Understanding Disparities in Vaccination Coverage among Indian Children

by

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Dedication

Dedicated to Shanya and Sudhanshu

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List of Abbreviations

BCG – bacille Calmette-Guérin (vaccine against tuberculosis)

DTP1 – First dose of diphtheria and tetanus toxoid with pertussis containing vaccine

DTP3 – Third dose of diphtheria and tetanus toxoid with pertussis containing vaccine

HepB –Hepatitis B vaccine

HepB3 – Third dose of hepatitis B vaccine

MCV1 – First dose of measles-containing vaccine

VPD- Vaccine Preventable Diseases

SC - Scheduled Castes

ST - Scheduled Tribes

OBC-Other Backward Classes

LPC- Lower Privileged Class

NFHS- National Family Health Survey

DLHS- District Level Household and Facility Survey

WHO- World Health Organization

GVAP - Global Vaccine Action Plan

PHC- Primary Health Centers

ANC- Antenatal care

TT- Tetanus Toxoid

Abstract

India has one of the lowest immunization rates of any country in the world, and accounts for more than 20 percent of the child deaths under 5 years of age worldwide. Poor vaccination coverage has been identified as one of the leading causes of high child mortality rates in India, despite the government's longstanding Universal Immunization Program, which provides select vaccines free of charge for children. Interrupting transmission of a vaccine preventable disease requires an adequate number of children be immune to that disease through full vaccination administered in a timely manner. Delayed vaccination against childhood diseases is known to result in increased mortality and morbidity. The overarching aim of this dissertation research was to identify barriers to receiving the recommended vaccinations among Indian children, using the District Level Household and Facility Survey Data, 2007-08 (DLHS-3).

The first study investigated the association between socio-cultural characteristics and risk of under-vaccination and non-vaccination. The results suggested that the reasons for under- and non-vaccination in India were similar. Inequities in vaccination coverage among social and religious groups were clearly evident after controlling for all the traditional risk factors of vaccination. Additionally, children living in urban areas were at a higher risk of poor vaccination outcomes compared to children living in rural areas.

The second study examined vaccination timeliness utilizing data from children both with and without a vaccination card in a novel application of an existing statistical methodology. Vaccine administration at the recommended time or by the maximum recommended age is

considered timely. The results indicated that relatively small percentages (approximately 35%) of Indian children received vaccinations at the ages recommended by India's national immunization schedule. Furthermore, the state-specific analysis found that considerable variation in vaccination probabilities existed across Indian states. An ecological analysis was conducted to investigate the state-specific probability of DPT3 vaccination by six months of age and under-five mortality, and we found strong associations.

The third paper examined state-level factors that influence childhood vaccination, controlling for individual-level confounders. Both state-level and individual-level characteristics had independent effects on childhood vaccinations. Average population served by a primary health center and the state-level poverty were variables which explained some of the between state variability in full-vaccination coverage. Additionally, the association of religion with vaccination was found to depend on the percent Muslim population in a state.

The findings of this dissertation research further the current knowledge regarding the drivers of childhood vaccinations in developing countries like India, and demonstrate a novel application of a known methodology for studying vaccination timeliness to assess vaccination program performance in India; these results may help to shape interventions that reduce disparities in full vaccination among children of different demographic/cultural groups.

Chapter 1

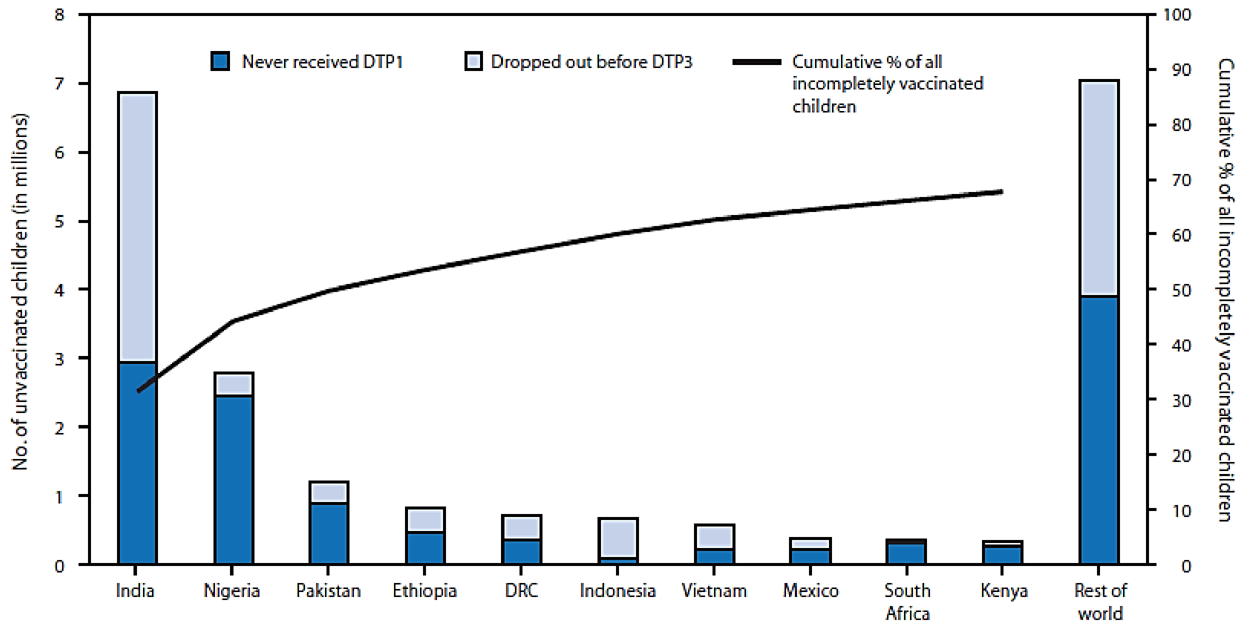
Introduction

Background

Immunizations are generally considered the most successful and cost-effective public health intervention employed today [1]. The widespread use of vaccines has resulted in the global eradication of smallpox, elimination of polio and measles from many countries, and substantial reductions in illness and death attributable to diseases like diphtheria, tetanus, and whooping cough [2]. According to the World Health Organization (WHO), approximately 2-3 million child deaths were averted in 2013 in all age groups from vaccination for diphtheria, tetanus, pertussis and measles. Furthermore, there is a potential to prevent many more deaths globally if WHO's recommended levels of vaccination coverage are attained and improvements made in the timeliness of the vaccines' administration [3].

A general and widely-used indicator of program success in completing the recommended childhood vaccination schedule globally is the coverage of third dose of Diphtheria-Pertussis-Tetanus (DPT3) vaccine series for children at one year of age [3]. According to WHO's 2013 estimates, the number of children under one year of age worldwide who did not receive DTP3 vaccine worldwide is 21.8 million [3]. More than fifty percent (10.9 million) of these children lived in three countries: India, Nigeria, and Pakistan. The challenge of meeting the demands of appropriately and fully immunizing children in India grows more daunting as the country adds a pool of 7 million partially immunized children each year [3]. (See Figure 1.1)

Figure 1.1 Estimated number of infants who did not receive 3 doses of diphtheria-tetanus-pertussis vaccine (DTP3) in 10 countries with the largest number of incompletely vaccinated children and cumulative percentage of all incompletely vaccinated children worldwide accounted for by these 10 countries, 2013[3]



Abbreviations: DTP1 = 1 dose of diphtheria-tetanus-pertussis vaccine; DRC = Democratic Republic of the Congo
Source: http://www.cdc.gov/mmwr/preview/mmwrhtml/figures/m6346a4f.gif

India has one of the lowest immunization rates of any country (Figure 1.1) , while at the same time struggling with the largest national birth cohort globally, comprising over 26 million new babies each year [4]. According to the 2011 estimates, India contributed to more than 20 percent of child deaths in the world, and the under-five mortality was 66 per thousand live births [4]. It was estimated that increasing immunization coverage (especially for DPT, Measles, Polio and Hepatitis B) would reduce childhood mortality to 55 per thousand live births [5].

In order to attain sufficient herd immunity for a disease in a community, to interrupt transmission of a vaccine preventable disease requires an adequate number of children be immune to that disease through full vaccination which is also administered in a timely fashion. Fully-vaccinated children receive all the doses of all recommended vaccines including those requiring multiple dose regimens. Children receiving fewer doses of vaccines than those recommended are considered to be under-vaccinated, and children who do not receive any vaccinations are non-vaccinated. Although it is well established from studies in other developing countries that the epidemiology of non-vaccination differ from under-vaccination [30, 31], most of the studies in India have dichotomized the vaccination status as either complete or incomplete. Additionally, any delay in vaccination i.e., administering vaccine doses later than the national recommended schedule, predisposes children to risk of a vaccine-preventable disease (VPD) in the period when they have not acquired protective immunity through vaccinations.

This dissertation will explore the barriers to receiving the recommended vaccines in a timely manner among children in India through three studies: the first study characterizes risk factors for under-vaccination and non-vaccination of Indian children, the second analyzes delays in vaccine administration and its implications for improving vaccination timeliness, and the third study investigates the Indian state-level factors associated with childhood vaccination coverage.

Gaps in the literature

Predictors of childhood vaccinations

Numerous studies have been published on vaccination coverage and the factors associated with vaccination coverage in India, but the majority have focused on individual factors, such as gender, age, and birth order; and household factors, such as household size, number of children below 3 years of age, and household wealth index [6–13]. A few studies have considered socio-cultural factors, such as religion, caste, and maternal-education level as predictors of childhood vaccination status [6,14,15]. However, these studies have generally failed to adequately address confounding by state-level factors, which could affect vaccination outcomes. Health is, in part, a state-level issue as many state-level policies and programs affect health care availability and accessibility including access to vaccines; therefore, it is important to control for the state-level factors when analyzing the effect of individual-level predictors on childhood vaccination coverage.

In addition, previous studies have done an inadequate job of classifying important socio-cultural characteristics. Religion is typically limited to a binary Hindu and non-Hindu category and in examining the role of caste, scheduled caste (SC) and scheduled tribes (ST) have been collapsed into one category, or there has been a three-fold distinction between non-SC/ST Hindus, SC/ST Hindus, and “others,” which encompassed everyone else including Muslims, Christians, Sikhs, etc.[14–17]. This type of categorization completely neglects the fact that each religion has all of these castes embedded within them. Additionally, this limits our ability to understand the impact of religious designations and social stratification on the immunization status of children in India. The influence of these factors in India is especially crucial, as caste and religion are two distinct and important socio-demographic determinants of both socio-economic and health status [18,19].

Impact of Caste System

Indian society is characterized by a highly embedded system of social stratification based on an ancient caste system. Caste is a hereditary designation, in which the social code that an individual is expected to follow is determined at birth [20]. Caste is an indicator of inequity in economic status based on members' occupation, education, landholding, and other assets. Traditionally, the caste system was divided into 4 hierarchal categories—priests, warriors, merchants, and laborers. Below these categories and considered lowest in the social strata is a fifth group called "Dalits," comprising both SC and ST. An additional group of socially and educationally disadvantaged people are identified as "Other Backward Classes" (OBC). OBC is not a historical category, and is composed of several sub-castes that were identified by the central and state governments of India to be disadvantaged because of their low social, educational and economic status in society. In this dissertation, they will be referred to as "underprivileged classes." Individuals who do not belong to any of these three groups are traditionally labeled as "Others." Others comprise historically privileged social classes. Based on a 2005 national survey, the distribution of the social groups in India is as follows: 19% for SC, 8.2% for ST, approximately 41% for OBC, and approximately 32% for Others [21]. Although the caste system was officially abolished in 1950, India's constitution has developed specific procedural, legal and other safeguards in order to discourage caste discrimination, in recognition of the disadvantages suffered by the so-called underprivileged classes [22]. Despite this protective legislation, the legacy of the caste system in India endures, particularly in rural areas.

Most studies on caste examined inequality in terms of economic opportunities [18], education [23], occupation [24], and income [25], but a few studies have examined the effect of caste on health outcomes [19]. The studies that examined childhood vaccinations in the context of caste membership noted differences among castes; however these studies were largely descriptive and involved relatively small sample sizes [9].

Impact of State-level Factors on Childhood Vaccinations

Health is a state-level issue as many state-level policies and programs affect health care availability and accessibility; therefore, it is not only important to control for the state-level factors but also to study how the effect of these characteristics changes from one state to another. When we attempt to control for the state-specific effects by adding fixed effects for each state in the analytic model, we mask the nuances of the state specific factors. To obtain the effect of the factors of interest for each state, we will have to account for the interaction of that factor with the state variable for each state. India is a country characterized by great diversity, and huge variation in cultural practices, beliefs, governance and socioeconomic factors; therefore, it is important to understand state-by-state differences.

Importance of Vaccination Timeliness

A distinct gap in the vaccination literature is a notable lack of studies on vaccination timeliness in India. Timely vaccination is defined as administration of vaccine doses at a schedule recommended by India's national immunization schedule. Age-appropriate and timely vaccinations are an important indicator of vaccination program performance, as timely vaccinations maximize the protection and decrease the time for which children are at risk for various VPDs [26–28]. One study[29] showed that only 30% of Indian children received the first dose of measles vaccine at the recommended age of 9 months, and only 31% were vaccinated with DPT3 in the fourth month as recommended in India's national immunization schedule. However, the study findings may not be truly representative of the vaccination timings of all

Indian children as this study included only children who possessed vaccination cards (less than 35% children) at the time of the survey.

Overall, previous studies on vaccination coverage in India have not given adequate scholarly attention to the prevailing and deep-rooted socio-cultural factors; and the impact of those factors on childhood vaccination status. Majority of the studies in India have dichotomized the vaccination status as either complete or incomplete. However, previous literature from other countries have established the differences in risk factors for non and under-vaccination [30,31]. There is a lack of literature on the very crucial factor of vaccination timeliness. Additionally, state-level factors that influence the policy environment and the availability of immunization services in India have not thoroughly been investigated in the existing literature. This dissertation utilized rigorous statistical methods and addressed these limitations.

Specific Aims

The overarching goal of this research is to enhance our understanding of the myriad factors that influence vaccination status among children in India, and address some of the limitations of previous research conducted on this topic and presented above.

Aim 1: To characterize the association between socio-demographic characteristics and risk of under-vaccination and non-vaccination in Indian children using the District Level Household and Facility Survey Data, 2008 (DLHS-3).

Hypothesis: Risk factors associated with childhood under-vaccination and those associated with non-vaccination would be different.

Aim 2: To investigate the timeliness of administration of childhood vaccinations in India.

Aim 3: To examine state-specific differences in childhood vaccination coverage among rural populations.

Hypothesis: The impact of religion on childhood vaccination status will vary across states. Children in states with a higher percentage of poor people in the lowest wealth quintile will have lower odds of full vaccination compared to states with lower percentage of people in the lowest wealth quintile.

Data / Study Population

India's national survey, District Level Household and Facility Survey Data, 2007-08 (DLHS-3), is available from Indian Institute of Population studies, but is underutilized for research, in general. The DLHS-3 survey was conducted on a representative sample of households across India. The data was collected from 720,320 households and 601 districts across India, during December 2007 to December 2008. The DLHS3 utilized interviewer-administered questionnaires comprising separate surveys for ever-married women within the household, one for households, one for villages, and one for health facilities. Questionnaires in the local language and English were used to interview the ever-married women (aged 15-49 years), and the heads of household. The ever-married women questionnaire contained information on the woman's socio-demographic characteristics, maternal care, immunization and child care, and reproductive health knowledge. Household questionnaires contained questions related to information on all household members, socio-demographic characteristics, and assets possessed. Separate questionnaires for villages and health facilities were used to gather required information. Any adult who lives in the household could respond to household questionnaires. The village questionnaire were completed by 22,825 and consisted of information on availability of health, education and other facilities in the village. The village questionnaires were answered by the village sarpanch (head of the village).

The sampling technique used for the survey was probability proportional to size. The survey features a multi-stage stratified design, in which districts are nested within states. Rural villages and urban wards comprise primary sampling units (PSU), of which there were 50 in each of the 601 districts, for a total of 30,050 PSUs. The PSUs within a district were first stratified by the total number of households, percentage of scheduled caste (SC) and scheduled tribe (ST) in the population, and proportion of adult literate females. The PSUs were allocated to rural and urban areas of each district proportionally to the actual rural-urban population distribution. The dataset contains national-level weights to account for disproportionate sampling of women.

The child data that were used for analysis was created from the individual level data files for women. The record for each child includes selected characteristics of the child, mother, and household. The information on children comes from the ever-married women database. These women were interviewed about the children born to them after January 2004. The information regarding the immunization of their children was taken either from the vaccination card for the child, if it was available; otherwise, in the event of non-availability of the vaccination card, the immunization information was gathered based on mothers' recall. For the state-level analysis, information from the 2011 Indian census was obtained, which was linked to child's state of residence.

Summary of Chapters

This dissertation expands the existing knowledge surrounding the predictors of vaccination status among children in India. This research addresses the complex socio-cultural issues surrounding vaccinations, and the need for gaining a deeper understanding of the impact of religious/traditional beliefs and their implications for receipt of recommended immunizations. Additionally, this work also presents a new methodology to investigate vaccination timeliness in countries that lack both a hard copy and electronic immunization information system (IIS).

The first paper focusses on individual-level socio-cultural predictors of under-vaccinations and non-vaccinations among children in India, after controlling for state-level effects. The second paper examines vaccination timeliness utilizing data from children both with and without vaccination card using a new methodology. The third paper examines the state-level factors that influence childhood vaccination, after controlling for individual-level confounders. Finally, I discuss a summary of the dissertation's main findings, and the study conclusion that includes identifying potentially effective interventions to increase full vaccination coverage in Indian children, the public health implications of doing so, and suggestions for future research directions.

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Chapter 2

Predictors of Vaccination in Indian Children 12-36 Months of Age

Introduction

In 2012, one-quarter or 1.4 million of the 6.6 million deaths among children under 5 years worldwide occurred in India [1]. No other country approaches this level of childhood mortality, and the majority of these deaths could be prevented with vaccination [1]. A 2008 study estimated that almost three-quarters of the 826,000 total deaths in Indian children 1-59 months old per year were vaccine-preventable [2]. The leading causes of vaccine preventable death in Indian children include diarrhea, pertussis, measles, meningitis, and pneumonia, which collectively highlight the human cost of low vaccination coverage.

India has the world's largest annual birth cohort, comprising approximately 26 million newborns (19.5% of births worldwide[1]), while also possessing one of the lowest immunization rates of any country in the world (UNICEF 2012). The World Health Organization (WHO) estimated that in 2012, over 22 million infants world-wide had not received the third dose of the Diphtheria-Pertussis-Tetanus (DPT3) vaccine, which is often used as a proxy for the success of a country's immunization program, of which 30% or 7 million, reside in India [3].

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[1] Population Reference Bureau & The World Fact book (Central Intelligence Agency)

In 1978, the government of India launched the Expanded Program for Immunization (EPI) to cover the cost of recommended vaccines for all Indian children. The program was re-named the Universal Immunization Program (UIP) in 1985. The UIP provides the recommended doses of vaccines against the following 6 diseases to all infants in India at no cost: tuberculosis, diphtheria, pertussis, tetanus, polio, and measles. Up to 2010, UIP required all the children by the age of one to get 1 dose Bacillus Calmette–Guérin (BCG); 3 doses of DPT; 3 doses oral polio vaccine (OPV); and 1 dose measles-containing vaccine (MCV). Indian children who have received all recommended doses of these four UIP vaccines are considered fully vaccinated by WHO; a child lacking any of the recommended doses is considered under-vaccinated, and children who have not received any vaccinations are considered non-vaccinated. The District Level Household and Facility Survey (DLHS) is a nationally representative survey periodically performed by the Indian government, reported that only 54% of children aged 12-23 months were fully vaccinated, 41% were under-vaccinated, and the remaining 5% were non-vaccinated [4]. The challenge of meeting the demands of appropriately and fully immunizing children in India becomes even more daunting as the country adds a pool of 12.5 million partially immunized children each year [5].

Against this backdrop of overall low national vaccine coverage, significant variation exists in estimated vaccination coverage for children aged 12-23 months across the thirty-four Indian states and Union Territories. For example, based on the DLHS3 report, the percentage of fully vaccinated children ranged widely from a low of 13% in Arunachal Pradesh to a high of 82% in Tamil Nadu. Similarly, coverage disparities exist between districts within the states; in Madhya Pradesh, which is centrally located and is the second largest state in India, the percentage of fully vaccinated children ranges from a low of 17% in Datia District to a high of 70% in the Indore District [4].

To improve routine immunization coverage at the district level, the WHO endorsed the Global Vaccine Action Plan (GVAP) in May 2012. The GVAP's key goals include achieving and sustaining 90% DPT3 coverage nationally and at least 80% DPT3 coverage in every district of every state by the year 2015 and to maintain that coverage level through 2020 [6]. Although the Indian government has prioritized these targets, they are still far from being attained.

The causes of low vaccination coverage in India have recently received more scholarly attention. Numerous studies have focused on individual predictive factors, such as gender, age, and birth order; and others on household factors, such as family size, number of children below 3 years old, household wealth, caste, and maternal-education [7–14]. However, many of these studies [7,8] did not control for potential confounders such as religion, caste or state-level effects. Moreover, while it is well documented that the epidemiology of non-vaccination differ substantially from the epidemiology of under-vaccination [9,10], most of these studies [7,11,12] dichotomized vaccination status into complete vs. incomplete. The few studies [13] investigating predictors of childhood vaccination in India that did use three distinct vaccination categories (i.e. full, under, and non-vaccination), were limited by small sample sizes drawn from narrowly defined geographic areas such as a specific state, city, urban slum(s) or a few villages, potentially impacting the generalizability of these studies to the larger national population. Other research utilizing the 2005 National Family Health Survey (NFHS) and the DLHS3 used analytic methods that did not incorporate survey design variables, which likely biased the effect estimates and associations with the outcome variable(s) [14] .

This study focused on identifying the individual-level socio-demographic and cultural factors related to vaccination status in Indian children aged 12-36 months using a nationally representative sample from the DLHS3. Based on prior studies in countries other than India [9,10], we hypothesized that the risk factors associated with childhood under-vaccination and non-vaccination would be different. To avoid the confounding of the relationship between vaccination status and individual characteristics by healthcare infrastructure availability, accessibility, and prevailing policy environment in the state, state of residence was used as a control variable.

Methods

Data source and sample design

We used India's 2008 District Level Household and facility Survey data (DLHS3), which is currently the most recent immunization data available to researchers. The DLHS3 is a nationally representative sample collected from December 2007 through December 2008 from 720,320 households located in 601 distinct districts from 34 states. The survey used a multi-stage stratified design, in which districts were nested within states. Rural villages and urban wards comprise primary sampling units (PSU), of which there were 50 in each of the 601 districts, for a total of 30,050 PSUs. Certain categories of respondents were oversampled in DLHS3. However, use of calculated survey weights permitted unbiased estimation of population characteristics. Additional details regarding the sampling methodology of the DLHS3 are published elsewhere [4].

The DLHS3 utilized interviewer-administered questionnaires comprising separate surveys for ever-married women within the households, and another for the entire household.

Any adult over 18 years who lived in the household was permitted to respond for the household. Household questionnaires requested information on all household members, including socio-demographic characteristics and financial assets. The questionnaire for ever-married women included questions about her socio-demographic characteristics, her children, and receipt of maternal care and reproductive health knowledge. The childhood data used for this analysis was extracted from the ever-married women data file. Women were only asked about children born on or after January 1, 2004; specific information on their children's immunization status was obtained from the vaccination card for the child. If an immunization card was not available, then the reported immunization data was based on maternal recall.

Outcome Measure

The population used for this analysis consisted of the most recently born child per household who was aged 12-36 months at the time of data collection. We classified the outcome variable, vaccination status, into three categories: fully vaccinated, under-vaccinated, and non-vaccinated. A fully vaccinated child was defined child who had received all recommended UIP vaccines, i.e. one dose of BCG and MCV, and at least 3 doses of DPT, whether or not the doses were received at the recommended times. For example, if a child was 35 months of age at the time of interview and received BCG vaccine at 33 months, which is recommended for administration at birth, we still counted the child as vaccinated. Under-vaccinated was defined as any child who received at least one but not all of the recommended routine UIP vaccines, and non-vaccinated was defined as a child who did not receive any UIP vaccines. We did not include polio vaccine in our analysis because of an extended and extensive national campaign for polio vaccination, which has resulted in estimated immunization coverage close to 100% for OPV in all Indian states and territories.

Predictor Variables

The individual-level variables used as predictors of vaccination coverage can be broadly classified into four categories: child, maternal, household, and socio-cultural factors. Three child variables were used for children; age, gender and place of birth, all of which have been shown to be associated with vaccination status [8]. Maternal variables included were maternal age at childbirth, education level, participation in antenatal care services (ANC), and mother's receipt of tetanus vaccine; since all are known to be associated with their children's immunization status [15–18]. Maternal age at child birth was divided into 4 categories: 18 years or less at the time of child birth vs. 19-25 years, 26-35 years, or more than 35 years. Maternal education was segregated into: no formal schooling, 1-5 years of school completed, 6-12 years, or 13 and more years of school. If the mother had never been enrolled in a formal school system, even if she attended religious institutions such as a temple or madrasa, she was categorized as no formal schooling. For antenatal care checkup, a four category variable was used: no antenatal care visits during pregnancy, 1-2 visits, 3-6 visits, or 7 and more in order to assess whether the probability of child immunization becomes stronger with increasing number of visits. A dichotomous variable was used for maternal receipt of tetanus vaccine (yes vs no) which was considered a proxy for maternal attitude towards vaccination specifically, and health care services, generally.

Household characteristics included residence type (rural or urban), household wealth, and household size. The DLHS3 used a standard wealth index based on factor analysis, and classified into five quintiles (poorest to the wealthiest groups) based on household amenities, assets, and durables, which represents direct and indirect measures of household economic status. In the absence of direct information on income or expenditures, wealth index is considered a robust measure of income at the household level [19–21]. Family size was divided into four categories: 2-3 members, 4-5 members, 6-7 members, or more than 7 members. Family size was considered a proxy for competition for resources, especially maternal time [8]

Religion and caste[2] reflect cultural designations that influence parental beliefs and attitudes toward health-seeking behaviors including vaccination decisions about their children. Multiple studies have found gender gaps in immunization coverage in all states in India (11, 30, 48), and religion is often a primary factor in influencing family preferences for male children (24). Similarly, caste is also associated with cultural practices that express as preference for male children. For this study, religious groups were divided into five categories-- Hindu, Muslim, Christian, Sikh, and Others. The religious group "Others" comprise all other religious groups including Buddhist, Jains, Jews, and Parsis, each of which individually compose less than one percent of the total Indian population. Caste was used as a four category variable: scheduled tribe (ST), scheduled caste (SC), less privileged classes[3] (LPC) and "Others." The "Others" category are historically privileged groups and are not considered socially disadvantaged by the Indian Government. Conversely, the ST, SC, and LPC categories are historically underprivileged and remain socially disadvantaged, with ST considered to be at the lowest rung of the social caste hierarchy.

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[2] Scheduled castes/tribes are identified by the government of India as socially and economically disadvantaged and in need of special protection from social injustice and exploitation

[3] Officially Referred to as Other Backward Classes (OBC) by the Indian Government but referred to in this paper as "less privileged classes"

State of residence was used as an indicator of policy and programs affecting healthcare access and availability. States that did not have sufficient sample sizes under each vaccination category were collapsed into three clusters of neighboring states: Himachal Pradesh, Punjab, and Chandigarh as one group; Andhra Pradesh and Karnataka as another; and finally all the islands (Daman & Diu, Dadra Nagar Haveli, Goa, Lakswadweep, Pondicherry and Andaman Nicobar).

Statistical analysis

The analysis focused on ascertaining the risk factors that predicted for under and non-vaccination compared to full vaccination. The stratification, clustering, and weighting statements were used to account for the complex design characteristics. Residence type (rural or urban) was used as stratum variable and PSU as the cluster variable. The Taylor series linearization method was used to calculate the variance of the parameter estimates.

A bivariate analysis was conducted to examine the association of vaccination status with each of the potential predictor variables. The Rao-Scott design adjusted test statistic for the independence of the two variables was used. Based on these initial tests of association, all of the predictor variables appeared to have significant bivariate associations with vaccination status. To determine if these marginal associations remain significant when controlling for the other predictors and fixed effects for states, a multinomial logit regression model was fitted in STATA13. A subpopulation analysis was conducted as the study subjects were a subset (12-36 months) of all the children (0-5 years) in the dataset. The importance of each of these predictors was evaluated using the design-adjusted multi-parameter Wald test. The predicted probabilities based on the final model were investigated. The analysis was conducted using STATA 13 (StataCorp, College Station, TX).

Results

The DLHS3 included information on a total of 268,539 children aged 0 to 60 months. For this analysis, most recent born child in each family within the 12 to 36 months age range at the time of interview was chosen leaving 108,057 children (40% of the total) who met this criterion. Characteristics of the study population are summarized in Table 2.1. Slightly over half (53%) of the children in the sample were males. Approximately 72% of the children lived in rural areas, and three-quarters were Hindu, 15% Muslim, 5% Christian, 2% Sikh, and 1.3% from other religions. One-quarter of children belonged to privileged classes with the remainder from historically underprivileged classes; the percentages of ST, SC, and LPC population were 17, 19, and 41, respectively (Table 1). Approximately 40% of the children lived in households with a family size of 5 or less, 28% in households with 6-7 members and 32% with 7 or more household members. The majority of children (88%) had mothers whose age at the time of their birth was between 19-35 years, whereas 7% were born to younger mothers (18 years or less). A large proportion (42%) of children had mothers with no formal schooling; 14% had mothers with 1-5 years of schooling, and 42% with 6 or more years of formal schooling. More than half (55%) of the births were non-institutional, and 24% births occurred in government institutions like primary health centers (PHCs), community health centers, and district hospitals. The remaining 20% of births occurred in private institutions comprising private hospitals and clinics. Thirty percent (30%) of children's mothers did not receive any ante-natal care services and the remainder receiving various levels of ANC care ranging from 1 to 18 visits. Almost three-quarter of the mothers (71%) had been immunized with the tetanus toxoid (TT) during their pregnancy.

Vaccination status of children by individual vaccines and series completion was analyzed; the results are shown in Table 2.2. The overall national vaccination coverage is highest for BCG vaccine (86%) and lowest for DPT3 vaccine (62%). The percentages of fully vaccinated children in urban and rural areas were 66% and 54% respectively. The largest difference (59% vs 70%) between rural and urban vaccine coverage was for DPT3 vaccine. Only 57% children in the study population completed the DPT series; 31% did not complete the series (under-vaccinated), and 12% were non-vaccinated.

The bivariate relationships between the socio-demographic and economic characteristics by vaccination status are shown in Table 2.3. Among the different religions, Sikhs have the highest percentage (83%) of fully vaccinated and lowest percentage (3.36%) of non-vaccinated children. Muslim children had highest percentage of non-vaccination (19%), followed by Christian children (13%), and Hindu children (11%). Vaccination status by caste groups revealed that the historically disadvantaged groups i.e., ST, SC, and LPC have similar proportions of children in the non-vaccinated category, 12.5 – 14.7% vs. 8% for the privileged groups (i.e. "Others"). Further, 50-55% children from the underprivileged groups were fully vaccinated, vs. 67% from "Others". The children from the lowest wealth quintile (quintile1) had significantly poorer vaccination status with 22% non-vaccinated and 39% fully-vaccinated compared to other wealth quintiles. As the wealth quintiles increased, the vaccination status of the children progressively improved with 76% of children from the richest wealth quintile fully-vaccinated and 4% non-vaccinated. For children whose mothers had no schooling, 21% were non-vaccinated, while the children with mothers with higher education categories (6 or more years of schooling) had significantly lower proportions of non-vaccination at 5%. Children who were born in healthcare facilities (government and private institutions) had similar proportions of children who were fully vaccinated (70%, 73%), and under-vaccinated (24% and 21%). Among the children whose mothers did not receive any antenatal care, 34% were fully vaccinated, 38%

under-vaccinated, and 28% non-vaccinated. Conversely, approximately 80% of children whose mothers had 7 and more ANC visits were fully-vaccinated. Among the children whose mothers received tetanus injection during their pregnancy, 5.8%, 27.5% and 66.6% were non-vaccinated, under-vaccinated and fully-vaccinated respectively: however, children whose mothers did not receive TT during pregnancy, the percentage distribution of vaccination status was markedly lower at 28.4, 38.2 and 33.5, respectively.

The results for multinomial logistic regression models estimating the odds ratio of a child being non-vaccinated compared to fully-vaccinated and under-vaccinated compared to fully-vaccinated are summarized in Table 2.4.1. The fixed effects for states were included in the model, but the regression results are not shown in the table (available upon request). The effect of locality (urban residence) changes upon addition of wealth quintiles to the model ($OR_{\text{none compared to fully-vaccinated}}$ =0.68 & 95% CI=0.63, 0.73 in Model-1 to OR= 1.63 & 95% CI=1.52, 1.75 in Model-2). In Model-1, rural children had higher odds of both non- and under-vaccination compared to full-vaccination, but in Model-2, the urban children had higher odds for poor vaccination outcomes. This effect became stronger in the full model (Model-3) when the other predictors were added; for children living in urban areas compared to rural areas, the odds for being non-vaccinated compared to fully-vaccinated increased by 83% [OR=1.83, 95% CI=1.69, 1.98], and the odds of under-vaccination compared to full-vaccination increased by 13% [OR=1.13, 95% CI=1.04, 1.21].

Children from larger households (i.e. 7 or more family members) were more likely to be non-vaccinated [OR= 1.22, 95% CI=1.09, 1.37] and under-vaccinated [OR=1.16, 95% CI=1.09, 1.23] compared to children from households with 3 or less members. Children from family size of 6-7 members were at higher risk of under-vaccination but less so for non-vaccination.

When controlling for state, age, gender, household wealth and maternal education, the additional significant predictors of child's vaccination status are religion, caste, place of delivery, number of antenatal care visits and maternal tetanus shots which demonstrate large effect sizes. We found that religion is highly predictive of child's vaccination status; children who belong to Muslim families compared to Hindu families had 2.3 times greater odds of being non-vaccinated versus fully-vaccinated and 1.45 times higher odds of being under-vaccinated compared to fully-vaccinated. Christian and Sikh children compared to Hindu families were not significantly associated with non-vaccination, however Christian children had higher odds [OR= 1.22, 95% CI=1.09, 1.37] of being under-vaccinated compared to being fully-vaccinated. Children belonging to other religions (Buddhism, Jainism, Parsis, and Judaism) were less likely to be under-vaccinated and non-vaccinated compared to fully-vaccinated. Similarly, caste was found to be another strong cultural predictor of vaccination-status. Children belonging to ST groups compared to privileged groups had 36% higher odds of non-vaccination compared to full-vaccination and 20% higher odds of under-vaccination compared to non-vaccination. SC and LPC children compared to privileged groups children also had significantly higher odds of non-vaccination and under-vaccination compared to full-vaccination.

Additionally, the maternal characteristics exerting the strongest influence were place of delivery, receipt of ANC, and TT; maternal age also had statistically significant association with vaccination status but the effect was not strong. Children born to younger mothers i.e. age 18 years or less compared to mothers 19-25 years were at greater risk for both under and non-vaccination. Compared with fully-vaccinated children, under-vaccinated [OR=1.92, 95% CI=1.76, 2.09] and non-vaccinated children [OR=1.24, 95% CI=1.19, 1.28] were more likely to have non-institutional delivery as opposed to being born in government institutions. Also, children born in private institutions had greater odds [OR=1.50, 95% CI=1.31, 1.71] of non-vaccination compared to full vaccination, but there was no significant association with under-vaccination. Number of antenatal care visits and maternal receipt of tetanus vaccine demonstrated a strong protective effect for non-vaccination and under-vaccination of children.

Discussion

India's immunization coverage remained unacceptably low in 2008, with only 57% of 12-36 months old children fully vaccinated with the UIP recommended vaccines, 31% under-vaccinated, and 12% not vaccinated at all. Given an annual birth cohort of 26 million children, this translates into at least 12 million children at elevated risk for VPDs and partially explains the continued high burden of morbidity and mortality from VPDs in Indian children.

In particular, the findings of this study illustrate the importance of explicitly distinguishing between non- and under-vaccination; especially noteworthy is the one-third of the children were under-vaccinated. The reasons for under and non-vaccination were multifactorial, and complex. Although no single intervention can address all the identified barriers, some barriers can be targeted more easily than others. We hypothesized that the reasons for non-vaccination would be different than under-vaccination based on literature from other developing countries [10]. Contrary to our hypothesis, it was found that the risk factors were similar for both under- and non-vaccinated children; however, the effect sizes of the risk factors differed between the two vaccination outcomes, and both religion and caste had larger effect sizes for non-vaccination compared to under-vaccination. This is important information to guide formulation of strategies to decrease the number of under and non-vaccinated children.

In this population the coverage for BCG vaccine was 86%, which is indicative of some form of immunization services accessibility. A gradual decrease in the vaccination coverage from BCG (administered at birth) to DPT3 (administered at 6 months) could partly be explained by several reasons such as: difficulty in accessing immunization services, lack of understanding of completing the entire series, and /or loss in motivation for child vaccination. Difficulty in accessibility of health services could be explained by both social barriers imposed on parents belonging to lower caste and poorer households, and physical barriers such as unavailability of services due to long distances to health centers, unavailability of vaccines at the health center or non-availability of health workers.

Our study differs from previous studies regarding the impact of place of residence. Children from urban areas have been reported to have better vaccination outcomes compared to children residing in rural areas [8,11,15]. In contrast, we found children from rural areas had lower risk of non-vaccination and under-vaccination compared to children from urban areas after controlling for the effects of other potential risk factors for under and non-vaccination. Our analysis controlled for the effect of household wealth and other potential confounders such as maternal education, religion, caste, and ANC visits whereas most previous studies reporting the reverse relationship did not [7,8]. In general, when urban and rural averages are compared for most development indicators, urban averages tend to be better. However, concentration of wealth in urban areas likely masks the depth of urban poverty. The proportion of fully vaccinated children was higher in urban areas compared to rural areas, but when controlling for the effect of other factors (confounders), we found the opposite effect of place of residence. A possible explanation for this is that urban areas in India have both middle-class neighborhoods but also huge slum areas with high concentrations of poor and uneducated families, who largely lack access to healthcare facilities. However, data for urban areas generally do not distinguish between the urban areas of higher SES and the urban slums with which they are intertwined. The DLHS3 data did not contain specific information as to whether families lived in slums, but it intuitively makes sense that urban slum children living in extreme poverty, isolated from mainstream society, are at higher risk of non- and under-vaccination compared to children living in middle-class neighborhoods. Conversely, in poor rural areas there is an extensive network of primary health centers, sub-centers and community health workers (anganwadi workers), whose work is to mobilize children and pregnant women to receive health care center services; a comparable network is not present in urban areas. This would explain our results showing that urban children with same level of poverty, education, religion, and caste as rural children still have lower chances of being fully vaccinated. This is a particularly important finding because it has such significant implications for targeted immunization intervention programs and related policies.

We found significant disparities in vaccination coverage between the richest and poorest children, and between the children of mothers with high education and low education; these finding are in accordance with the previous literature [8,15–18,22]. These disparities persist despite the free UIP vaccinations provided by the government and numerous other maternal and child care outreach programs targeting poorer and more uneducated segments of society. It has been pointed out by other research that existing health inequities in India are due to a lack of attention to social determinants of health including education, employment, and the failure of the healthcare system to deliver to those in need [23]. The UNICEF 2009 study [24] highlighted the disparity in under five mortality among Indian children, particularly females (compared to males), rural (compared to urban), religion (Muslims compared to other religions), caste (SC/ST compared to others), and poorest (compared to richest); this study found the similar disparities existing in vaccination coverage among those same groups.

In addition, inequities in vaccination coverage among social and religious groups in India were clearly evident. Children from Muslim families had significantly poor vaccination outcomes and Christian children were also found to be at an elevated (although less high) risk for under-vaccination. However, children who belonged to Sikh and other religious affiliations such as Buddhist, Jains, Jewish, Parsis, had better vaccination coverage compared to all the other religious groups. Previous vaccination studies [11,15] that investigated effects of religion on vaccination coverage, dichotomized religion as Hindu and non-Hindu and concluded that non-Hindu religions have poor vaccination outcomes, whereas in this study we further categorized the non-Hindu religions and found that Sikhs and "Others" have significantly better vaccination outcomes than Hindu children.

These differences among the social and religious groups could be secondary to the religious beliefs and practices that may influence the uptake of medical practices like vaccination. When the current analysis was controlled for wealth and maternal education, the effect of religion became stronger (Table 2.4.2), suggesting strong influence of religion, independent of wealth and education. Detailed variables related to religious beliefs and attitudes were not available in the DLHS3, which may have permitted a better understanding of religion-associated differences in vaccine acceptance and uptake. Thus, given the magnitude of these disparities, a qualitative study on vaccination attitudes among different religious groups could be warranted. Similarly, we also found that the historically disadvantaged groups that were at the lower rung of the social strata, ST, SC, and LPC, had lower vaccination coverage. There are two likely explanations: it could be due to the practices and beliefs prevailing among these groups that act as impediments to vaccination access or uptake or it could be due to social barriers faced by these groups making it more difficult for them to utilize health care services for their children. Past studies on caste examined inequality in terms of economic opportunities [25], education [26], occupation [27], and income [28]. A few studies [29–31] that examined health in the context of caste membership have examined the prevalence of anemia, treatment of diarrhea, infant mortality, and childhood vaccination, noting children belonging to underprivileged classes are more vulnerable to poor health outcomes. Based on the findings of these studies, it is not hard to imagine that persons from castes in the lower hierarchical strata face systematic social discrimination, including from the medical establishment in India.

Our finding that children born in private institutions were at greater risk of non-vaccination compared to those who were born in government institutions has major policy implications. This can partly be explained by fact that private hospitals do not benefit from government's healthcare funding for poor people. Additionally, private institutions do not operate under any government mandate to deliver immunizations or increase immunization coverage whereas government institutions do. Equally important, government institutions have a readily available vaccination supply from the central government and private hospitals do not. This pattern is similar to US, where in the past private healthcare facilities were a risk factor for full-vaccination [32].

This study has many short- and long-term policy implications for childhood immunization in India. In the long term, the government programs should target improving maternal education. A significant proportion of the population in India has low levels or no education, particularly women; in the DLHS3 sample, approximately 43% of mothers had no formal schooling. Illiterate mothers have a greater chance being unfamiliar with the benefits of vaccination and may be equally skeptical of modern medicine. Improving education among women could result in a greater awareness of healthcare services and an increase in acceptance and demand for childhood vaccinations. Since household wealth is strongly associated with better health outcomes, and wealth is directly associated with income, further income is dependent on job status. More job opportunities should be created may be providing opportunities for vocational training in rural areas. However, these are big recommendations and these interventions will require long time before tangible results can be obtained, and the government of India is working towards this goal. These limitations raise the question of what could be some short term but effective recommendation for improving vaccination in India.

Based on our findings, we propose few short term recommendations for improving the vaccination coverage rates in India. Significant benefits could be realized from enrolling women in ANC programs and encouraging institutional deliveries. It would also be helpful if a mandate for private hospitals/ healthcare facilities to immunize children covered under the UIP program. Thirdly, a functional immunization registry will be effective in tracking immunizations and be a reminder for completing the recommended number of vaccine dosage. The Indian government has made efforts in this direction by instituting maternal and child tracking system (MTCS) in 2011, but fewer than a quarter of pregnant women are enrolled and the dropout rates are high. It has been demonstrated in other parts of the world that a functional registry is an efficient way to improve childhood immunizations [33], and this may also hold true for India.

The study, like many that use national survey data, has several limitations. The vaccination information on children was based on mothers' recall in cases where vaccination cards were not available which is a common problem in developing countries lacking an immunization registry. However, previous studies have reported that in countries that lack proper immunization records, maternal recall provides accurate population level estimates of vaccination coverage [34]. Furthermore, this analysis could not include few variables due to unavailability of that information in the dataset. For example, previous literature reported that under-vaccination were mainly associated with immunization systems factors and access to services, such as training of health workers to reduce missed opportunities, communication of benefits of vaccination, lack of adequate vaccine supply, and inconsistent scheduling of vaccination supply; these factors were unavailable for our analysis. DLHS3 is cross sectional data providing a snap shot in time so there is no causal inference can be drawn, only statistical association. Also, due to insufficient sample size from a few states, they were grouped together.

Our study also has several important strengths. First, it was nationally representative and very large sample of children that permitted significant statistical power controlling for confounders. We used appropriate survey methods in the analysis of this data to account for the complex sample design of the data; most past studies have not, which might have resulted in biased effect estimates and biased hypothesis tests. This is also the first study to characterize the differences between risk of under-vaccination and un-vaccination among Indian children using a national dataset. The national dataset provided a huge sample size, and we were able to test many associations with significant statistical power, controlling for confounders. Additionally, the socio-economic characteristics were accurately assessed in this survey.

Overall, this study using a large, nationally representative sample found that in 2008 immunization uptake in Indian children was low with many children under- and non-vaccinated contributing to the significant burden of VPD in children. There continue to be powerful social determinants of vaccination including religion, caste, wealth, and education among others which require multifaceted public health programs to successfully address. Religion and caste are indicators of certain beliefs and practices that need further exploration to get to the root cause of poor vaccination coverage. Addressing those misconceptions regarding vaccination through targeted health education programs will help in improving coverage. The Indian government may want to place special emphasis on developing a national IIS to improve ongoing tracking of immunization levels, while also encouraging pregnant women to enroll in ANC programs and ensuring institutional births in order to improve childhood vaccination levels.

Table 2.1 Socio-demographic and economic characteristics of children 12-36 months old, born between January 2004 and December 2008 in India (DLHS2008 data

Characteristics	Categories	Un-weighted sample sizes	Weighted Percentages	95% CI
Locality		108,057		
	Rural		71.70	(63.68, 78.54)
	Urban		28.30	(21.45, 36.32)
Religion		106,430		
	Hindu		76.06	(75.38, 76.74)
	Muslim		15.49	(14.69, 16.31)
	Christian		5.10	(4.88, 5.33)
	Sikh		2.06	(1.91, 2.23)
	Other*		1.29	(1.20, 1.37)
Caste		106,033		
	Scheduled Caste		18.60	(17.85, 19.37)
	Schedules Tribe		16.88	(15.90, 17.92)
	Other Backward Classes		41.38	(40.67, 42.09)
	Others		23.13	(22.31, 23.97)
Household Size		108,057		
	≤ 3 members		8.01	(7.81, 8.22)
	4-5 members		31.13	(30.81, 31.45)
	6-7 members		28.40	(28.05, 28.78)
	7+ members		32.44	(32.10, 32.78)
Wealth Quintile		108,043		
	Poorest (Quintile 1)		18.44	(16.94, 20.03)
	Poor (Quintile 2)		19.37	(18.16, 20.64)
	Middle (Quintile 3)		19.46	(18.74, 20.19)
	Rich (Quintile 4)		20.82	(20.22, 21.44)
	Richest (Quintile 5)		21.90	(19.17, 24.91)
Mothers Age at Child birth		108,057		
	<=18 years		7.22	(6.90, 7.55)
	19-25 years		53.48	(53.06, 53.89)
	26-35 years		34.99	(34.44, 35.54)
	35+ years		4.32	(4.16, 4.49)
Maternal Education		107,778		
	No School		42.58	(40.84, 44.35)
	1-5 years school		14.44	(14.09, 14.81)
	6-12 years school		36.53	(35.38, 37.68)
	13+ years School		6.45	(5.60, 7.41)
Number of ANC Visits		108,057		
	No visits		28.54	(27.45,29.66)
	1-2 visit		23.20	(22.71,23.70)
	3-6 visits		35.94	(35.20,36.69)
	7 and more visits		12.32	(11.56,13.12)
Maternal Tetanus vaccination		108,057		
	No		28.97	(27.86,30.10)
	Yes		71.03	(69.90,72.14)

Characteristics	Categories	Un-weighted sample sizes	Weighted Percentages	95% CI
Sex of the Child		108,055		
	Male		52.78	(52.47, 53.08)
	Female		47.22	(46.91, 47.53)
Delivery place		105,871		
	Institutional Gov.		24.42	(23.67, 25.18)
	Institutional Private		20.45	(18.98, 21.99)
	Non-institutional		55.14	(52.95, 57.31)

*Other religious group comprises of following religions: Buddhist, Jain Jewish, Parsi, no religion

Table 2.2 Vaccination status by type of residence of children aged 12-36 months, born between January 2004 and December 2008 in India (Weighted percentages along with 95% confidence interval)

Variable	Rural (n=87,643)	Urban (n=20,414)	Overall (n=108,057)
BCG	84.76 (84.34, 85.19)	88.91 (88.25, 89.54)	85.94 (85.50,86.37)
DPT1	76.22 (75.69, 76.75)	83.13 (82.21, 84.02)	78.18 (77.56, 78.79)
DPT2	69.45 (68.94, 69.96)	78.56 (77.35, 79.72)	72.03 (71.32, 72.72)
DPT3	58.90 (58.37, 59.44)	70.33 (68.82, 71.80)	62.14 (61.31, 62.96)
Measles	68.52 (68.03, 69.00)	78.07 (76.82, 79.26)	71.22 (70.51, 71.93)
Fully-Vaccinated	53.58 (53.05, 54.10)	65.63 (63.97, 67.25)	56.99 (56.14, 57.83)
Under-Vaccinated	33.07 (32.71, 33.43)	24.43 (23.16, 25.75)	30.62 (30.04, 31.21)
Non-Vaccinated	13.35 (12.97, 13.75)	9.94 (9.40, 10.52)	12.39 (12.01, 12.78)

*All comparisons were statistically significant at the level P<0.001

Table 2.3 Vaccination status of children aged 12-36 months at levels of socio-demographic and economic characteristics using DLHS3

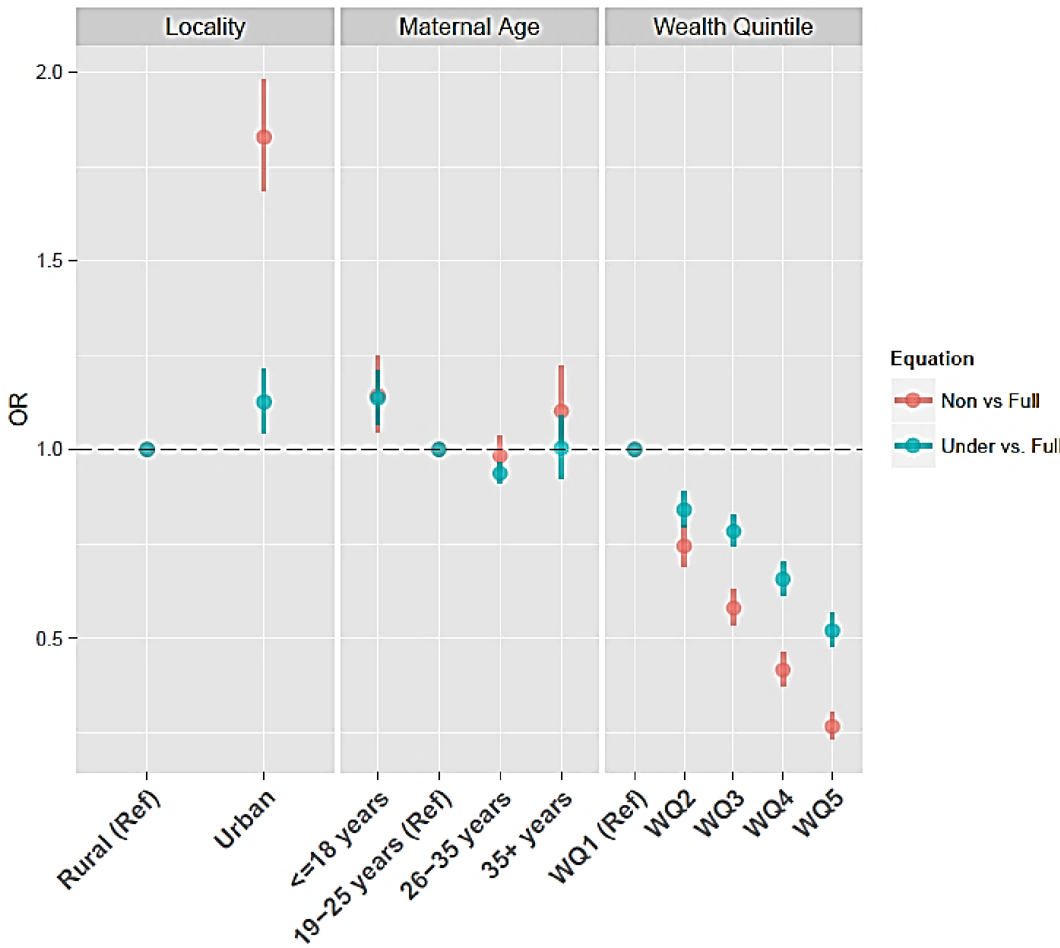
Characteristics	Non-Vaccinated	Under-vaccinated	Fully-vaccinated
Religion			
Hindu	11.13	30.70	58.17
Muslim	19.46	33.31	47.23
Christian	13.01	31.18	55.81
Sikh	3.36	13.52	83.12
Other	7.30	20.20	72.50
Caste group			
Scheduled Caste	12.5	31.71	55.79
Scheduled Tribe	14.72	34.54	50.75
Backward Classes	13.93	31.44	54.63
Others	7.81	25.28	66.90
Household-Size			
≤3 members	10.16	28.04	61.80
4-5 members	10.93	29.12	59.95
6-7 members	13.25	31.18	55.57
7+ members	13.59	32.22	54.19
Wealth Index quintile			
Poorest (quintile 1)	21.77	39.23	39.00
Poor (Quintile 2)	17.29	36.33	46.39
Middle (Quintile 3)	12.02	32.91	55.07
Rich (Quintile 4)	8.15	27.17	64.67
Richest (Quintile 5)	4.53	19.58	75.89
Maternal Age			
≤18	13.03	34.65	52.33
19-25 years	10.39	29.87	59.74
26-35 years	14.08	30.28	55.65
35+	22.45	36.02	41.53
Maternal education			
No School	20.93	38.45	40.61
1-5 years	10.85	32.58	56.57
6-12 years	4.83	23.38	71.8
13+ years	2.08	15.35	82.57
ANC visits			
No visits	27.88	38.09	34.04
1-2 visit	10.24	37.55	52.21
3-6 visits	4.49	25.1	70.41
7-9 visits	3.62	16.4	79.99
Maternal Tetanus Injection			
No	28.36	38.18	33.46
Yes	5.88	27.54	66.58
Sex of the child			
Male	11.57	30.39	58.04
Female	13.31	30.88	55.81
Delivery Place			
Govt. Institution	4.97	24.77	70.26
Private Institution	5.26	21.52	73.22
Non-institutional	18.27	36.66	45.08

Table 2.4 Weighted estimates of adjusted odds ratios from the multinomial logistic regression model of childhood vaccination status along with design based 95% confidence interval

Covariates	**Model 1**		**Model 2**		**Model 3**	
	Non vs Full	Under vs. Full	Non vs Full	Under vs. Full	Non vs Full	Under vs. Full
Locality						
Rural	ref	ref	ref	ref	Ref	ref
Urban	0.68	0.69	1.63	1.05	1.83	1.13
	(0.63, 0.73)	(0.64, 0.74)	(1.52, 1.75)	(0.98, 1.13)	(1.69, 1.98)	(1.04, 1.21)
Religion						
Hindu	ref	ref	ref	ref	ref	ref
Muslim	2.92	1.68	2.87	1.62	2.26	1.45
	(2.71, 3.15)	(1.58, 1.79)	(2.66, 3.09)	(1.52, 1.73)	(2.08, 2.45)	(1.36, 1.54)
Christian	1	1.13	1.06	1.18	1.12	1.22
	(0.83, 1.21)	(1.01, 1.26)	(0.88, 1.26)	(1.06, 1.32)	(0.92, 1.35)	(1.09, 1.37)
Sikh	0.61	0.72	0.88	0.84	0.78	0.79
	(0.49, 0.77)	(0.61, 0.84)	(0.69, 1.12)	(0.71, 0.99)	(0.6, 1.02)	(0.67, 0.93)
Other	0.52	0.6	0.69	0.68	0.64	0.71
	(0.39, 0.7)	(0.51, 0.7)	(0.52, 0.91)	(0.58, 0.79)	(0.47, 0.87)	(0.6, 0.83)
Caste						
Others	ref	ref	ref	ref	ref	ref
SC	2.4	1.62	1.51	1.26	1.25	1.12
	(2.18, 2.65)	(1.52, 1.72)	(1.38, 1.66)	(1.18, 1.34)	(1.13, 1.38)	(1.05, 1.19)
ST	3.32	1.94	1.88	1.4	1.36	1.20
	(2.97, 3.71)	(1.82, 2.06)	(1.67, 2.12)	(1.31, 1.5)	(1.22, 1.53)	(1.13, 1.28)
LPC	1.9	1.34	1.47	1.17	1.28	1.08
	(1.77, 2.03)	(1.28, 1.41)	(1.37, 1.59)	(1.11, 1.23)	(1.19, 1.38)	(1.03, 1.14)
Wealth Quintiles						
Poorest			ref	ref	ref	ref
Poor			0.61	0.76	0.74	0.84
			(0.57, 0.65)	(0.72, 0.80)	(0.69, 0.8)	(0.79, 0.89)
Middle			0.36	0.62	0.58	0.78
			(0.33, 0.39)	(0.59, 0.65)	(0.53, 0.63)	(0.74, 0.82)
Rich			0.18	0.44	0.42	0.66
			(0.16, 0.2)	(0.42, 0.47)	(0.37, 0.46)	(0.61, 0.7)
Richest			0.07	0.27	0.27	0.52
			(0.06, 0.08)	(0.25, 0.29)	(0.23, 0.3)	(0.48, 0.57)
Household Size						
≤ 3 membs (1)					ref	ref
4-5 membs (2)					1.04	1.07
					(0.94, 1.16)	(1.01, 1.13)
6-7 membs (3)					1.09	1.09
					(0.98, 1.22)	(1.03, 1.15)
7+ membs (4)					1.22	1.16
					(1.09, 1.37)	(1.09, 1.23)
Mothers Age						
<=18 (1)					1.14	1.14
					(1.05, 1.25)	(1.07, 1.21)
19-25 (2)					ref	ref

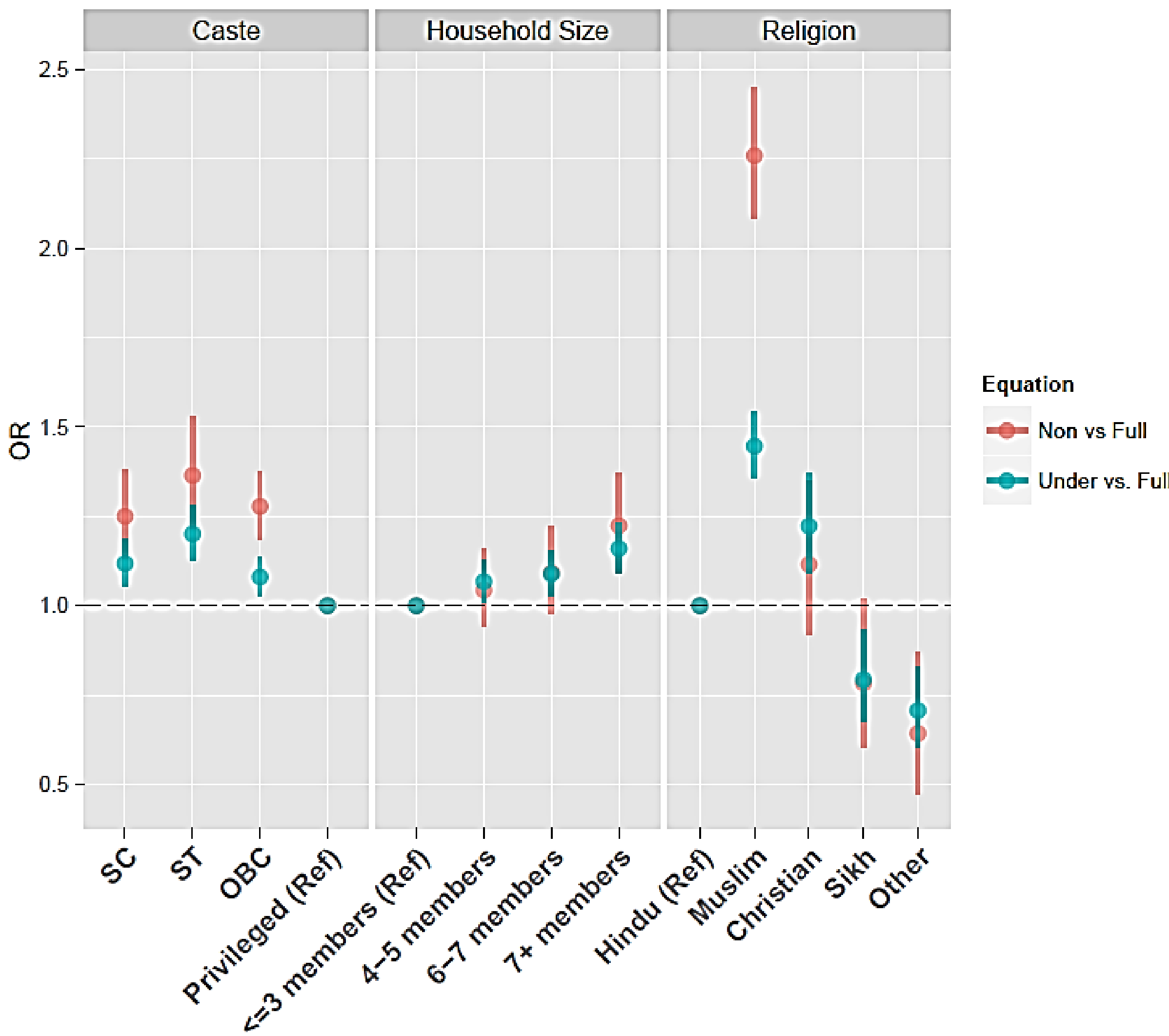
26-35 (3)	0.98 (0.93, 1.04)	0.94 (0.91, 0.97)
35+ (4)	1.1 (0.99, 1.22)	1 (0.92, 1.09)
Maternal Education		
No School (1)	ref	ref
1-5 years(2)	0.61 (0.57, 0.66)	0.81 (0.77, 0.85)
6-12 years (3)	0.38 (0.35, 0.41)	0.65 (0.62, 0.68)
13+ years (4)	0.27 (0.2, 0.37)	0.53 (0.47, 0.59)
ANC visits		
0 visits	ref	ref
1-2 visit	0.97 (0.84, 1.12)	0.93 (0.84, 1.04)
3-6 visits	0.66 (0.56, 0.77)	0.72 (0.64, 0.81)
7+ visits	0.75 (0.61, 0.91)	0.62 (0.55, 0.7)
Maternal tetanus vaccine		
No	ref	ref
Yes	0.23 (0.2, 0.27)	0.66 (0.59, 0.73)

Figure 2.1Adjusted* Odds ratios associated with under-vaccination vs full-vaccination and non-vaccination vs full vaccination by different subgroups (Locality, Maternal Age, Wealth Quintile) of children 12-36 months old born between January 2004 and December 2008 in India (DLHS2008 data). Bars indicate 95% confidence intervals



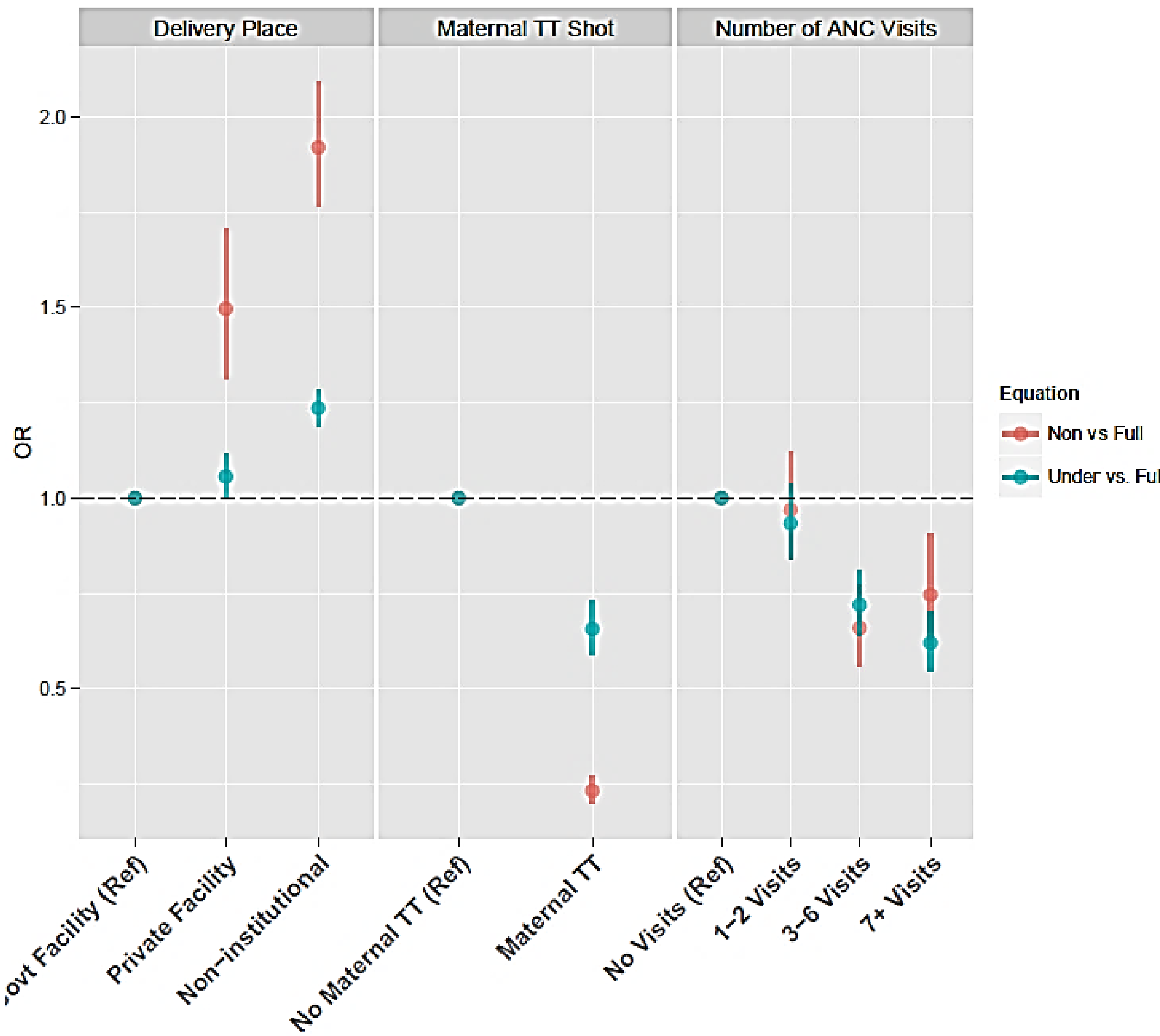
*These ORs were obtained from models adjusted for fixed effects of state, religion, caste, household size, maternal education, antenatal care visits, maternal tetanus, and place of delivery, child's age, and gender

Figure 2.2 Adjusted* Odds ratios associated with under-vaccination vs full-vaccination and non-vaccination vs full vaccination by different subgroups (caste, religion, household Size) of children 12-36 months old born between January 2004 and December 2008 in India (DLHS2008 data). Bars indicate 95% confidence intervals.



*These ORs were obtained from models adjusted for fixed effects of state, locality, wealth quintile, household size, maternal age, maternal education, antenatal care visits, maternal tetanus, place of delivery, child's age, and gender

Figure 2.3 Adjusted* Odds ratios associated with under-vaccination vs full-vaccination and non-vaccination vs full vaccination by different subgroups (place of delivery, maternal tetanus status, and antenatal care visits) of children 12-36 months old born between January 2004 and December 2008 in India (DLHS2008 data). Bars indicate 95% confidence intervals.



*These ORs were obtained from models adjusted for fixed effects of state, locality, wealth quintile, household size, religion, caste, maternal age, maternal education, antenatal care visits, maternal tetanus, child's age, and gender

Table 2.5 Unadjusted and adjusted odds ratios from multinomial logistic regression model, step by step change in OR by religion and caste for under vs full-vaccination and non vs full-vaccination, when controlled for known risk factors

	Religion										**Caste**							
	Non vs Full					Under vs Full					Non Vac vs Full				Under vs Full			
Model	Hindu	Muslim	Christian	Sikh	Others	Hindu	Muslim	Christian	Sikh	Others	Priv	SC	ST	LPC	Priv	SC	ST	LPC
Model 1	1.0	2.15	1.2	0.21	0.5	1.0	1.3	1.1*	0.3	0.5								
Model 2	1.0	2.3	1.8	0.4	0.7	1.0	1.4	1.3	0.5	0.6								
Model 3											1.0	1.9	2.5	2.2	1.0	1.5	1.8	1.5
Model 4											1.0	1.0*	1.2	1.4	1.0	0.9*	1.1	1.2
Model 5	1.0	2.7	0.9*	0.3	0.4	1.0	1.5	0.8	0.3	0.4	1.0	2.5	3.1	2.3	1.0	1.7	2.0	1.5
Model 6	1.0	2.4	1.9	0.5	0.8*	1.0	1.4	1.2	0.5	0.6	1.0	1.3	1.3	1.5	1.0	1.1*	1.2	1.2
Model 7	1.0	2.6	1.8	0.4	0.8*	1.0	1.5	1.3	0.4	0.6	1.0	1.3	1.3	1.5	1.0	1.1*	1.2	1.2
Model 8	1.0	2.5	1.2*	0.7	0.6	1.0	1.5	1.2	0.8	0.7	1.0	1.3	1.4	1.3	1.0	1.1	1.2	1.1

Model1: Religion
Model 2: religion, maternal education, wealth quintile
Model 3: Caste
Model 4: Caste, maternal education, wealth quintile
Model 5: religion, caste
Model 6: Religion, caste, maternal education, wealth
Model 7: Religion, caste, maternal education, wealth quintile, maternal age, and antenatal care visits
Model 8: Religion, caste, maternal education, wealth quintile, maternal age, antenatal care visits, state of residence
*These were not statistically significant at the level $P<0.001$
Abbreviations: Priv- Privileged categories, SC- Scheduled caste, ST- Scheduled tribes, LPC- less privileged class

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Chapter 3

Vaccination Timeliness in Indian Children

Introduction

India has the greatest number of deaths among children under five years of any country worldwide; the majority of these deaths are due to vaccine preventable diseases (VPDs) [2].Timely vaccination is essential to developing adequate immunity and minimizing susceptibility to these diseases [1–3]. Timely vaccination is defined as administration of vaccine doses at the recommended time or by the maximum recommended age. Most inactivated vaccines on the childhood immunization schedule require two or more doses for development of an adequate and persisting antibody response. Studies have demonstrated that adhering to the recommended ages and intervals between doses of the same antigen(s) provides optimal protection and the best evidence of efficacy [4].

Although vaccination coverage rates among children is used as a basic indicator of vaccination program performance, some studies have shown that high vaccination coverage rates for individual vaccines do not necessarily imply timely vaccination or adequate levels of population immunity [5,6]. A 2004 study using the national Health Interview Survey (NHIS) data from US reported that although 84% of children were up-to-date (UTD) for the fourth dose of Diphtheria Pertussis Tetanus (DTP4), only 46% received the doses in a timely manner, i.e., at the age recommended by Advisory Committee on Immunization Practices (ACIP) [7]. Up-to-date UTD vaccinations are defined as the number of vaccinations accumulated by a specified age, which does not take into account possible delays in actual administration of a given vaccine[3,8]. A few studies have reported high UTD vaccination coverage rates, but low age-appropriate vaccinations[5,6,9,10].

Vaccination coverage is usually provided for a specified age interval, such as 12-24 months. Children in this age range are sampled, and their current vaccination status is recorded. Children who are not vaccinated at the time of interview may receive a recommended vaccination later within an acceptable interval; however this would not be counted in the study (a child 14 months of age and not vaccinated at the time of interview but vaccinated at 18 months is counted as not vaccinated which can lead to underestimation of coverage proportions.

Delays in vaccinations predispose children to an unnecessarily prolonged risk of diseases at an age where they may be most vulnerable to more severe morbidity or mortality [1,2,11,12]. Thus, vaccination delays may contribute to the persistence of VPDs. In a Bangladeshi study, delayed administration of the bacillus Calmette-Guerin (BCG) was associated with increased mortality, while timely administration improved survival among children aged up to 5 years [13]. Therefore, timeliness is an important criterion for evaluating immunization program performance since relying solely on vaccination coverage may not reveal systematic delays in vaccine administration and result in a false assumption of disease protection.

Currently, significant resources are being directed at increasing vaccination coverage for routine immunization in many developing countries worldwide; however, scant literature exists regarding the timeliness of actual vaccine administration. One study [14] evaluated the delays in administration of vaccine in 45 low-income countries including India, and estimated that only 30% of children receive BCG by 4 weeks (recommended at birth), 28% receive the first dose of diphtheria, pertussis, and tetanus vaccine (DPT1) by 8 weeks (recommended at 6 weeks), and only 12% receive measles containing vaccine (MCV) by the recommended age of 9 months.

Another study [15] analyzed the timeliness of DPT3 and measles vaccines in India, using data from the District Level Household and Facility Survey (DLHS3) and found that only 31% of the children vaccinated with the first three doses of DPT (i.e. DPT3) completed the vaccinations by the recommended age of 14 weeks. The same study reported that 30% of the vaccinated children received measles vaccine at the recommended age of 9 months and 15% received it too early (less than 9 months), indicating that 55% of children had delayed MCV vaccination. However, this study was limited to just children who had vaccination cards with immunization dates. Given that the DLHS3 shows only 35% and 31% of children (1 and 2 years, respectively) possessed vaccination cards with dates for DPT3 and MCV, the findings are not fully representative and likely overestimate timely vaccination. These estimates may also have been biased because the analysis did not account for survey weights.

The difficulty of assessing vaccination timing in India is, in part, due to the lack of an electronic vaccination record system such as an immunization information system (IIS). Consequently, reliable vaccination dates are only available for children with vaccination cards at the time of the survey interview; less than 40% of all the children surveyed in the DLHS3 had a card at the time of interview. Furthermore, approximately 2% of the vaccination cards had vaccinations recorded without dates.

Using the traditional methods [16] of investigating timeliness of vaccine administration would limit the sample to only those children with known vaccination dates. Thus, any inferences about timeliness of vaccine administration in Indian children would be drawn from less than 40% of the children in the DLHS. Therefore, to understand the full spectrum of vaccination timeliness, we needed to identify techniques that can use data from children both with and without vaccination cards (and therefore, with and without vaccination dates) to compute the cumulative probability of vaccination at specific ages and thus understand the full spectrum of vaccination timeliness.

Established statistical methods are available to deal with this challenge. These methods, which use statistical techniques for censored data, have not been fully used to date in the vaccination literature. The Turnbull estimator of the cumulative distribution function is one such technique that can accommodate both right and left censored data.

This study has two aims. First, we seek to understand the timeliness of the administration of childhood vaccinations in India utilizing data from children both with and without vaccination dates and incorporating mothers' recall of vaccination status, to compute the estimated probability of vaccination at different age points. Using this approach, the available sample size for analysis is greatly expanded, in turn yielding more accurate estimates of vaccination coverage at any given age. The second aim was to investigate the associations between state-specific probabilities of vaccination at recommended ages and both state-specific infant mortality rates (IMR) and under-5 mortality rates (U5MR).

Methods

Study Population

India's District Level Household and facility Survey data from 2008 (DLHS3) was used for this study, which is the most recent, nationally representative immunization data for children in India available to researchers; although the DLH4 has now been completed, it is not yet available. This analysis includes all children in the survey who met two criteria: birth after

January 1, 2004 and for whom birth dates were available (birth month and year of the child were missing for 0.1% of children); and the interview with the child's mother was conducted between December 2007 and December 2008. At the time of the DLHS3, India's national immunization program, referred to as universal immunization program (UIP), included bacille calmette-guerin (BCG) vaccine for tuberculosis, oral polio vaccine (OPV), diphtheria, pertussis and tetanus vaccine (DPT), and measles-containing vaccine (MCV). Timeliness of BCG, DPT, and MCV were considered for this analysis. According to the UIP, recommended age for administration of BCG vaccine is at birth; the 3 doses of the DPT vaccine series are recommended at 6 weeks, 10 weeks, and at 14 weeks; and the single dose of MCV is recommended at 9 months of age. Due to insufficient sample size, we were not able to estimate probabilities for 7 out of 34 Indian states and Union Territories including Chandigarh, Daman & Diu, Dadra Nagar Haveli, Goa, Lakshadweep, Pondicherry, and Nagaland.

State-specific infant mortality rates (IMR) and under five mortality rates (U5MR) were obtained from the Indian Ministry of Health and Family Welfare[4] for 27 and 20 states, respectively. IMR data were available for each year from 2005 onwards. The state-specific IMR were averaged from years 2005 to 2009. The state-specific U5MR was only available for the year 2009.

Outcome

The outcome of interest is child's age at vaccination for each vaccine type and dose. Vaccination age was calculated by subtracting the birthdate from the date of vaccination. For birthdate, only birth month and year were available, therefore the birth date for each child was

[4] http://www.indiastat.com/table/health/16/infantmortalityrate/17794/444222/data.aspx

set to the first of the month. Vaccination age (in months) was calculated as follows: For children with vaccination cards with dates recorded, vaccination age could be calculated. For children who did not have a vaccination card (i.e. no recorded vaccination dates), the child's age at vaccination was right censored at the age of interview if the mother indicated that the child was not vaccinated. For children whose mothers recalled vaccination, but did not remember the specific date or for children who had vaccination cards with invalid dates of vaccination (e.g. "999", indicating that the vaccination date was unknown), the child's age of vaccination was left censored at the age of interview.

The proportion of children with "on time vaccination," i.e., administered within a month after the recommended age (as per the ACIP guidelines), was estimated based on the Turnbull method, as described below. Vaccinations administered at least 32 days after the recommended age were considered delayed. Children with negative vaccination age (i.e., vaccination recorded as occurring prior to the birth date) were excluded from the current analysis.

Statistical analysis

To estimate the age-specific probability of vaccination (i.e., the cumulative distribution function (CDF), of ages at vaccination), the Turnbull estimator was used, which allows for left, right and interval censoring. The CDF was computed using the *lifereg procedure* of SAS software, Version [9.3] (SAS Institute, Inc., Cary, NC, USA). To produce unbiased CDF estimates, the weight statement was used to incorporate sample survey weights as specified by the DLHS3 documentation. To produce accurate standard errors of CDF estimates, we needed procedures that account for the survey design variables: the lack of available survey procedures under this method limited our ability to incorporate these survey variables, which will result in underestimation of the confidence intervals. For each vaccine, the CDF estimates were plotted to obtain the weighted vaccination timeliness curves. A reference line at the recommended vaccination age was added to each plot, which intersects the CDF at the probability of vaccination by the target age.

The median age at vaccination for each vaccine dose was calculated for all children. Additionally, the median ages at vaccination for each vaccine dose among those who were delayed were calculated: these were calculated from the CDF estimates of cumulative vaccination probability using the estimated age at which 50% of the children not vaccinated by the recommended age were vaccinated.

To investigate the association between timely vaccination and child mortality rates, state-specific vaccination timeliness curves were computed, and estimated probabilities of vaccination by the recommended ages were calculated. The state-specific IMR and U5MR, where known, were regressed against estimated state-specific probabilities of DPT3 vaccination by the recommended age using simple linear regression.

Results

The DLHS3 included information on a total of 268,553 children aged 0 to 60 months. The distribution of children in each age group (1-12, 13-24 months, etc.) is shown in Table 3.1. There were approximately 65,000 children in each of the three younger age groups (0-12, 12-24, and 24-36 months), but because only the two youngest children were chosen for the survey, there were substantially smaller numbers for the 36-48 months and 48-60 months age groups. The vaccination ages were computed for children who had complete vaccination dates on the cards, less than one percent of children in each vaccine category had negative vaccination ages (Table

3.2), i.e., their recorded birthdates were later than the vaccination dates recorded on the card. Eighty percent of the negative vaccination ages occurred in the states of Bihar and Uttar Pradesh; these children were not included in the analysis. The number of children finally included in the timing analysis of BCG, DPT1, DPT2, DPT3, and MCV were 266,316, 266,562, 266,647, 266,753, and 268,099 respectively.

The percentage of children having vaccination cards varied in each age group and for each vaccine dose; however, the general trend was that the children in the older age groups were less likely to have the vaccination cards at the time of interview. For all 3 doses of DPT and the single dose of MCV, the highest percentages of vaccination card retention were in the ages 12-24 months: 39% for DPT1, 38% for DPT2, 35% for DPT3, and 31% for MCV. In the older age groups much lower percentages (approx. 19%) of children had vaccination information obtained through the card for all vaccines and doses. The vaccination dates recorded on the cards were mostly complete and valid, except in a few children (1 to 3.5%) where the day, month or year was missing or invalid and only the receipt of the vaccination was recorded.

Figure 3.1 shows the estimated probability of vaccination at each age, from birth to 5 years, for each vaccine type and dose. The estimated vaccination probability plateaus for each vaccine around the age of 24 months except for MCV, which increases by 5% after 24 months of age.

Table 3.3 gives the estimated coverage at varying ages (based on the CDF estimates shown in Figure 3.1) for BCG, DPT1, DPT2, DPT3 and MCV, using card with dates, cards with no dates, and mothers' recall of vaccination. The estimates of cumulative vaccination probability increased in the older age groups up to age 24 months for each of the vaccine doses, illustrating the large proportion of children with delayed receipt of vaccines. Even including a one month grace period, only 31% had timely BCG vaccination, even though 87% received BCG vaccine by 5 years. Timely administration of DPT1 and DPT3 were only 41% and 19%, respectively, even though the five year coverages were 78% and 63%, respectively. For MCV1, the timely and 5-year coverages were 34% and 76%, respectively.

Table 3.4 shows the summary of delays in vaccine administration among Indian children. The time interval at the population level between the first and second dose of DPT was approx. 2 months; and between second and third dose of DPT was 3 months. For DPT1 and DPT3, the median ages at vaccination among those who were delayed were 6 and 15 months, respectively. Overall 69% of the BCG doses, 81% of DPT3 doses, and 65% of MCV doses were delayed.

Figure 3.1 also shows missed opportunities when a vaccination dose could have been administered but was not, at the time a child was administered a different vaccination. Missed opportunity for DPT vaccination was defined as the extent to which opportunities were lost to administer missed doses of DPT vaccine when children received MCV, which is given later in the vaccination schedule. The differences in the cumulative probability of MCV and DPT3 at ages 9 months and later represent the lost opportunity for DPT2 and especially DPT 3 vaccinations. (The line representing the cumulative probability of MCV in Figure 1 crosses the line for DPT3 at 12 months.). By age 24 months, the cumulative probability of vaccination was approx. 10% greater for MCV than DPT3 and 13 % greater at 60 months as shown in Table 3.

State-level vaccination timeliness for BCG, DPT3 and MCV are shown in Figures 3.2, 3.3, and 3.4. Although the vaccination timeliness curves are more or less parallel for each state, a wide variation in the estimated probability of vaccination can be observed among the states. For DPT3 vaccination Uttar Pradesh had the lowest probabilities of vaccination at each age; 32% at 12 months and 37% at 24 months, followed by Meghalaya, 38% and 42% at 12 and 24 months respectively. The highest DPT3 vaccination probability was for Tamil Nadu, 87% at 12 months and 88% at 24 months. Thus, better performing states like Tamil Nadu and Jammu and Kashmir had little difference (0.68%) in the estimated probability of vaccination at 12 months and at 24 months, whereas poor performing states such as Bihar and Jharkhand had an increase of 6% or more in the vaccination probability between 12 months and at 24 months. As shown in Figure 1, vaccination coverage increased only incrementally after 24 months across states.

We investigated whether vaccine delay was associated with childhood mortality both within the first year of life and within the first five years. Figures 3.5 and 3.6 show the state-specific association between probability of DPT3 vaccination at the recommended age and IMR and U5MR, respectively. We found a10 percent increase in DPT3 vaccination by the recommended age was associated with a decrease of 3.6 deaths per 1000 live births in the first year of life. Moreover, state-specific associations between DPT3 vaccination probability and U5MR was investigated : a 10 percent increase in the probability of DPT3 vaccinations by 6 months was associated with 8.8 fewer deaths per 1000 live birth among children less than 5 years old.

Discussion

Our analysis of India's DLHS3 data revealed that administration of the majority of required childhood vaccines in India are delayed resulting in two-thirds or more BCG, DPT3, and MCV doses being given after the recommended ages. We also found the lack of vaccination timeliness went in both directions with 7% of MCV doses were received earlier than the recommended age. The implications of systematic delays in the receipt of the majority of vaccine doses in most Indian children for vaccine preventable disease-related morbidity and mortality is significant. This is especially important in India with its 26 million annual birth cohort in the context of perpetually building an ever-expanding reservoir of VPD-susceptible children. The presence of this pool of susceptible is also a potential risk for VPD outbreaks. Past studies in other countries have shown that delayed vaccination is an important determinant of VPD morbidity. Timely administration of a second dose of DPT was significantly associated with reduced disease severity and lower hospitalizations due to pertussis in Germany [17], New Zealand [18], and Australia [2]. A 2002 study among German children showed that early measles vaccination could lead to considerable reductions in measles-morbidity[12]. These study findings are particularly important because of the similarities to India in the context of MCV coverage in young children below the level needed to achieve measles elimination accompanied by endemic transmission of wild type measles virus. Vaccination delays coupled with low rates of vaccination coverage and low vaccine effectiveness due to malnutrition, which is widely prevalent in India, can be an especially lethal combination for accelerated rates of outbreaks [19]. Thus, frequent measles outbreaks in India [20], can partially be explained by poor measles timeliness.

The burden of VPDs is highest in Indian children 1-5 years, followed by 5-15 years old. In an epidemiologic investigations of measles in an unvaccinated population in India the attack rate was highest for children in the age group 9-11 months and 1-4 years [21]. The most common measles complications among children include ear infections and diarrhea, and severe measles complications include pneumonia (1 out of 20children with measles) and encephalitis (1 in 1000 cases) [22] . Therefore, vaccination delay predisposes the most vulnerable group at risk for VPD morbidity and unnecessarily prolongs susceptibility.

The results of this analysis showed no increase in population level vaccination coverage after 24 months, indicating either a failure or absence of public health programmatic efforts to vaccinate older children. Additionally, there is considerable variation among the states; however, the pattern remained substantially similar in that the cumulative vaccination curves plateaued for all the states at 24 months. The reasons for this relatively early plateau are not clear. This finding is of considerable concern since all protective maternal antibodies will have completely disappeared by 2 years of age. Additionally, these older children might start to move into congregate care settings where they are with other children and could, therefore, represent more transmission risk to others, compared to a child who will mostly like just be with his/her mother.

Finally, a strong association between DPT3 vaccination probability at recommended age and IMR and DPT3 vaccination and U5MR was found. This strong association is likely due to both direct and indirect benefits of vaccination. Direct benefits include preventing VPD mortality among vaccinated children. Furthermore, it prevents spread of VPDs to other children and adults because of higher herd immunity. Indirect benefits include getting access to preventive health care services, which provide an opportunity for delivery of other much needed preventive services, as has been shown in studies of U.S. children [23]. It could be possible that states where children are able to access vaccination services the most are the states where these children have most access to health care services.

Published literature shows that both individual and contextual factors are essential for utilization of health services [24], like immunizations. Unfortunately, we were unable to investigate reasons for delayed administration of vaccines in India nor are there any other previous studies on this topic in Indian children to the authors' knowledge. However, previous studies of reasons related to untimely vaccinations in other developing countries, suggest the factors associated with vaccination delay include low parental education, income below poverty level, and living in a household with two or more children [9,25,26]. Research in African countries suggest the individual factors related to vaccination delays are greater number of children, being in lowest wealth quintile, and non-institutional delivery [27]. In our previous analysis, we found similar factors were associated with risk of under and non-vaccinations, it might be possible that these factors may partially explain vaccination delays in India. However, in India the contextual challenges of the vaccination programs include logistics such as storage of sufficient vaccine stocks, cold chain maintenance, and inadequate staffing at health centers [28,29]; further exploration is needed to study the association of these contextual factors with vaccination delays.

The fact that the MCV coverage was better than the DPT3 coverage points to missed opportunity for DPT administration as MCV is given at nine months which represents an opportunity to "catch up" on DPT vaccinations. Missed opportunities for DPT3 may occur when the vaccination card is not presented at the time of MCV vaccination and the health staff does not know what vaccines the child needs unless they investigate by asking additional questions to the caregiver. Frequently, children in India do not have a vaccination card at all. In the absence of a vaccination record, it is advised that health staff should make additional effort to find out whether the child is eligible for additional vaccine (e.g. DPT) when they administer the MCV. The finding of missed opportunities for DPT3 immunization indicates the importance of maintaining a system that reliably permits the collection of childhood immunization records such as a functioning IIS. The electronic vaccination database could be used to identify children with missing doses and recall them for vaccination in a timely way. A review study assessing the capabilities of IIS in many different countries, suggested IIS is critical in improving vaccination rates, timeliness and preventing vaccine preventing VPDs (ref). In India, a web based system to track pregnant women and their children, known as Mother and Child Tracking System (MCTS), was introduced by Government of India in December, 2009. However, this system is facing several challenges such as: incomplete reach in urban areas due to poor government health care infrastructure; many government facilities such as primary health centers and sub-centers were not included in the web-based database; shortage of trained manpower to maintain the electronic database at the point of service delivery; and lack of internet facilities etc. Additionally, it is a complicated system due to its multiple interface with several levels and types of providers, program officers, and the amount of data being tracked. This has resulted in less than optimum performance of MCTS; for example, during 2012-2013 year, it showed 39% of children received DPT3 and 17% received MCV, much lower than any immunization survey in India. India lacks a functional IIS, which could help in not only addressing the issue of missed opportunities but also improving timeliness of vaccine administration, and increasing full-vaccination coverage rates.

The need to track vaccination timeliness is going to become even more important in the future as Indian government decides to add more vaccines to the UIP. The current Indian immunization schedule provides for only one MCV at 9 months; however, the UIP program has introduced a second measles dose in states where MCV coverage has reached 80%. Furthermore, discussions are ongoing for the addition of rotavirus vaccine. According to WHO position paper [30], rotavirus vaccination should be administered as soon as possible after 6 weeks of age, along with DPT vaccination, to ensure induction of protection prior to natural rotavirus infection. The safety and benefits of rotavirus vaccination depend on timeliness and coverage; therefore, it becomes even more critical to assess timeliness of vaccination to prevent VPDs and thereby for a successful UIP program.

Vaccination timeliness at the population level has been described and graphically visualized using Kaplan-Meier (KM) methods [16]. Several studies [8–10,12,26,27] have used KM methods to analyze vaccination timeliness and reported significant delays in the administration of vaccines. KM method takes into account the censoring of the data and provides accurate estimation of proportion vaccinated at a given age. Additionally, it also provides graphic presentation of timing of vaccination in a population, and thus comprehensive approach to describe timing of vaccination [16]. However, the KM method is not very useful in studying vaccination timeliness in countries that lack vaccination record systems. This is because the KM method allows for right censoring, it does not allow for left censoring. Right censoring is especially important when the sample includes children who might still be vaccinated at a later age, while left censoring allows the researcher to include those who are vaccinated but do not have a vaccination record such as we were able to do in this study

Only a few studies [10,27] exist on vaccination timeliness in countries which do not maintain proper vaccination records, and those few have been very small-scale and primary designed to collect data for studying timeliness. However, one study that attempted to assess timeliness in low and middle-income countries using secondary survey data [14]. In that study, single imputation was used to replace missing vaccination ages with a random draw from the overall distribution of vaccination ages for children with similar characteristics, including residence (rural/urban), place of delivery (home/ hospital), and mother's education, maternal age at birth, child's birth order, and child's age. One of the limitations of this method could be that the regression model used to estimate the vaccination age of the child included child's age at interview as a covariate. This could result in a predicted vaccination age of the child older than his/her age at interview. In our analysis, children who did not have vaccination dates but were considered as vaccinated based on mother's recall, were left censored at the interview age, which assisted in computing the probability of vaccination by that age for all the children who were not vaccinated at the time of interview. This is a robust methodology for assigning probabilities at specific age points, and it is the first time this technique has been introduced to analyze vaccination timeliness.

This method, known as the Turnbull estimation technique, has as its primary advantage over traditional methods of estimating vaccination coverage in that it allows for simultaneous right and left censoring. Also, by including all data this technique provides improved estimation of vaccination probabilities at different age points. It also appropriately accounts for the limitations in information on vaccination dates, i.e. less than 40% of the children aged 0-60 month in India had vaccination cards at the time of survey, and even fewer percentages had valid vaccination dates recorded for each vaccine. This issue of non-availability of vaccination dates has previously limited the scope of analyzing vaccination timeliness among countries that lack proper vaccination records. This new approach will enable researchers and policy makers to study vaccination timeliness at the population level using the national survey in countries that lack vaccination record systems.

The analysis of this study is subject to some limitations. Only birth month and year were available for children, so birthdates were not precise and for this study each child's birthday was set to 1st of the birth month. For vaccines with recommended ages of administration between birth and 14 weeks, precision of birthdates (only month and year available) made estimation of premature vaccination difficult, especially for series of vaccines administered at close intervals. Therefore, we could not estimate premature and invalid vaccination doses for DPT1, 2, and 3. Moreover, children who died were not included in the survey, and they might not have been vaccinated before death; this could potentially over-estimate the cumulative probabilities of vaccinations.

This study also has several strengths. This study used a large, nationally representative sample. Most importantly, the study presents estimated coverage of vaccinated children at each age by including all children with and without vaccination cards. In contrast, all the previous studies only included children with vaccination cards for vaccination timelines, and vaccination card use may be associated with a greater probability of being vaccinated (Simpson DM, AJPM 1997, [31]). The estimates of this study are free from such bias. The method shown in this paper to compare the vaccination timeliness in different states can be an important tool to compare the vaccination program performance in different regions of the country. The similar method could be used to monitor the progress of a vaccination campaign over time.

In conclusion, lack of timely vaccinations remains a significant problem in India. We found that the majority of Indian children received delayed vaccinations, especially for DPT3 and MCV and that vaccination timeliness was associated with lower under-five-mortality. India's vaccine delivery programs must make additional effort to vaccinate children at the recommended ages, in addition to increasing the overall coverage. Overall, the findings of this study indicate the need for substantial improvements in the vaccine delivery programs in India.

Table 3.1 Quality of survey data for vaccination information by child's age at interview for children up to 5 years in the District Level Household and facility Survey data from 2008 (DLHS3)

Child's age at interview in months (Total number surveyed)	0- 12 (67,032)	12-24 (65,620)	24-36 (65,123)	36-48 (57,173)	48-60 (13,563)
BCG given (%)	76.91 (51,555)	86.19 (56,558)	84.1 (54,770)	81.85 (46,796)	83.85 (11,373)
BCG recorded on card, with date (%)	43.74 (29,320)	39.33 (25,811)	28.14 (18,324)	20.92 (11,958)	19.78 (2,683)
BCG recorded on card, no date (%)	2.42 (1621)	2.51 (1646)	1.86 (1210)	1.61 (920)	1.39 (189)
Mothers recall of BCG (%)	30.80 (20,644)	44.39 (29,128)	54.13 (35,250)	59.35 (33,933)	62.70 (8,504)
DPT1 given (%)	62.19 (41,686)	78.85 (51,743)	75.18 (48,962)	72.72 (41,576)	73.41 (9,957)
DPT1 recorded on card, with date (%)	38.86 (26,048)	39.48 (25,910)	26.65 (17,356)	21.00 (12,005)	19.97 (2,708)
DPT1 recorded on card, no date (%)	1.54 (1,033)	1.77 (1,162)	1.45 (942)	1.22 (700)	0.94 (128)
Mothers recall of DPT1 (%)	21.82 (14,624)	37.62 (24,684)	45.56 (29,670)	50.51 (28,876)	52.51 (7,122)
DPT2 given (%)	46.89 (31,433)	71.9 (47,184)	69.06 (44,973)	67.09 (38,359)	68.61 (13,563)
DPT2 recorded on card, with date (%)	30.41 (20,382)	37.93 (24,888)	27.48 (17,895)	20.51 (11,726)	19.62 (2,661)
DPT2 recorded on card, no date (%)	1.51 (1,010)	1.76 (1,154)	1.39 (903)	1.19 (680)	0.85 (115)
Mothers recall of DPT2 (%)	15.0 (10,053)	32.24 (21,155)	40.2 (26,180)	45.40 (25,957)	48.15 (6,530)
DPT3 given (%)	32.53 (21,803)	61.61 (40,428)	58.92 (38,368)	57.7 (32,991)	59.92 (8,127)
DPT3 recorded on card, with date (%)	21.90 (14,677)	34.85 (22,870)	25.87 (16,847)	19.46 (11,128)	18.81 (2,551)
DPT3 recorded on card, no date (%)	2.20 (1,473)	2.73 (1,794)	1.99 (1,298)	1.62 (928)	1.13 (153)
Mothers recall of DPT3 (%)	8.44 (5,660)	24.04 (15,774)	36.62 (20,226)	36.62 (20,938)	39.99 (5,424)
MCV given (%)	15.21 (10,197)	67.67 (44,405)	70.16 (45,690)	69.19 (39,557)	72.62 (9,849)
MCV recorded on card with date (%)	5.57 (3,735)	30.93 (20,295)	24.42 (15,901)	18.59 (10,629)	17.95 (2,434)
MCV recorded on card, no date (%)	2.39 (1,603)	3.53 (2,318)	2.39 (1,557)	1.87 (1,069)	1.45 (197)
Mothers recall of MCV (%)	7.25 (4,862)	33.22 (21,800)	43.35 (28,234)	48.73 (27,863)	53.23 (7,219)

Table 3.2 Number and percent of children with negative vaccination age for each vaccine in the District Level Household and facility Survey data from 2008 (DLHS3)

Vaccine (dose)	Negative Vaccination age (n)	Total number of vaccination dates available (n)	Percentage
BCG	366	93,682	0.39
DPT1	276	88,992	0.31
DPT2	214	81,414	0.26
DPT3	206	73,719	0.28
Measles	147	59,738	0.25

Table 3.3 Age-specific estimated probability of vaccination (standard error) for BCG, DPT, and MCV (CDF estimates based on the Turnbull method, as shown in Figure 1)

Age in months	**BCG (Birth)**	**DPT1 (1.5mnth)**	**DPT2 (2.5 month)**	**DPT3 (3.5 month)**	**MCV (9 month)**
0-1	31 (0.13)	3.17 (0.04)			
1.5	44.66 (0.15)	7.38 (0.06)			
2	55.35 (0.13)	19.8 (0.11)			
2.5	64.17 (0.12)	40.94 (0.10)	5.31 (0.05)		
3	69.16 (0.10)	53.41 (0.11)	13.34(0.08)		
3.5	72.64 (0.10)	60.43 (0.10)	27.96 (0.10)	3.85 (0.04)	
4	74.85 (0.09)	64.37 (0.09)	40.44(0.1)	8.85(0.06)	
4.5	76.53 (0.09)	66.89 (0.09)	48.58 (0.10)	18.6 (0.08)	
6	79.5 (0.08)	70.74 (0.08)	59.79(0.09)	41.36(0.1)	
9	82.08 (0.07)	73.57 (0.08)	65.84(0.08)	53.68(0.09)	12.31(0.08)
10	82.56(0.07)	74.1 (0.08)	66.73(0.08)	55.4(0.09)	34.44(0.11)
11	82.94(0.07)	74.45 (0.08)	67.37(0.08)	56.55(0.09)	51.62(0.11)
12	83.3 (0.06)	74.82 (0.07)	67.9(0.08)	57.39(0.09)	58.72(0.1)
18	85.25 (0.06)	76.99 (0.07)	70.52(0.08)	60.37(0.08)	67.8(0.09)
24	85.71 (0.06)	77.5 (0.07)	71.28(0.07)	61.5(0.08)	71.47(0.08)
30	85.99 (0.06)	77.84 (0.07)	71.71(0.08)	62.01(0.08)	72.62(0.08)
36	86.09 (0.06)	77.96 (0.07)	71.92(0.08)	62.28(0.08)	73.44(0.08)
42	86.26 (0.06)	78.13 (0.07)	72.13(0.08)	62.5(0.09)	73.76(0.08)
48	86.37 (0.06)	78.22 (0.35)	72.26(0.08)	62.57(0.47)	74.13(0.1)
60	86.59 (0.09)	78.42 (0.65)	72.67(0.74)	63.29(0.83)	75.63(0.73)

BCG: bacille calmette-guerin vaccine
DPT: diphtheria, pertussis and tetanus vaccine
MCV: measles-containing vaccine
CDF: cumulative distribution function

Table 3.4 Description of delays in vaccine administration among children 0-5 years of age using DLHS3 data (Turnbull method*)

Vaccine	UIP Recommendation (Lower age limit – Upper age limit) in months	Median age at vaccination in months	Median age at vaccination among those who were delayed	Percentages of doses delayed
Primary doses				
BCG	0 -1	1.74	2.6	69%
DPT1	1.5-2.5	2.83	6	59%
MCV	9.0-10.0	10.84	17	65%
Booster doses				
DPT2	2.5-3.5	4.63	8.3	96%
DPT3	3.5-4.5	7.59	15.5	81%

*computed CDF estimates of probability of vaccination at specific ages, based on Turnbull method

Figure 3.1 Cumulative Probability of Vaccination for bacille calmette-guerin vaccine (BCG), 3 doses of diphtheria, pertussis and tetanus vaccine (DPT1, DPT2, and DPT 3), and measles-containing vaccine (MCV)

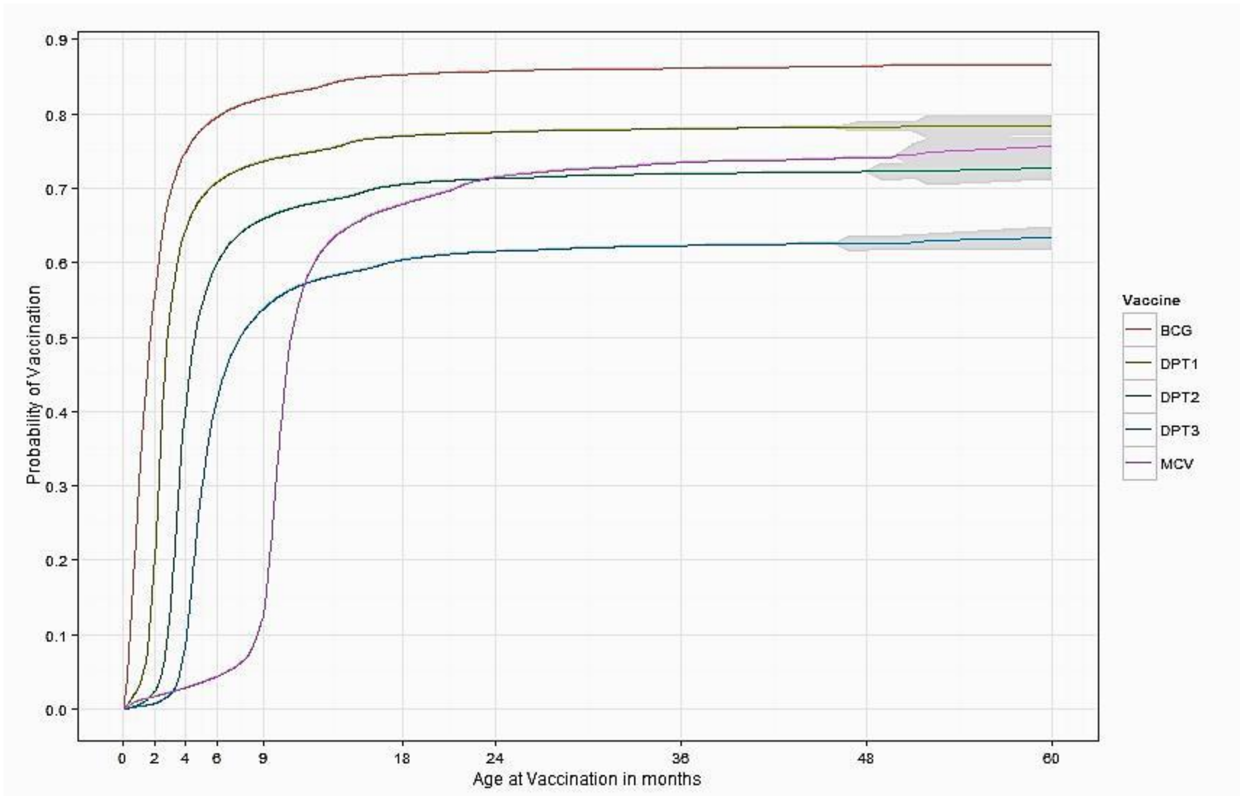


Figure 3.2 State-specific cumulative probability of vaccination for bacille calmette-guerin vaccine (BCG)

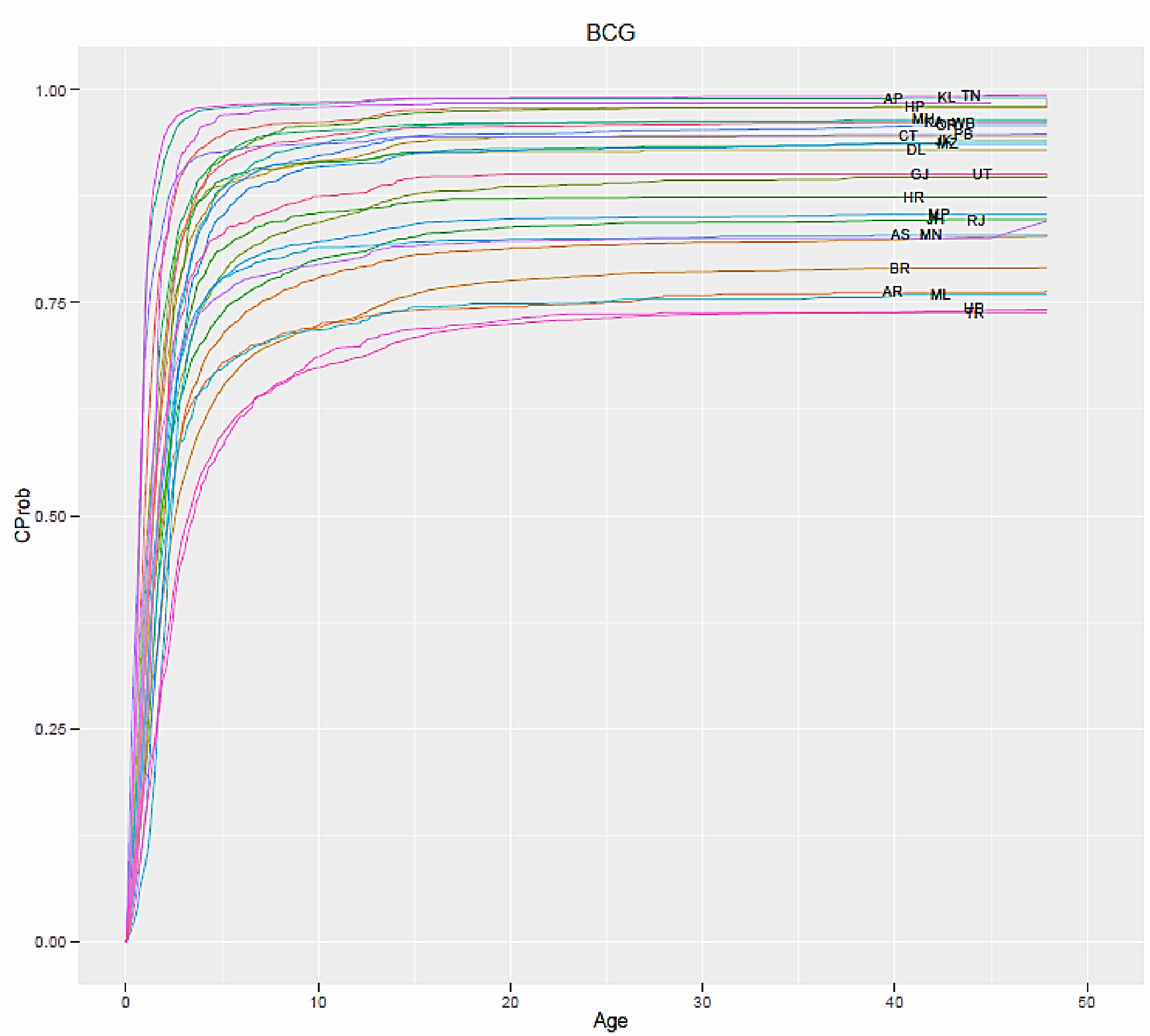


Figure 3.3 State-specific cumulative probability of vaccination for third dose of diphtheria pertussis tetanus (DPT) vaccine

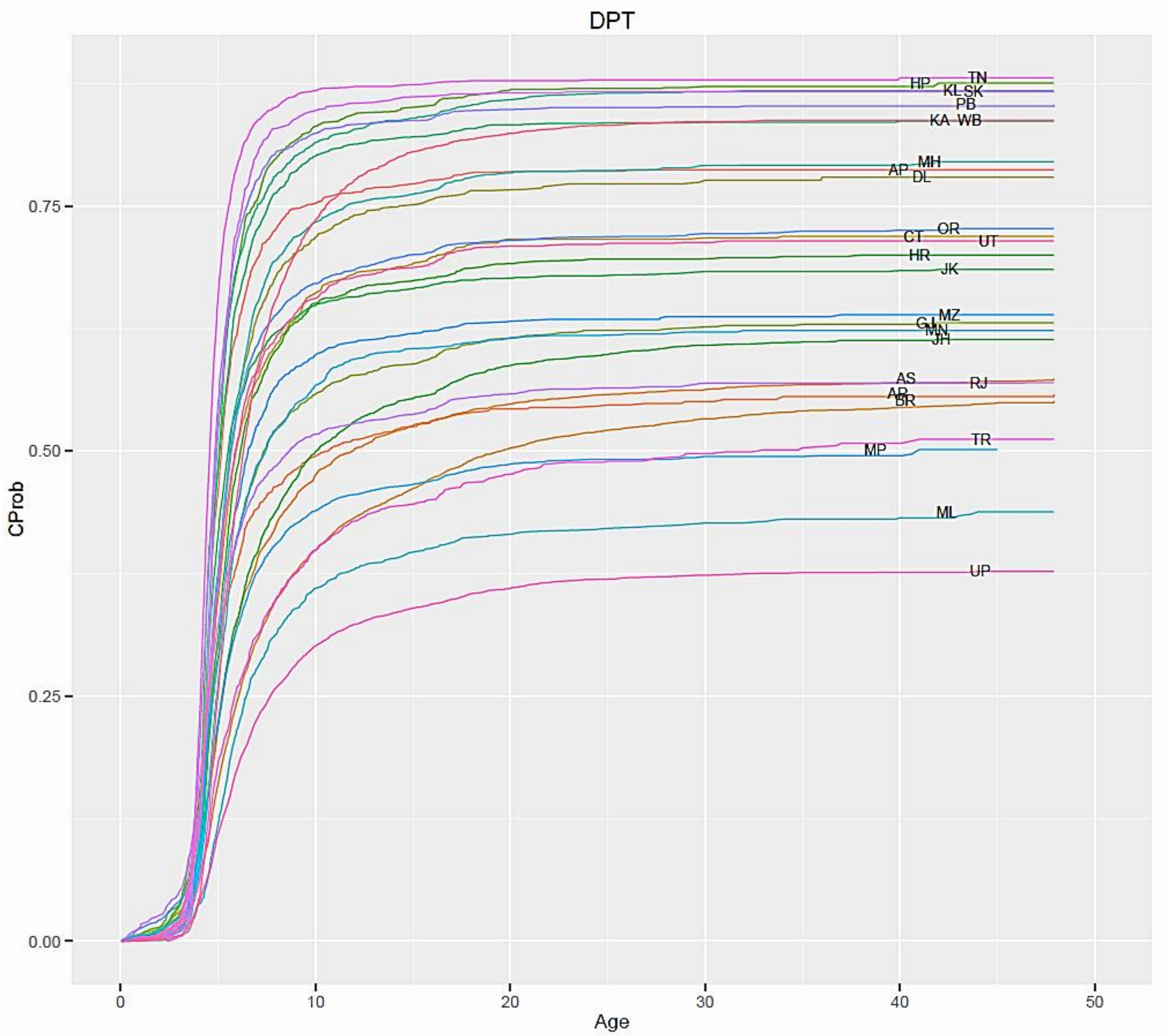


Figure 3.4 State-specific cumulative probability of vaccination for measles containing vaccine (MCV)

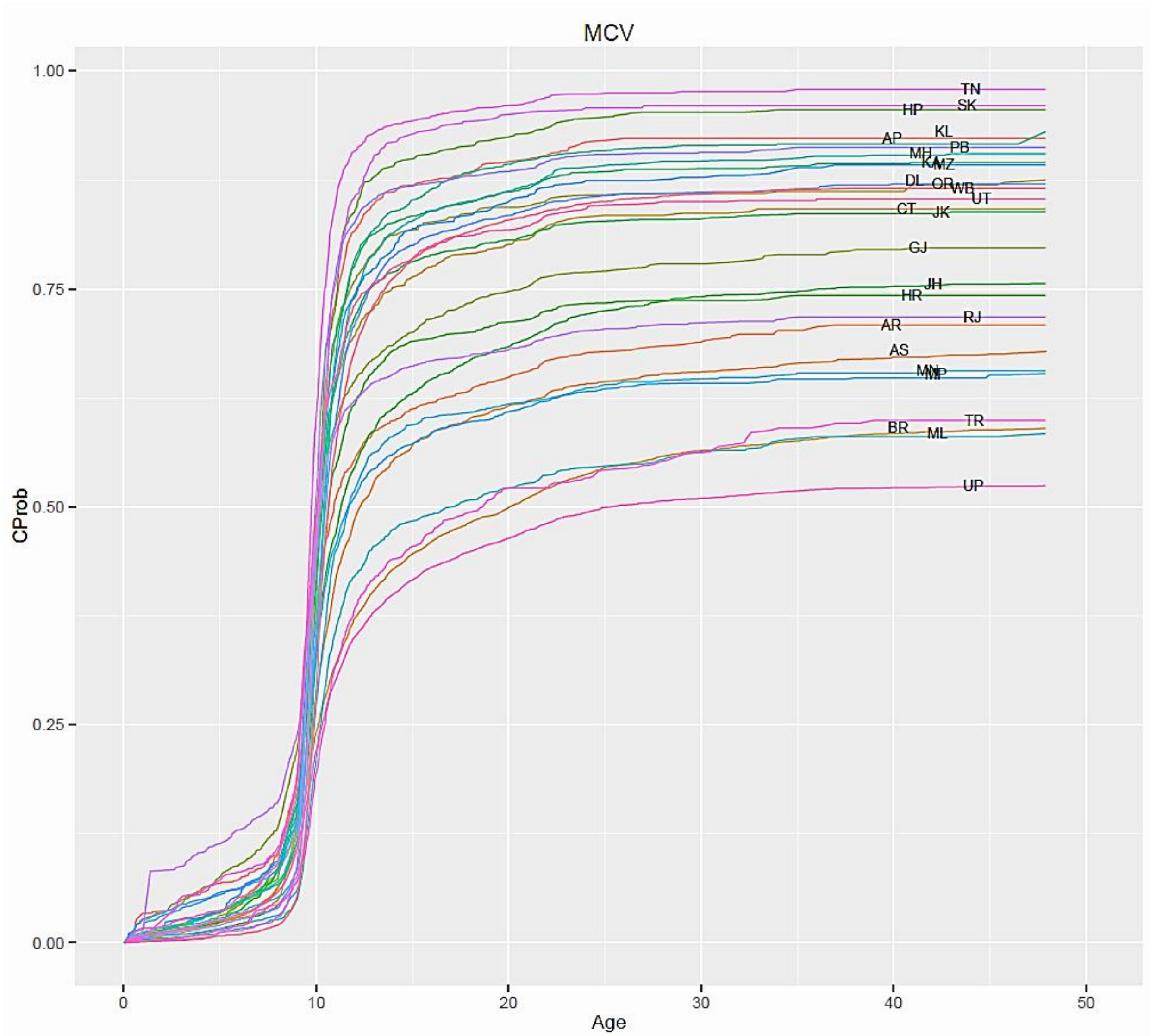
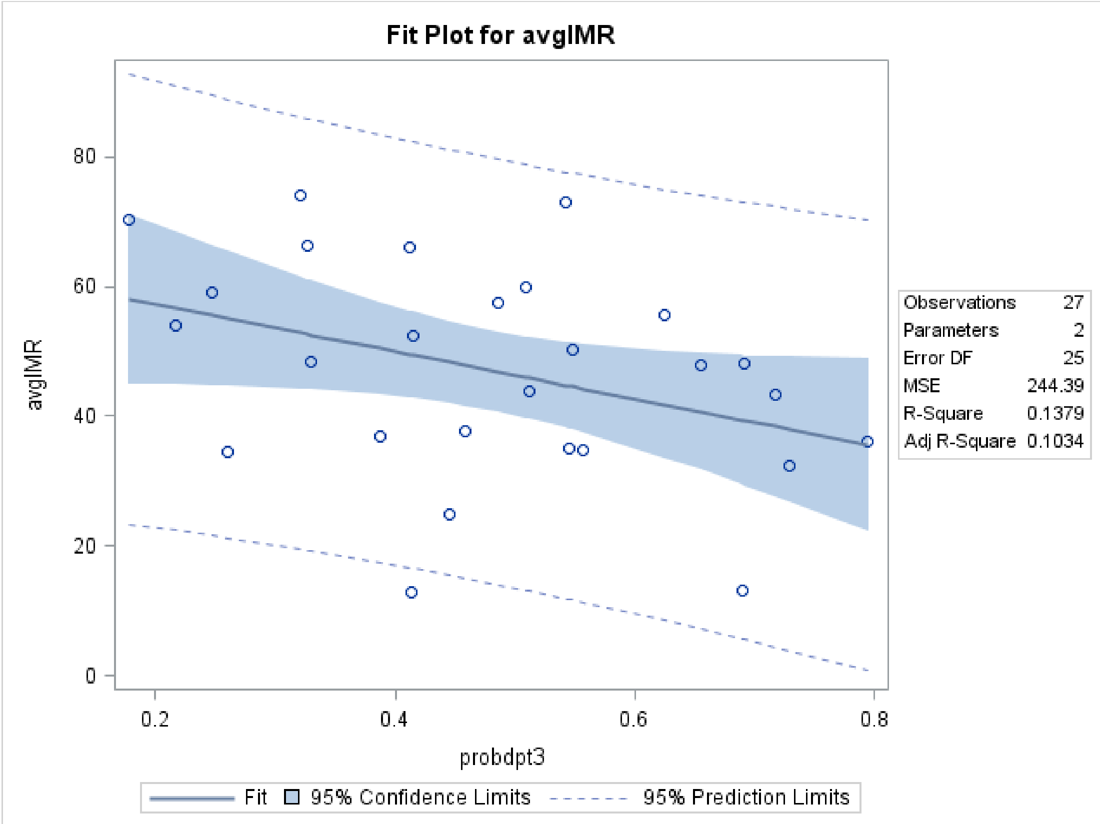
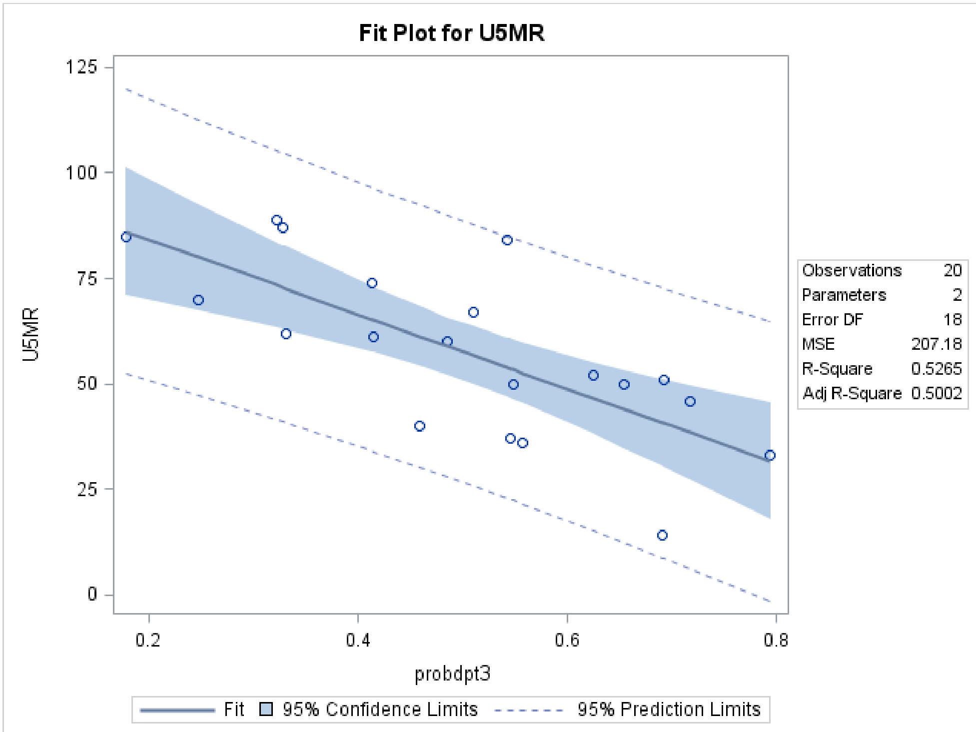


Figure 3.5 Regression of state-specific probability of dpt3 vaccination at 6 month and infant mortality rates (27 states)



Parameter Estimates				
Variable	DF	Parameter Estimate	Standard Error	Pr > |t|
Intercept	1	64.55751	9.29451	<.0001
probdpt3	1	-36.48336	18.24278	0.0565

Figure 3.6. Regression of state-specific probability of DPT3 vaccination at 6 month and under-five-mortality rate, 2009 (20 states)



Parameter Estimates				
Variable	DF	Parameter Estimate	Standard Error	Pr > |t|
Intercept	1	101.85147	10.44346	<.0001
probdpt3	1	-88.46328	19.77197	0.0003

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Chapter 4

Impact of State-Specific Differences on Childhood Vaccination Coverage in India

Introduction

Low vaccination coverage and inequities in coverage continue to exist in India, despite the existence of a long standing national immunization program. In 1978, the government of India launched the Expanded Program for Immunization (EPI) to cover the cost of recommended vaccines for all Indian children, which was re-named as Universal Immunization program (UIP) in 1985. Based on the United Nations Children's Fund's (UNICEF) coverage evaluation survey, childhood vaccination coverage in India improved little during the two decade span from 1990 to 2010. India's national District Level Household and Facility Survey-2008 (DLHS3) estimated the percentage of fully-vaccinated children 12-23 months of age as 54%; however, this average masks the extreme variation in coverage across states, ranging from 82% in states like Himachal Pradesh and Tamil Nadu to 13% and 30% in Arunachal Pradesh and Uttar Pradesh (See Appendix Table A.1). It is plausible that at least some of the lack of progress in increasing vaccination coverage in India is due to state-specific factors [1].

Numerous studies have focused on individual predictive factors for vaccination in India, such as gender, age, and birth order; other studies have focused on household factors, such as family size, number of children below 3 years old, household wealth, and maternal education [1–

5]. However, as far as the authors know, none of these studies have taken into account the effects of state level factors on vaccination such as policy environment, governance structure, and socio-cultural differences across states. India is a uniquely diverse country with over 2000 spoken dialects and languages, reflecting a tremendous variation in local and regional traditions, cultural practices, religious beliefs, and socioeconomic pressures. Given this degree of variability, state-level differences could reasonably be assumed to influence the expression of individual-level predictors of childhood vaccination, especially since many state-level policies and programs directly impact health care availability and accessibility.

There is a relative paucity of research investigating state-level differences in risk factors for child health outcomes in India. A 2010 study reported variation in disparities by gender and area of residence for child health outcomes in different states of India [6]. Another paper by De and Bhattacharya examined the factors affecting childhood vaccination in Madhya Pradesh (MP), Bihar, Uttar Pradesh (UP), and Rajasthan, and specifically reported better vaccination coverage among Muslim children from MP compared to other religious groups; Scheduled Tribe (ST) children in all the states had the poorest coverage levels [7]. A 2008study comparing childhood immunizations in two different states (Maharashtra and Bihar) reported that the probability of complete vaccination coverage was higher for children in rural areas compared to urban areas of Maharashtra, unlike the situation in Bihar [8] where the higher vaccination coverage was in the urban areas. Furthermore, Kumar et al. reported that higher overall inequity in vaccination coverage was observed in Maharashtra compared to Bihar, which is economically a much poorer state [9].

Although these studies demonstrated state-specific differences in the associations of various risk factors and child health outcomes, all were characterized by significant limitation.

Most compared few states, generally no more than four, and most are largely descriptive in nature [10]. Additionally, these studies [7,9] have used broad and inconsistent categories of predictors. Some simply categorize religion into Hindu and non-Hindu; caste into scheduled caste (SC)/ scheduled tribe (ST) and others; and household wealth index into three categories (low, medium and high). Overly broad categories like this result in a loss of important detail and can lead to a failure to capture the effects of the combined subcategories on the outcome variable. For example, non-Hindu religion includes Christians, Muslims, Sikhs, Buddhist, Jains, Parsis, atheists, and self-proclaimed secularists. Each of these religions has different religious and cultural practices, beliefs and attitudes that may influence their health behavior. Collapsing them all into one category will dilute the effect of each which may have a completely different association with the outcome variable. For example, a few studies [7,11] classified social categories into four groups: privileged Hindus (i.e., they excluded Hindus who were SC, ST), under-privileged Hindus (Hindus who belonged to SC, ST), Muslims, and others (including all the other religious groups irrespective of their caste). This categorization neglects the fact that each religion has all of these castes; these religious and socio-cultural differences may be expressed differently based on the prevalent policy environment for vaccination coverage in different states.

Contextual state-level variables include characteristics of the communities in which children reside, including their social and economic characteristics, as well as the availability of healthcare resources. Such community-level factors may influence parental decisions for the receipt of preventive services (such as vaccination for their children) independent of individual-level characteristics [12]. For example, an uneducated mother living in a progressive state with substantial vaccination outreach programs may be more likely to receive vaccination for her children because of her social interactions, accessibility of healthcare services, and prevailing social norms. Thus, a clearer understanding of the relative influence of state-level factors, along with individual factors including religion and caste, is needed for developing interventions to improve delivery of vaccination services at the population level.

This study examines state-specific differences in childhood vaccination coverage among the rural population in India, using a nationally representative sample of children aged 12-36 months while also presenting an analysis of state-specific differences among socio-cultural factors such as religion in predicting childhood vaccinations in India. The specific objectives for this analysis were to analyze the state-specific differences in the association of religion with childhood vaccination status; to identify the state-level characteristics that are predictive of childhood immunizations; and to identify the state-level characteristic that explains the differences in the effects of cultural predictors. To the authors' knowledge no previous study has reported on state-specific differences across 26 Indian states looking at risk factor association for childhood vaccination

Methods

Data source and sample design

Data for this study was derived from two different datasets. Data for individual-level child characteristics came from India's district level household and facility survey data-2008 (DLHS3). The data was collected from 720,320 households during December 2007 to December 2008. The child data used in the analysis was extracted from the individual women data file. The state factors analyzed in the study used DLHS3 state-level data. Additionally, we also used state-level data from 2011 Census, which was linked to child's state of residence. The target population was children born through January 2004 to December 2007 who were in the age range of 12-36 months old at the time of the interview. In cases where more than one child in a household met these criteria, the most recent born child in the family was selected in order to minimize over-representation of women with more than one child in the referenced age category. The record for each child includes selected characteristics of the child, mother, household, and state information.

Outcome variable

The vaccination status of the child was dichotomized as either fully-vaccinated or not fully-vaccinated. Fully-vaccinated children were defined as those who had received all doses of a set of nationally recommended vaccines: 1 dose of bacillus calmette-guerin (BCG), 3 doses of diphtheria-pertussis-tetanus (DPT) and oral polio vaccine (OPV), and 1 dose of measles containing vaccine (MCV); children receiving fewer doses of vaccines than the full set are considered to be not fully-vaccinated. Timeliness of vaccine doses was not considered for this analysis.

State-level factors

State-level variables considered for the analysis were broadly classified as: Healthcare services availability, socio-cultural and, socio-demographic characteristics. The indicators for healthcare services availability were: average population covered by primary health center (PHC), percentage of PHCs with availability of medical officer, percentage of PHCs having regular power supply, and percentage of PHCs having cold chain equipment. Socio-cultural characteristics were represented by percent Muslim population in a state, percent SC, ST in the state; and socio-demographic characteristics consisted of percentage of households in the lowest national wealth quintile, percent literate, and population density of states. Covariates for HC availability and percent of households in the lowest national wealth quintile were obtained from DLHS3 state-level file. The remaining state-level information was acquired from the 2011 Indian census, state data.

Healthcare services accessibility and availability is an important predictor for vaccination [1]. The covariates for HC availability were correlated (see Table 4.3); therefore, we decided to use average population served by a PHC as an indicator of availability and accessibility of immunization services in a state The Indian government recommends that the average population served by a PHC be 30,000. In rural areas, the Indian government delivers maternal and child health services through sub-centers, and PHCs. PHC is the most proximate level of planning for the immunization services, and therefore we chose this covariate as an indicator for availability and accessibility of immunization services in a state.

The state-level literacy rate was obtained from the 2011 Indian census and it is defined as percent of population, aged 7 years or more, who can read and write. For this analysis, percent of population in the lowest national wealth quintile and state literacy rate in a state were considered as indicators for the state-level policies related to opportunities for human development and economic progress. A lower state literacy rate was associated with higher percentage of poor population. We also considered state-level literacy as an indicator for progressive state-level policies.

The composition of individuals belonging to specific religions and castes can be considered proxy indicators for cultural diversity of a state. We treated percent Muslim as an indicator of religious diversity since approximately 75% of Indian population is Hindu, although there are other significant religious minority groups. The percent of SC and ST population in a state were considered as proxy for the prevailing social norms, for instance reluctance to seek modern medical care. SC and ST populations in India were traditionally considered at the lowest rung of the social hierarchy system in India. (See chapter 1 for a more detailed discussion of the caste system.)

Individual-level covariates

Individual-level characteristics were considered potential confounders of the relationship between state-characteristics and child's vaccination status. Individual-level covariates included child's gender and age, maternal age at child's birth, religion, caste, maternal education, maternal receipt of ante-natal care (ANC) services, and place of delivery.

Statistical analysis

The sampling design of DLHS data is such that certain categories of respondents were oversampled. Therefore, we used the calculated survey weights to enable unbiased estimation of population characteristics, and the stratification, clustering and weighting statements were used to account for the complex design characteristics. The Taylor series linearization method was used to calculate variance of the parameter estimates. We conducted a subpopulation analysis as our study subjects were a subset (12-36 months of age and residing in rural areas) of all the children (0-5 years) in the dataset. Descriptive statistics for the individual-level and state-level characteristics were calculated.

Based on the results of previous analysis (chapter 2 and chapter 3), we found wide variation in vaccination coverage among the Indian states. Our first objective was to understand differences in the proportion of children with complete vaccination among religious groups across states in India. Design adjusted descriptive statistics were used to compute proportion of fully vaccinated children for the target population in different states. Additionally, we investigated the differences in association of religion with vaccination status, controlling for all individual level characteristics as confounders. To conduct this analysis we first attempted to include a two-way interaction of religion with state, but a two-way interaction of individual-level religion with state variable could not be performed due to insufficient sample size under Christian, Sikh and other religious groups in many states, we therefore created a categorical predictor, "religion-state". This was defined as religion=1 and state=01, then religion-state=101, for all the religious groups (n≥40) present in a state. This categorical predictor was then added to the logistic regression model with individual-level predictors; this analytic method is equivalent to having a two-way interaction, but we could not statistically test interaction like this. However, this method can accomplish our aim of computing vaccination probabilities for each religious group across states. We then computed the predicted probabilities for religion-state variable based on this model using the *margins* command in STATA; further the predicted probabilities were plotted for the ease of interpretation of the results using *marginsplot* command. The margins command compute the probabilities of full vaccination as if everyone in the dataset is at a set level (for example religion=1, religion=3, and so on); then averages it out for overall marginal probabilities.

Our next objective was to investigate the mechanics that drive the variability in complete vaccination coverage within and among the states. Therefore, to identify the state-level factors that may influence the expression of individual-level characteristics for childhood vaccination, we included the state-level characteristics in an individual level model. A two-way scatter plot of the potential state-level predictors with state-level outcome (percent fully-vaccinated) was first investigated to assess the functional form (see Figure 4.1) of the association. Since the scatter plots did not show linear association, categorical versions of continuous variables with levels defined by quintiles were created (see Figure 4.2 and Table 4.3 for the description of quintiles).

Multivariable logistic regression model was used to investigate the association of state-level socio-demographic characteristics with childhood vaccination status, before and after adjusting for individual and state-level covariates. The logistic regression models reported multicollinearity issues, indicating collinearity between the state-level characteristics. The candidate state-level predictors were all categorical variables, therefore, the gamma measures of association between ordinal quintile variables was investigated (see Table 4.4, 4.5, and 4.6). In the multivariate model we only included those predictors that were most relevant to our model and were not statistically associated with each other. We adjusted for individual-level characteristics in order to eliminate biases related to systematic differences in the ways that individuals with different characteristics (maternal education, age at child birth, religion, caste, number of ANC visits, child's gender and place of delivery) may perceive a similar state-level environment.

Finally, we tested if any differences in association by individual's religion could be explained by concentration of the Muslim population (diversity) by including a two-way interaction term between individuals' religion and percent Muslim population of the state in the full model. To test the significance of two-way interaction to the model fit, design-adjusted multi-parameter Wald test was used, which rejected the null hypothesis of no contribution. We then computed the predicted probabilities for state-level factors and the interaction term based on this model using the margins command in STATA; further the predicted probabilities were plotted for the state-level predictors using *marginsplot* command.

Results

Descriptive Analysis

The un-weighted sample size of all the children residing in the rural areas and in the age group 12-36 months was 86,882. Table 4.1 shows the estimated distributions of socio-economic characteristics and the vaccination status of the study population. Based on our analysis, 53% of the target population was fully vaccinated. The majority of the study population was Hindu (78%). More than half (50%) of children had mothers with no schooling, 18% with 1-6 years of schooling, and 32% with 7 or more years of formal schooling. Almost two-thirds (55%) of births were non-institutional, and 20% of births occurred in government institutions like primary health centers, community health centers, and district hospitals. The remaining 20% of births were in private institutions that could be private hospitals, clinic or nursing homes. Approximately 30% of mothers of the children in our study did not receive any ante-natal care (ANC) services, while the remainder received various levels of ANC care.

Table 4.2 shows characteristics of the twenty-six Indian states that were included in the analysis. The mean percentage of population living in the lowest wealth quintile was 16% (Range: 0.5% to 49%). The population density in states ranged from 17 to 1,102. The mean percent of Muslim population was 12% with percent of Muslim population in states ranging from 1% to 67%.

Figure 4.2 shows the intra-and inter-state variation in percentage of fully vaccinated children among different religious groups. The Indian states of Uttar Pradesh (UP) and

Chattisgarh had the highest percentage of full-vaccination in Christian children but in the states of Bihar and Maharashtra, Christian children had the lowest levels of full vaccination. Muslim children had the lowest percentage of fully-vaccinated children in multiple states including Jammu & Kashmir (JK), UP, Uttaranchal, Rajasthan, Jharkhand, Manipur, Arunachal Pradesh, Haryana, and West Bengal, Karnataka, Kerala. However, in the states of Tamil Nadu, Meghalaya, Tripura, and Sikkim, Muslim children had the highest rates full-vaccination coverage. Sikh children generally had the highest levels of full-vaccination compared to other religion in almost every state where they are present except Assam.

For this study we defined high disparity as a difference of 10% or more percentage points in full vaccination coverage among different religious groups within a state which characterized Bihar, Rajasthan, Manipur, Arunachal Pradesh, Assam, Mizoram, J&K, Haryana, and Kerala states. The states of Madhya Pradesh, Gujrat, Andhra Pradesh, and Himachal Pradesh had less disparity, defined as less than 10% difference in full-vaccination across religious groups.

Figure 4.4 describes the probability of fully-vaccinated by religious groups across states. The probabilities used to plot Figure 4.2 were computed using the regression model and were controlled for other individual level predictors of vaccination status.

In table 4.7 (Model 1 and 2), unadjusted and adjusted odds ratios for full-vaccination are compared for state –level characteristics. The comparison showed that an increase in both percent poor and population density was associated with higher odds of complete vaccination. However, there was no consistent pattern by the quintiles for average population per PHC and percent Muslim (Table 4.7, Model 2). We found a slight change in the strength of association for each of the state-level predictors, mostly in the same direction but the greatest change for population density and percent Muslim.

Table 4.8 compares the ORs from three different models; Model 3 includes only individual level characteristics, Model 4 includes individual and state-level characteristics, and Model 5 includes the effects of religion in quintile 1 of percent Muslim and percent Muslim effects for Hindu religion. We found that children living in bigger households (members >7), born in non-institutional settings, and of female gender had their own independent effect of lower odds of complete vaccination, and the strength of associations did not change after adjusting for state-factors ($OR_{hh>7 \text{ compared to hh size of 3}}$: 0.81, CI: 0.76, 0.81; OR_{female}: 0.91, CI: 0.88, 0.94; $OR_{\text{non-institutional compared to government institutions}}$: 0.76, CI: 0.73, 0.79) (see Table 4.8 Model 3 and Model 5). There was a slight increase in the odds of full-vaccination with an increase in individual-level wealth when adjusted for state-level factors. Similarly, children from ST families had lower odds of complete vaccination compared to children from privileged families (OR: 0.77, CI: 0.72, 0.83); this association was slightly stronger compared to the association found when the model was not adjusted for state-level factors. Additionally, we found that adjusting for state-level factors slightly attenuates the strength of association of maternal education, and ANC visits with complete-vaccination.

State-level factors had significant association with childhood vaccination; vaccination probability first decreased and then increased along a gradient of increasing percentage poor in a state, (Figure 4.4a).Conversely, as average population served by a PHC increased, there was a corresponding initial increase in the probability of complete-vaccination followed by a sharp decrease (Figure 4.4b). By population density, only middle quintile (mean population density of 341 persons per sq. km) had significant association with vaccination status with children having significantly higher odds of vaccination compared to children in places with sparser population density.

In Figure 4.5, we compared the predicted probability of complete vaccination for religious groups by quintiles of percent Muslim population in a state. Figure 4.5a, shows the results of main effects model (Table 4.8, Model 4). We found that Sikh children had the highest probability of complete vaccination, and Muslim children had the lowest probability of the same.

Based on the results of the interaction model (Table 4.8, Model 5), we found that the association of various religious groups with childhood vaccination is modified based on the percent of Muslim population in the state of their residence (Figure 4.5). In states with the lowest percent of Muslim concentration (mean % of Muslim population = 1.7), none of the religious groups had significant associations with vaccination status, except Christian children who had lowest probability of being completely vaccinated. In quintile 2 (mean % of Muslim population = 4.8), Sikh children had the highest probability and Muslim children had the lowest probability of complete vaccination. In quintile 3 (mean % of Muslim population = 9), Sikh children had the highest probability and Muslim and Christian children the lowest probability of complete vaccination. In quintile 4 (mean % of Muslim population = 14), Christians and Others' had higher probability and Muslim and Sikh children lower probability. In quintile 5 (mean % of Muslim population = 33), other religious group children remained at the highest probability and Sikh and Muslim children remained at the lowest probability for complete vaccination.

Discussion

We found significant interstate and intrastate variation in children's full-vaccination coverage throughout India. States with less disparity in full-vaccination coverage by religion were generally those with either the very lowest rates of fully-vaccinated children (approx. 40%) and those with the highest percentage (75% or above), with only Gujarat and Orissa states with full-vaccination coverage of 57% and 66%, respectively, as exceptions. It's likely that states with better immunization services, and thus higher full vaccination rates, benefits all residents of the state and therefore reducing disparities. In those states with the lowest full-vaccination coverage rate, it seems all religious groups fare equally poorly. In contrast, states with highest disparities were those with mid-level full vaccination coverage ranging from 45% to 63%. It is likely that when the healthcare resources such as immunization services are limited, only a few groups benefit from it, causing a large disparity in full-vaccination coverage among the religious groups.

We found differences in the full-vaccination coverage rates among different religious groups within a state and across states. Living in a state with poor availability of primary health care services provided by the national network of primary health centers increased the risk for incomplete childhood vaccinations which makes sense given that vaccinations are commonly delivered by these clinics. Similarly, states with higher population densities had lower full-vaccination which may represent population pressure on immunization services. The inequality in full-vaccination due to some of the individual level characteristics such as gender of the child, place of birth (institutional vs. non-institutional) did not change upon controlling for state-level factors.

We also found that the differences in effect for two important individual level predictors, maternal education and ANC care slightly diminished upon controlling for state-level characteristics. Similar results have been reported by a few previous studies from India and Bangladesh: strength of maternal education relationship significantly declines after controlling for individual-level and community-level SES controls [13–15]. Vikram et.al in their study demonstrated that well-educated mothers tend to live in villages with other well-educated mothers and better access to medical care [13]. Based on these findings, if we assume that literacy has a linear relationship with healthcare availability, i.e., there is a higher concentration of illiterate people in the areas with poorer healthcare services, then improving the access to primary health centers could help address inequities in vaccination coverage in areas characterized by lower levels of maternal education. This is especially important since half of Indian mothers in the survey lacked any formal schooling. Maternal education has long been established as an important predictor of childhood vaccination in every country, including India, but in a nation with such a disproportionately large number of mothers without formal schooling, attempting to improve education levels could take many years. Providing more easily accessible immunization services through the already existing national network of PHC could be easier and more rapid to achieve in terms of addressing this barrier in immunization uptake.

Important individual level characteristics that did not appear to be influenced by state-level factors included household size, gender, and setting of birth (institutional vs. not). Several studies have pointed to the existence of gender disparities in accessing immunization services in India and our study had similar findings [4]. This may indicate that making healthcare services more readily available may not be enough to successfully address this issue. Rather, there may be a need to implement targeted intervention programs in some states or regions of India to specifically decrease gender disparities in access to care. Similarly, births in non-institutional setting are often an indication of non-availability or non-utilization of healthcare centers although non-institutional birth can also be due to cultural practices and beliefs. One study pointed out that a key reason for poor uptake of reproductive child health services by women in India is the lack of perceived needs to use medical care [16] . Similarly, children living in bigger households (7 or more members) were less likely to be fully-vaccinated which makes sense as the mothers living in joint families had

As noted, state-level poverty was treated as a proxy for the presence of progressive state policies. We found a V-shaped relationship between state-level poverty and vaccination coverage rate; that is, an increase in state-poverty was accompanied by a decrease in complete vaccination coverage until percentage of poor reached 11% which was thereafter associated with a steady increase in vaccination coverage. It could be that the states with higher proportions of poor people recognized the need for implementing special outreach programs for the poor and/or receive more governmental assistance for these programs, and therefore, these states had higher coverage despite a higher proportion of poor populations. Additionally, large inequity in the full-vaccination coverage among the rich and poor people, such that higher vaccination rates among the richest strata of the state may drive a higher overall vaccination rate for that state. The states in the 4th and 5th quintile were Maharashtra, Rajasthan, UP, Orissa, Manipur, and Bihar. A 2013 study on inequity in full-vaccination coverage among all the states [10], reported that these above mentioned states had significantly high differences in vaccination rates among the richest and poorest strata.

With an increase in average population served by PHC, we found a decrease in vaccination coverage rates. According to the Indian Public Health guidelines, average population served by each PHC should be approx. 30,000 and when the number of people served by a PHC exceeds that, it may impact service delivery including vaccinations. The direct implication of this finding is that increasing the number of PHCs could help prevent over burdening existing health centers. A review study [1] has shown that proximity to health center was associated with child's vaccination status and our study findings are in accordance with that. However previous studies used the distance between child's residence and the nearest health facility and we assessed it differently. It would seem that additional PHCs that are appropriately distributed would create a greater probability of placing children closer to a PHC generally.

Our study has several strengths; this is the first study of which the authors are aware that investigates the state-specific differences in childhood vaccination status in India while also describing differences in vaccination coverage rates of different religious groups across states. Previous literature [1] has reported that Muslim families had the lowest vaccination coverage compared to other religious groups in India in mostly all states which is mostly true. However, we found that in a few states, Muslim children actually had highest full-vaccination coverage rates. No previous study has analyzed the state specific factors that are associated with childhood vaccinations, and the state specific factors that may influence the individual level predictors of vaccinations especially for such a large number of states Our study was also unique in looking at the modification of religion's impact on vaccination status by size of Muslim population which we treated as a proxy for cultural diversity. Although a more appropriate representation of cultural diversity in a state would probably include the percentage of SC and ST population, previous studies have identified a significant independent association between caste and economic indicators precluding their inclusion in the analysis.

There are some limitations of this work that warrant discussion. We limited our study to rural populations as we did not have indicators for healthcare availability for the urban population. However, since 80% of the DLHS3 data comprises rural residents, we had a sufficiently large sample size to permit investigation of various associations with sufficient statistical power. Another limitation of this study was that we were unable to include all the Indian states as the sample sizes available from a few smaller states were not large enough. Additionally, states like Delhi and Chandigarh are mostly urban and consequently not included, since adding them to the analysis may result in bias in state-level effect estimates. While interpreting the effects of these predictors in different quintiles we also have to realize that it may be possible that overall effect of one state-level predictor in a quintile can be dominated by a larger state in that quintile.

Given the complex interactions between state-level characteristics and the policy environment, modelling these factors becomes challenging, and this represents but a first step towards understanding the impact of the confluence of these factors on vaccination completion. Future studies investigating the influence of policy and cultural factors on individuals' vaccination status should perhaps examine district level factors and their influence, as districts level factors exert neighborhood level effects and therefore have more proximal association with vaccination status.

Overall, this study investigated the association of individual-level factors and state-level factors with vaccination status of children in India using a nationally representative dataset. The distribution of full-vaccination coverage differed among religious groups within a state and across Indian states. We found that individual and state-level characteristics had their independent effects on childhood vaccination. An increase in average population served by a PHC over 30,000 was associated with a decrease in full-vaccination coverage. An increase in state-poverty was accompanied by a decrease in full-vaccination until percentage of poor reaches a certain extent, which was then associated with steady increase in vaccination coverage. Religions' association with vaccination was dependent on prevailing cultural environment.

Table 4.1 Descriptive table for individual-level characteristics of children 12-36 months of age, DLHS3

Characteristics	Categories	Un-weighted Sample sizes	Weighted Percentage (95% CI)
Vaccination Status		86882	
	Fully-vaccinated		53.2 (52.7 , 53.7)
	Not-Fully Vaccinated		46.8 (46.3 , 47.3)
Religion		85459	
	Hindu		78.3 (77.9 , 78.7)
	Muslim		13 (12.5 , 13.5)
	Christian		5.3 (5.1 , 5.6)
	Sikh		2 (1.9 , 2.2)
	Other		1.4 (1.3 , 1.5)
Caste		85221	
	SC		19.6 (18.8 , 20.6)
	ST		20.4 (20 , 20.9)
	Underprivileged		40.2 (39.4 , 41)
	Privileged		19.8 (19.4 , 20.2)
Wealth Quintile		86872	
	Poorest		24.8 (24.3 , 25.3)
	Poor		24.8 (24.4 , 25.2)
	Middle		22.5 (22.1 , 22.8)
	Rich		18.5 (18.1 , 18.8)
	Richest		9.5 (9.1 , 9.8)
Household Size		86882	
	3 members		7.6 (7.4 , 7.8)
	4-5 members		30.4 (30.1 , 30.7)
	6-7 members		29.1 (28.7 , 29.5)
	7+ members		32.9 (32.6 , 33.2)
Maternal Age		86882	
	<= 18 years		8.3 (8.1 , 8.5)
	19-25 years		53.4 (52.8 , 53.9)
	26-35 years		33.6 (33.1 , 34.1)
	35+ years		4.7 (4.6 , 4.9)
Child gender		86879	
	Male		52.7 (52.4 , 53)
	Female		47.3 (47 , 47.7)
maternal Education		86882	
	No school		50.3 (49.6 , 50.9)
	1-6 years		18.2 (17.9 , 18.4)
	7+ years		31.5 (30.9 , 32.2)
Delivery Place		85189	
	Gov. Institution		20.7 (20.4 , 21)
	private Institution		14.1 (13.7 , 14.5)
	Non-institutional		65.2 (64.6 , 65.8)
No. of ANC visits		86882	
	No visits		33.3 (32.8 , 33.9)
	1-2 visits		41.9 (41.4 , 42.5)
	3-6 visits		19.9 (19.5 , 20.3)
	7+ visits		4.9 (4.7 , 5)
Maternal tetanus vaccination		85192	
	No		32.7 (32.2 , 33.2)
	yes		67.3 (66.8 , 67.8)

Table 4.2 Descriptive table for state-level characteristics of the target population

Variable	No. of states	Mean	Std. Dev.	Min	Max
Percent SC Pop	25	14.2	7.9	0.1	31.9
Percent ST Pop	24	22.7	26.0	0.6	94.4
Avg. Pop per PHC	26	42,138	36,479	5,216	158,275
Percent PHC with MO	26	77.8	14.3	51.8	100.0
Percent PHC with CC	26	65.2	23.1	21.4	97.2
Percent PHC with regular power Supply	26	42.1	26.9	6.3	96.9
Percent Literates	26	75.3	8.2	61.8	94.0
Population density(Person per square Km)	26	373.0	297.2	17.0	1102.0
Percent Muslims	26	11.9	13.8	1.1	67.0
Percent in lowest WQ	26	15.8	14.1	0.5	48.5

Figure 4.1 Scatter plot of state-level characteristics and percentage fully-vaccinated children in by state (The size of the bubble indicates the population size of the state)

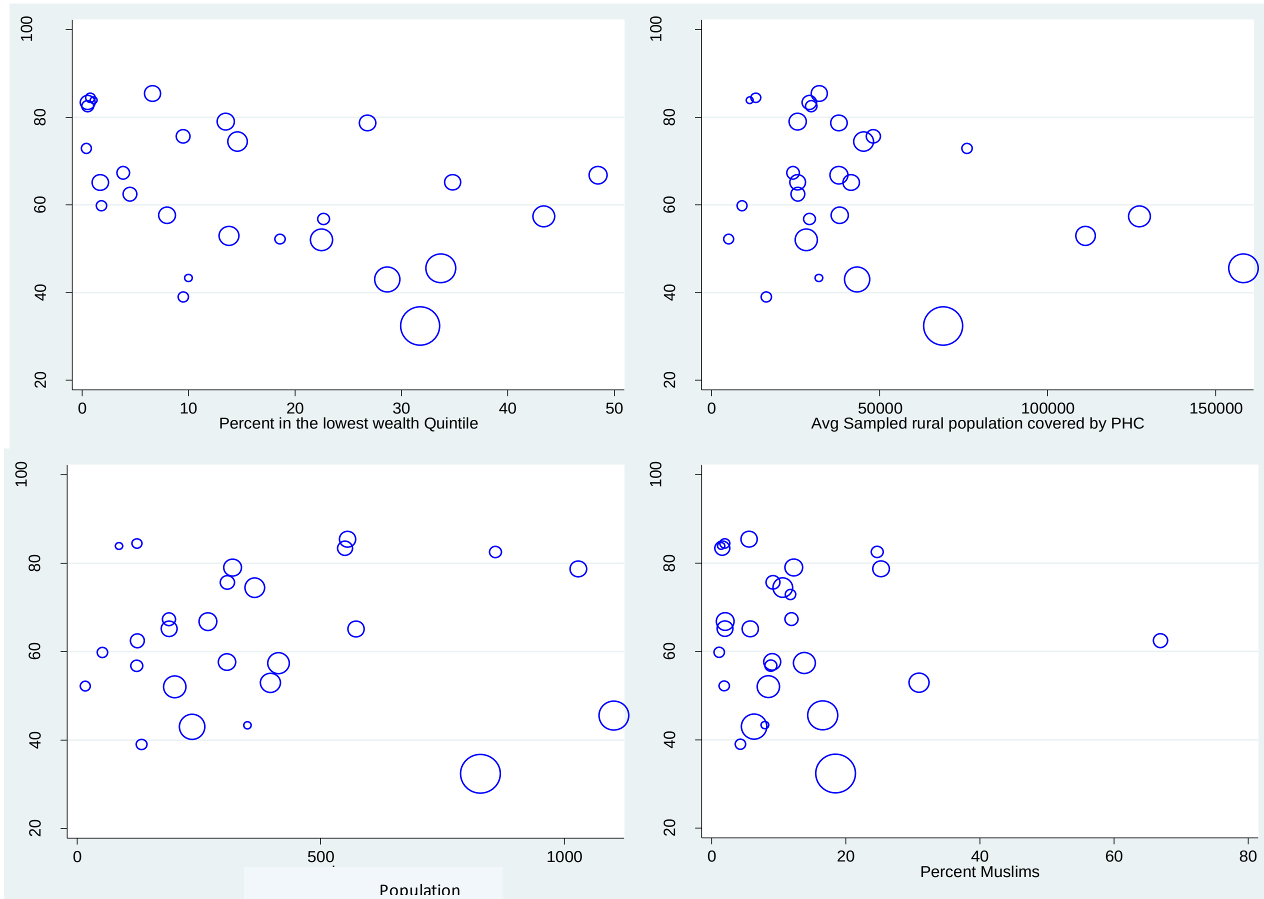


Figure 4.2 Box-plot of state-level predictors (Percent poor, Average Population per PHC, population density, Percent Muslim)

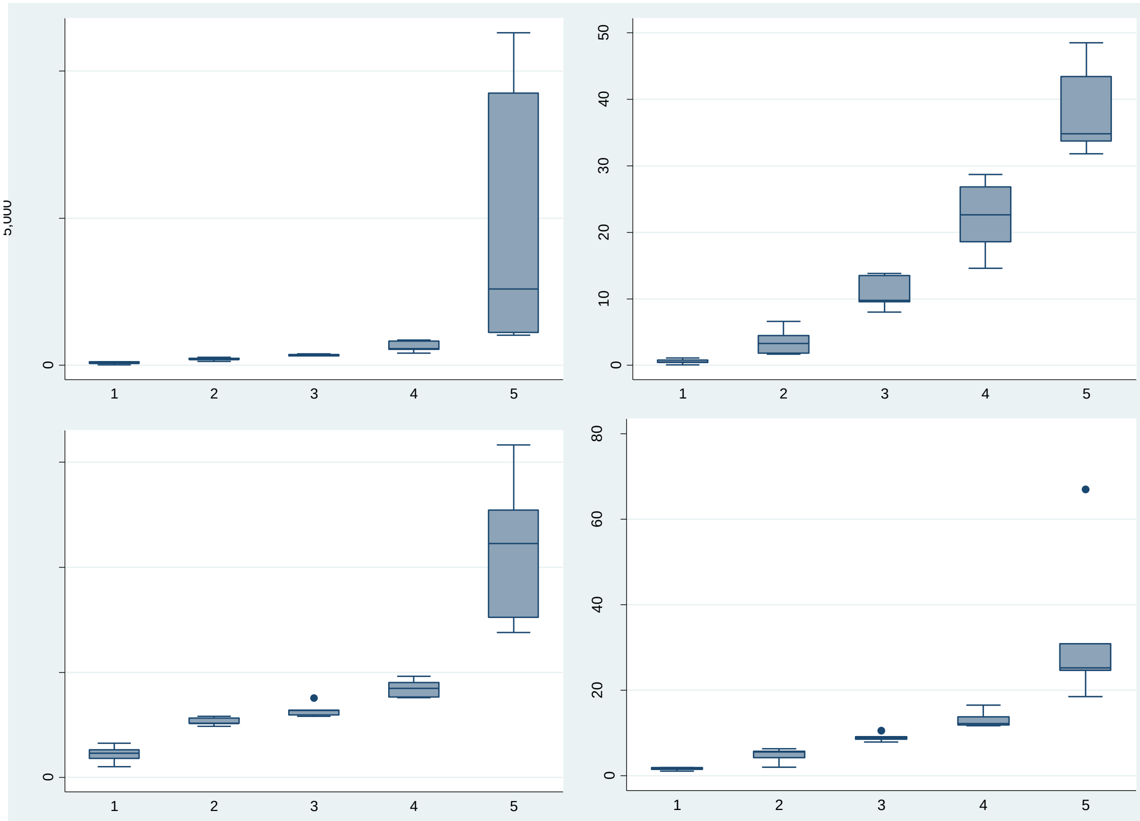


Table 4.3 Description of quintiles of state-level characteristics included in the study

	No. of States	Mean	Std. Dev.	Min	Max
Percent in Lowest WQ					
1	4	0.7	0.3	0.5	1.1
2	5	3.7	2	1.7	6.6
3	6	10.7	2.4	8	13.8
4	6	22.3	5.2	14.6	28.7
5	5	38.4	7.1	31.8	48.5
Avg Pop served per PHC					
1	5	11064	4181	5216	16311
2	6	26505	1817	24410	29157
3	5	32160	3445	29206	37867
4	6	42402	4001	37978	48110
5	4	116504	37150	69037	158275
Pop Density					
1	6	87	44	17	124
2	6	202	47	132	269
3	6	341	36	308	397
4	6	630	175	414	859
5	2	1065	52	1029	11297
Percent Muslim					
1	6	1.7	0.3	1.1	2
2	5	4.8	1.7	2.1	6.4
3	6	9	0.9	8	10.6
4	4	13.6	2.1	11.9	16.5
5	5	33.2	19.3	18.5	67

Table 4.4 Pearson correlations coefficients among state-level covariates for health services availability

	AvgPop/SC	AvgPop/PHC	% MO	% CC	% RegElectricity
AvgPop/SC	1				
AvgPop/PHC	0.70	1			
% MO	0.43	0.54	1		
% CC	0.10	0.00	0.16	1	
% RegElectricity	-0.35	-0.27	0.09	0.43	1

Abbreviations: Avgpop/SC- average population served by sub-centre
AvgPop/PHC-average population served by primary health centre
%MO- percent of PHCs with medical officers
%CC- percent of PHC with cold chain
%RegElectricity- percent of PHC with regular poser supply

Table 4.5 Gamma measures of association for state-level predictors using state-level data

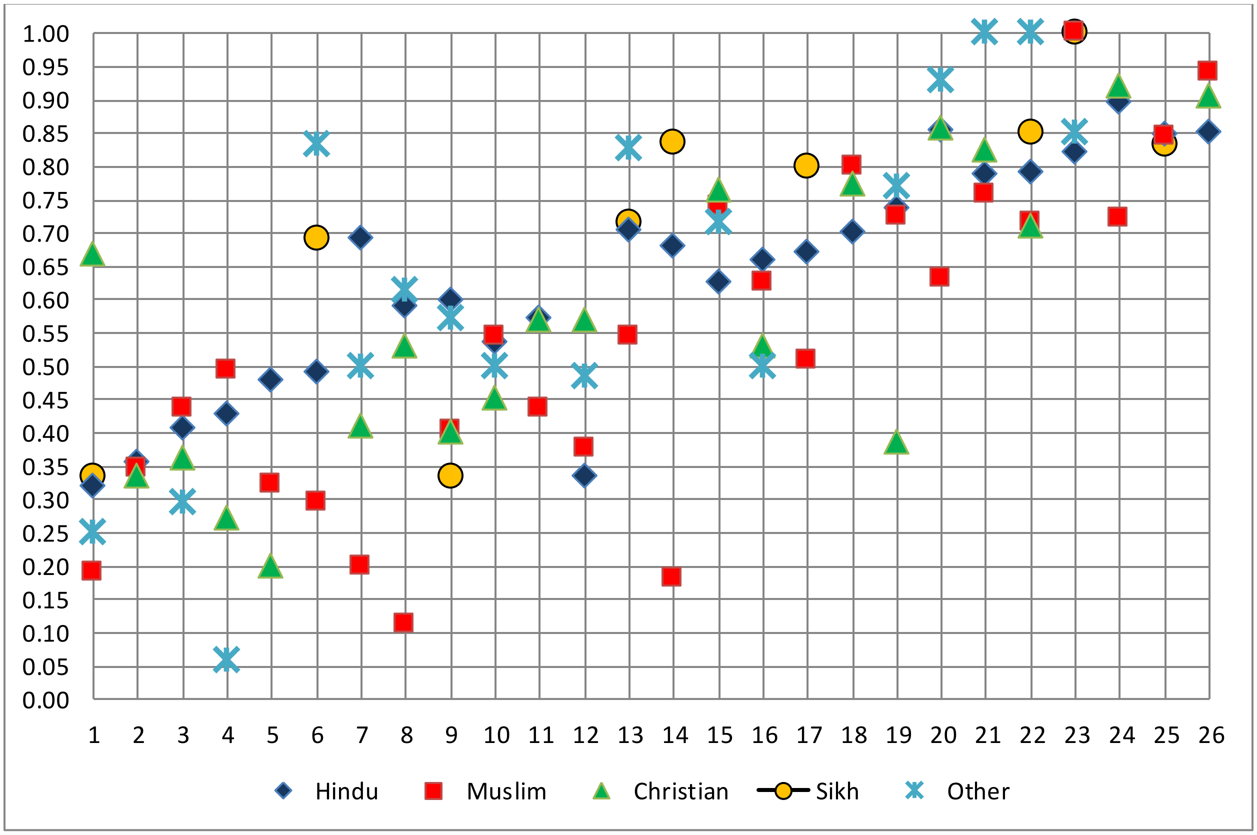
	QSC	QST	Qlit	QPercentPoor	Qpopsense
QSC	1.00				
QST	-0.61	1.00			
Qlit	-0.01	-0.06	1.00		
QPercentPoor	-0.06	0.14	-0.62	1.00	
Qpopsense	0.41	-0.63	0.18	-0.07	1.00

Table 4.6 Gamma measures of association for state-level predictors at individual level

	QSC	**QST**	**Qlit**	**QPercentPoor**	**Qpopsense**
QSC	1.00				
QST	-0.68	1.00			
Qlit	0.03	-0.03	1.00		
QPercentPoor	0.18	-0.26	-0.60	1.00	
Qpopsense	0.37	-0.73	-0.10	0.32	1.00

Abbreviations
QSC- quintiles of proportions of scheduled caste population
QST- quintiles of proportions scheduled tribes
QPercentPoor- quintiles of percent population in the lowest wealth quintile
Qpopdense- quintiles of population density

Figure 4.3 Percentage of Fully-vaccinated children by religion among Indian states, DLHS 2008 data



1=UP	2=MP	3=ML	4=TR	5=BR	6=RJ	7=MN	8=AR
9=AS	10=GJ	11=JH	12= MZ	13=JK	14=HR	15=CT	16=OR
17=UT	18=AP	19=MH	20=WB	21=KA	22=PB	23=SK	24=KL
25=HP	26=TN						

Figure 4.4 Predicted probability of full-vaccination by religious groups across Indian states, controlling for all other individual-level predictors of vaccination-status

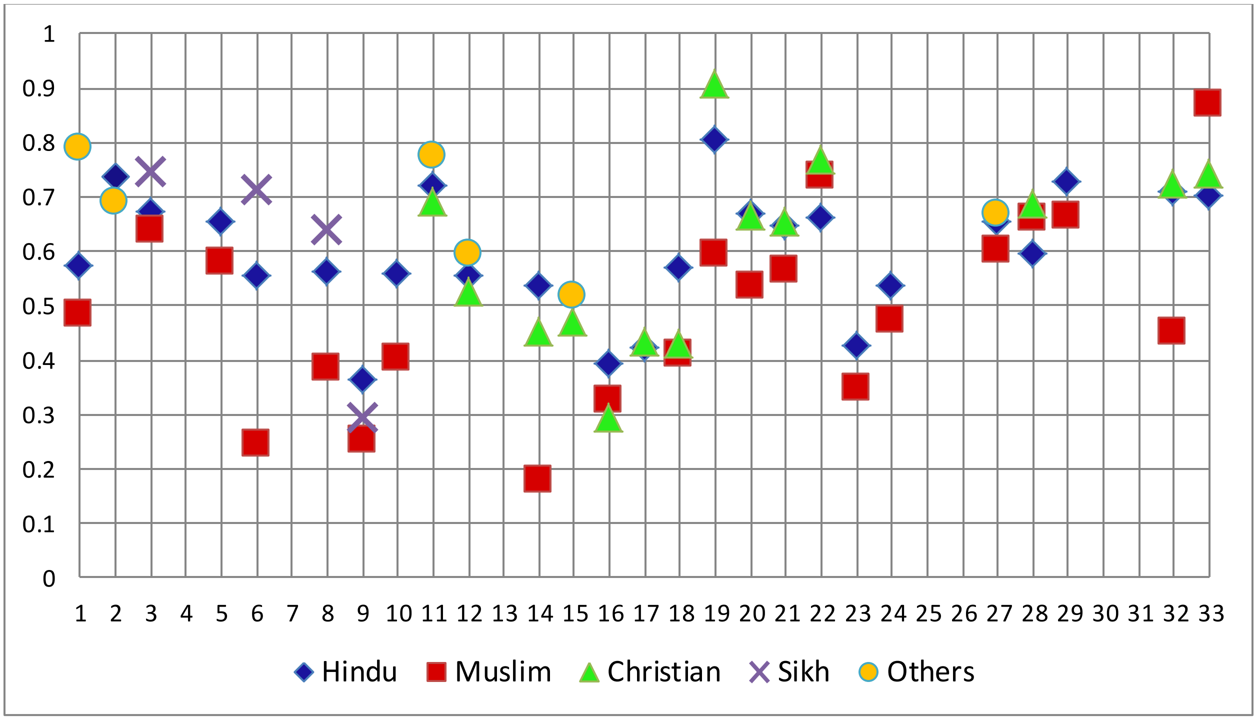


Table 4.7. Odds ratios for full-vaccination for state-level characteristics from binary logistic regression models

Covariates	Model 1 (Unadjusted OR)	Model 2 (Adjusted OR)
Percent Poor Quintiles		
2	0.39 (0.36, 0.44)	0.4 (0.35, 0.45)
3	0.27 (0.25, 0.3)	0.12 (0.1, 0.14)
4	0.23 (0.21, 0.25)	0.25 (0.22, 0.28)
5	0.15 (0.14, 0.16)	0.41 (0.37, 0.47)
Avg Population per PHC # Quintiles		
2	1.2 (1.1, 1.3)	0.99 (0.86, 1.14)
3	1.87 (1.72, 2.04)	1.58 (1.38, 1.8)
4	0.89 (0.82, 0.95)	0.54 (0.47, 0.63)
5	0.47 (0.44, 0.51)	0.25 (0.21, 0.3)
Population Density Quintiles		
2	0.63 (0.59, 0.68)	1.1 (0.98, 1.23)
3	1.11 (1.03, 1.2)	7.54 (6.53, 8.71)
4	0.58 (0.54, 0.62)	1.37 (1.25, 1.5)
5	0.72 (0.67, 0.78)	1.56 (1.42, 1.72)
Percent Muslim Quintiles		
2	0.5 (0.47, 0.54)	1.29 (1.1, 1.51)
3	0.61 (0.56, 0.66)	0.73 (0.64, 0.82)
4	0.54 (0.5, 0.58)	1.48 (1.29, 1.69)
5	0.35 (0.32, 0.37)	0.91 (0.8, 1.04)

OR: Odds Ratio
PHC: Primary Health Centers

Table 4.8 Adjusted Odds ratios for full-vaccination from multivariate binary logistic regression models

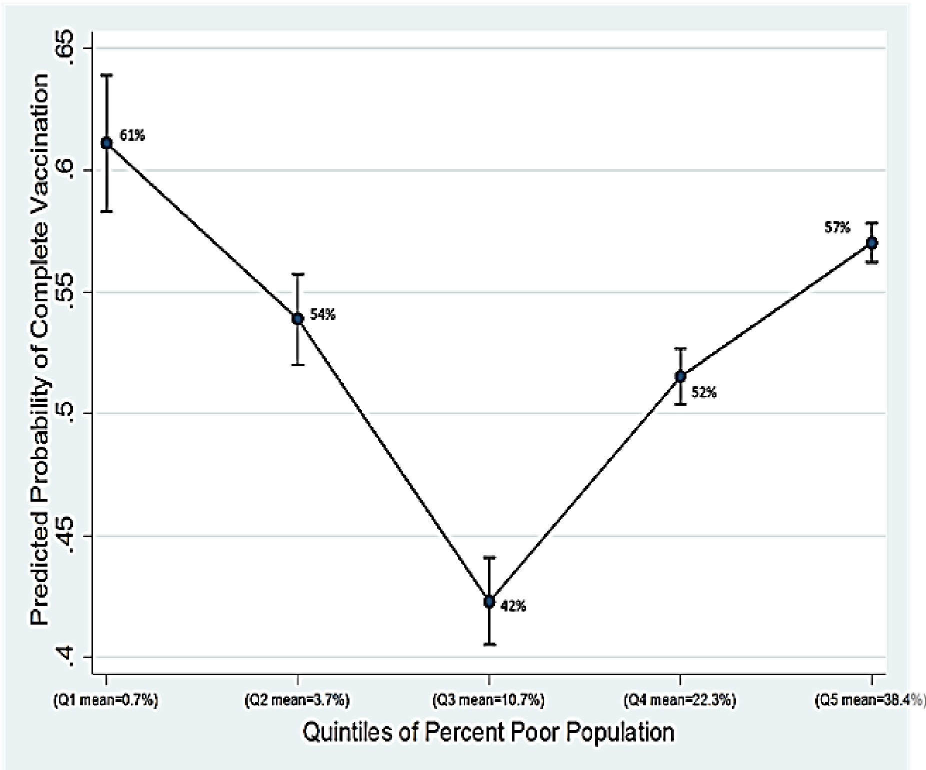
Covariates	Model 3	Model 4	Model 5
Religion			
Muslim	0.55 (0.52, 0.59)	0.56 (0.52, 0.6)	0.77 (0.41, 1.47)
Christian	0.7 (0.64, 0.77)	0.77 (0.69, 0.87)	0.6 (0.49, 0.74)
Sikh	2.3 (1.96, 2.69)	1.21 (0.99, 1.49)	1.23 (0.94, 1.61)
Other	1.43 (1.22, 1.67)	1.1 (0.93, 1.31)	1.07 (0.86, 1.32)
Caste			
Priveleged	Ref	Ref	Ref
SC	0.89 (0.83, 0.94)	0.89 (0.83, 0.95)	0.9 (0.84, 0.97)
ST	0.84 (0.79, 0.89)	0.78 (0.73, 0.84)	0.77 (0.72, 0.83)
Underprivileged	0.81 (0.77, 0.86)	0.87 (0.82, 0.92)	0.88 (0.83, 0.93)
Wealth Quintile			
Poorest	Ref	Ref	Ref
Poor	1.19 (1.12, 1.26)	1.17 (1.11, 1.24)	1.17 (1.11, 1.24)
Middle	1.3 (1.23, 1.37)	1.32 (1.25, 1.39)	1.32 (1.25, 1.39)
Rich	1.48 (1.38, 1.58)	1.52 (1.41, 1.64)	1.52 (1.42, 1.64)
Richest	1.57 (1.44, 1.7)	1.76 (1.6, 1.92)	1.76 (1.61, 1.93)
Household Size			
3 members	Ref	Ref	Ref
4-5 members	0.99 (0.93, 1.05)	0.95 (0.9, 1.01)	0.95 (0.9, 1.01)
6-7 members	0.94 (0.88, 1.01)	0.92 (0.86, 0.99)	0.92 (0.86, 0.99)
7+ members	0.81 (0.76, 0.86)	0.81 (0.76, 0.87)	0.81 (0.76, 0.87)
Maternal age			
<=18 years	0.96 (0.92, 1.01)	0.93 (0.88, 0.98)	0.93 (0.89, 0.98)
19-25 years	Ref	Ref	Ref
26-35 years	1 (0.97, 1.04)	1.04 (1.01, 1.08)	1.04 (1, 1.08)
35 + years	0.92 (0.84, 0.99)	0.96 (0.89, 1.04)	0.96 (0.89, 1.03)
Child's gender			
Male	Ref	Ref	Ref
Female	0.92 (0.89, 0.95)	0.91 (0.88, 0.94)	0.91 (0.88, 0.94)
Child's age (in months)	1 (1, 1.01)	1 (1, 1.01)	1 (1, 1.01)

Maternal Education			
No formal School	Ref	Ref	Ref
1-6 years	1.45 (1.39, 1.52)	1.35 (1.29, 1.42)	1.35 (1.29, 1.42)
7+ years	1.91 (1.83, 1.99)	1.75 (1.67, 1.84)	1.75 (1.67, 1.84)
Place of Birth			
Govt. Institutions	Ref	Ref	Ref
Private Institutions	0.91 (0.86, 0.96)	0.92 (0.87, 0.98)	0.92 (0.87, 0.98)
Non-institutional	0.72 (0.69, 0.75)	0.76 (0.73, 0.79)	0.76 (0.73, 0.79)
No. of ANC visits			
No visits	Ref	Ref	Ref
1-2 visits	1.1 (0.98, 1.22)	1.15 (1.02, 1.28)	1.15 (1.02, 1.28)
3-6 visits	1.96 (1.74, 2.2)	1.57 (1.37, 1.79)	1.56 (1.37, 1.78)
7+ visits	2.28 (2.01, 2.58)	1.52 (1.33, 1.74)	1.51 (1.32, 1.73)
Maternal TT shot	2.18 (1.96, 2.41)	2.14 (1.92, 2.38)	2.14 (1.92, 2.38)
Percent Poor Quintiles			
2		0.62 (0.54, 0.71)	0.69 (0.58, 0.81)
3		0.36 (0.3, 0.42)	0.38 (0.31, 0.46)
4		0.56 (0.49, 0.64)	0.61 (0.52, 0.71)
5		0.76 (0.66, 0.88)	0.81 (0.69, 0.95)
Avg Population per PHC # Quintiles			
2		1.08 (0.9, 1.28)	1.11 (0.9, 1.37)
3		1.35 (1.15, 1.59)	1.55 (1.26, 1.91)
4		0.67 (0.56, 0.8)	0.75 (0.6, 0.94)
5		0.37 (0.3, 0.47)	0.42 (0.33, 0.54)
Population Density Quintiles			
2		1.08 (0.94, 1.23)	0.99 (0.85, 1.15)
3		3.07 (2.64, 3.58)	2.78 (2.33, 3.32)
4		1.11 (0.99, 1.25)	0.99 (0.86, 1.13)
5		1.29 (1.15, 1.46)	1.14 (0.99, 1.32)

Percent Muslim Quintiles		
2	0.98 (0.83, 1.16)	0.85 (0.71, 1.02)
3	0.72 (0.63, 0.83)	0.66 (0.58, 0.77)
4	1.7 (1.47, 1.97)	1.52 (1.31, 1.76)
5	0.88 (0.75, 1.02)	0.77 (0.66, 0.9)

Model 3: Includes only individual level characteristics
Model 4: Includes individual and state level characteristics
Mode 5 includes the parameter estimates of the full model that includes religion effects for quintile 1 of percent Muslim and state effects for religion1; the specific two way interaction effects of religion with state are not shown in the table
PHC: Primary Health Center

Figure 4.5 Predicted probability of complete vaccination by quintiles of percent of population in the poorest wealth quintile (a), and Average population served by the Primary Health Center (b), these probabilities were computed based on Model 5, Table 4.7



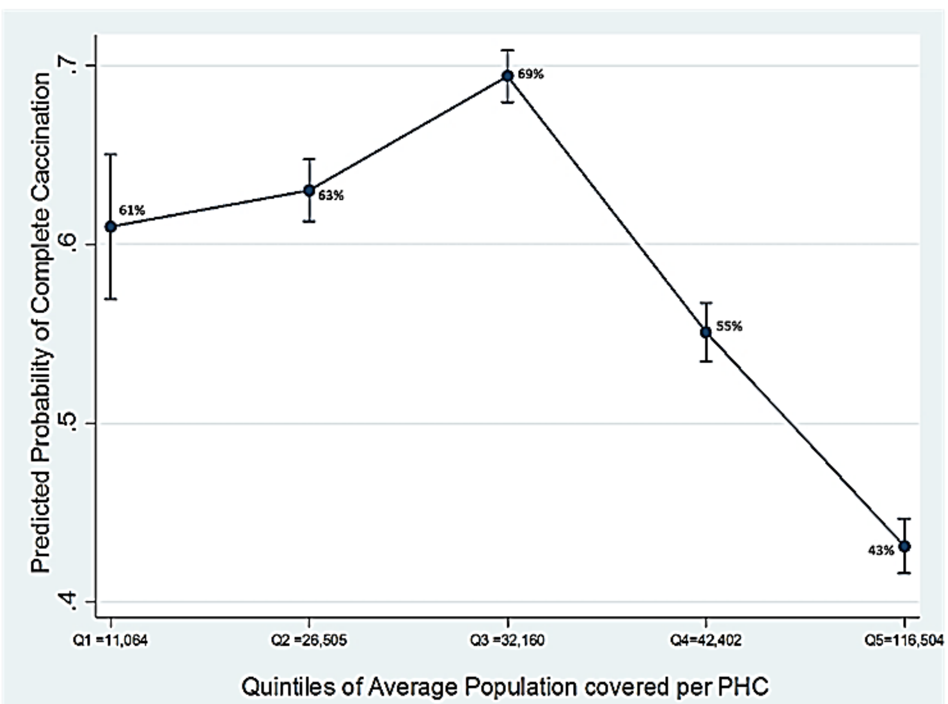
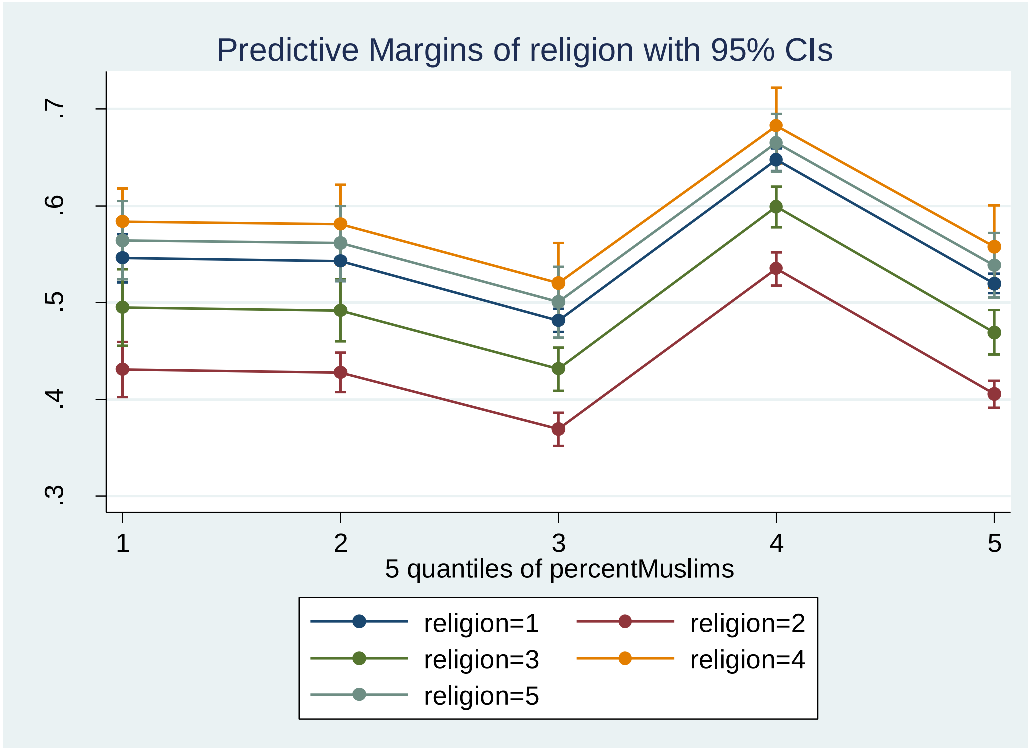
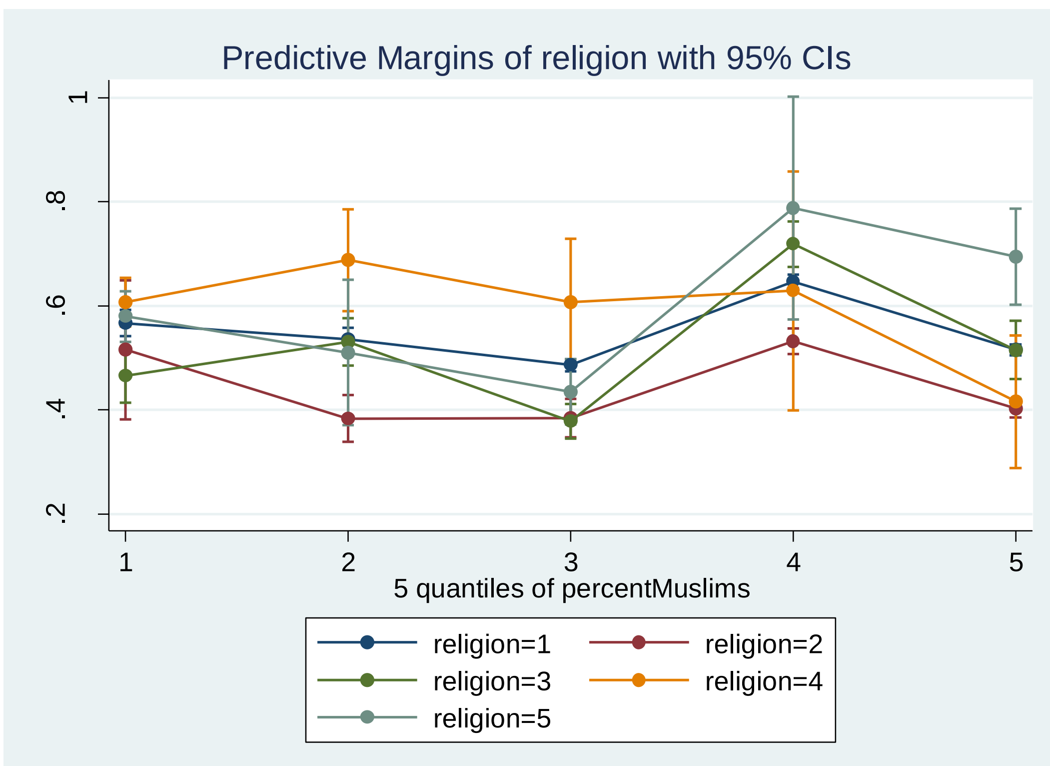


Figure 4.6.Predicted probability of complete vaccination by quintile of percent Muslim population (a) is predicted probability from main effects model (Model 4) and (b) is predicted probability from model with interaction (Model 5)





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Chapter 5

Discussion

Summary of main findings

India's childhood immunization coverage was unacceptably low in 2008, with nearly 30% children under-vaccinated and 12% completely non-vaccinated. The extremely high burden of vaccine preventable diseases (VPDs) among Indian children could, in part, be explained by the low levels of full-vaccination for these diseases. This dissertation extends current knowledge regarding the drivers of childhood immunizations, and contributes to development of a new methodology for studying vaccination timeliness to assess vaccination program performance in India. We used India's District Level Household and facility Survey data from 2008 (DLHS3) for this dissertation. It is a nationally representative sample collected from 720,320 households located in 601 distinct districts and represents the most recently available national data set on childhood immunization currently available to researchers.

In chapter 2, we characterized the risk factor for under and non-vaccinations among Indian children 12-36 months old. We found that in 2008, India had a high burden of under- and non-vaccinated children. This is the first study of its kind to comprehensively identify the factors associated with under and non-vaccination in India compared to previous studies which have focused on relatively few factors such as maternal education, household wealth, and gender disparities.

Perhaps not surprisingly, inequities in vaccination coverage among social and religious groups in India were clearly evident after controlling for all the traditional risk factors for vaccination. Children from Muslim families had significantly poorer vaccination outcomes than Hindus (the dominant religion in India) as well as Christian children were also found to be at an elevated risk for under-vaccination. Children who belonged to Sikh and other religious affiliations such as Buddhist, Jains, Jewish, Parsis, had better vaccination coverage compared to Hindus and other religious groups.

Urban children at the same level of poverty, education, religion, and caste as rural children had lower chances of being fully vaccinated. This finding is contrary to those from other studies in the literature which have reported that children from urban areas have better vaccination outcomes compared to children residing in rural areas [1–3]. Children born in private institutions were also at a higher risk of poor vaccination outcomes compared to children born in governmental institutions.

The findings of this study were important in that they suggest the reasons for both under- and non-vaccinations in India were similar. However, studies from other developing countries have proposed that the epidemiology of non-vaccination and under-vaccination are different [4,5]. Overall, this study found that religion and caste were powerful social determinants of vaccination status. Religion and caste are indicators of certain closely held beliefs and practices and their impact on immunization coverage needs further exploration.

In chapter 3, we investigated the timeliness of childhood vaccination administration. The level of mortality in India due to VPDs surpasses that or all other countries in the world [6]. Timely receipt of vaccination at the recommended intervals is critically important to achieve adequate protection against these vaccine preventable diseases [7–10]. Worldwide, vaccination timeliness has been recognized as an important indicator of vaccination program performance. However, little has been reported on vaccination timeliness in India due to the lack of available vaccination dates and other key immunization data. Consequently, using current methods to analyze vaccination timeliness [11] could only include 40% of children, i.e., those who possessed vaccination cards with vaccination dates recorded.

In chapter 3, we used a novel analytic technique, the Turnbull estimator, to compute the age-specific vaccination probability of children using the vaccination information from both children with and without a vaccination card. The findings of this study demonstrate significant delays in childhood vaccination with 81% of DPT3 doses and 65% of the MCV doses given after the recommended time period. Among children who received delayed vaccination, the delay in administration was highest for DPT3 (delayed by 11 months) and MCV (delayed by 7 months) doses. Also, the higher estimated coverage of MCV (71%) compared to DPT3 (62%) in children 10 months and older, indicates a significant missed opportunity for administering the DPT3 dose since they are typically given simultaneously.

We also examined vaccination timeliness across the Indian states. Although the timeliness curves were more or less parallel for all states, a wide variation existed in the estimated probability of vaccination that was observed among the states. Furthermore, state-specific associations between probability of DPT3 vaccination at the recommended age and under five mortality rate was investigated : a 10 percent increase in the probability of DPT3 vaccinations by 6 months was associated with 8.8 fewer deaths per 1000 live birth among children less than 5 years old.

Based on the results of previous two studies (chapter 2 and chapter 3), we found wide variation in vaccination coverage among the states. The results of chapter 2 indicated that Muslim children had the highest risk of being under- and non-vaccinated compared to children from all other religious groups including Hindus, the dominant religion in India. Therefore, we wished to investigate if that held true across all states, i.e., whether the Muslims children in every state had the worst vaccination outcome. In chapter 4, we investigated the distribution of fully-vaccinated children by religious group across states. We found that vaccination coverage by religious groups differed significantly across the Indian states. In the majority of Indian states, Muslim children had the lowest proportion of full vaccination; however, there were few states where Muslim children had the highest proportion of fully vaccinated children. Sikh children always had the highest proportion of children fully vaccinated in every state where they were present, except in Assam, where Sikh children had the lowest proportion of fully vaccinated children. Overall, we found a wide variation in vaccination coverage by religion within the states and across the states.

Next, we investigated the mechanics that drive the variability in full-vaccination coverage within and among the states. We wanted to investigate whether state-level factors were associated with vaccination status, and whether the size of the Muslim population in a state modifies the relation between religion and vaccination status. The state-level factors including poverty and health care availability were important predictors of vaccination status. Additionally, individual level factors had their own independent effect and were not confounded by the state-level factors. However, the risks associated with not fully-vaccinated for each religious groups were modified based on the concentration of Muslim population in the state.

Strengths

The data used for this analysis, DLHS3, was nationally representative survey and therefore, we had a very large sample size (n= 256,000) that permitted significant statistical power to test various associations after controlling for confounders. Given that DLHS3 has a complex sampling design, it was critical to use design based analytic methods to obtain unbiased variance parameter estimates. We are not aware of any other study in the literature that accounted for the complex sample design of the DLHS3data in the analysis for vaccination coverage/probabilities.

We were able to capture the effects of subcategories of predictors such as place of delivery, religion, and caste, which previous literature has lacked. For example, since we had three categories for setting of birth: government institutions, private institutions, and non-institutional, we were able to establish that children born in private institutions were at higher risk of non-vaccination which has important policy implications.

The vaccination timing study used a novel method to analyze data from children with and without vaccination cards to compute the estimates of age-specific vaccination probability. This estimation technique is known as Turnbull estimator of the cumulative distribution function, and it can accommodate both right and left censored data. This is the first time the Turnbull estimator technique has been used in the vaccination literature. Using this technique, we were able to generate vaccination timing curves representative of children in India. Additionally, we also computed the vaccination timeliness for each state in India and collectively graphed them in order to compare the timeliness across Indian states. This study is the first study to investigate vaccination timeliness in Indian children, and the first study to compare vaccination timeliness by state.

The state-specific study characterized the differences in childhood vaccination status across the states in India. No previous study has analyzed the state-specific factors that are associated with childhood vaccinations, and how and whether those factors may influence the individual level predictors of vaccinations; specifically for such a large number of Indian states (26 out of 35). Another unique contribution of our study is the investigation of modification of religion's association with vaccination status by concentration of Muslim population.

Limitations

Our study, like other studies that use national survey data, has several limitations. Population-based vaccine coverage surveys that rely on vaccination cards, or parental recall, or both, tend to overestimate vaccination coverage [12]. Using the vaccination information based on mothers' recall may produce measurement error in the coverage estimates .This is a common problem in most developing countries that lack immunization registries. However, in countries with no proper records of vaccination, mothers' recall is considered an accurate methodology for population level estimates [13–15].

Another major limitation is the use of cross sectional data providing a snap shot in time, which limits causal inference, and only permits statistical associations to be investigated. We did not have sufficient sample size from a few smaller states; therefore, in chapter 2, we collapsed some states which may have resulted in loss of precision for the collapsed state estimates. In study 3, we excluded those states with smaller sample sizes for vaccination timeliness by state.

The available birthdates for children in the dataset were not precise, only birth month and year were available. Therefore, each child's birthday was set to 1st of the birth month. Precision of birthdates made estimation of premature vaccination difficult, especially for vaccines with recommended ages of administration between birth and 14 weeks and vaccine administered at close intervals. Therefore, we were not able to estimate premature and invalid vaccination doses for DPT doses 1, 2, and 3.

The state-specific analysis was limited to rural population, only, because we lacked indicators for healthcare availability for urban populations. We were also unable to include other relevant policy indicators such as per capita health care expenditure by the state government, average population served per doctor, and vaccine shortages, which may explain some of the differences observed across the states in vaccination coverage.

The associations of state-level characteristics and vaccination status should be considered in light of limitations that could affect the validity of the results. For example, while interpreting the effects of state-level predictors for different quintiles of state-level factors (percent poor, average population covered by a PHC, population density, and percent Muslim population), it is important to recognize that the effects in a given quintile can be heavily influenced by one large state. For instance, quintile 5 of average percent poor population used data from Uttar Pradesh and Bihar states with a sample size of 19,000 and 11,000, respectively, whereas the states of Chattisgarh, Jharkhand, and Orissa had sample sizes of 3000, 5800, and 4000, respectively. Consequently, the effects in this quintile will be dominated by state(s) with larger sample sizes. Additionally, in the process of forming the quintiles, states with very different characteristics were grouped together. For example Karnataka with full-vaccination coverage of 80% was grouped with Assam, which has full-vaccination coverage rate of 52%.

The assumption for state-specific analysis was that the state-level characteristics mediate the effects of individual-level characteristics on vaccination status of children. However, the findings of this study were contrary to our assumption; we found slight changes in the effect for a few individual-level characteristics while controlling for state-level factors. These results indicate our assumptions were weak (or wrong), or the measures for state-level policy and socio-demographics were simply too crude. However, we continue to believe that there are contextual effects of the neighborhood that need further examination. One thought would be to examine the most immediate neighborhood contextual factors, i.e., district level effects. The proposed method for district-level analysis is discussed in the section on future directions.

We were unable to explain the reason for the differences in the religions' association with vaccination status and the modification of those associations based on concentration of Muslim population. Religion is a proxy for a set of cultural characteristics. Even the Hindu religion comprises further subgroupings based on caste and traditional family occupation. For example, the religious beliefs and practices within the Hindu religion vary significantly between a person of privileged caste and of lower caste such as SC, which further impacts their SES. This dissertation research did not make an attempt to disentangle those complexities because we lacked any specific data on religious beliefs, practices and attitudes.

Public Health Implications

The level of vaccination coverage needed to achieve sufficient herd immunity to interrupt transmission of vaccine preventable diseases has been estimated at 94% for pertussis, 84% for diphtheria, and 94% for measles [16]. In India, we found that the estimated coverage for DPT3 and MCV were 62%, and 71%, respectively, which is far below the needed levels of herd immunity. It has been reported that vaccination coverage among children in India has been stagnating for more than a decade [17]. The sustained high burden of morbidity and mortality among Indian children has attracted significant attention from scholars in India and from the international community. Although the Indian government has made significant efforts to improve vaccinations among Indian children, the results of those efforts are modest based on the DLHS3 data. The results of our study have important policy implications for improving vaccination coverage among children.

We found that vaccination coverage differs among religious groups and social categories. These differences could be secondary to the religious beliefs and practices that may influence the uptake of medical practices like vaccination. Differences in cultural beliefs often influence individuals' decision-making processes about healthcare seeking behavior and it is important, therefore, for public health to educate people so that they can make informed decisions. Our finding that the association between religion and vaccination is modified by percent of Muslim population in a state, implies that religious beliefs and practices can be shaped based on the social norm. Social norms can be changed by educating people and making them aware of the benefits of vaccination. Targeting immunization intervention programs specifically to address religious and cultural beliefs that may support opposition to immunizations should be an important part of public health programs. The immunization programs should be sensitive to cultural practices and be locally designed.

Urban children had a lower likelihood of full vaccination when compared with rural children after controlling for literacy, poverty, and other traditional risk factors, indicating that there are concentrations of urban population without access to immunization services. The evidence for this is in the lack of primary health care services and the network of community health workers in urban slums. To decrease the risk of under and non-vaccinations among high risk urban populations, efforts should be made to create and/or improve primary healthcare infrastructure in the rural slum areas to enhance immunization opportunities through greater availability of services.

The study finding that children born in private institutions were at greater risk of non-vaccination compared to those who were born in government institutions may indicate a lack of initiatives or specific efforts in the private institutions aimed at promoting vaccinations. This may be explained, in part, by the fact that private hospitals do not benefit from the government's healthcare funding for poor people and so may be less likely to develop or promote programs targeting improved immunization.

In India, the general indicator for vaccination program performance is vaccination coverage of children 12-24 months old. We suggest that in addition to vaccination coverage, vaccination timeliness should also be considered as a key indicator of vaccine program performance. In order to successfully decrease the morbidity and mortality due to VPDs, it will be important to not only increase full-vaccination coverage among children, but also to improve the actual timeliness of vaccine administration. The most efficient way to help improve timeliness would be to institute a functional, national immunization registry. This would enable the immunization service providers to keep track of eligible vaccine doses for each child while also maintaining an accurate record of all doses that have been administered (and when). We found in our study that there were significant missed opportunities for administering DPT3 doses. Instituting a functional immunization registry will certainly be an important step to address the issues of delay and missed opportunities for vaccinations.

Vaccinating children at the recommended ages is critically important for the success of the vaccination program, as the government of India currently plans to include rotavirus vaccine in its national immunization schedule. The efficacy and safety of rotavirus vaccine is highly dependent on timeliness of vaccine administration, more so than other vaccines. WHO recommends introduction of rotavirus vaccine should be accompanied by measures to ensure high vaccination coverage and timely administration of each dose. Additionally, it is recommended that the first dose of rotavirus vaccine be administered as soon as possible after 6 weeks of age, along with first dose of diphtheria-tetanus-pertussis (DTP1) vaccination, to ensure induction of protection prior to natural rotavirus infection [18]. Based on our results, DPT1 coverage at 6 weeks of age was estimated at 7%, and increased to 41% by 2.5 months of age.. In India natural infection occurs early, so completion of the immunization schedule early in infancy is necessary. However, based on our study findings it is possible that rotavirus vaccination coverage fails to reach adequate coverage level at the recommended age. Furthermore, as we observed substantial delays in administration of all vaccine doses among Indian children, it is not hard to imagine that the timeliness of rotavirus vaccination administration also gets affected in a similar fashion The fact that the impact of rotavirus vaccination depends on effectiveness, timeliness and coverage, failing to reach adequate coverage level early in infancy and delayed rotavirus vaccine administration would result in lower vaccine efficacy and an increased risk of rotavirus vaccine related adverse events among Indian children. Intussusception among infants as an adverse event associated with rotavirus vaccination, has been more commonly seen with delayed vaccination. Thus, reducing the delays in vaccine administration must be an important programmatic goal for vaccination programs in India, especially given that new vaccines are going to be introduced in the national immunization program.

The plateauing of vaccination coverage level after 24 months of age indicates that no vaccination efforts for children older than 2 years are ineffective, and this pattern was observed across all Indian states. Incentivizing Healthcare providers for vaccinating children may help to increase childhood full-vaccination coverage. Any interaction of children with the health care provider should be taken as an opportunity to vaccinate children with the doses they are lacking.

Major campaigns on vaccinations and its benefits should be targeted towards women and families living in areas of low literacy and poverty. The families who are unaware of vaccination benefits may be hesitant to make a decision in favor of vaccination even if the healthcare provider offers the opportunity to vaccinate their children. These targeted education programs should be in local languages and mostly broadcasted on television and radio as opposed to just the print media, because a large proportion of women in in rural areas had no formal schooling, so they are perhaps not able to benefit from the information on print media (newspapers, bill boards and pamphlets). Another effective way of improving childhood vaccinations in the rural population would be to educate uneducated women regarding the benefits of vaccinations through community health workers known as accredited social health activists (ASHA). ASHAs are well known among the community as they are typically the members of the society and they can motivate pregnant women and children to visit clinics for vaccination services.

Future Directions

The analyses in this dissertation highlight the complexity of the association among various individual and state-level characteristics associated with vaccinations in Indian children. This dissertation research addresses gaps in the vaccination coverage literature for India. Chapter 2 suggests that religion and caste are powerful social predictors of childhood vaccination status, while chapter 3 reveals that beyond poor full-vaccination coverage, there are also significant and systematic delays in vaccine administration. Chapter 4 suggests that the majority of the individual-level predictors of vaccinations and state-level predictors have their own independent association with vaccination; however, the association of individuals' religion with vaccination is modified by the cultural environment.

The ultimate goal of this research is to not only further knowledge about vaccination disparities in India but to also help inform the development of intervention programs and policies that will improve vaccination coverage among children in India and reduce these disparities. This will require a deeper understanding of the mechanisms driving the associations observed here. For example, we found an interaction of socio-cultural predictors of vaccination status. Religion and caste are indicators of certain beliefs and practices that need further exploration. Future research should aim to identify the vaccination attitudes that are shaped by religious and cultural beliefs. There is a need for further study of parental beliefs, and knowledge about vaccinations and vaccine preventable diseases. The evidence provided through these studies will be highly beneficial to plan effective immunization intervention strategies, such as health education and behavior programs for the local population and educating them about VPDs and the many benefits of vaccination.

The DLHS3 report lists the reasons for non-vaccination among children in India. Almost half of the parents of non-vaccinated children were not aware of the need for immunizations. Another one-third was either fearful of the potential side effects of vaccinations or had no faith that vaccinations actually work. As mentioned in chapter 2, to achieve full protection against a VPD, a child needs to receive the full series of recommended doses. And, if the child is under-vaccinated, he/she will not be fully protected. If a child falls sick after receiving one or two vaccine doses but less than the full complement of recommended doses, the parents may lose faith in vaccination. They might not possess the knowledge that a complete series is needed to achieve full protection against the disease. If they are provided more complete information about the number of vaccine doses needed and the importance of the timing of those doses, that may help them make informed decisions for vaccinating their children. Additionally, an understanding of the vaccination decision-making processes among mothers from different cultural groups could be very helpful in improving the vaccination delivery programs.

Urban areas had overall high vaccination coverage compared to rural areas, but there can be pockets of urban areas with very low levels of vaccination. The low likelihood of full vaccination of urban children when compared with rural children after controlling for literacy, poverty, and other traditional risk factors, is an indication that there may be concentrations of urban population that do not have access to immunization services. Therefore, further studies should investigate the availability and effects of rural healthcare infrastructure in predicting vaccination status.

To improve vaccination coverage, it is critically important to understand the effect of not only the individual level factor, but also the effect of contextual factors. We found in our analysis that state-level effects presented a mixed picture, which needs further investigation. We may need to go to a level closer to individuals, such as district level-characteristics (vs. state level). The characteristics of districts may exert more direct influence on individuals through neighborhood effects. However, it could be very difficult to obtain district level data for the entire country although it may be possible to obtain it for few states. It may be possible to use combinations of data; first, for a few characteristics we can use the individual level data and aggregate it to district level; second, we can request some district-level data from select states, such as number of licensed doctors in their districts, number of community health workers, number of primary health centers and private clinics in the district. Using those factors, we can compute variables that are indicators of availability and accessibility of immunization services. Thus, in the future, I would be interested in investigating the influence of district-level policy and cultural factors on individuals' vaccination status.

The state-specific analysis presented valuable findings, i.e., the differences in the religions' association with vaccination status and the modification of those associations based on concentration of Muslim population. Although, we were unable to fully explain these results, it leads us to an important future direction. We know from the current analysis that religion and caste are important overall characteristics of Indian children that give rise to striking differences in vaccination coverage, but the differences are difficult to explain as we move across the states. There needs to be further exploration of what those factors are as religion and caste are not sufficient as there are dimensions within them as well as other factors that interplay with them creating population subgroups. For example, within a religious group there are different sub-religions, within sub-religions there are castes (ranging from upper caste to lower caste), within a caste there will be people from various levels of wealth and income. It is the religious subgroups that may be different in terms of caste, income, education, and we have not made an attempt to look at the interaction among these variables. We could do an extensive set of analysis (if we have additional sub-religion information) that involves interaction among these variables, although those could be difficult to conduct and interpret. However, it is not clear if it is religious subgroups that are the issue. It may be worthwhile in an exploratory setting to move to classification and regression trees analysis (CART). CART will assist in identifying important interaction in a data-adaptive way, and a picture of the tree will provide insight into which variables are important and at what position. This will help in identifying the subgroups within the broad religious categories that have very different vaccination rates. The only limitation of the CART method is that since it is a data-adaptive method, the results may not be replicable. However, the main aim of this analysis will be to identify the most important interactions (sub-groups within religious groups) that are significant and are critical for developing an understanding of complex socio-demographic interactions in India.

The next round of DLHS survey has already been undertaken but is not yet available to researchers. I would be interested in analyzing DLHS4 data to replicate these studies. I will be interested in conducting the vaccination timeliness studies using the methods described in this dissertation and compare the vaccination timeliness curves over the two periods (2008 and 2014). Such an analysis could help investigate the factors associated with delay in vaccine administration as well as providing a clearer understanding of the improvement, deterioration or stagnation in vaccination program performance in Indian states.

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Appendix A

Table A.1 Vaccination coverage among children aged 12 to 36 months by State (percentages in parenthesis) using the DLHS2008 data

S. No.	State name	Non-vacc	Partial	Full	Total
1	Jammu & Kashmir	169 (6.58)	791 (30.79)	1,609 (62.63)	2,569
2	Himachal Pradesh	22 (1.83)	155 (12.87)	1,027 (85.3)	1,204
3	Punjab	111 (4.05)	359 (13.09)	2272 (82.86)	2,742
4	Chandigarh	3 (3.13)	14 (14.58)	79 (82.29)	96
5	Uttaranchal	181 (8.62)	514 (24.48)	1,405 (66.9)	2,100
6	Haryana	316 (9.55)	885 (26.75)	2108 (63.71)	3,309
7	Delhi	80 (6.28)	271 (21.29)	922 (72.43)	1,273
8	Rajasthan	1,040 (16.45)	2,078 (32.87)	3,204 (50.68)	6,322
9	Uttar Pradesh	4,526 (23.46)	8,641 (44.79)	6124 (31.75)	19,291
10	Bihar	2,035 (18.36)	4,026 (36.33)	5,021 (45.31)	11,082
11	Sikkim	8 (1.15)	103 (14.86)	582 (83.98)	693
12	Arunachal Pradesh	293 (21.26)	382 (27.72)	703 (51.02)	1,378
13	Nagaland	No data	No data	No data	
14	Manipur	276 (16.32)	465 (27.5)	950 (56.18)	1,691
15	Mizoram	74 (5.5)	471 (35.02)	800 (59.48)	1,345
16	Tripura	190 (25.47)	245 (32.84)	311 (41.69)	746
17	Meghalaya	317 (22.76)	545 (39.12)	531 (38.12)	1,393
18	Assam	752 (15.15)	1,597 (32.18)	2,614 (52.67)	4,963
19	West Bengal	116	599	2,611	3326

		(3.49)	(18.01)	(78.5)	
20	Jharkhand	862	1698	3,311	5,871
		(14.68)	(28.92)	(56.4)	
21	Orissa	171	1,195	2,693	4,059
		(4.21)	(29.44)	(66.35)	
22	Chhattisgarh	127	988	2,014	3,129
		(4.06)	(31.58)	(64.37)	
23	Madhya Pradesh	1,178	3601	3,292	8,071
		(14.6)	(44.62)	(40.79)	
24	Gujarat	416	1,196	2,139	3,751
		(11.09)	(31.88)	(57.02)	
25	Daman & Diu *	3	38	265	306
		(0.98)	(12.42)	(86.6)	
26	Dadra & Nagar Haveli *	12	63	111	186
		(6.45)	(33.87)	(59.68)	
27	Maharashtra	143	1097	3,571	4,811
		(2.97)	(22.8)	(74.23)	
28	Andhra Pradesh	47	584	1,807	2,438
		(1.93)	(23.95)	(74.12)	
29	Karnataka	99	696	2,986	3,781
		(2.62)	(18.41)	(78.97)	
30	Goa	0	15	180	195
		(0.00)	(7.69)	(92.31)	
31	Lakshadweep *	0	28	214	242
		(0.00)	(11.57)	(88.43)	
32	Kerala	15	278	1,408	1,701
		(0.88)	(16.34)	(82.77)	
33	Tamil Nadu	10	466	2,820	3,296
		(0.30)	(14.14)	(85.56)	
34	Pondicherry *	254	52	175	481
		(52.81)	(10.81)	(36.38)	
35	Andaman & Nicobar Islands *	6	40	170	216
		(2.78)	(18.52)	(78.7)	
	Total	13,852	34,176	60,029	108,057
		(12.82)	(31.63)	(55.55)	

Table A.2 States in each quintile of state-level characteristic

PercentPoor	Q1	Q2	Q3	Q4	Q1
	Punjab	Haryana	Gujarat	Maharashtra	Uttar Pradesh
	Kerala	Mizoram	Meghalaya	Arunachal Pradesh	Bihar
	Himachal Pradesh	Puduchery	Andhra Pradesh	Rajasthan	Chattisgarh
	Sikkim	Uttarakhand	Tripura	Manipur	Jharkhand
		Jammu & Kashmir	Karnatka	West bengal	Orissa
		TamilNadu	Assam	Madhya Pradesh	
Avpop/PHC					
	Arunachal Pradesh	Uttarakhand	Manipur	Orissa	Uttar Pradesh
	Mizoram	Karnatka	Kerala	Gujarat	Assam
	Sikkim	Chattisgarh	Tripura	Haryana	Jharkhand
	Himachal Pradesh	Jammu & Kashmir	TamilNadu	Madhya Pradesh	Bihar
	Meghalaya	Rajasthan	West bengal	Maharashtra	
		Punjab		Andhra Pradesh	
Popdense					
	Arunachal Pradesh	Meghalaya	Andhra Pradesh	Jharkhand	West Bengal
	Mizoram	Chhatisgarh	Gujarat	Punjab	Bihar
	Sikkim	Uttaranchal	Karnataka	Tamil Nadu	
	Manipur	Rajasthan	Tripura	Haryana	
	Himachal Pradesh	Madhya Pradesh	Maharashtra	Uttar Pradesh	
	Jammu & Kashmir	Orissa	Assam	Kerala	
Percent Muslim					
	Mizoram	Odisha	Tripura	Uttarakhand	Uttar Pradesh
	Sikkim	Meghalaya	Rajasthan	Karnataka	Kerala
	Punjab	Tamil Nadu	Manipur	All-India	West Bengal
	Arunachal Pradesh	Haryana	Gujarat	Jharkhand	Assam
	Chhattisgarh	Madhya Pradesh	Andhra Pradesh	Bihar	Jammu & Kashmir
	Himachal Pradesh		Maharashtra		