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Time is of the essence: exploring a measles outbreak response vaccination in Niamey, Niger

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The current World Health Organization recommendations for response during measles epidemics focus on case management rather than outbreak response vaccination (ORV) campaigns, which may occur too late to impact morbidity and mortality and have a high cost per case prevented. Here, we explore the potential impact of an ORV campaign conducted during the 2003–2004 measles epidemic in Niamey, Niger. We measured the impact of this intervention and also the potential impact of alternate strategies. Using a unique geographical, epidemiologic and demographic dataset collected during the epidemic, we developed an individual-based simulation model. We estimate that a median of 7.6% [4.9–8.9] of cases were potentially averted as a result of the outbreak response, which vaccinated approximately 57% (84 563 of an estimated 148 600) of children in the target age range (6–59 months), 23 weeks after the epidemic started. We found that intervening early (up to 60 days after the start of the epidemic) and expanding the age range to all children aged 6 months to 15 years may lead to a much larger (up to 90%) reduction in the number of cases in a West African urban setting like Niamey. Our results suggest that intervening earlier even with lower target coverage (approx. 60%), but a wider age range, may be more effective than intervening later with high coverage (more than 90%) in similar settings. This has important implications for the implementation of reactive vaccination interventions as they can be highly effective if the response is fast with respect to the spread of the epidemic.

Keywords: epidemiology; vaccination; measles

1. INTRODUCTION

Measles epidemics represent a continuing public health problem in countries that have not effectively implemented routine immunization programmes, as recommended in the WHO/UNICEF measles mortality reduction strategy (WHO 2001). In the event of an epidemic, the key issue is whether a reactive vaccination campaign is worth mounting. The current World Health Organization (WHO) recommendations for responding to measles epidemics in urban areas focus on case management rather than outbreak response vaccination (ORV). This is because the latter is generally thought to occur too late to have an impact on morbidity and mortality; instead, the associated cost of mortality prevention may be more effective if spent on post-infection health care (WHO 1999). If implemented, the WHO recommendations suggest that vaccination interventions should be concentrated only in areas, where measles virus transmission has not yet occurred, or in closed high-risk populations, such as refugee camps, military camps or schools. Limited resources may be more effectively used to strengthen routine measles coverage. Some previous studies suggest that reactive vaccination will not stop epidemics because measles transmission is so rapid (Aylward *et al.* 1997; Grenfell *et al.* 2001; Strebel & Cochi 2001). Other analyses, however, point to the potential benefits of vaccination interventions in high-burden settings (Broutin *et al.* 2005; Grais *et al.* 2006*a*,*b*).

During a recent outbreak in Niamey, Niger (2003–2004), the Ministry of Health (MoH) and WHO organized an ORV campaign in the city, with the support of the medical non-governmental organization, Médecins Sans Frontières (MSF). The campaign began

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161 days (23 weeks) after the beginning of the epidemic (defined by a sharp increase in reported cases over a period of three weeks). The goal of this activity was to vaccinate 50% of all children aged 6–59 months (the age group at highest risk) living in Niamey. Considering the extent of the epidemic and limited resources available at that time, this objective was reached over 10 days, during which approximately 57% of children aged 6–59 months received measles vaccine regardless of previous vaccination status or disease history; 84 563 vaccines were dispersed across the risk group, estimated to comprise 148 595 individuals.

Three key questions arose from this ORV campaign: (i) What was the impact of the intervention in terms of the number of cases averted? (ii) How many cases could have been averted had the intervention occurred earlier? (iii) What difference would it make if the target age range was expanded to all children aged 6 months to 15 years? Mathematical models are useful to address these questions and provide important insights into the impact of reactive vaccination campaigns (Tildesley *et al.* 2006). Although a large body of research has been devoted to modelling measles transmission dynamics and routine vaccination strategies (Remme *et al.* 1984; McLean & Anderson 1988*a*,*b*; Nokes *et al.* 1990; Bolker & Grenfell 1996; Bjørnstad *et al.* 2002; Scott *et al.* 2004; Cummings *et al.* 2006), little research has focused on control of measles outbreaks in high-burden settings once epidemics have taken off.

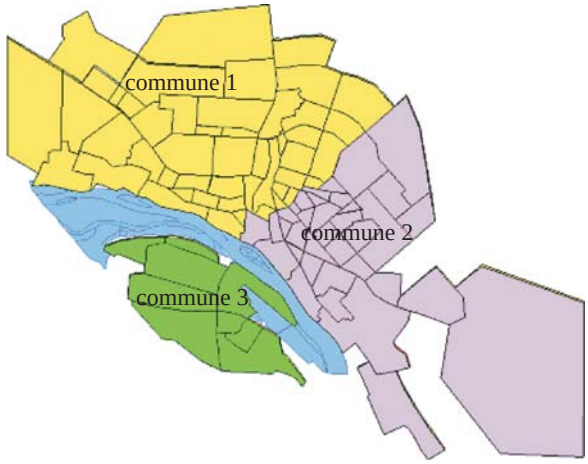
The slow stochastic spatial spread of measles in Niger revealed by previous studies suggests that a prompt reactive intervention may reduce morbidity (Grais *et al.* 2006*a*,*b*). Here, we explore the impact of ORV on the 2003–2004 epidemic in Niamey, Niger. We examine the impact of the intervention and the probable impact of other campaigns, using an individual-based simulation model, firmly rooted in epidemiological data.

2. METHODS

2.1. Study setting

Measles exhibits seasonal outbreaks in Niamey with increased incidence during the dry season (November to May). Over a longer timeframe, major epidemics have occurred in Niamey every 2–4 years, with 1–3 years of reduced incidence following major epidemics. The epidemic in 2001 reported 9184 measles cases (WHO 2004*a*).

The national measles routine vaccination strategy consists of one dose of vaccine, administered to infants between 9 and 11 months, but with all children under age 5, being eligible to receive vaccine (WHO 2004*b*). There is no routine second opportunity for measles immunization (i.e. a two-dose schedule) currently in place (WHO 2004*b*). Supplementary mass vaccination campaigns, called SIAs, have been organized previously with one occurring in 2001, 2 years before the 2003–2004 epidemic. The WHO/UNICEF coverage estimate for the country in 2003 was 64% (WHO 2004*b*).



Q3 Figure 1. Map of Niamey, Niger showing the three communes and quartiers.

2.2. Data sources

2.2.1. Population, surveillance and vaccine coverage. The city of Niamey is divided into three communes (districts; figure 1). Within these are 33 Centre de Santé Intégré (CSI) or health centres, serving 104 quartiers (neighbourhoods). Estimates of the size and age structure of the population were obtained from the 2001 Niger National Population Census. Assuming a 4.8% annual growth rate, the city population at the time of the epidemic was estimated to be 769 454. Only total quartier population sizes were available. The population served by CSIs was assumed to be the sum of each of the quartiers in the catchment area. The population of each commune was estimated as the sum of all quartiers in the commune. As both the at-risk population for measles and the target population for intervention were children under 15 years, we restricted our analysis to this age group. Given the age pyramid for Niger in 2005 (Brown *et al.* 1999; US Census Bureau 2005), 45% of the population was estimated to be under 15 years, of which 46% are estimated to fall in 6–59 months age range and 54% in the 5–14 years range.

Surveillance data consisted of reported measles cases to each CSI between 1 November 2003 and 6 July 2004. Measles was diagnosed clinically using the WHO case definition and laboratory confirmation was not routinely performed (Guris 2001). At the beginning of the outbreak, 10 cases were laboratory confirmed by the MoH through detection of measles-specific IgM antibodies in sera collected after rash onset. The start of the epidemic was identified retrospectively as occurring during the last week of October 2003, when four cases were reported in commune 1. The peak in case reports were in March 2004 with the epidemic beginning to subside in April 2004. In total, the epidemic lasted 30 weeks (1 November 2003 to 6 July 2004) with 10 880 cases reported citywide. At the commune level, 5789 cases were reported in commune 1, 3598 cases in commune 2 and 587 cases in commune 3 (Dubray 2004; Dubray *et al.* 2006). Cases were first reported in commune 1, spreading several weeks later to commune 2 and were not reported in commune 3 until later in the epidemic (see figure 2 for epidemic curves by commune and figure 3 for the citywide

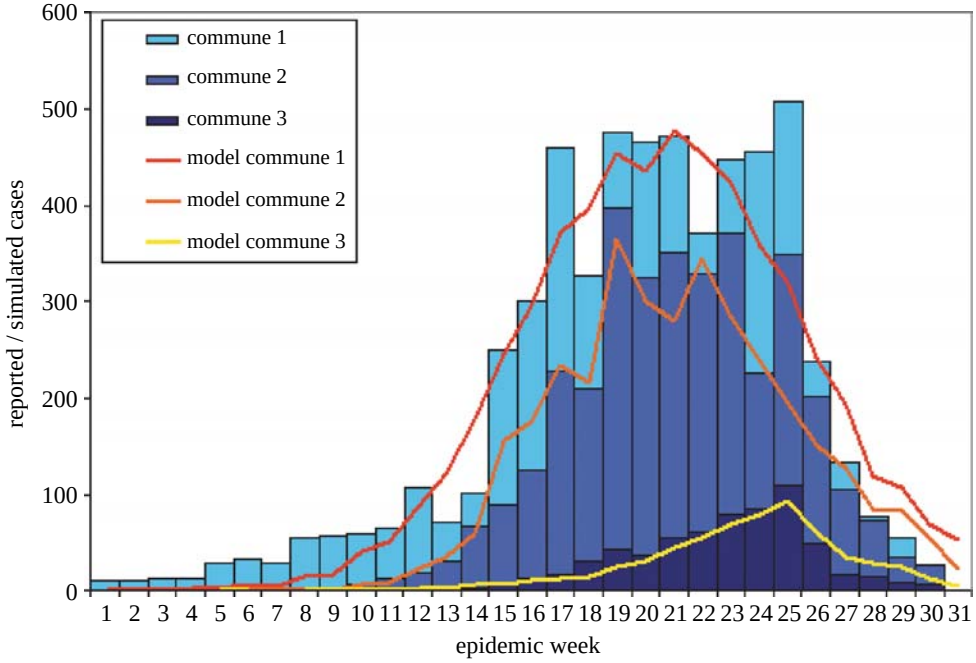


Figure 2. Reported measles cases in Niamey, Niger (November 2003 to July 2004) by commune and the performance of the model by commune. The solid lines depict the median forecast epidemic curve over 1000 simulations including the vaccination intervention targeting 50% of children aged 6–59 months for each commune.

epidemic curve). Further epidemiological details of this epidemic have been described previously (Dubray 2004; Dubray *et al.* 2006).

In 2003, measles vaccination coverage (VC) in children aged 9–11 months was estimated to be 62.0% in commune 1, 68.0% in commune 2 and 75.4% in commune 3 by the MoH (Dubray 2004). The citywide VC estimated by a Lot Quality Assurance Survey was 60.1% (95% CI: 57.9–61.9) before the vaccination intervention and 70.9% (95% CI: 68.8–72.6) after the intervention, based on both parental recall and vaccination card confirmation (Dubray *et al.* 2006).

2.3. Model structure

We developed an individual-based computational model for the 2003–2004 measles epidemic in Niamey. The infection process was modelled stochastically using a discrete-time model formulation with a 1-day time-step.

Our previous study of this epidemic (Grais *et al.* 2006*b*) revealed a slow spatial spread between communes, with more rapid local transmission within quartiers. Children were therefore assumed to belong to one of the 104 quartiers of the city. We assumed the probability of a susceptible child becoming infected to be a function of the numbers of infectious children at the quartier, CSI catchment, commune and citywide scale with a reduced rate of interaction at each greater scale. On day $t+1$, the probability $P_{q,t+1}$ that a susceptible child in quartier q is infected is assumed to be governed by

$$P_{q,t+1} = 1 - \exp\left\{-\left(\frac{\beta_{\text{quartier}} I_{q,t}}{N_q} + \frac{\beta_{\text{CSI}} I_{\text{CSI}_q,t}}{N_{\text{CSI},q}} + \frac{\beta_{\text{commune}} I_{\text{commune}_q,t}}{N_{\text{commune},q}} + \frac{\beta_{\text{city}} I_{\text{city},t}}{N_{\text{city}}}\right)\right\}, \quad (2.1)$$

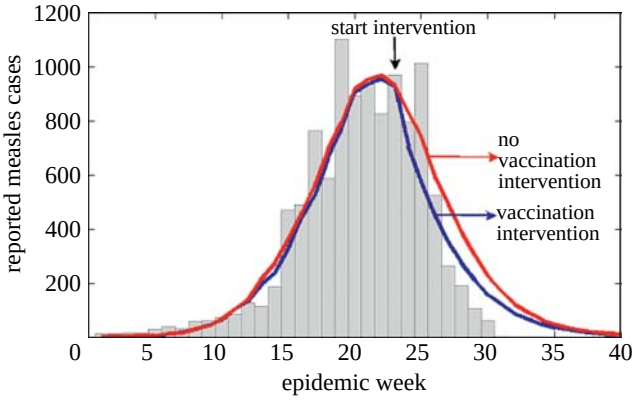


Figure 3. Simulation of epidemic with and without vaccination intervention. The number of reported measles cases per week is shown in the grey histogram. The blue line depicts the median forecast epidemic curve over 1000 simulations including the vaccination intervention targeting 50% of children aged 6–59 months. The red line shows the median of 1000 simulations of the forecast epidemic curve without any intervention.

where β_{quartier} is the transmission rate between children within the same quartier, β_{CSI} within the same health centre catchment area, β_{commune} within commune and β_{city} as the citywide scale. The variables $I_{q,t}$, $I_{\text{CSI}_q,t}$, $I_{\text{commune}_q,t}$ and $I_{\text{city},t}$ are the quartier-specific number of infectious individuals on day t, i.e. $I_{\text{CSI}_q,t}$ is the number of infectious individuals in the particular CSI that contains quartier q, etc. The parameters $N_{\cdot}$ represent the appropriate scale-specific total population sizes for each quartier, CSI catchment area, commune and the citywide total.

At each time-step, susceptible children are assumed to be infected with a binomial probability $p_{q,t+1}$, i.e. $I_{q,t}+1 \sim \text{Binom}(S_{q,t+1},\ P_{q,t+1})$. Once infected, the

infectious process is assumed to be deterministic; children are infected but not infectious (latent) for 10 days and infectious for 6 days (Heymann 2004). Upon recovery, children progress into the removed class and are assumed immune for the remainder of the epidemic (and the remainder of their life).

We evaluated the result of the ORV in terms of response time and the target coverage percentage. For enhanced realism, we assumed a 15-day delay between the decision to intervene and the implementation of the Q4 ORV, based on MSF experience (Medecins Sans Frontiers 1999). Once vaccinated, children were assumed to progress through a period of 3 days during which they have partial protection (50%) before full immunity (Heymann 2004). We quantified the effect of the ORV as the ratio of the predicted final size of the epidemic with intervention to that without.

Given the estimated citywide VC (see above) and natural immunity, we assumed that 30% of children under 15 years of age were susceptible (not vaccinated, unsuccessfully vaccinated or have no naturally acquired immunity). Of these, we assumed that 75% would be children between 6 and 59 months based on the age pyramid (see above) and an assumption that prior immunity (natural or vaccine provided) was higher in the 5–15-year group than in the younger age group. Vaccines were assumed distributed at random across the risk group. Vaccine efficacy during the ORV was assumed to be 85% (with allowance for the partial immunity during the 3 days just after vaccination; WHO 2004*b*).

We simulated 1000 stochastic epidemics over a period of 365 days beginning from an index case located in the same quartier where the first case was reported in commune 1. A paired Wilcoxon rank sum test was used to evaluate the performance of the model fit: if the p-value obtained is greater than 0.05, then the null hypothesis that simulated and observed epidemic curves are from the same distribution cannot be rejected. For this assessment, only simulated epidemics that 'took off'—for which at least 10 cases were predicted—were included. We performed the statistical test for each simulation run and for the median epidemic.

2.4. Model calibration

As the surveillance data available to calibrate the model included the ORV campaign targeting 50% of children aged between 6 and 59 months living in Niamey over a 10-day period at week 23 (day 161), we calibrated the model including the campaign. We assumed that only a fraction of cases would be detected by the surveillance system, estimated at 50% based on previous analyses (Médecins sans Frontières 1996; Arudo *et al.* 2003; Grais 2006*b*).

Previous research on the data for this epidemic provided the estimates of the overall transmission rate within the city (Grais 2006*a*,*b*), following the removal Q5 method developed by Ferrari *et al.* (2005). The assumptions of this method are that on the time-scale of the *epidemic generation time* (Δt=latent+infectious period) of around two weeks, the epidemic progressed according to a chain-binomial model (e.g. Bailey 1957; Ferrari *et al.* 2005), in which the binomial denominator is the pool of susceptible individuals, S_t, and the associated probability distribution for the expected number of new cases, $I_{t+\Delta t}$, is

$$P(I_{t+\Delta t} = I) = \binom{S_t}{I}(1-\mathrm{e}^{-\beta S_t I_t})^I(\mathrm{e}^{-\beta S_t I_t})^{S_t - I}. \quad (2.2)$$

Noting that $S_t = S_0 - \sum_{j=1}^{t} I_j$, where S_0 is the initial number of susceptible individuals, we can write a full likelihood for the time-series of case counts, I_t, in terms of the overall (i.e. ignoring within-city spatial heterogeneities) transmission rate, β, and the initial number of susceptibles, S_0, according to standard likelihood theory (Ferrari *et al.* 2005).

To carry out this estimation, the time-series of day-specific case reports were aggregated in two-week time-intervals as detailed by Grais *et al.* (2006*a*). Based on this prior analysis and our assumption that transmission was more rapid at smaller spatial scales, the scale-specific transmission rates were chosen and fixed as 10 for local transmission within a quartier, 5 for transmission across quartiers within any given CSI catchment area, 2.5 between catchment areas within any given commune and 1.25 for citywide transmission.

2.4.1. Scenario analysis. Our principal aim was to study the impact of the intervention and explore the consequences of any earlier implementation. Although the survey conducted just after the epidemic provided an estimate of baseline pre-intervention VC (approx. 60%), we also used the model to examine higher (90%) and lower (50%) level of coverage and their associated predicted outcomes, given the ORV intervention strategies. We further explored several other candidate interventions by comparing proportions of cases potentially prevented by interventions at different times in the epidemic, the proportion of children targeted during the outbreak response intervention and different intervention lengths. We examined decisions to intervene at 60, 90 and 120 days from the start of the epidemic, with proportions of children (except those children who were classified as infectious) vaccinated between 30 and 100% at 10% increments. We explored vaccination interventions lasting 6, 10 and 14 days, and the difference between targeting only children aged between 6 and 59 months and targeting all children aged 6 months to 15 years. Results are presented as the median percentage of cases potentially averted compared to final epidemic size in the absence of intervention.

3. RESULTS

Overall, the median forecast epidemic curve from 1000 simulations is in good agreement with the observed dynamics of the 2003–2004 epidemic (paired Wilcoxon rank sum test, p=0.25; figure 3). No cases were predicted in 6% of 1000 simulations; in those runs for which cases were reported, 92.3% were in good agreement with the observed dynamics (paired Wilcoxon rank sum test, α-level=0.05).

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In commune 1, where the epidemic began, cumulative cases were overestimated by a median of 0.5% (paired Wilcoxon rank sum test, $p=0.63$). The model performed less well in commune 2 (paired Wilcoxon rank sum test, $p=0.81$) and commune 3 (paired Wilcoxon rank sum test, $p=0.57$), where cumulative cases were overestimated by a median of 11.3 and 13.4%, respectively, over 1000 epidemics (figure 2). The reasonable fit shown here—despite the simplicity of the model—gives us some confidence in our predictions regarding different scenarios of intervention.

Comparing the simulated epidemic with and without the implemented vaccination intervention with an objective of vaccinating 50% of children between 6 and 59 months at week 23 (day 161) from epidemic onset, we estimated a median of 7.6% [4.9, 8.9] cases averted (figure 3).

3.1. Scenario analysis

First, we examined the impact of the implemented intervention under two extreme scenarios of population susceptibility. Assuming only 10% of the eligible population susceptible, vaccinating children between 6 and 59 months yielded a median estimated reduction of 55.9% [41.1, 59.3] cases. Expanding the age range to include children aged 6 months to 15 years yielded a median reduction of 70.8% [58.6, 88.6] cases compared with no intervention. Less benefit was seen when we assumed a VC of 50% in the eligible population susceptible. In this case, i.e. vaccination of children between 6 and 59 months, we estimated that a median 18.1% [12.4, 20.2] of cases could be averted.

Second, we explored the proportion of cases potentially averted for interventions targeting from 30 to 100% of non-infectious children aged 6–59 months with a decision to intervene at 60, 90 and 120 days from the start of the epidemic (figure 4). A target proportion of 50% of children (except ill children) resulted in up to 38, 27 and 20% of cases averted for campaigns at 60, 90 and 120 days from the start of the epidemic, respectively. For campaigns at day 60, increasing the target proportion vaccinated from 30 to 40% led to up to an additional 18% of cases averted. Increasing the proportion vaccinated between 40 and 90% led to 5–9% additional cases averted for each 10% increase in coverage. There was little benefit in increasing the proportion vaccinated from 90 to 100%. Campaigns at 90 and 120 days followed a similar pattern, with the greatest proportion of cases averted when the proportion vaccinated was increased from 30 to 40%, and no benefit was observed in increasing coverage from 90 to 100%.

Third, we examined the proportion of cases averted if the intervention targeted all children aged 6 months to 15 years. For a campaign with an objective of vaccinating 50% of non-infectious children aged 6 months to 15 years, up to 93% of cases were potentially averted at day 60, 81% at day 90 and 52% at day 120. Expanding the target population resulted in substantially more cases averted, but little additional gain was seen when increasing the proportion vaccinated during the intervention above 70% (figure 5).

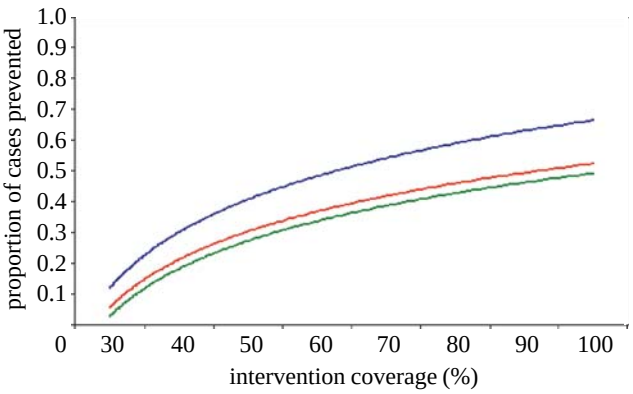

Figure 4. Estimated proportion of cases averted with a vaccination intervention targeting children aged between 6 and 59 months for a vaccination intervention lasting 10 days. The blue line shows an intervention at 60 days, the red line an intervention at 90 days and the green line an intervention at 120 days.

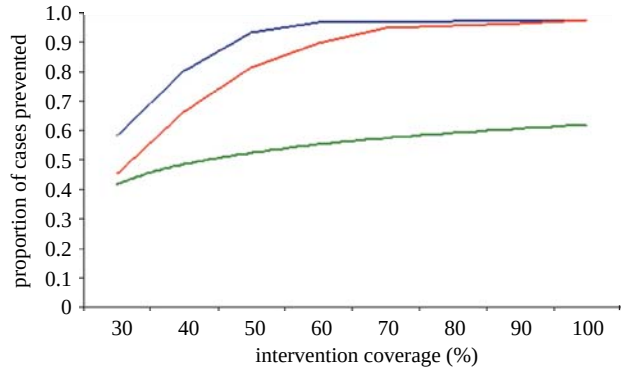

Figure 5. Estimated proportion of cases averted with a vaccination intervention targeting children aged 6 months to 15 years for a vaccination intervention lasting 10 days. The blue line shows an intervention at 60 days, the red line an intervention at 90 days and the green line an intervention at 120 days.

Increasing the length of the intervention from 10 to 14 days, holding all else constant, did not markedly change the forecast number of cases prevented (data not shown). There was no difference in the forecasted proportion of cases prevented when all age groups were targeted at vaccination target levels above 60%. For intervention vaccination objectives under 60%, there was a median 1% increase in the number of cases averted. Similarly, reducing the intervention length to 6 days, holding all else constant, with target intervention coverage levels above 60% gained a median of an additional 1% of cases averted. In contrast, the 6-day intervention at lower coverage levels led to an additional median 2% increase in averted cases with an intervention proportion to be vaccinated of 50%, 3% of averted cases at 40% vaccinated and 4% of averted cases at 30% vaccinated.

4. DISCUSSION

Our analysis shows that substantial numbers of measles cases may be averted through the timely implementation of measles ORV. Moreover, the proportion of

cases averted is associated with the VC obtained and the number of birth cohorts targeted for vaccination. The operational implication of this analysis is that, from a public health perspective, it may be preferable to intervene earlier, across a wide age range even if a high intervention VC is not feasible, than waiting until sufficient resources are mobilized to conduct a mass campaign capable to reach 90–100% of targeted children. The key result is that ORV can be highly effective if the response is fast with respect to the spread of the epidemic. In Niamey, where epidemic spread is slow due to the spatial structure and mixing within the city, outbreak response may be particularly effective. While the predictions herein are specific to the Niamey model, we would expect the general utility of ORV to hold for any situation where the spread is slow relative to the response. Exploring further the relationship between spatial spread and reactive vaccination is an important area for future research.

Early interventions may work in two ways: first, vaccination may immunize a child before they become infected; and second, the vaccination response can slow down the epidemic and thereby reduce the total number of unvaccinated people who would be infected during the current outbreak. An early but inefficient response could be working in both ways, mostly through the first effect, but partly through the second.

We estimate that as a result of the intervention in Niamey, where the target was 50% of children aged between 6 and 59 months and the intervention took place about 161 days after the epidemic began, approximately 7% of cases were averted. Had this same intervention occurred earlier in the epidemic, we estimate from our model that up to 38% of cases could have been averted if the intervention had occurred at day 60 of the epidemic, up to 27% if it had occurred at day 90 and up to 20% if it had occurred at day 120.

Our results highlight the potential benefits of rapid intervention, even if a high intervention vaccination objective is not possible. Targeting children aged 6 months to 15 years was much more effective in preventing cases than limiting vaccination to children aged 6–59 months. Experience in many parts of the world has found measles vaccination campaigns across wide age ranges to be much more effective in preventing periodic measles outbreaks (Arudo *et al.* 2003; Kambire *et al.* 2003; Munyoro *et al.* 2003). This is likely due to the role older children play in transmission to younger children and also the importance of limiting opportunities for virus reintroduction through population movement.

In any large measles epidemic, ORV averting 7% of cases can mean many lives saved. A retrospective mortality survey after the Niamey epidemic estimated a case fatality ratio in children under age 5 of 3.9% (Grais *et al.* 2007). In 2005, a mass vaccination campaign targeting children under age 15 was conducted in Niger. Surveillance data will be an important indicator of whether wide age range and wide geographical area campaigns impact measles epidemics in future years.

Our model explicitly took into account the slow spatial progression of the epidemic (Grais 2006*b*). As we expected, the analysis showed that the timing of the intervention plays a more important role than the proportion of children vaccinated. Intervening very early in the epidemic (60 days after the start), at relatively low VC, still led to a substantial proportion of cases averted. The added benefit of intervening at day 60 decreased for vaccination objectives over 60%. The same pattern emerged when intervening 90 days after epidemic onset, where little added gain was seen for target coverage levels above 70%. Interventions 120 days after epidemic onset still led to more than half of reported cases averted, when targeting all children aged 6 months to 15 years. A more intensive intervention (lasting for 6 days, versus 10 or 14 days) yielded slightly more averted cases than a longer intervention. Our results are also in agreement with a recent theoretical analysis, which found that the average outbreak size grew exponentially with the delay from the start of an outbreak to the implementation of an intervention, highlighting the importance of early intervention (Drake 2005).

Our goal was to identify the key factors driving the number of potentially averted cases, and, as with all models, ours simplifies reality in a number of respects. Although model simulations were in agreement with the observed epidemic dynamics, we did not consider the details of the spatial dynamics. We are currently exploring the data using a full meta-population model with an explicit distance function for transmission. An additional area for refinement would also be to consider different assumptions concerning the distributions for the latent and infectious periods. Our analysis was constrained by the use of constant contact rates in the two age groups. Previous research on the force of infection for measles in pre-vaccination England and Wales has shown it to be strongly age dependent (Grenfell *et al.* 2001). In cities like Niamey, or other dense African cities, there is likely to be much greater inter-age-group contact, due to differences in household structure and formal education (Remme *et al.* 1984; Scott *et al.* 2004), and although we suspect that the impact of this simplification on our findings may not be significant, this warrants further investigation. We also assumed that the proportion of susceptibles was the same in all quartiers, whereas a more refined model would consider heterogeneities.

Although we used surveillance data from a well-documented epidemic to calibrate the model and began to estimate the impact of ORV, the results presented here are only suggestive of potential trends. The individual-based computational model we used provided a preliminary analysis to expose questions for future research and where data collection needs to be focused. A more detailed model, exploring different timeframes and modes of intervention, is required. This can be accomplished via theoretical models of epidemic diffusion and through a more in-depth analysis of other well-documented epidemics in similar contexts. We chose scenarios that were considered operationally feasible. An in-depth analysis considering different population immunity profiles and a more complete range of scenarios is required to investigate how the lessons learned here may be applied to other contexts.

Future collection of epidemiologic, demographic and geographical data in other measles epidemics in similar settings is also a high priority.

The model presented here captures only one component of the complex decision whether or not to implement measles ORV activities in an urban area, and we were able to evaluate the impact of this intervention with the aid of retrospective data. Early intervention depends upon a sensitive and functioning surveillance system and rapid response capacity, both of which may be difficult to achieve in resource-poor contexts. Moreover, most large measles outbreaks tend to occur in countries with poorly performing health systems with chronically low routine immunization coverage. Determining whether a measles epidemic is occurring remains difficult, especially in contexts where surveillance systems are neither comprehensive nor sensitive, and data from previous years are unavailable for comparison. ORV in these settings will often occur late in the timeline of an epidemic due to difficulties caused by inadequate surveillance, poor logistics, competing public health priorities, and cost and lack of trained personnel.

The decision to implement measles ORV activities in an urban area also depends on the population size, previous routine measles immunization coverage, history of vaccination campaigns and spatial characteristics of the city itself. In a city such as Kinshasa, DRC, where approximately one-half of the population is under age 15, this means that an intervention during an epidemic could target potentially millions of children, which is not operationally feasible. An additional constraint during interventions is that an 'efficient' campaign, like that modelled here, is selective (targeting only children who were not previously vaccinated). This is not always realistic in settings where children do not always have comprehensive medical records and where the precise age of children may not be available. Further, as providing children with a second-dose of measles vaccine affords increased protection, efficiency must be balanced with issues of logistics, economic and ethical constraints.

We demonstrate here that implementing a measles ORV activity early in a measles epidemic in a resource-poor urban setting with chronically low measles VC, like Niamey, may lead to substantial reductions in morbidity and subsequent mortality. However, ultimately the decision whether or not to intervene and the means to do so depend upon the political will of public health authorities, and weighing the potential number of cases averted with the economic and political costs of conducting a measles vaccination campaign.

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