Empirically Calibrated Simulation Experiment of Non-Medical Vaccine Exemptions and Disease Outbreak Potential in California

An increasing number of children are entering U.S. kindergartens and childcare centers without having received state-mandated vaccination. It is primarily due to the rise of “non-medical exemptions” (NMEs) from school vaccination requirements—exemptions that are based philosophical/religious rather than medical reasons (Omer et al. 2006). NMEs tend to cluster spatially and create pockets of low immunization coverage (Atwell et al. 2013; Birnbaum et al. 2013; Carrel and Bitterman 2015; Imdad et al. 2013; Lieu et al. 2015; Omer et al. 2008; Safi et al. 2012). Previous simulations studies show that cluster of beliefs about vaccination increases the chance of outbreaks (Eames 2009; Salathé and Bonhoeffer 2008). The effects of theoretical network characteristics (e.g., influence process, small world vs random network, and different networks for influence and infection transmission) have been examined.

This study takes a different approach and calibrate the model with the actual spatial distribution of NMEs in California. The synthetic population contains fine-grained details of the socio-demographic heterogeneity (e.g., race/ethnicity, education) across space. We also empirically calibrate the social contexts for children to come into contact with each other using actual locational data.

The model is then used to examine the effects of NMEs and social contexts on disease outbreak potential. Due to high vaccination coverage in developed countries, vaccine preventable disease outbreaks are highly stochastic events. Large-scale, empirically calibrated simulation models are needed to identify conditions that would affect the probability of outbreaks and explore what-if scenarios, e.g., a drastically higher prevalence of NMEs or potential intervention strategies (Eubank et al. 2004; Ferguson et al. 2005; Halloran et al. 2002).

Data and Methods

Population. The agents in the simulation are all three million 3-10 year-old children in California in 2010. Figure 1 describes the synthetic population and their assignment to focal points (i.e., schools and shopping center). The population can be extended to a wider age range to capture the effect of NMEs on children too young to be vaccinated and older children whose protection from vaccination has begun to wane.

Prevalence of NMEs. The number of NMEs in each school is assigned according to the NME data published by the Immunization Branch of the California Department of Public Health. The Immunization Branch have records of the number of NMEs among entrants to childcare centers, public and private kindergartens.

Disease transmission parameters. In the preliminary runs, 10 cases are infected randomly. The number of secondary cases an infected child generates depends on (1) transmission probability after contact, (2) infectious period, and (3) probability of contact under different contexts. In the simulation, the infection probabilities and infectious periods are chosen to mimic the transmission of measles. The transmission probabilities after contact are set to be 3% if the uninfected child is vaccinated and 90% if she is unvaccinated. The infectious period is set to be about 4 days before symptoms appear, after which it is assumed that the child will be quarantined.

The probabilities of contact under different social contexts are chosen arbitrarily. Robustness test will be conducted to test the model sensitivity to these parameters. For the initial runs, the probabilities of contact are set to be 100% between siblings, 10% between same grade classmates, 0.1% between students in the same school but not the same grade, and 0.001% if they go to the
same shopping center. The shopping centers assume the role of community focal points outside of school and can be replaced by other types of focal points (e.g., parks, library, or community center).

Figure 1. A. Population Density: 3 million children aged 3-10 with the associated race/ethnicity and age characteristics are distributed according to census 2010 block-level data. B. Socio-demographic characteristics: Distributions of median property values and % of mothers working at the block group level from the census are used to impute data at the block group level. Birth record data from 2001 to 2007 are used to impute mothers’ ages and mothers’ years of education for each race/ethnicity group in each zip code. They are also used to impute sibship size. C. School types: A model based on the National Household Education Survey data assigns probabilities of attending a (1) child care center, (2) Head Start program, (3) public elementary school, and (4) private elementary school according to a child’s age and socioeconomic status. D & E. Assigning children to focal points by distance and capacity: Conditional on the
probabilities of attending particular types of schools, children are assigned to a school according to (1) distance to school and (2) school capacity. Shopping centers serve as an alternative venue to meet outside of school. Families “attend” up to three shopping centers according to the inverse distances.

**Expected Results**

The simulation model will be used to examine the disease outbreak potential at the current level of NMEs at different values of contact probabilities. The results will be compared to the scenario that the current population has the prevalence and spatial distribution of NMEs in 1992. The model can quantify the relative contributions of (1) the spatial clustering and (2) prevalence of the current NMEs pattern to the increase in disease outbreak potential. The effects of hypothetical distributions of NMEs will also be explored.

The model is also expected to identify the relative contribution of different social contexts to outbreak potential. Figure 2 shows some preliminary results. The full model scenario allows contact under all three social contexts—home, schools and shopping centers. The no sibling effect scenario only allows contact at schools and shopping centers (i.e., each family has only child). The no mall effect scenario allows contact at school and home. 20 simulations were run under the three scenarios. The number of cases generated after 30 weeks in each of the 20 runs are plotted from the lowest number of cases to the highest number of cases by scenario.

The results show that, although disease outbreaks are relatively rare, epidemics can happen given the model parameters. Not surprisingly, allowing social contact under all three contexts leads to the highest disease outbreak potential. Reducing contact outside home and school reduce the average size of the outbreaks. However, contact at home have the greatest impact on outbreak potential. This finding cannot be simply explained by the number of secondary cases that are inflected by at home. (If it was the case we should expect outbreak potential that are about half the size of the full model.) Nonetheless, the finding can be explained by the fact that sibling links provide many local bridges across types of schools (preschool and kindergarten) and grades, which make the network much more permeable for disease transmission.

![Figure 2](image_url)

**Figure 2. Population-level impact of contact under different social contexts on disease outbreak potential**
Implications

Whether NMEs should be permitted is heavily debated. Many states are considering tightening their legislation in light of recent outbreaks of Pertussis and Measles in the U.S. (Clemmons et al. 2015; Winter et al. 2012). In California, Senate Bill 277 was signed into law on June 29, 2015, which will disallow personal and religious belief exemptions from school vaccination requirements. However, some advocates of NMEs are seeking ways to repeal Bill 227 before it takes effect in 2016. This empirically calibrated simulation experiment on the potential effect of a lower prevalence of NMEs on disease outbreak potential and herd immunity are relevant to the policy debates.

References


