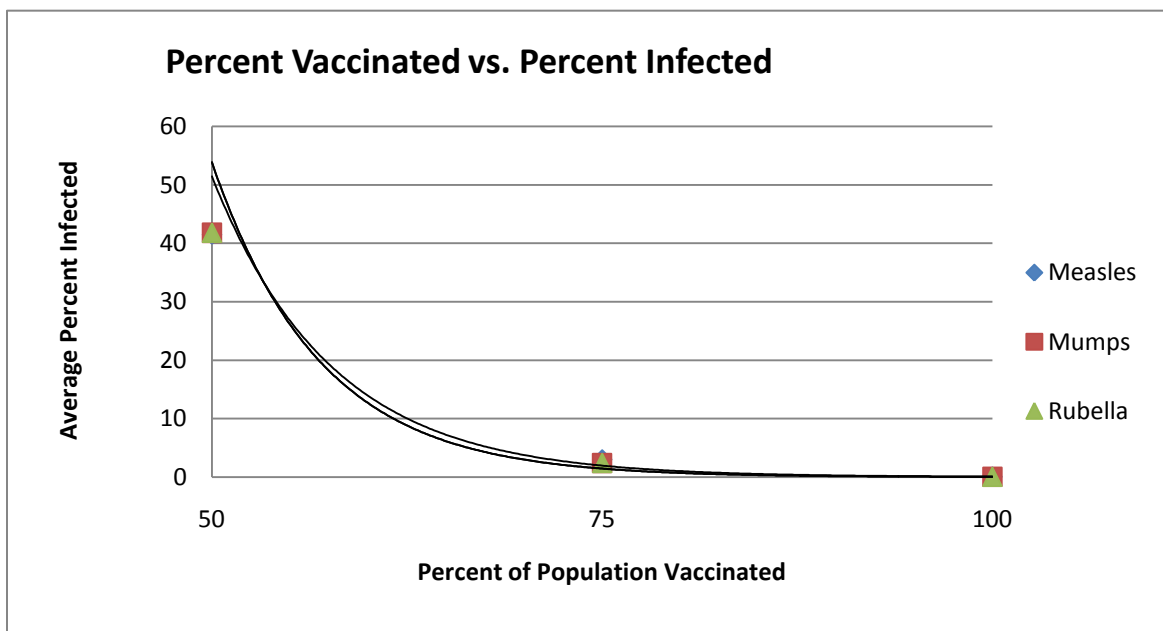
Fig. 2. Shows the relationship between the average percent vaccinated and the average percent infected of the population for each measles, mumps and rubella. Also displays exponential best fit line for all three diseases.

Discussion

The spatial model showed that as the percentage of population vaccinated increase, the percentage of the infected population decreases. Also, the spatial model proved that it wasn't necessary for 100% of the population to be vaccinated to prevent the spread of disease; this supports the theory of herd immunity. Measles, mumps, and rubella all had similar herd immunity levels within the range of 75-97% of population requiring vaccination to stop the spread of the diseases and protect those who are not vaccinated, as seen in Table 4.

Table 4. Shows the percent of the population necessary to be vaccinated to achieve herd immunity (CDC 2010).

	Herd Immunity
Measles	83-94%
Mumps	75-85%
Rubella	83-85%

Herd immunity has a substantial impact because it can prevent epidemics without the expectation of 100% of the population being vaccinated. People who can get vaccinated should be vaccinated to protect those who cannot receive a vaccine due to having a suppressed immune system. Many people don't want their children to be vaccinated or think paying for vaccines is simply for pharmaceutical gain. However, vaccines are not for any monetary gain. If everyone who is healthy enough to get a vaccine received one, it would ensure that the population stays above the limits of herd immunity and not have to deal with an epidemic. It is necessary for those with strong enough immune systems to receive vaccines, to protect those who are incapable of being vaccinated (Szabo 2010).

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Authors' Biographies:

Caitlyn Cardetti has lived in Minnesota for the past ten years. She is currently working on earning a Bachelor of Science degree in Human Biology with a minor in Mathematics. She will be returning for her second year as a Community Advisor at MSU, Mankato and is also currently a certified nursing assistant back home. After graduation, she hopes on attending the University of Minnesota to get a Master's degree in Biomedical Informatics and Computational Biology. She hopes to follow a career path in research relating to the biomedical field. She had conducted this research as a sophomore with two fellow students for her Mathematical Modeling in Biology class, under the direction of Dr. Anne-Marie Hoskinson and Dr. Namyong Lee.

Katie Groskreutz is from Pemberton, MN, and is currently attending Minnesota State University – Mankato. She is in the process of earning a Bachelor's degree in Mathematics and is minoring in Biology. Upon graduation, she plans on attending graduate school in the Midwest. Then, she hopes to find a job that involves mathematical and biological research. In addition to going to school, Katie works a part-time job at Kwik Trip in North Mankato. She worked on research with Caitlyn Cardetti and Melissa Zins with direction from Dr. Anne-Marie Hoskinson and Dr. Namyong Lee her sophomore year at MSU. Katie plans on being involved with research throughout her undergraduate career.

Melissa Zins grew up in Madison, WI. She graduated high school in 2008 and came to Minnesota State University Mankato to begin her journey toward a bachelor of science degree initially in astronomy and physics. After losing heart and interest in astronomy, Melissa changed her major to Biology and Pre-Medicine with the plans to eventually go on to graduate school and become a pediatric cancer research doctor. Melissa's many volunteer opportunities and experiences within her community has guided her toward helping others, especially children, as a professional career one day. The URC has allowed Melissa to get her feet wet in research and start at the bottom, in attempts to work her way up. Melissa has plans to continue going to school and take up new research opportunities in biology and medicine along the way