Personal Belief Exemptions to Vaccination in California: A Spatial Analysis
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abstract

BACKGROUND: School vaccination rates in California have fallen as more parents opt for personal belief exemptions (PBEs) for their children. Our goals were to (1) spatially analyze PBE patterns over time, (2) determine correlates of PBEs, and (3) examine their spatial overlap with personal medical exemptions (PMEs).

METHODS: PBE and PME data for California kindergarten classes from the 2001/2002 to 2013/2014 school years were matched to the locations of schools. Nonspatial clustering algorithms were implemented to group 5147 schools according to their trends in PBE percentages among kindergartners. Cluster assignments were mapped and hotspot analysis was performed to find areas in California where schools sharing trends in PBEs over time were colocated. Schools were further associated both with school-level data on minority enrollment and free and reduced price lunch participation and with charter/private and rural/urban status. Spatial regression was implemented to determine which school-level variables were correlated with PBE rates in the 2013/2014 school year.

RESULTS: Distinct spatial patterns are observed in California when PBE cluster assignments are mapped. Results indicate that schools belonging to the “high PBE” cluster are spatially buffered from those in “low PBE” areas by “medium PBE” schools. Further, PBE rates are positively associated with the percentage of white students, charter status, and private schools.

CONCLUSIONS: Hotspots of high PBE schools are in some cases colocated with schools that have elevated PME rates, prompting concern that herd immunity is diminished for school populations where students have no choice but to remain unvaccinated.

WHAT’S KNOWN ON THIS SUBJECT: An increasing number of children are unvaccinated at entry into public schools, potentially endangering children who cannot be vaccinated for medical reasons and threatening herd immunity. Voluntary exemptions from immunizations vary geographically and by parental characteristics.

WHAT THIS STUDY ADDS: We find that exemption behavior is highest in peripheral areas of cities and that specific types of student populations are associated with high exemption rates. Additionally, there is spatial overlap between clusters of high personal exemption and medical exemption populations.
An ongoing measles outbreak has sparked heated debate about vaccine-preventable diseases (VPDs) and the choice of parents to not vaccinate their children. Parents who choose to not vaccinate their children are primarily motivated by concerns over vaccine safety or feelings that children are not at risk for these VPDs due to their geographic location.1–6 Measles elimination was maintained via high rates of vaccination coverage, and there is concern that the protective effect of herd immunity will wane as large numbers of children remain un- or underimmunized, resulting in the reemergence of VPDs in the United States.7,8 Studies find that when belief exemptions to vaccination guidelines are permitted, vaccination rates decrease.9,10 Additionally, vaccination refusal is associated with increased infection with and transmission of VPDs in unvaccinated children.11–15

In 2003, May and Silverman16 warned against the rise in families claiming personal belief or other nonmedical exemptions to public school requirements for vaccination and their tendency to cluster geographically. Data have indicated that clusters of high exemption rates are spatially congruent with outbreak clusters of pertussis and measles.17–20 Within California, there is high heterogeneity in the rates of personal belief exemptions (PBEs), with northern and southern coastal regions exhibiting higher PBE proportions.21,22 This spatial heterogeneity exists at higher geographic scales as well, with high variation in exemption rates among US states.23 High exemption rates have been correlated with schools that have higher numbers of white students and greater wealth, and with charter and private schools.17,24

The current study examines PBE data from California between the 2001/2002 and 2014/2015 school years to determine spatial patterns of PBEs in kindergartners as well as the type of school populations associated with higher rates of PBEs. We explore the spatial overlap between schools with high PBE rates and high rates of personal medical exemptions (PMEs) for students who are unable to receive childhood immunizations. This analysis identifies locations of children who are unprotected from VPDs not by choice and are surrounded by other students who remain unprotected because of parental choice.

**METHODS**

The California Department of Public Health (CDPH) records the total number of PBEs and PMEs for individual schools. PBEs recorded before the 2014/2015 year represent both philosophical and religious exemptions. Data were acquired from the CDPH on the number of PBEs and PMEs and total enrollments in kindergarten classes from the 2001/2002 through the 2014/2015 school years.25 CDPH suppresses data from schools with fewer than 10 kindergartners. Proportions of kindergartners claiming a PBE or PME were calculated for each school in each school year.

Using unique school codes, we then matched CDPH data to the locations of schools and their sociodemographic characteristics from California Department of Education (CDE) data.26 School locations were geocoded by using latitude and longitude coordinates from (1) the CDE dataset, (2) geoprocessing services provided by Texas A&M University,27 and (3) Google Earth. Ninety-eight schools were assigned as either suburban or nonsuburban.28,29

Descriptive maps of PBEs and PMEs in 2001/2002 and 2013/2014 were generated to visualize how rates have changed over both space and time. Interpolation methods create a continuous surface over space based on observed measurements at specific points. Inverse distance-weighted methodology was used to interpolate PBE and PME rates in these 2 school years, where estimations of PBEs and PMEs at unsampled points were more strongly influenced by nearby schools rather than those far away.

PBE proportions within individual schools are likely to be highly correlated over time, given that the population of students (and their parents) who attend each school does not dramatically change year to year. The nonspatial clustering algorithm mclust (Model-Based Clustering, Classification, and Density Estimation)30,31 was used to group schools according shared PBE characteristics across the years of the study. Model clustering algorithmically partitions observations into groups based on similarity of n characteristics; in this case, annual proportions of PBEs, varying the size and shape constraints and total number of clusters detected. A reverse-scored Bayesian information criterion (BIC) was used to determine which number of clusters and which size/shape clusters best fit the data, where the highest BIC is selected. In addition to
accounting for correspondence in the behavior of schools’ PBE rates over the 2001/2002 to 2013/2014 school years, the clustering algorithm reduced the complexity of our outcome variable of interest, from individual PBE proportions for 13 separate years to a multinomial indicator of cluster membership. As mclust will not execute on datasets containing missing values, only schools with PBE data in all years of the study (ie, not schools that open/closed during the duration of the study) were included in the cluster and subsequent regression analysis (n = 5147).

Cluster assignments were mapped and a local Moran I test determined whether cluster assignments were spatially autocorrelated and the location of significant hotspots of cluster membership. Local Moran I tests indicate areas of significantly high density of schools with the same cluster assignment. “High-high” schools are those with elevated PBEs surrounded by other high PBE schools, “low-low” are low PBE schools surrounded by low PBE schools, and “transitional” schools are those that are dissimilar from their neighbors.

To determine if cluster membership varied significantly according to hypothesized covariates, $\chi^2$ tests were performed. Within the $\chi^2$ tests, a percentage deviation also was calculated to indicate the degree to which the observed frequency of cluster membership within that covariate category (eg, charter versus noncharter) deviated from what is expected under a null hypothesis of even cluster membership across categories.

Spatial multivariable linear models were run in the spdep (Spatial Dependence: Weighting Schemes, Statistics and Models) package in R, by using 2013/2014 PBE proportion as the outcome variable and the previously mentioned sociodemographic variables as predictors. Spatial models control for spatial dependence among the variables (ie, that people live near people who are like them). This allows us to understand how factors such as the percentage of students who are white are correlated with PBE percentages without the inflating effect of spatial autocorrelation. Spatial weights were calculated based on the nearest neighbors to a school, 3 sets of weights were generated (knn = 3, 5, 7).

Although 2014/2015 data were not included in the model clustering or spatial regression, the current PBE rates in schools are highly relevant to the ongoing measles outbreak. Scatterplots of PBE versus PME proportions were generated and schools that fell below the 90% to 95% thresholds generally considered necessary for herd immunity to measles to be effective were mapped. High PBE hotspots as determined by local Moran I were overlaid with interpolated data on school-level PMEs to evaluate spatial concordance.

FIGURE 1
Interpolated rates of PBEs and PMEs in California schools during the 2001/2002 and 2013/2014 school years. Darker shading indicates higher rates of exemptions.
RESULTS

PBE percentages in the 2013/2014 school year ranged from 0% to 79.1%, and PMEs ranged from 0% to 17.3%. In contrast, PBE percentages in the 2001/2002 school year had a range of 0% to 63.2% and PMEs ranged from 0% to 19.23%. PBE rates increased across much of the state, with the exception of persistently low rates in the Central Valley (Fig 1). Although PMEs do not increase as much as PBEs do, areas reporting no PMEs decreased between 2001/2002 and 2013/2014.

A 3-cluster option best fit the PBE data, as determined by the highest BIC score. The mclust model choice and the number of clusters were robust for samples down to approximately 20% of the full dataset. The mean proportion of PBEs among schools in each cluster across years was calculated and provides an indication of how schools were assigned to each cluster (Fig 2).

Cluster 1 is composed of schools with low average PBE proportions across all years of the study. Cluster 2 schools have higher PBE proportions than those in cluster 1, with an increase observed staring in the 2008/2009 school year. Cluster 3 schools have high PBE proportions in the 2001/2002 school year and these PBE proportions climb over time. Thus, the clustering algorithm has divided schools into “low,” “medium,” and “high” PBE schools (Fig 3).

Local Moran I tests show locations of significantly nonrandom hotspots of cluster membership. A map focused on Southern California shows that statistically significant high-high hotspots (meaning schools sharing a cluster 3 designation) are located primarily along the coast (Fig 4). Transitional hotspot schools (meaning schools that belong to either the medium PBE cluster [cluster 2] or are neighbored by schools with higher or lower cluster assignments) are located between these high-high hotspots and the central urban area of Los Angeles, primarily composed of low-low hotspots (all schools in cluster 1 neighbored by schools in cluster 1).

School profiles by cluster assignment are shown in Table 1. The $\chi^2$ tests indicate that sociodemographics in schools vary significantly by cluster assignment (Table 2).
numbers of private schools and public charter schools are included in the high PBE cluster than expected under a null hypothesis of nondifferential group membership. Among public schools, those without a religious affiliation have higher than expected membership in the high PBE cluster (cluster 3), whereas religious schools have higher than expected membership in the low (cluster 1) and medium (cluster 2) PBE clusters.

More suburban schools are assigned to the high PBE cluster than expected. Public schools with high proportions of white students had higher than expected membership in the low and medium PBE clusters and lower than expected membership in the high PBE cluster, whereas schools with low proportions of white students had higher than expected membership in the low PBE cluster and lower than expected membership in the medium and high PBE clusters.

The situation reverses for FRL. Public schools with high percentages of students receiving subsidized lunches have higher than expected membership in the low PBE cluster and lower than expected membership in the medium and high PBE clusters, whereas schools with few students receiving FRL have low membership in the low PBE cluster (cluster 1) and medium and high PBE cluster membership. Relationships among cluster membership, white percentages, and FRL percentages are strongest for the low and high PBE clusters, with the medium PBE cluster exhibiting similar but weaker patterns to the high PBE cluster.

Given the spatial dependence in cluster membership, spatial autoregressive multivariable models were implemented to explore the association of sociodemographic characteristics with 2013/2014 PBE proportions. PBE rates, rather than cluster assignments, were used because of methodological limitations in spatial multinomial modeling; however, cluster assignments strongly correlate with 2013/2014 PBE rates. Parameter estimates from the final models are seen in Table 3. In public schools, the percentage of students who are white or on FRL and being a charter school are significant positive predictors of PBE rates. Suburban location is a significantly negative predictor. There is a significant interaction between FRL percentages in a school and charter status, with charter

### TABLE 1
Counts of Schools Assigned to Clusters 1 to 3, Stratified by Potential Correlates of PBE Rates

<table>
<thead>
<tr>
<th>Cluster</th>
<th>1 (Low)</th>
<th>2 (Medium)</th>
<th>3 (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total, n (%)</td>
<td>1186 (23)</td>
<td>2849 (55.3)</td>
<td>1112 (21.6)</td>
</tr>
<tr>
<td>Public, n (%)</td>
<td>1040 (87.6)</td>
<td>2460 (86.3)</td>
<td>782 (70.3)</td>
</tr>
<tr>
<td>Charter</td>
<td>10 (0.8)</td>
<td>80 (2.8)</td>
<td>63 (5.7)</td>
</tr>
<tr>
<td>Private, n (%)</td>
<td>146 (12.3)</td>
<td>389 (13.7)</td>
<td>330 (29.7)</td>
</tr>
<tr>
<td>Nonreligious</td>
<td>12 (1)</td>
<td>67 (2.4)</td>
<td>118 (10.6)</td>
</tr>
<tr>
<td>Religious</td>
<td>134 (11.3)</td>
<td>322 (11.5)</td>
<td>212 (18.1)</td>
</tr>
<tr>
<td>Rural-urban commuting area, n (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban</td>
<td>79 (6.7)</td>
<td>182 (6.4)</td>
<td>169 (15.2)</td>
</tr>
<tr>
<td>Nonsuburban</td>
<td>1107 (93.3)</td>
<td>2657 (93.6)</td>
<td>943 (84.8)</td>
</tr>
<tr>
<td>2013/2014 white, n (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0%–25%</td>
<td>1016 (85.7)</td>
<td>1404 (49.3)</td>
<td>90 (8.1)</td>
</tr>
<tr>
<td>26%–50%</td>
<td>20 (1.7)</td>
<td>657 (23.1)</td>
<td>185 (16.6)</td>
</tr>
<tr>
<td>51%–75%</td>
<td>4 (0.3)</td>
<td>369 (13.1)</td>
<td>377 (33.9)</td>
</tr>
<tr>
<td>76%–100%</td>
<td>0 (0)</td>
<td>28 (1)</td>
<td>130 (11.7)</td>
</tr>
<tr>
<td>NA</td>
<td>146 (12.3)</td>
<td>389 (13.7)</td>
<td>330 (29.7)</td>
</tr>
<tr>
<td>2013/2014 FRL, n (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0%–25%</td>
<td>8 (0.7)</td>
<td>445 (15.6)</td>
<td>269 (24.2)</td>
</tr>
<tr>
<td>26%–50%</td>
<td>30 (2.5)</td>
<td>452 (15.9)</td>
<td>207 (18.8)</td>
</tr>
<tr>
<td>51%–75%</td>
<td>101 (8.5)</td>
<td>582 (20.4)</td>
<td>201 (18.1)</td>
</tr>
<tr>
<td>76%–100%</td>
<td>901 (78)</td>
<td>980 (34.4)</td>
<td>105 (9.4)</td>
</tr>
<tr>
<td>NA</td>
<td>146 (12.3)</td>
<td>389 (13.7)</td>
<td>330 (29.7)</td>
</tr>
</tbody>
</table>

NA, refers to private schools, given that data on race and FRL % were unavailable for private schools.

FIGURE 4
Location of schools designated as belonging to statistically significant hotspots, as determined by the PBE cluster assignment, within the Los Angeles area. Schools that were not members of statistically significant hotspots of high-high, low-low, or transitional PBE clusters are not shown.
status moderating the positive relationship between FRL and PBE. In private schools, religious affiliation is significantly negatively associated with elevated PBE rates, whereas suburban status has a positive but nonsignificant relationship with PBEs.

The maximum rate of PBEs in California kindergartens increased from 79.1% in 2013/2014 to 84.21% in 2014/2015. The colocation of schools with elevated PBEs and elevated PMEs is of particular concern given the rising numbers of students claiming philosophical exemptions to immunizations. Figure 5A shows the rates of 2014/2015 PBEs and PMEs in schools. With PBE or PME rates higher than 5% and 10% are highlighted because vaccination rates below 90% to 95% are considered dangerous to measles herd immunity. Figure 5B indicates the location of schools that do not meet this threshold.

A local Moran I on PBE rates in 2014/2015 indicates several statistically significant areas of the state where schools with high PBE rates are neighbored by other schools with high rates. These are overlaid on interpolated rates of PMEs from the same school year to indicate where herd immunity shortfalls may pose the greatest risk to students who cannot medically be vaccinated (Fig 6). There are a few areas of spatial overlap, including in the areas south of Los Angeles, near Santa Cruz, and around Redding in the north.

**DISCUSSION**

The study addresses gaps in the cited literature. By using a longer time span than other studies, we are better able to elucidate temporal patterns of PBEs in California. Previous studies primarily use areal (county, zip code, Census tract) data, which may not reflect student populations, particularly when multiple schools are assigned to the same area or when considering charter and private schools. Our analysis is at the level of the individual elementary school, avoiding assumptions about whether nearby residents are reflective of student or parent characteristics. Additionally, our use of spatial autoregressive methods accounts for dependency in the spatial patterns and more accurately establishes what characteristics of a student population are associated with increased PBEs.

Data from the 2013/2014 school year versus the 2001/2002 school year indicate that increasing PBEs are not confined to urban areas but are widely distributed across the state (Fig 1). By using trends in PBEs, California schools can be classified into 3 types: those that have high rates of PBEs from 2001/2002 through 2013/2014 (cluster 3), those with lower PBE rates that experience an increase during the years of the study (cluster 2), and those with consistently low rates of PBEs (cluster 1). Although cluster assignments were derived without consideration of spatial relationships, these types of schools exhibit interesting and significantly nonrandom patterns. The Central Valley of California, a primarily agricultural region with small and medium-size cities, is dominated by schools in the low and medium PBE clusters (Fig 3). High PBE cluster schools appear across much of northern California and in the suburban or peripheral areas of large urban areas. The Los Angeles area exhibits a distinctive spatial pattern of cluster assignments, with hotspots of low PBE schools centrally located, ringed by transitional hotspots and high PBE hotspots located along the coast to the north and south (Fig 4).

This could indicate that (1) belief exemptions are diffusing from suburban/peripheral areas of cities inward toward the urban core, or (2) that those with specific vaccine beliefs have left the core and moved to the periphery.
significantly according to cluster membership (Table 2). Low PBE schools are more likely to be public, noncharter, and nonsuburban, with lower percentages of white students and higher percentages of students on subsidized lunch. High PBE schools tend to be charter or private nonreligious schools located in suburban areas with high percentages of white students and low percentages of students receiving subsidized lunch.

Regression results using percent PBEs in 2013/2014 as the outcome of interest indicate a more complex story. Although the general pattern of findings is consistent with the literature, controlling for the inflationary effect of spatial autocorrelation on coefficients and significance values produces unexpected results. Among public schools, the correlation between percentage of students who are white and charter status had the expected relationship, both being significant and positive predictors of increased PBEs (Table 3). Suburban location had a negative relationship with PBEs, opposite of what was anticipated given the maps of cluster assignments. However, determining what is and is not a suburban area is somewhat subjective, and these findings suggest that (1) our definition needs to be revised, (2) that high PBE rates are no longer confined to a suburban ring around cities but have also increased in urban cores, or (3) might be influenced by the location of high PBE schools in smaller urban aggregations. The positive and significant coefficient for percentage of students receiving subsidized lunch was unanticipated, given the literature on philosophical exemptions being positively associated with income. The coefficient for percent FRL is small, and a statistically significant interaction term with charter status suggests that the lack of geographically distinct attendance boundaries for charter schools, with students drawn from across a school district and admitted by lottery, may

FIGURE 5
A, PME versus PBE rates. Schools with PBE and/or PME rates higher than 10% are highlighted with black triangles, those with PBE or PME rates of 5% to 10% are in gray squares. B, Spatial locations of schools that are above this threshold for PBEs or PMEs are indicated.

FIGURE 6
Hotspots of high PBE rates in the 2014/2015 school year overlaid on interpolated PME rates from the same year.
generate schools with simultaneously high FRL and high PBE rates. Among private schools, those with a religious affiliation were significantly associated with decreased PBE rates. Suburban location was not a significant predictor of PBEs in private schools, likely because, similar to charter schools, they draw in students from a variety of areas.

The potential for spatial overlap between schools with high PBE rates and high PMEs is particularly concerning, especially where rates of exemptions exceed 5% to 10% and threaten the protective effects of measles herd immunity. There are more than 800 schools in the 2014/2015 school year that exceeded this threshold of exemptions, primarily because of PBEs. These schools are located principally in the areas surrounding Los Angeles, San Francisco, and Sacramento (Fig 5). Statistical analysis indicates that significant hotspots of PBEs in 2014/2015 also overlap with areas of elevated PMEs (Fig 6). When outbreaks of measles or pertussis do occur, these are places where students with PMEs may be at greatest risk.

Our analysis was confined to those schools with complete PBE and PME data from 2001/2002 through 2014/2015. We thus are not capturing trends and correlates of PBEs and PMEs in schools that either opened or closed during these years. Additionally, our analysis of private schools was limited by data availability, namely that there is not a reliable way to determine the race/ethnicity or FRL profile for these schools. Finally, it is possible that exemptions coded as PME in the dataset actually represent a PBE; whereas a written statement from a physician documenting the medical exemption is required for a PME classification, there could be cases in which a philosophical/religious belief is actually the underlying motivation. However, given the relative ease of registering a PBE before January 2014, when no consultation with a health care professional was required, and the need to consult a health care provider for either a PME or PBE designation since that time, this is likely to characterize a limited number of observations.37

CONCLUSIONS

PBE rates are increasing across California. The decrease in the protective effects of herd immunity are coupled with an increase in the potential for children with PBEs and PMEs to overlap, both within schools and surrounding communities. This suggests that clinicians with PME patients should inquire about the location and type of school the child attends. The steady upward trend in PBEs in schools across cluster assignments and across the rural/urban divide in California suggests that public health departments across the state will need to spatially target schools with riskier populations for containment/quarantine activities in the event of VPD outbreaks. We identify areas where high-risk schools are located in close spatial proximity, indicating key places where intervention and education might reduce the incidence of PBEs, protect herd immunity, and hopefully limit future outbreaks.

ABBREVIATIONS

BIC: Bayesian information criterion
CDE: California Department of Education
CDPH: California Department of Public Health
FRL: free or reduced price lunch
PBE: personal belief exemption
PME: personal medical exemption
VPD: vaccine-preventable diseases

REFERENCES

13. Glanz JM, McClure DL, Magid DJ, et al. Parental refusal of pertussis vaccination is associated with an increased risk of


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