Polysaccharide Vaccination (PMC) Strategy on the Meningitis Outbreak in Ghana

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INTRODUCTION

The Meningitis Belt in Africa encompasses the country of Ghana; in this region peaks of infection of bacterial meningitis occur once a year during the dry season. One of the primary vaccines in Ghana, PMC, was modeled in this paper to compare the effects of both vaccination rate and migration rate of people into the population on the incidence of infection. The graph of initial peaks of infection in regard to vaccination rate show that there is a negative logarithmic curve between initial peak value and vaccination rate with no such impact of migration rate on the amplitude of the outbreak. The infection rates at the fifth peaks (5 year mark) of infection showed a negative linear relationship with a lower migration rate having a smaller value at the fifth peak.

Bacterial Meningitis is a bacterial infection of the meninges, or the layers surrounding the brain and the spinal cord. The infection causes the membranes to swell cutting off blood flow and potentially resulting in brain damage or even death. While children under 2 years of age are the most susceptible, adolescents ranging from 0-19 years old have also been found to be to the most common victims of the disease (Woods et al.). The bacteria can be found in the nose and respiratory system and is, therefore, transmitted through the air and also through person to person contact. First symptoms of the infection include a high fever, headache, and stiffness of the neck. As the onset of the symptoms is rapid, it is imperative for patients to seek medical treatment immediately. Progression of the infection can result in seizures and can quickly become life threatening if allowed to progress. (Varaine et al.). Even those who do not succumb to the illness can be maimed with life long impairments, including brain damage and paralysis.

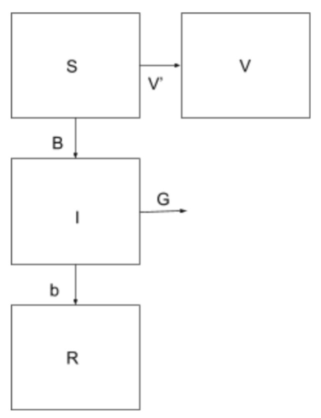
While many of the citizens in the United States have received the meningococcal vaccine and are thus immune to the infection, those in third world nations are still highly susceptible to the infection (Woods et al.). Specifically, the Meningitis Belt across western Africa has been prone to an annual outbreak of the disease correlating with the dry season which begins in mid-February. The dry season decreases the cleanliness and hygiene of the region allowing the bacteria to manifest and spread much more rapidly than it does in the dry season. Additionally, people tend to overcrowd in the dry season because of the cold weather from the harmattan In this region, there can be up to 1000 cases per 100,000 people per year (Kaburi et. al). The worst epidemic of Meningitis ever seen hit Ghana in 1997, when over 18,000 cases were reported resulting in nearly 1,500 deaths in the population (Varaine et al.). The susceptibility of the belt is largely due to the lack of proactive vaccination. There are currently two primary types of vaccines for use in Ghana. The first, a polyvalent meningococcal polysaccharide (PMP), is a cheaper vaccine. However, it only provides immunity for 3 years. Given the annual outbreaks in Ghana, this is not ideal as the person will soon be susceptible once again. Due to cost needs, however, this is the vaccine primarily used once an outbreak has occurred. The second vaccine, a polyvalent meningococcal conjugate (PMC), is a more expensive version of the vaccine that guarantees 15 years of immunity; given that you are most susceptible from 0-19 years, this translates to almost complete immunity for all individuals who receive this immunization (Woods et al.). In the United States, the PMC vaccine is what is given as a proactive immunization. However, in Ghana the PMP vaccine is almost exclusively used with it being implemented generally 2-3 weeks into an outbreak (Kaburi et. al)

In our model, modelled a Meningitis outbreak in Ghana using a SIR model (Susceptibility-Infected-Recovered). This model took into account the potential of migration of people into Ghana as well as different potential vaccination rates as these rates depend on available funding and resources. In addition, we added a fourth compartment to the SIR model that represented vaccination. Overall, we attempted to discover the optimum rate of vaccination using PMC vaccination in Ghana considering the effects on migration into the population.

METHOD

The five year trajectory of infection in Ghana was modeled on the *Big Green Differential Equation Machine* to compare the values of the first and fifth peaks of infection based on the rate of vaccination as well as the rate of migration into the population. The equations were derived from the SIR infection model with an alteration to the model to account for the effects of vaccination on the populations of the susceptible, infected, recovered, and vaccinated individuals. The data used for the parameters, data from a 2015 study of the meningitis belt in Ghana was used. Once the values of the initial peaks at different vaccination rates were known, the data was entered into excel. The curve of initial peaks for a migration rate of .003 was then compared to that of a migration rate of .001. On the *Big Green Differential Equation Machine*, we ran the infection curve for each potential vaccination rate: 10, 20, 30, 40, 50, 60, 70, 80, 90, 95 for 2000 days at a migration rate of .001 and a migration rate of .003.

DESCRIPTION OF MODEL



Description of Variables

b	Rate of recovery (per day)
G	Death rate from infection (per day)
B	Attack rate (per day)
V'	Rate of vaccination (per day)
S	Number of susceptible individuals (per 100)
I	Number of infected individuals (per 100)
R	Number of recovered individuals (per 100)
V	Number of vaccinated individuals (per 100)

The amount of susceptible individuals, S, depends the most on the rate at which people leave the susceptible pool and become infected as well as the rate at which members become vaccinated and the rate at which people migrate into the population. The initial condition of S is the percentage of the population that is not vaccinated. The rate of change for S is

$$S' = -B(\sin(2\pi/365)*t+1)*S*I + \text{Migration} - .001*S$$

The amount of infected individuals, I, depends on the attack rate, B, (the rate at which individuals become infected) subtracted by the rate at which individuals recover, b, and rate at which individuals die, G, from the disease. The initial condition was assumed to be .00001 as we wanted to data to show the data starting at the beginning of an outbreak but at least one infected individual is required for a disease to outbreak. The rate of change for I is:

$$I' = B(\sin(2\pi/365)*t+1)*S*I - G*I - b*I$$

The amount of recovered individuals depends on the rate at which individuals recover from infection, b. The initial condition of R is zero because at the beginning of an outbreak there are no recovered individuals. This makes the rate of change of R:

$$R' = b*I$$

To calculate the vaccination rate, V', we made the initial condition of V the percentage of the population that is vaccinated. We then assumed the birth rate of Ghana to by .001. This meant that the rate at which the population of vaccinated individuals increases, V', is

$$V' = .001*S$$

as children are born into the susceptible pool.

The attack rate, B, was modeled as a sine function of time with a period of 365 days. This varying attack rate accounts for the spike in meningitis infection in Ghana during the dry season. Because the attack rate of the bacterial infection cannot be negative we had to add one to the function. To find the initial condition of B we had to test values until the graph of the infected population represented the sinusoidal curve peaking during dry season, seen in studies of Ghana. (Yaesoubi et. al).

$$B(\sin(2\pi/365)*t+1)$$
$$B = .0065$$

The death rate, G, was assumed to be 9.7% which was the Overall Case Fatality Rate for bacterial meningitis measured in northern Ghana in 2015.
(Kaburi et. al)

The recovery rate, b, used in our model was .085 as it takes between 7-10 days to recover from bacterial meningitis if you recover as measured in the same study above in Ghana (Kaburi et. al).

RESULTS

Because of the sinusoidal nature of the attack rate, the infection rate reflected a similar pattern as seen in figure 3. With the addition of the PMC vaccine, fewer members went from the susceptible to infected pool and therefore the number of infected individuals went down with each successive outbreak eventually reaching a steady period state in which the infected individuals peaked at the same rate every 365 days. For all runs, the initial peak had the highest value and reached a steady period state around the fifth peak, after five years following an initial outbreak.

Figure 1 compares vaccination rates versus amount of infected individuals at the fifth peak for two different migration rates, .001 and .003. This figure shows a predominantly inverse linear relationship between vaccination rate and amount of infected individuals at the fifth peak of infection. This figure also shows that there is an impact on the amount of individuals at the fifth peak on infection depending on the migration rate into the population. This data shows that a lower migration rate will lead to a lower value at this fifth peak.

Figure 2 compares vaccination rates versus the amount of infected individuals at the initial peak of infection for the two different migration rates as well, .003 and .001. This figure shows that at the first peak, there is no effect on the amount of individuals in the initial peak from the rate of migration into the population over time. The data for both migration rates showed a negative logarithmic curve. This means that increasing the vaccination rate at lower levels decreases the incidence of initial infection at a steeper rate than at higher vaccination rates.

Figure 1: .003 migration rate in blue, .001 migration rate in red

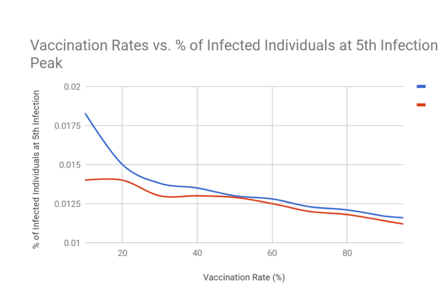


Figure 2: .003 migration rate in red, .001 migration rate in blue. Lines overlap each other.

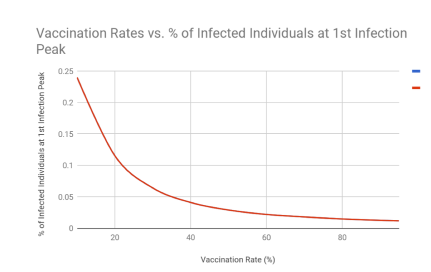


Figure 3: The 5 year projection of amount of infected individuals with a 40% vaccination rate and a .003 migration rate into the population (time in days)

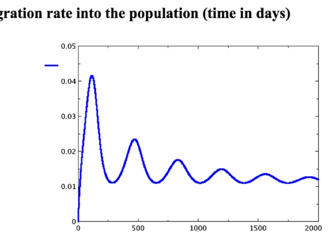
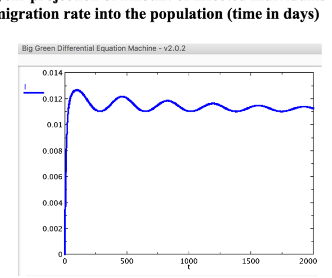


Figure 4: The 5 year projection of amount of infected individuals with a 90% vaccination rate and a .003 migration rate into the population (time in days)



CONCLUSIONS

Based off the mathematical model, it can be concluded that vaccination rate had a significant impact on how much of the population succumbed to the infection in the initial outbreak. Specifically, in Figure 2 the slope before the 40% vaccination level is extremely steep, suggesting that if Ghana could vaccinate just 40% of their population, they would have significantly smaller Meningitis outbreaks each year. The slope continues to decline between the 40-80% vaccination rate level. While we would still recommend vaccinating as many people as possible, this model suggests that vaccinating just 40% of the population will significantly diminish the infection and that vaccinating over 80% of the population prevents the outbreak almost completely. It appears that at 80% vaccination, the population gains herd immunity meaning that enough people have been vaccinated that the population is almost completely immune to the infection. The migration rate into the population had no effect on amplitude of the initial outbreak, regardless of the vaccination rate. These optimal vaccination rates can be achieved through infant immunization and proactively vaccinating the population rather than retroactively distributing vaccines once an outbreak has already begun. In order to make this a genuine possibility, the availability and cost-accessibility of the PMC would have to be substantially increased, changing the culture around vaccines in Ghana to make them much more normalized.

Figure 1 modeled the amplitude of the outbreak 5 years after the initial outbreak and vaccination began. The graphs differed slightly based on the rates of migration into the population. We found that a greater migration rate (0.003) into the population led to larger outbreaks in the long term. This is because more people are entering the population that are all susceptible to the disease. This means there are more people that are able to be infected which weakens the immunity of the population as a whole. In order to combat this, Ghana could require all people entering their country to be vaccinated with PMC. Furthermore, they could require PMC vaccination at birth. These methods would eliminate that added meningitis risk that migration into the population adds over the long term.

FUTURE DIRECTIONS...

To further understand the most effective vaccination strategy for bacterial meningitis in Ghana, mathematical modeling can be done with other viable vaccines. Specifically, the vaccination efficiency of PMC can be compared to a cheaper, reactive vaccine for meningitis that provides temporary immunity, PMP. The timing of implementation of PMP as well as the cost effectiveness of PMP could be compared in order to model the most effective and cost efficient way to minimize the meningitis outbreaks in Ghana.

ACKNOWLEDGEMENTS

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