**Working Title:**

The impact of human mobility and imperfect vaccines on waning herd immunity and optimal oral cholera vaccination strategies

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**Abstract**

**Introduction**

Vaccine-derived herd immunity wane over time due to factors including short-lived vaccine efficacy or an influx of susceptible individuals into a vaccinated community. The duration of herd immunity (DHI) can be an important operational marker for how long vaccination protects a community before needing complementary interventions or revaccination.

**Methods and Findings**

We developed a compartmental model to simulate routine and mass vaccination in a population with varying degrees of migration, transmission intensity, and vaccine coverage. Using the example of oral cholera vaccines, we show that migration and waning vaccine efficacy strongly influence DHI while birth/death processes have minimal impacts. We find that a blended “Mass then Maintain” strategy can protect a community longer than either periodic mass vaccination or routine vaccination alone. Finally, we demonstrate that mass vaccination may be best targeted at populations with intermediate degrees of mobility as compared to communities with very high or very low population turnover.

**Conclusions**

We show that vaccines, and specifically oral cholera vaccines, can be powerful tools for quickly protecting a population for a certain period of time until complementary interventions can be installed. Vaccine-derived herd immunity can be sustained most efficiently by a blended “Mass then Maintain” strategy whereby a single mass vaccination campaign is followed by routine vaccination of susceptible individuals. These findings help explain why an outbreak was sustained in the Protection of Civilians Camp in Bentiu, South Sudan despite two mass vaccination campaigns in the previous two years.

**Introduction**

The goal of routine and mass vaccination campaigns is frequently to achieve a state of herd immunity,1–3 which occurs when the expected number of infections per case is reduced below one (i.e., the effective reproductive number Re < 1). Herd immunity emerges when vaccine coverage (VC) and vaccine efficacy (VE) are sufficiently high; conversely, herd immunity can be lost over time when VE decreases (e.g., for short-lived vaccine direct effects) or when VC decreases (e.g., through a net influx of susceptible, unvaccinated individuals).

Although much attention is given to measuring the duration and magnitude of VE, many questions regarding the duration of herd immunity (DHI) remain. In practice, vaccines can be a relatively quick stopgap measure to protect an at-risk population until longer-term solutions can be instituted, but there is a need to know how much time is “bought” by such a vaccination campaign. For routine vaccination, the decision of when to boost or revaccinate will depend in part on the DHI following vaccination. Lastly, it remains to be seen how strongly, and in what direction, population mobility should be considered when prioritizing target populations for vaccination.

We study the model system of oral cholera vaccines (OCV) to address these questions. Due to a reliable VE profile and high VC through mass campaigns, cholera vaccines can generate powerful herd protection effects.4,5 The WHO manages an OCV stockpile to facilitate vaccine usage in three settings: high-endemicity “hot spots”, high-risk humanitarian crises, and outbreak response.6 While the value of reactive vaccination in response to outbreaks depends on the short-term (e.g., 0-6 month) OCV effectiveness,7 the value of pre-emptive vaccination strongly depends on the duration of time we can expect to prevent a cholera outbreak.

These are not merely hypothetical concerns. In the Bentiu Protection of Civilians (PoC) Camp in South Sudan, mass vaccinations with high VC were performed in July 2014 and June 2015, yet the camp sustained an outbreak of 381 cases beginning in October 2016.8 Possible driving factors for the Camp’s susceptibility to an outbreak include waning VE, influx of susceptible individuals through birth and migration, and death and resettlement of vaccinated individuals; however, the relative contributions of these factors and whether they are sufficient explanations remains to be seen.

Following a large scale-up in control measures, such as mass vaccination, a period of low incidence, called the honeymoon period, is expected.9 Modeling studies of other disease systems (e.g., HIV,10,11 measles,12 pertussis,13 and rubella14) have shown a relationship between herd immunity and factors such as the VE profile, VC, demographic turnover, and R0, but no study to our knowledge has demonstrated the relative contributions of these driving factors nor considered the impact of human migration on waning herd immunity and vaccination policy.

In this paper, we use mathematical models to study the implications of vaccine waning and human mobility on herd immunity over time. We compare how well several common vaccination strategies sustain herd immunity and demonstrate the non-monotonic relationship between migration rate and the projected impact of mass vaccination. Finally, we provide a tool that can help guide decisions regarding the expected duration of herd immunity for any given context (<https://coreypeak.shinyapps.io/herd_protection_estimator/>).

**Methods**

*Disease Model*

We developed a compartmental model framework of a population that is being targeted with vaccination. The population groups of principle interest for this study are individuals who are fully susceptible to disease () and those who were vaccinated *n*-months ago () (Fig 1). In order to account for the observation that vaccine direct effects do not tend to wane exponentially, we created an ensemble of *n* monthly stages (), which collectively generate an Erlang-distribution for the duration of time in the -ensemble.15,16 We set the mean time residing in any ­ compartment to 30.5 days; therefore, individuals move from compartment to for months [0,1) post-vaccination on average, to for months [1,2) post-vaccination, etc.

We assume individuals within the population are well-mixed and individuals emigrate from the population at a rate that is equal for all compartments. Unless otherwise noted, the total system size is held constant by offsetting emigration with an equal rate of immigration. Our main results assume that immigration is entirely into the compartment, meaning incoming migrants bring neither vaccine-derived nor naturally acquired immunity into the population.

The system of ordinary differential equations generated by the model was solved using the *deSolve* package17 in the statistical software program R (version 3.2.4). All code used to generate this paper can be found at <https://github.com/peakcm/cholera>.

*Vaccine Efficacy Parameterization*

We adapted monthly estimates using data from Clemens et al.18 that were re-analyzed by Durham et al.19 We define to be the VE for months [0,1) post-vaccination, to be the VE for months [1,2) post-vaccination, etc. We parameterized the time-varying distribution of WC and BS-WC vaccines using tables provided by Durham et al.19 and linear interpellations between 6-month mean VE estimates, bounded at zero and one. As the WC vaccine is more commonly used, especially through the WHO OCV Stockpile, we focus our main results on the WC vaccine and present results for the BS-WC vaccine in the supplement.

*Mobility Parameterization*

We estimated migration rates from three settings where OCVs have been used in order to create benchmarks for realistic mobility rates. First, to represent a more stable population, we estimate a migration rate of from the observation that only 9% of an OCV study population in Calcutta changed in the two years following vaccination in 2006.20 Secondly, to represent a highly mobile population, we estimate a migration rate of from the observation that 58% of a study population in Dhaka had relocated over two years.21 Thirdly, to represent a displacement camp with intermediate mobility, we estimate a migration rate of in the Bentiu PoC Camp in South Sudan in the period from February to October 2016, during which IOM reports a rather stable population of 104,000 people and approximately 2,000 entries/exits per month [<http://www.iomsouthsudan.org/tracking/>].

*Outcome Measurements*

We define the duration of herd immunity (DHI) as the time following a vaccination campaign with an effective reproductive number () below one. We calculate

where is the proportion of the population susceptible at time *t*,

and is the total population size at time *t* and is constant unless otherwise noted. Due to the special behavior of deterministic models, when a simulation asymptotically approaches from below, we define DHI as the time until .

We use our measurement of to estimate the probability of the community sustaining an outbreak given the introduction of a single case. For this calculation, we assume a Poisson distribution of secondary infections and define an outbreak as at least 10 cases (see supplemental information for different outbreak thresholds).22 The closed-form solution for the probability of a small outbreak of size () initiated by a single infectious case is defined by the Borell-Tanner distribution:22,23

*Re-Vaccination Strategies*

We consider three vaccination strategies: (1) routine vaccination; (2) periodic mass vaccination; and (3) mass vaccination followed by routine vaccination, i.e., “Mass then Maintain.” Routine vaccination includes the daily allocation of a certain number of vaccine courses to individuals who happen to be susceptible at the time (such as those entering the population through immigration or birth). Currently, a complete vaccine course of OCVs includes two doses administered approximately two weeks apart.6 However, because the timescale of interest for this study is measured in years, not days, we assume mass vaccination campaigns elapse instantaneously. Furthermore, we focus on the number of vaccine courses rather than the number of actual vaccines per course for generalizability across disease systems.

*Bentiu PoC Camp Case Study*

To demonstrate the value of estimating waning herd immunity, we focus on the recent experiences with vaccination, population changes, and an outbreak in the Bentiu PoC Camp. To approximate the Camp population size, we isolated four key periods of population change: (1) nearly linear growth from February 2014 to June 2014; (2) nearly exponential growth from June 2014 until a peak in December 2015; (3) nearly exponential population decay until stabilization in May 2016; and (4) nearly constant population size until the end of the case study in December 2016 (Fig S1). Of the three million persons targeted for health resources in broader South Sudan, including the Bentiu PoC Camp, UNFPA expects 335 deliveries per day, which equates to birth rate of approximately .24 We assumed this to be our demographic turnover rate as a conservatively high estimate, which we show to still be slow relative to other drivers of waning herd immunity.

We estimated the susceptibility profile over time () in six scenarios (Table 1). In the first scenario, we used empirical measures of all four key drivers of waning herd immunity, specifically: an empirical distribution of for Shanchol; a dynamic population size () described above; routine migration observed through entries and exits; and the conservatively high birth/death rate of . We compare this “observed” scenario with counterfactual scenarios that eliminate at least one of these drivers and will therefore cause herd immunity to wane more slowly. We constructed a composite counterfactual “best case” scenario in which: was held constant at its maximum value ( = 0.583) for all time since vaccination with Shanchol; the population size was held constant at approximately the level observed during the outbreak ( = 100,000); routine migration rates were set to zero; and birth/death rates set to zero. To isolate the impact of each driver of waning herd immunity, we simulated univariate counterfactual scenarios under which one driver is set to the “observed” condition while the other three were held at the counterfactual condition (Table 1).

Next, we create a measure of attributable percent to assess the relative strength of each driver of waning herd immunity in this case study. We calculate on Oct 16, 2016 in each univariate counterfactual scenario and for the composite counterfactual scenario. For each univariate scenario , we calculate the difference . Finally, we calculate the percent of waning herd immunity attributable to each driver .

**RESULTS**

*Duration of herd protection depends on VE and migration*

In a static population (i.e., no births, deaths, or migration), vaccination can provide some herd protection as long as direct vaccine efficacy remains, which we estimate to be 4.2 years for the WC vaccine in our deterministic model framework (Fig 2, dotted line). The inclusion of migration can substantially decrease this duration. In a high-migration setting with an average duration of residence of 2 years, the duration of any herd protection decreases to 3.6 years following mass vaccination with the WC vaccine and 9.2 years even for a perfect vaccine (which retains VE=1 indefinitely) (Fig 2, solid lines). Between the three primary forces causing herd immunity to wane, namely waning direct effects, migration, and demographic turnover through births and deaths, we find that the first two are substantially more influential than the third. Even pessimistic estimates of a life expectancy of 40 years only result in a 2% decrease in the duration of herd protection as compared to setting rates of birth and death to zero (Fig S2). Of interest to policy-makers is not just the duration of any herd protection, but specifically the DHI. Fig S3 shows the strong positive dependence of DHI on high initial VC and low R­0­­.

*Outbreak probability changes over time with Re(t)*

Although deterministic models exhibit threshold-like behavior once the reproductive number exceeds one, an outbreak in reality is possible below the threshold and is not guaranteed above the threshold.25 Holding vaccine coverage at 100%, Fig 3 shows that mass vaccination reduces, but not eliminates, the probability of an outbreak for a duration of time that depends critically on the vaccine efficacy profile and migration rate. DHI can be inferred from the time of crossing the horizontal grey line, which corresponds to Re = 1 and, consequently, a 24.6% chance of an outbreak 10 cases. For a setting with high transmission potential and high migration (red solid line), mass WC vaccination may not be able to achieve herd immunity, but can still drastically reduce by nearly 50 percentage points the probability of an outbreak given introduction.

*Optimizing revaccination with “Mass then Maintain” strategies*

We considered several operational strategies for sustaining herd immunity through vaccination alone. We find that for a fixed vaccine allotment, “Mass then Maintain” strategies that complement a single mass vaccination campaign with routine vaccination can maintain herd immunity longer than either recurring mass vaccination or routine vaccination strategies alone (Fig 4). The intuition behind this complementary strategy is that recurring mass campaigns have diminishing returns per vaccine once herd immunity is achieved; meanwhile routine vaccination alone requires a long period of time to build-up herd immunity. We found that in a population with size , R0=1.5, and high population turnover, provision of up to vaccine courses can sustain herd immunity for 3.6 years through annual mass vaccination, 5.0 years through “Mass then Maintain”, and 4.0 years through routine vaccination (Fig 4).

*Optimizing mass vaccination by targeting intermediate mobility settings*

In addition to the strong influence of migration on DHI, one may posit that communities with higher migration rates are also more likely to have cholera imported. In order to optimize OCV impact, there is a tension between targeting remote communities, where OCV protection is long-lasting but cholera introduction is rare, and highly mobile communities, where the opposite is expected. Fig 5 shows that communities with intermediate levels of connectedness may experience the largest vaccine-derived decrease in the probability of an outbreak introduced via migration. In the example of Fig 5, where R0=1.5 and the probability an incoming migrant is infectious is 1/N, the migration rate recorded in Bentiu in mid-2016 is near the optimal condition for maximizing the impact of a single mass vaccination campaign in the 4-6 year time horizon. If one is interested in shorter time horizons since vaccination, the migration rate that maximizes vaccine impact favors mobile communities, similar to the high population turnover observed in Dhaka in the study by Qadri et al.21

*Case Study: Bentiu PoC Camp*

The Bentiu PoC Camp grew from 4,291 occupants in February 2014 to a peak of 140,101 in December 2015 and then converged to approximately 100,000 in May 2016 (Fig 6A). Two large OCV campaigns were performed using enough vaccines to achieve coverage of 82% in July 2014 and 90% in June 2015. We estimate the population fraction susceptible increased to by October 16, 2016, at which time the first cholera case of the outbreak was detected (Fig 6B). For example, if we assume =1.5, then on October 16, 2016 would equal 1.18, which corresponds to a sizeable 30% probability that the introduction of a single cholera case would spark an outbreak of at least 50 cases (Fig 6C). To assess what may be plausible in this setting, we estimated the time-dependent reproductive number from the observed case data using multiple retrospective methods. We found that a mean of up to 3 was consistent with these data (Fig S4).

The drivers of waning herd immunity in this population, from strongest to weakest, were population growth , routine migration, waning , and lastly births/deaths (Table 1). In the counterfactual scenario lacking these drivers, we would expect the proportion susceptible on October 16, 2016 to be as low as , which would render herd immunity even when .

**Table 1. Drivers of waning herd immunity in Bentiu PoC Camp**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Scenario** |  |  | **Birth &**  **Death** | **Routine Migration** | **on Oct 16, 2016** |  | **Attributable Percent** |
| **Composite Counterfactual** | VE=0.583 | N=100,000 | 0 | 0 | 0.46 | -- | -- |
| **Only waning** | Empirical | N=100,000 | 0 | 0 | 0.51 | 0.05 | 11.6% |
| **Only changes** | VE=0.583 | Empirical | 0 | 0 | 0.66 | 0.20 | 46.5% |
| **Only Births/Deaths** | VE=0.583 | N=100,000 |  | 0 | 0.49 | 0.02 | 4.7% |
| **Only Routine Migration** | VE=0.583 | N=100,000 | 0 |  | 0.62 | 0.16 | 37.2% |
| **Observed** | Empirical | Empirical |  |  | 0.78 | 0.32 | **--** |

**DISCUSSION**

Our results can help inform decision-makers about the time window they can expect a population to resist a cholera outbreak even if the pathogen were to be introduced. During this window, WASH interventions can be scaled-up to provide longer-term protection, or a data-driven routine re-vaccination schedule can be determined. We developed an interactive tool to facilitate implementation of these results for a user-defined setting (<https://coreypeak.shinyapps.io/herd_protection_estimator/>).

One practical implementation of “Mass then Maintain” can include a high-coverage mass campaign followed by routine vaccination of new members of the population (through birth or immigration). Recent work has also shown serological triggers for periodic mass vaccination can be an effective and efficient method to maintain herd immunity.26 The authors suggest that in high-incidence areas (or when VE is moderate or low), serological triggers could come so often that frequent planned vaccinations may be more appropriate. Indeed, in our example with imperfect OCVs, at least annual mass vaccination may be needed to maintain herd immunity.

Current guidelines for the optimal use of the OCV stockpile recommend the consideration of “areas with important population movements.”27 The role of mobility in connecting a heterogeneous transmission landscape was demonstrated by Azman et al.28 Here we further show there are two competing effects of high mobility on expected vaccine impact. First, we expect settings with high migration rates to experience more frequent introduction of cholera, all else being equal. Therefore, the expected probability of an outbreak in a population with higher migration is larger. Second, settings with high migration rates will also experience faster waning of herd protection. Therefore, the expected benefit of mass vaccination has a shorter duration in high-mobility settings. Together, these competing forces would suggest that a setting with intermediate degree of mobility would have a moderate risk of cholera introduction but also a moderate duration of protection afforded by vaccination. In order to operationalize this finding, data on migration rates from sources such as censuses or mobile phone call data records must be collected to define “intermediate” mobility for a given context. We find that the optimal migration rate shifts lower (i.e., preferring less mobile populations) in settings with a high average R0. Our primary results assume an outbreak is at least 10 cases. If this threshold is increased to 100 or 1,000 cases, the probabilities of “outbreaks” decreases, but the optimal migration rate is not affected. These findings focus only on cholera outbreaks introduced through migration and assume that each imported infection is independent, that infectious cases are imported at the very beginning of their disease experience, and that the count of secondary cases follows a Poisson distribution.22

We demonstrate that even for a population that recently underwent a mass OCV campaign, there is a risk of cholera re-emergence in the near future, but the probability of an outbreak can be reduced by high vaccine coverage. Such re-emergence does not imply vaccine failure, but instead can result from population turnover, waning of direct effects, or pernicious seasonal forcing. Additionally, non-random mixing of populations can result in patches with outbreak potential within a population with an average Re below the threshold of one.29

Our results depend on several simplifying assumptions. By assuming a well-mixed population, we are assuming no heterogeneity in contact patterns or local reproductive numbers. In reality, we expect diseases, especially ones with environmental transmission characteristics like cholera, to exhibit substantial spatial heterogeneity in transmission intensity. In sub-regions with high transmission potential, outbreaks may be more likely to occur, but likewise other areas of the region with lower potential will have a probability of outbreaks lower than the mean effective reproductive number would here suggest. These differences become crucial if, as we may expect, migration may occur at higher rates in settings with higher transmission potential due to confounders like poverty and temporary infrastructures. In that case, we would expect the routine vaccination of migrants to be even more crucial.

Our model assumes a leaky mode of vaccine action, whereby the direct effect of the vaccine wanes over time for a given recipient. However, our calculation of proportion susceptible (X(t)) is robust to other assumptions regarding vaccine action, including all or nothing. The equation for X(t) is blind to whether it is the number of vaccinated or the vaccine efficacy which changes over time, for an all or nothing and leaky vaccine, respectively (Fig S5). This can be rapidly shown by simplifying the model to a single vaccine compartment V and a total population size N(t)=1:

The migration rates estimated from the three settings are intended for benchmarking and not to imply that these rates are constant, or generalizable, for the whole population. However, the settings do exemplify the wide range of human mobility and its possible impact on OCV decision-making.

Cholera vaccine efficacy has been shown to vary by age of recipient,18,19 however for simplicity we do not model this age structure in the main results. If children are members of a mass vaccination campaign and respond poorly to OCV, we would expect herd immunity would wane more quickly, and especially so if children are disproportionate sources of transmission.

The model we present is not limited to cholera or other diseases with only short-duration or leaky vaccines such as the typhoid capsular polysaccharide vaccine.30 We find the “Mass then Maintain” strategy continues to outperform routine vaccination or periodic mass vaccination even when there is a perfect vaccine (i.e., VE=1 indefinitely) (Fig S6). We also find that intermediate levels of migration continue to maximize vaccine impact for a perfect vaccine, but the optimal migration rate increases with vaccine performance (Fig S7). These findings support the use of mass vaccination to quickly introduce a new vaccine that henceforth is to become a member of the routine immunization program, as was done when the Salk inactivated polio vaccine was licensed in the 1950’s and was distributed *en masse* before becoming a routine childhood vaccine.3

The phenomenon of waning herd immunity also has strong implications on disease control strategies that include mass vaccination or “mop up” vaccination, such as measles31 and yellow fever.32 For yellow fever in particular, fractional vaccine doses have been used to extend vaccine supply under the assumption that VE of fractional doses lasts at least one year.33 Following the mass vaccination of 25 million people in Angola and The Democratic Republic of the Congo, routine vaccination may be the most efficient way to henceforth sustain herd immunity in these populations, should this be the goal. Human mobility and waning herd immunity are key considerations for when these urban populations should be revaccinated.

Herd immunity is a key target for the control of vaccine-preventable diseases and can be monitored over time using information on the VE(t) profile and population turnover rates. We show this information can be essential for optimizing revaccination strategies, targeting vaccine stockpiles, and explaining re-emergence of outbreaks in a previously vaccinated population.

**FIGURE CAPTIONS**

**Fig 1. Compartmental model framework.**

Individuals in a well-mixed population include explicit compartments for susceptible () and vaccinated (). Individuals enter and leave the system through birth, death, and migration (grey dashed arrows) and progress between stages in the population (black arrows). The force of infection for individuals in a compartment Vi is reduced by a factor of . Disease progression compartments for exposed but not yet infectious (E), infectious (I), and recovered (R) are shown, but are not explicitly modeled due to the focus of this study on vaccine-derived herd immunity. We show a direct disease transmission process and a leaky vaccine action model.

**Fig 2. Changes in the proportion of the population susceptible () as a function of years since vaccination.**

Population susceptibility following mass vaccination (100% coverage) of WC vaccine and a hypothetical vaccine with VE=1 increases more quickly in the presence of high migration rates (solid lines) as compared to low migration rates of (dashed lines) or no migration (dotted lines). When migration rates are low or none, X(t) for the WC vaccine is seen to decrease then increase due to the parameterization of VE(t) which peaks one year post-vaccination as estimated by ref19.

**Fig 3. Changes in the probability of an outbreak as a function of years since vaccination.**

The probability of an outbreak, defined as at least 10 transmission events following a single introduction, increases with time since mass vaccination (100% coverage) of WC and a hypothetical vaccine with VE=1 for all time. Settings with basic reproductive numbers of 1 (blue), 1.5 (green), and 2 (red) have increasingly high asymptotic outbreak probabilities of 24.6% (horizontal grey line), 59.7%, and 79.7%, respectively. Settings with high migration rates for (solid lines) demonstrate substantially faster growth in the probability of an outbreak than settings with low migration rates of (dashed lines).

**Fig 4. Revaccination strategies to maximize DHI.**

(A) Recurring mass vaccination with 100% coverage of susceptibles every year (dashed line) or two years (dotted line) is shown to periodically achieve then lose herd immunity, as recorded by the faded horizontal lines below. (B) Mass vaccination of 80% followed by routine vaccination of 8 (green), 12 (teal), or 16 (purple) individuals per day is shown to maximize DHI. (C) Routine vaccination only. The following are held constant for all simulations: population size = 10,000; maximum vaccine courses = 30,000; R0 = 1.5; migration rate = ; and birth and death rates = .

**Fig 5. Vaccine targeting optimized in settings with intermediate rates of migration.**

Vaccine impact is measured by the decrease in the N-year cumulative probability of an outbreak comparing a mass WC vaccination campaign with VC=1 versus no vaccination, and is shown to reach maxima (triangles) at intermediate levels of connectivity. The time since vaccination (colored lines) modifies these maxima. Vertical grey lines denote the estimated migration rates for Calcutta, Bentiu PoC Camp, and Dhaka as described in Methods. In this example, R0 is set to 1.5 and the average probability that a migrant is infected is 1/N, where N is the community size. See Supplemental Information for alternative parameters sets.

**Fig 6. Bentiu PoC Camp case study.**

(A) Estimated population size (blue line), individuals vaccinated assuming two-dose coverage (green bars), and case counts in October and November (grey bars). IOM began reporting entries and exits in December 2015 and are represented by the feint green and red ribbons around the blue line. (B) The proportion susceptible over time decreases due to mass vaccination events, and increases quickly during periods of population growth due to influx of new camp residents assumed to be susceptible. (C) The probability that a single case sparks an outbreak of at least 50 cases increases with .

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**SUPPLEMENTAL INFORMATION**

**Fig S1. Bentiu PoC Camp population estimates over time.**

In order to simulate the Bentiu PoC Camp, we separated the IOM population estimates (black line) into four segments (vertical dashed lines). During the first segment from February 2014 to June 2014, we assumed linear growth (blue line). During the second segment from June 2014 to December 2015, we simulated exponential growth at a rate of . During the third segment from December 2015 to May 2015, we assumed exponential decay at a rate of . During the fourth and final segment beginning May 2015, we assumed population size was constant. The use of exponential and constant functions allowed for population size to change dynamically within a compartmental model framework, and provided population estimates that were visually reasonable. Our deterministic simulations began on June 15, when vaccination first occurred.

**Figure S2. Changes in the proportion of the population susceptible () as a function of years since vaccination.**

As per Fig 2, but with the addition of high birth/death rates () and the BS-Whole Cell vaccine profile.

**Fig S3**. **Duration of Herd Immunity (DHI) as a function of vaccine coverage and basic reproductive number.**

DHI is maximized in settings with high vaccine coverage and low basic reproductive numbers. Due to a longer duration of moderate VE but shorter duration of any VE, the WC vaccine possesses a wider parameter space of long DHI (blue), but an earlier fade to low or no DHI (red or white) as compared to the BS-WC vaccine. Migration rates are set to zero. Uncolored regions never obtain herd immunity.

**Fig S4. Time-dependent effective reproductive number () and daily cholera case counts in Bentiu PoC between October and November 2016.**

We assumed a generation interval with mean of 5 days and following a gamma distribution with shape=0.5 and rate=0.1 as per ref 34.

**Fig S5. Calculation of robust to leaky or all or nothing modes of vaccine action.**

For a simple exponentially waning vaccine direct effect, an All or Nothing vaccine mode of action (left panel) retains a constant (dashed line) while the number of individuals in the compartment decreases over time (dotted line). For the Leaky vaccine (right panel), individuals stay in the compartment, but wanes. Regardless, the proportion susceptible(solid line) follows the same profile for both vaccine modes of action.

**Fig S6.** **Revaccination strategies to maximize DHI assuming a non-waning vaccine.**

As per Fig 4, except the vaccine now retains the maximum efficacy estimated for Shanchol (0.583) for all time. Mass then Maintain strategies again maximize DHI for a fixed vaccine supply.

**Fig S7**. **Vaccine targeting optimized in settings with intermediate rates of migration.**

As per Fig 5, except for a perfect vaccine (VE=1 indefinitely).

{ Preliminary:

To account for seasonal forcing, the transmission parameter is allowed to vary with each day (t) according to a sinusoidal function where *f* is the magnitude of seasonal forcing and is a frameshift parameter accounting for the time of initial vaccination campaign (τ=0 if vaccination occurs at the peak transmission season, τ=π if vaccination occurs at the trough of transmission season). Therefore, we assume an annual cycle, but note that some regions such as Dhaka may exhibit biannual cycles [cite].

Our primary results assume a “leaky” vaccine mode of action, but analysis using an “all or none” mode of action was repeated using a time-invariant VE estimate and creating paths from each vaccine compartment back to the S compartment so that the duration of time in the V­n ensemble is variable (????). In summary, the results presented in the main text were robust to the assumed mode of vaccine action.

Furthermore, our primary results assume a direct transmission route of cholera, while some models prefer transmission through an intermediary such as a water reservoir [cite]. Our results regarding the duration of herd protection are insensitive to assumptions regarding transmission route, as they deal with vaccine effects and changes to the population demographic via birth/death or migration.

*Disease Model Parameterization*

During simulations with disease transmission, we utilize compartments for individuals who are exposed but not yet infectious (), infectious (), and recovered and immune () (Fig 1). Mean transition rates between these compartments are defined as following: for the incubation period ();35 for the duration of infectiousness ();36,37 and for the duration of natural immunity ().38–40 Infection of susceptible individuals () is driven by a density-dependent force of infection such that R0 = . The force of infection on vaccinated individuals () is scaled by .

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