Adherence to Timely Vaccinations in the United States

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abstract

OBJECTIVES: To estimate (1) the proportion of children not adhering to the Advisory Committee on Immunization Practices (ACIP) recommended early childhood immunization schedule and (2) associations between schedule adherence, sociodemographic characteristics, and up-to-date immunization status by 19 to 35 months of age.

METHODS: We used 2014 National Immunization Survey provider-verified vaccination data to classify vaccination patterns as “recommended” (ie, in line with ACIP dose- and age-specific recommendations), “alternate” (ie, in line with either limiting the number of shots per visit or skipping at least 1 vaccine series), or “unknown or unclassifiable” (ie, not in line with ACIP recommendations or clearly limiting shots per visit or vaccine series). We evaluated the association between vaccination patterns and up-to-date status for all ACIP-recommended vaccinations (including rotavirus and hepatitis A vaccines) using Poisson regression.

RESULTS: The majority of children’s patterns were classified as “recommended” (63%), with 23% and 14% following alternate or unknown or unclassifiable patterns, respectively; 58% of children were up-to-date with all ACIP-recommended immunizations by 19 to 35 months. Not being up-to-date was associated with alternate (prevalence ratio = 4.2, 95% confidence interval: 3.9–4.5) and unknown or unclassifiable (prevalence ratio = 2.4, 95% confidence interval: 2.2–2.7) patterns.

CONCLUSIONS: High vaccine coverage by 19 to 35 months of age may miss nonadherence to the recommended immunization schedule in the first 18 months of life, leaving children vulnerable to preventable diseases. With more than one-third of US children not following the ACIP schedule, targeted interventions are needed to minimize vaccine delays and disease susceptibility.

WHAT’S KNOWN ON THIS SUBJECT: Early childhood vaccine coverage is high. Parents and providers may be modifying the Advisory Committee on Immunization Practices–recommended schedule through selective vaccine delay and/or refusal. Non- and under-vaccinated children are at increased risk of vaccine-preventable diseases and their complications.

WHAT THIS STUDY ADDS: Our methods estimate (1) Advisory Committee on Immunization Practices–recommended vaccination schedule adherence and (2) the association between vaccination patterns and the comprehensive up-to-date status of vaccines recommended for 19- to 35-month-old children in a large, nationally representative population, including associations with sociodemographic characteristics.

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The United States Centers for Disease Control and Prevention's (CDC) Advisory Committee on Immunization Practices (ACIP) recommends children be vaccinated against 14 potentially serious illnesses in their first 2 years of life.[1] The CDC annually assesses vaccination rates through the National Immunization Survey (NIS). Although NIS-reported coverage for 19- to 35-month-old children is generally high (eg, 94.7% for the third dose of diphtheria, tetanus, and acellular pertussis [DTaP] vaccine in 2014), some vaccine-specific coverage rates are lower than optimal (eg, 57.5% for the hepatitis A vaccine second dose), and pockets of under-vaccinated children exist, leaving populations vulnerable to outbreaks of preventable diseases.[2–10]

Concerns about the need for, and safety and effectiveness of, vaccines have led to decreases in vaccine confidence,[11–14] including parental desire to modify children's vaccination schedules on the basis of concerns with vaccinations in general and the number of vaccinations given at each visit.[15–18] Previous research has indicated that both providers and parents have reservations about administering too many vaccinations at 1 time, which can contribute, directly or indirectly, to some delay in vaccine administration.[19,20] Additionally, sociodemographic characteristics (eg, race, ethnicity, poverty status) are associated with differences in vaccine uptake.[18,21–26]

Most vaccine coverage research is focused on the up-to-date status as reported by the CDC (ie, receipt of the following numbers of doses: ≥4 DTaP vaccine, ≥3 poliovirus vaccine, ≥1 measles-containing vaccine, ≥3 *Haemophilus influenzae* type b (Hib) vaccine, ≥3 hepatitis B vaccine, ≥1 varicella-containing vaccine, ≥4 pneumococcal conjugate vaccine [PCV]) by 19 to 35 months of age.[2,27–32] We sought to expand the understanding of childhood vaccination classification in 2 ways. First, we included 2 additional vaccines in the recommended childhood schedule not routinely included in the up-to-date definition: hepatitis A and rotavirus.[33–35] Although >90% of young children receive most of the recommended childhood vaccinations, only 57.5% of those in the 2014 NIS received both doses of hepatitis A vaccine (85.1% had received 1 dose), whereas 71.7% received the rotavirus series.[2] Thus, including these additional vaccines in the up-to-date series provides a full and accurate picture of comprehensive compliance with the vaccine schedule. If some routinely recommended vaccines are excluded, the ability to identify groups of children who are not receiving the most recently recommended vaccinations is impeded, hindering the ability of public and private health care providers to take needed actions.

Second, analyses that are focused on up-to-date status at a specific age range (eg, 19–35 months of age) may miss vaccination delays early in life, when children may be unnecessarily at risk for disease.[32,36,37] Although studies have evaluated early variation in vaccine schedule adherence in specific states, those findings alone lack generalizability to the United States as a whole.[28,29,38]

To address these knowledge gaps, we analyzed national-level, provider-verified immunization history data to assess adherence to the ACIP-recommended immunization schedule throughout early childhood in the United States.

METHODS

Data Source

We used the 2014 NIS for this analysis because this was the latest year for which NIS data were available at the time of our analysis. NIS methodology has been previously described.[39] Briefly, NIS is an annual telephone survey that collects vaccination status information about a geographically representative sample of US children aged 19 to 35 months. Participants are recruited via cell phone and landline random digit dialing, and permission is sought to verify children's vaccinations through their health care provider(s). This analysis was restricted to the 15 059 children living in the 50 states and Washington, DC, with provider-verified vaccination data.

Vaccination Pattern

We classified vaccination patterns as recommended (ie, following ACIP guidelines), alternate, or unknown or unclassifiable (neither a recommended or alternate pattern was discernable). Alternate patterns were further categorized as restrictive (ie, spaced out), selective (ie, skipped entirely), or both restrictive and selective. Pattern definitions were based on those described by Nadeau et al[38] with expansion to include vaccinations recommended through 19 months (Table 1). To ensure that vaccinations were valid doses, we excluded vaccinations delivered before earliest valid ages because early vaccinations are recommended to be repeated later.[40] Influenza vaccinations were not included in this analysis because those recommendations are seasonal and dependent on a child's month of birth (which is not included in NIS data).

To identify the vaccination schedule pattern present, coverage was examined at 5 time points. This assessment encompassed the number of vaccines and the core antigen or antigen group included in each vaccine received, with up to 2 unique vaccination dates during the fifth time point. Pattern determination used the number of vaccines and the child's age in days at vaccination for each group of early childhood vaccinations (Table 2). The 5 time points were based on ages for eligible

TABLE 1 Classification of Patterns of Vaccination in Early Childhood

Schedule Type	Description
Recommended schedule	Received all age-appropriate vaccines as of 19 mo of age on at least 4 separate occasions, with no more than 6 vaccine visits
Alternate	
Restrictive	Had at least 6 visits with ≤3 vaccines at each visit
Selective	Omitted at least 1 vaccine (eg, the child did not receive a single dose of a vaccine against a specific disease by 580 d of age)
Restrictive and selective	Did not receive >3 age-appropriate recommended vaccines at each visit and omitted at least 1 vaccine
Unknown or unclassifiable	Did not follow a recommended or alternate schedule

immunizations identified in Glanz et al's[40] white paper on vaccine safety and occur when a child is of the following ages: 0 to 30, 38 to 92, 66 to 153, 94 to 214, and 361 to 580 days, corresponding to vaccines recommended to be administered at birth and 2, 4, 6, 9, and 12 to 19 months of age. Each time point begins 4 days before the minimum age each vaccine may be given and ends at the end of the month of the age recommended by the ACIP. To account for the complexity of the ACIP's recommendations, and to allow some flexibility in our definition of a recommended vaccination pattern, several vaccines with expected receipt between 12 and 15 months of age (Hib; PCV; measles, mumps, and rubella [MMR]; and varicella) were included in the 12- to 19-month time point, rather than creating a separate 12- to 15-month time point. Additionally, we accounted for the possibility that hepatitis B and IPV may be given from 6 to 19 months of age in the numbers of immunizations expected at both of the final 2 time points. When evaluating the completeness of the Hib and rotavirus vaccinations, much latitude was used when considering whether all doses were received. This was necessary because these vaccines have different dose schedules based on formulation, with vaccination formulation information often unavailable.

Vaccination schedule was assessed in 3 sequential steps. First, children coded as adhering to the recommended schedule on at least 4 of the 5 vaccination time points (with a total of no more than 6 unique vaccination ages) were considered to have a vaccination pattern that was overall adherent with the recommended schedule. Some flexibility was allowed with the definition of adhering to a recommended schedule to account for circumstances that may have delayed some vaccinations that are unaccounted for in NIS data (eg, illness, travel, or other logistics).

Children not classified as in adherence with the recommended schedule were next assessed to determine if they were following an alternate pattern of vaccine administration. Given that 4 or more vaccinations may have been given on 1 vaccination day during 4 time points, children who received 3 or fewer immunizations per date on at least 6 unique vaccination dates were coded as following a restrictive pattern. Children who received no doses of at least 1 vaccine type at any vaccine-eligible visit were coded as

TABLE 2 Classification Structure for Early Childhood Vaccination Recommended Schedule Type, With Single- and Multiantigen Vaccines Due at Each Vaccination Time Point Enumerated

	Birth	2 mo	4 mo	6 mo	12–19 mo
Age, d	0–30	38–92	66–153	94–214	361–580
Days required since previous vaccination	—	—	24	24	—
Vaccines scheduled[a]	Hepatitis B	DTaP Hib PCV Polio Rotavirus	DTaP Hib PCV Polio Rotavirus	Hepatitis B[b] DTaP Hib[c] PCV Polio[b] Rotavirus[b]	Hepatitis B[b] DTaP Hib[c] PCV Polio[b] MMR Varicella Hepatitis A
No. vaccines required to be considered as adhering to the recommended schedule	1	5	5	4 (Hep B, DTaP, PCV, polio)	≥5[d] ≥3 for visit 1 and ≥3 for visit 2 (if at least visit 1 or visit 2 is ≥4)
No. vaccination visits expected	1	1	1	1	1 or 2

At least 4 of the 5 time points must be coded as recommended for the participant to be considered as following a recommended schedule overall. —, not applicable.

a The second dose of hepatitis B is recommended to be delivered between 24 and 92 d of age and is not included in the coding scheme because of its lack of synchronicity with other recommended vaccinations.

b Vaccine should be received between 94 and 580 d of age to be on time.

c Vaccine may not be needed, depending on brand.

d Only 4 are required to be classified as adhering to a recommended schedule if the child classified as adhering to recommended schedule at 6 mo.

following a selective pattern. Children could be both restrictive and selective concomitantly. Finally, children who were not following recommended, restrictive, or selective patterns were coded as following an "unknown or unclassifiable" pattern (Table 1).

Up-to-date Status

We assessed participants' up-to-date status as of the survey date if they met the standard NIS up-to-date definition in addition to 1 dose of hepatitis A vaccine (children >24 months of age required 2 doses) and 2 doses of rotavirus vaccine, regardless of when the vaccines were given. By definition, no children with selective vaccination patterns were classified as up-to-date, but children following all other vaccinations schedules (recommended, restricted, or unknown or unclassifiable) could be either up-to-date or not up-to-date. Supplemental Tables 6 through 10 contain illustrative examples of each vaccination pattern and up-to-date status.

Sociodemographic variables were considered as potential predictors, including respondent-identified race and ethnicity; poverty status; number of vaccine providers; provider facility type; child's birth order; maternal education level; census region; child's receipt of benefits from the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC); child having moved across state lines since birth; insurance type; and the child's ever-uninsured status. Because of the observed interaction between race and ethnicity and poverty status in previous studies on adherence to vaccine recommendations, we included this interaction term in our analyses.[41] For several variables, we combined levels of response options to ensure sufficient sample size (recoded levels described in Table 3).

Additionally, we created variables to specify (1) children who received at least 1 vaccine after the recommended vaccination time point, (2) the total number of vaccination visits, and (3) the average number of vaccinations per child per visit.

Univariate and Bivariate Analyses

Univariate frequencies of each vaccination pattern, up-to-date status, and any lateness of vaccine receipt were computed. Bivariate associations were measured between (1) vaccine schedule adherence with up-to-date status and (2) sociodemographic predictors and vaccination pattern. We computed the average number of vaccination days and average number of vaccinations per vaccination day by vaccination pattern and up-to-date status.

Multivariable Models

Three independent weighted Poisson regression models were assessed[42] for outcomes of up-to-date vaccination status and vaccine pattern. Poisson regression estimates were exponentiated to obtain incidence rate ratios, which for binomial outcomes are interpreted as adjusted prevalence ratios. Insurance variables were excluded from the regression models because of missing information (see Supplemental Table 11 for detailed descriptions of insurance variable missing data).

The first 2 models used Poisson regression to identify important predictors of alternate or unknown or unclassifiable patterns, respectively, versus recommended schedule adherence.[43] All predictors, as well as the interaction between race and ethnicity and poverty status, were included in this model to fully understand sociodemographic characteristic associations with vaccination patterns; no elimination-based model building was conducted.

The third model was used to assess the association between vaccine pattern and up-to-date vaccination status. All sociodemographic predictors and interaction between race and ethnicity and poverty status were included in the initial model. The final model was selected by using the backward change in estimate approach to control for confounding between predictors and ensure a parsimonious model.[44] No sociodemographic variables were retained in the final model.

All associations were evaluated at an α of .05. Analyses were performed by using SAS version 9.4 (SAS Institute, Inc, Cary, NC) by using complex survey procedures with survey weighting provided with the publicly available NIS data set.[45] The Institutional Review Board of Emory University determined that this secondary analysis of previously collected, deidentified data did not meet the definition of human subjects research.

RESULTS

Vaccination Pattern

Most children's (63%) vaccination patterns were consistent with the ACIP-recommended schedule; nearly one-quarter (23%) followed an alternate pattern, and ~15% were in the unknown or unclassifiable category (Table 3). Children who moved across state lines, were not firstborn, lived in the Northeast (versus the South), and were non-Hispanic black or multirace below the poverty level (versus non-Hispanic white above poverty) were more likely to follow an alternate vaccination pattern compared with the recommended schedule. Children who received WIC benefits, were living below poverty, moved across state lines since birth, and received vaccinations from public facilities only (versus private providers) were more likely to be in the unknown or unclassifiable schedule category, compared with the recommended schedule.

Up-to-date Status

Approximately 58% of the children were up-to-date for recommended

TABLE 3 Bivariate Proportions and Multivariate Predictors of Vaccine Pattern, NIS, 2014

	Bivariate Analysis			Multivariate Analysis	
	Recommended Schedule	Alternate	Other	Alternate Versus Recommended	Other Versus Recommended
	n (%)	*n* (%)	*n* (%)	aPR (95% CI)	aPR (95% CI)
Overall (*n* = 14 893)	9845 (62.8)	3160 (22.7)	1888 (14.5)	N/A	N/A
Race and ethnicity[a] poverty					
Non-Hispanic white, above poverty (*n* = 7151)	5001 (69.0)	1503 (21.3)	647 (9.7)	Referent	Referent
Non-Hispanic white, below poverty (*n* = 1259)	691 (52.7)	374 (31.6)	194 (15.6)	1.50 (1.25–1.81)	1.27 (0.95–1.70)
Non-Hispanic black, above poverty (*n* = 682)	452 (65.6)	140 (20.5)	90 (14.0)	1.03 (0.78–1.37)	1.19 (0.77–1.85)
Non-Hispanic black, below poverty (*n* = 638)	346 (48.8)	161 (30.2)	131 (20.9)	1.46 (1.14–1.89)	1.62 (1.13–2.30)
Non-Hispanic multiple race or other, above poverty (*n* = 1394)	936 (62.5)	272 (24.4)	186 (13.1)	1.16 (0.92–1.46)	1.32 (0.95–1.84)
Non-Hispanic multiple race or other, below poverty (*n* = 549)	302 (52.6)	125 (25.5)	122 (21.8)	1.21 (0.92–1.46)	1.73 (1.21–2.48)
Hispanic, above poverty (*n* = 1397)	976 (71.7)	246 (16.4)	175 (11.9)	0.81 (0.64–1.02)	1.05 (0.75–1.49)
Hispanic, below poverty (*n* = 1331)	826 (55.4)	230 (20.7)	275 (23.9)	0.95 (0.73–1.25)	1.87 (1.38–2.53)
Missing	492	N/A	N/A	N/A	N/A
Maternal education					
<12 y (*n* = 1630)	918 (57.2)	384 (24.5)	328 (18.4)	1.27 (1.01–1.61)	0.94 (0.69–1.29)
12 y (*n* = 2660)	1602 (57.8)	637 (24.0)	421 (18.2)	1.13 (0.92–1.39)	1.18 (0.91–1.54)
>12 y, noncollege graduate (*n* = 3827)	2466 (63.4)	817 (22.3)	544 (14.4)	1.06 (0.89–1.26)	1.08 (0.83–1.40)
College graduate (*n* = 6776)	4859 (69.0)	1322 (21.1)	595 (9.8)	Referent	Referent
Missing	0	N/A	N/A	N/A	N/A
Child ever received WIC benefits					
Yes (*n* = 6923)	4247 (59.1)	1467 (22.7)	1209 (18.2)	0.87 (0.73–1.03)	1.34 (1.05–1.70)
Not yes[b] (*n* = 7970)	5598 (67.8)	1693 (22.7)	679 (18.2)	Referent	Referent
Missing	0	N/A	N/A	N/A	N/A
Geographic mobility					
Has moved across state lines since birth (*n* = 1508)	816 (45.2)	445 (33.4)	247 (21.4)	1.59 (1.32–1.93)	1.55 (1.17–2.05)
Has not moved across state lines since birth (*n* = 13 385)	9029 (64.7)	2715 (21.5)	1641 (13.7)	Referent	Referent
Missing	0	N/A	N/A	N/A	N/A
Child's birth order					
Firstborn (*n* = 9295)	5934 (60.9)	2054 (23.6)	1307 (15.4)	Referent	Referent
Not firstborn (*n* = 5598)	3911 (65.5)	1106 (21.4)	581 (13.2)	1.13 (1.00–1.28)	1.10 (0.90–1.33)
Missing	0	N/A	N/A	N/A	N/A
Census region					
South (*n* = 5397)	3649 (63.5)	1037 (20.7)	711 (15.8)	Referent	Referent
Northeast (*n* = 2786)	1765 (57.7)	709 (30.0)	312 (12.3)	1.48 (1.29–1.69)	0.86 (0.70–1.06)
Midwest (*n* = 3282)	2214 (64.0)	675 (23.3)	393 (12.7)	1.05 (0.91–1.22)	0.92 (0.76–1.11)
West (*n* = 3428)	2217 (63.8)	739 (20.7)	472 (15.5)	1.02 (0.83–1.25)	0.97 (0.75–1.26)
Vaccine provider facility type					
All private facilities (*n* = 8127)	5653 (65.8)	1573 (21.2)	901 (12.9)	Referent	Referent
All hospital facilities (*n* = 2235)	1452 (59.2)	500 (26.6)	283 (14.3)	1.12 (0.96–1.31)	1.01 (0.80–1.26)
All public, military, other, unknown (*n* = 1934)	1097 (55.6)	460 (22.6)	377 (21.9)	1.02 (0.83–1.26)	1.37 (1.06–1.77)
Mixed facility types (*n* = 2450)	1643 (64.4)	480 (21.5)	327 (14.1)	1.10 (0.88–1.38)	0.85 (0.64–1.13)
Missing	146	N/A	N/A	N/A	N/A
No. vaccine providers					
0 (*n* = 147)[c]	0 (0.0)	147 (100.0)	0 (0.0)	N/A	N/A
1 (*n* = 11 775)	7851 (63.1)	2465 (22.6)	1459 (14.3)	Referent	Referent
2+ (*n* = 2971)	1994 (63.7)	548 (20.3)	429 (16.0)	0.82 (0.67–1.00)	1.24 (0.96–1.61)
Missing	0	N/A	N/A	N/A	N/A
Insurance[d]					
Employer or union plan					
Yes (*n* = 8321)	5899 (67.7)	1623 (21.3)	799 (11.0)	N/A	N/A
Not yes[b] (*n* = 6376)	3840 (58.5)	1467 (23.6)	1069 (17.9)	N/A	N/A
Medicaid or S-CHIP					
Yes (*n* = 3547)	2187 (59.5)	738 (20.9)	622 (19.6)	N/A	N/A
Not yes[b] (*n* = 5328)	3760 (69.9)	971 (19.6)	487 (10.6)	N/A	N/A

TABLE 3 Continued

	Bivariate Analysis			Multivariate Analysis	
	Recommended Schedule	Alternate	Other	Alternate Versus Recommended	Other Versus Recommended
	n (%)	*n* (%)	*n* (%)	aPR (95% CI)	aPR (95% CI)
Indian Health Service Military Health Care, Tricare, CHAMPUS, or CHAMPVA					
Yes (*n* = 876)	561 (60.8)	199 (22.1)	116 (13.8)	N/A	N/A
Not yes[b] (*n* = 13 737)	9158 (63.1)	2894 (22.5)	1685 (14.5)	N/A	N/A
Other insurance					
Yes (*n* = 991)	676 (64.1)	199 (22.1)	116 (13.8)	N/A	N/A
Not yes[b] (*n* = 13 658)	9036 (62.9)	2881 (22.5)	1741 (14.6)	N/A	N/A
Any time no insurance?					
Yes (*n* = 1044)	578 (53.4)	300 (32.8)	166 (13.8)	N/A	N/A
Not yes[b] (*n* = 13 107)	8893 (64.7)	2589 (20.8)	1625 (14.6)	N/A	N/A
Late initiation of vaccination on at least 1 time point					
Yes (*n* = 3706)	862 (21.0)	1456 (40.2)	1388 (38.8)	N/A	N/A
No (*n* = 11 187)	8983 (79.1)	1704 (15.9)	500 (5.0)	N/A	N/A

aPR, adjusted prevalence ratio; CHAMPUS, Civilian Health and Medical Program of the Uniformed Services; CHAMPVA, Civilian Health and Medical Program of the Department of Veterans Affairs; N/A, not applicable; S-CHIP, state Children's Health insurance Program.

[a] aPR.

[b] Not yes includes no, do not know, and refused to answer responses.

[c] Children with 0 documented health care providers were classified as following the selective subset of alternate schedule adherence, with no variability in vaccination schedule adherence, and thus were not able to be included in the multivariable regression model.

[d] A full detailed account of missing data and refused or do not know responses for individual insurance variables is available in Supplemental Table 11.

vaccinations at the time they were surveyed (Table 4). Compared with children vaccinated according to the recommended schedule, children with an alternate pattern were 4.2 times as likely to not be up-to-date (95% confidence interval [CI]: 3.9–4.5), and children following unknown or unclassifiable patterns were ~2.4 times as likely (95% CI: 2.2–2.7) to be not up-to-date (Table 4). By definition, no children vaccinated under selective patterns were considered to be up-to-date. No sociodemographic predictors were retained in the final model measuring association between schedule adherence and up-to-date status.

Approximately 66% of children who were not up-to-date had initiated vaccination late on at least 1 time point. On average, up-to-date children with alternate vaccination patterns had ~3 more vaccination visits and received 1 fewer vaccine per visit than up-to-date children following recommended or other patterns (Table 5). Generally, up-to-date and not up-to-date children received similar numbers of vaccines per visit, although children who were not up-to-date had fewer visits.

DISCUSSION

In this analysis of national-level, provider-verified immunization history data, >60% of children followed a recommended vaccination schedule, and these children were more likely to be up-to-date for recommended immunizations than children following alternate or unknown or unclassifiable vaccine schedule patterns. To create a comprehensive up-to-date classification, we included the hepatitis A and rotavirus vaccines in our up-to-date definition. These 2 vaccines, relatively recent additions to the early childhood vaccination schedule with complex delivery recommendations, are not routinely reported by the CDC from the NIS.[33–35] Therefore, our up-to-date classification, although more comprehensive in the vaccines considered, was stricter than that routinely reported by the CDC, leading to a lower estimate of up-to-date children (58%, compared with 71% reported up-to-date for the combined series reported in the NIS).[2] The vaccine pattern classification structure we used allows for flexibility of circumstances due to chance and access issues (eg, if a provider lacked a particular vaccine and it was received on a different day than other age-appropriate immunizations or the child briefly lacked health coverage and vaccination was delayed) that might hinder a family attempting to adhere to the recommended schedule.

As our analyses illustrate, vaccination patterns are strongly associated with up-to-date status but notably not confounded by sociodemographic variables. This may indicate that the strength of the association between schedule adherence pattern and up-to-date status may overcome the effects of sociodemographic characteristics. However, this does not diminish their importance, as seen in the specific sociodemographic characteristics that are associated with schedule adherence patterns.

TABLE 4 Bivariate Proportions and Multivariate Predictors of Vaccination Status, NIS, 2014

	Not Up-to-date[a]	Multivariate Regression
	n (%)	OR (95% CI)
Overall (n = 14 893)	6054 (41.7)	N/A
Vaccination pattern		
Recommended schedule (n = 9845)	2240 (21.6)	Referent
Alternate (n = 3160)	2875 (90.4)	4.18 (3.88–4.52)
Restrictive only (n = 486)	201 (39.4)	N/A
Selective only (n = 2158)	2158 (100.0)	N/A
Selective and restrictive (n = 516)	516 (100.0)	N/A
Other (n = 1888)	939 (52.4)	2.43 (2.16–2.72)
Race and/or ethnicity and poverty		N/A
Non-Hispanic white, above poverty (n = 7151)	2785 (39.6)	
Non-Hispanic white, below poverty (n = 1259)	660 (54.2)	
Non-Hispanic black, above poverty (n = 682)	284 (40.2)	
Non-Hispanic black, below poverty (n = 638)	306 (50.9)	
Non-Hispanic multiple race or other, above poverty (n = 1394)	520 (39.6)	
Non-Hispanic multiple race or other, below poverty (n = 549)	258 (53.3)	
Hispanic, above poverty (n = 1397)	517 (32.0)	
Hispanic, below poverty (n = 1331)	531 (41.0)	
Maternal education		N/A
<12 y (n = 1630)	770 (46.8)	
12 y (n = 2660)	1207 (45.3)	
>12 y, noncollege graduate (n = 3827)	1644 (42.8)	
College graduate (n = 6776)	2433 (34.6)	
Child ever received WIC benefits		N/A
Yes (n = 6923)	3057 (44.5)	
Not yes[b] (n = 7970)	2997 (37.9)	
Geographic mobility		N/A
Has moved across state lines since birth (n = 1508)	747 (52.4)	
Has not moved across state lines since birth (n = 13 385)	5307 (40.5)	
Child's birth order		N/A
Firstborn (n = 9295)	2056 (38.9)	
Not firstborn (n = 5598)	3998 (43.6)	
Census region		N/A
South (n = 5397)	2205 (42.7)	
Northeast (n = 2786)	1087 (41.8)	
Midwest (n = 3282)	1333 (42.4)	
West (n = 3428)	1429 (39.6)	
Vaccine provider facility type		N/A
All private facilities (n = 8127)	3111 (40.0)	
All hospital facilities (n = 2235)	925 (44.4)	
All public, military, other, unknown (n = 1934)	905 (46.4)	
Mixed facility types (n = 2450)	966 (38.6)	
No. vaccine providers		N/A
0 (n = 147)	147 (100.0)	
1 (n = 11 775)	4759 (42.2)	
2+ (n = 2971)	1148 (37.5)	
Insurance		N/A
Employer or union plan		
Yes (n = 8321)	3043 (38.0)	
Not yes[b] (n = 6376)	2909 (44.9)	
Medicaid or S-CHIP		
Yes (n = 3547)	1576 (43.8)	
Not yes[b] (n = 5328)	1912 (37.6)	
Indian Health Service Military Health Care, Tricare, CHAMPUS, or CHAMPVA		
Yes (n = 876)	386 (42.7)	
Not yes[b] (n = 13 737)	5547 (41.5)	
Other insurance		
Yes (n = 991)	389 (46.0)	
Not yes[b] (n = 13 658)	5542 (41.3)	

Role of Vaccination Pattern

The nonadherence of nearly 40% of the children in the 2014 NIS to the recommended schedule is consistent with several trends reported by American doctors in recent years, including parental requests to limit the number of vaccinations given at each visit, increased need for a strong and consistent physician recommendation for vaccination, and potentially wavering vaccine confidence.[23,46–48] In previous reviews, authors have highlighted concern over the number of shots per visit as a reason for reduced vaccination coverage in the United States and other developed nations.[22] The findings in this study reaffirm that deviations from the recommended immunization schedule, whether as the result of parents following an alternate schedule or other factors, result in many children remaining out-of-date for an extended period of time.

In the New York State–based study that informed our vaccination pattern classifications, it was found that ~25% of children born in the state between 2009 and 2011 followed an alternate schedule, roughly similar to the proportion we observed in our study.[38] However, researchers in that study classified ~5% of children as following an unknown schedule, whereas our analysis estimated a proportion that was nearly 3 times higher. One potential reason for this increase in unknown or unclassifiable vaccination patterns is the increased number of vaccinations and time included for children in our study; the New York State study only included vaccinations through 9 months of age.[38] This study, assessing older children, anticipated at least 2 additional vaccination visits, providing additional opportunities for deviation from known schedules.

We also found associations between children receiving vaccines on an

TABLE 4 Continued

	Not Up-to-date[a]	Multivariate Regression
	n (%)	OR (95% CI)
Any time no insurance?		
Yes (n = 1044)	519 (49.9)	
Not yes[b] (n = 13 107)	5095 (39.7)	
Late initiation of vaccination on at least 1 time point		N/A
Yes (n = 3706)	2385 (65.8)	
No (n = 11 187)	3669 (32.3)	

CHAMPUS, Civilian Health and Medical Program of the Uniformed Services; CHAMPVA, Civilian Health and Medical Program of the Department of Veterans Affairs; N/A, not applicable; OR, odds ratio; S-CHIP, state Children's Health Insurance Program.

a Children who are up-to-date have received the following doses: ≥4 DTaP vaccine, ≥3 poliovirus vaccine, ≥1 measles-containing vaccine, ≥3 Hib vaccine, ≥1 hepatitis A vaccine (≥2 for children >24 mo of age), ≥3 hepatitis B vaccine, ≥1 varicella-containing vaccine, ≥4 PCV, and ≥2 rotavirus vaccine.

b Not yes includes no, do not know, and refused to answer responses.

unknown or unclassifiable schedule and sociodemographic and logistic factors, including poverty; receiving vaccines in public, military, other, or unknown facility types; use of WIC benefits; and movement between states. This combination of factors suggests that many parents in this category may be attempting to adhere to a recommended schedule but, because of external circumstances, fall behind on the appointments required to maintain a recommended schedule. Further research should be done to investigate these associations and provide evidence for future public health interventions supporting recommended vaccine schedule adherence and, ultimately, higher levels of children who are up-to-date for immunizations.

Role of Sociodemographic Characteristics

One meaningful difference in the population of under-vaccinated children illustrated in this study is the difference in the observed association of poverty with different races and ethnicities. In this study, children above the poverty level, across all racial and ethnic categories, were more likely to both follow the recommended schedule and be up-to-date than those below the poverty level. This observed effect was weaker among Hispanic children, in part because Hispanic children tended to be more likely to be up-to-date. Our observed differences in vaccination patterns among various racial and ethnic groups echo those found in studies of human papillomavirus and early childhood vaccines wherein Hispanic groups are more likely to follow recommended schedules than other groups.[28,41,49] These findings support previous assertions that race and socioeconomic class should not be assessed independently of each other with regard to health disparities.[50] High vaccine coverage among Hispanic children offers an opportunity to evaluate factors related to vaccine confidence and financial and logistical barriers to vaccination to identify best practices that can serve as a basis for future interventions.

Our study indicates that some disparities (eg, by maternal education, receipt of WIC benefits, poverty status) persist for vaccine uptake patterns. These findings are similar to those from other NIS analyses, which also found associations between up-to-date status with maternal education, firstborn status, race and ethnicity, mobility, insurance status, and geographical region of residence.[30,49]

Strengths and Limitations

This study has several limitations. First, because we could not examine motivations for adherence or nonadherence to the recommended vaccine schedule, misclassification of the vaccination pattern variable is possible. However, in our approach to classifying vaccination schedule patterns, we assessed consistency across all visits; thus,

TABLE 5 Average Number of Vaccination Visits and Vaccinations per Visit Among 2014 NIS Participants Following Recommended, Alternate, and Other Patterns, Stratified by Up-to-date Status

	Up-to-date[a]			Not Up-to-date		
	n (%)	Average No. Visits	Average No. Vaccines per Visit	n (%)	Average No. Visits	Average No. Vaccines per Visit
Overall (n = 14 893)	8839 (58.3)	7.36	3.47	6054 (41.7)	5.99	3.46
Vaccination Pattern						
Recommended schedule (n = 9845)	7605 (78.4)	7.25	3.51	2240 (21.6)	6.49	3.71
Alternate (n = 3160)	285 (9.6)	10.27	2.50	2875 (90.4)	5.66	3.11
Restrictive only (n = 486)	285 (60.6)	10.27	2.50	201 (39.4)	9.04	2.67
Selective only (n = 2158)	0	—	—	2158 (100.0)	4.51	3.37
Selective and restrictive (n = 516)	0	—	—	516 (100.0)	8.87	2.36
Other (n = 1888)	949 (47.6)	7.25	3.50	939 (52.4)	5.96	3.91

—, not applicable.

a Children who are up-to-date have received the following doses: ≥4 DTaP vaccine, ≥3 poliovirus vaccine, ≥1 measles-containing vaccine, ≥3 Hib vaccine, ≥1 hepatitis A vaccine (≥2 for children >24 mo of age), ≥3 hepatitis B vaccine, ≥1 varicella-containing vaccine, ≥4 PCV, and ≥2 rotavirus vaccine.

misclassification is likely limited. Second, because NIS only contains data on vaccination visits, we could not track missed opportunities for vaccination involving health care provider visits without vaccination, limiting our ability to identify health care usage patterns related to schedule adherence. Future research using electronic medical records to fully understand these patterns is needed. Additionally, child ages at NIS ranged from 19 to 35 months, so older children had a longer period of time to become up-to-date; however, up-to-date status was similar among all children >19 months of age (Supplemental Table 12). We were unable to determine specific reasons for vaccinations not delivered according to the recommended schedule. Our findings should help with the development of future research tools to better classify childhood vaccine schedule adherence and interventions to improve compliance.

Finally, our up-to-date estimates should not be directly compared with other literature because most other reports using NIS data do not include rotavirus and hepatitis A vaccines. Inclusion of these vaccines is an asset to this study because they provide a more accurate measurement of up-to-date status and also more comprehensively demonstrate parental acceptance of the recommended vaccine schedule. Additionally, we considered timing between doses and minimum age at vaccination as described in the literature in constructing our up-to-date variables.[40] The steps we took to ensure appropriate age and spacing of vaccination, in addition to the use of provider-verified vaccination data only, limit misclassification of vaccination status and are considerable strengths of this study. The use of the NIS's geographic weighting allows us to provide a snapshot of early childhood vaccination generalizable to the United States.

CONCLUSIONS

Although most US children adhere to a recommended schedule and are up-to-date for early childhood immunizations, adherence differs by key sociodemographic characteristics. Vaccine schedule adherence patterns are strongly associated with up-to-date status, and future research should be focused on identifying the parent actions and circumstances that increase the likelihood of deviating from the recommended schedule. Interventions should target both providers (to ensure that all eligible vaccines are offered) and parents (to ensure that all eligible vaccines are received), ultimately contributing to greater numbers of US children who are up-to-date for all recommended immunizations.

ABBREVIATIONS

ACIP: Advisory Committee on Immunization Practices
CDC: Centers for Disease Control and Prevention
CI: confidence interval
DTaP: diphtheria, tetanus, and acellular pertussis
Hib: *Haemophilus influenzae* type b
MMR: measles, mumps, and rubella
NIS: National Immunization Survey
PCV: pneumococcal conjugate vaccine
WIC: Special Supplemental Nutrition Program for Women, Infants, and Children

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REFERENCES

1. Robinson CL; Advisory Committee on Immunization Practices (ACIP), ACIP Child/Adolescent Immunization Work Group. Advisory committee on immunization practices recommended immunization schedules for persons aged 0 through 18 years–United States, 2016. *MMWR Morb Mortal Wkly Rep*. 2016;65(4):86–87
2. Hill HA, Elam-Evans LD, Yankey D, Singleton JA, Kolasa M. National, state, and selected local area vaccination coverage among children aged 19-35 months - United States, 2014. *MMWR Morb Mortal Wkly Rep*. 2015;64(33):889–896
3. Centers for Disease Control and Prevention. *Epidemiology and Prevention of Vaccine-Preventable Diseases*, 13th ed. Washington, DC: Public Health Foundation; 2015
4. Bednarczyk RA, Orenstein WA, Omer SB. Estimating the number of measles-susceptible children and adolescents in the United States using data from the national immunization survey-teen (NIS-Teen). *Am J Epidemiol*. 2016;184(2):148–156
5. Phadke VK, Bednarczyk RA, Salmon DA, Omer SB. Association between vaccine refusal and vaccine-preventable diseases in the United States: a review of measles and pertussis. *JAMA*. 2016;315(11):1149–1158
6. Glanz JM, McClure DL, Magid DJ, Daley MF, France EK, Hambidge SJ. Parental refusal of varicella vaccination and the associated risk of varicella infection in children. *Arch Pediatr Adolesc Med*. 2010;164(1):66–70
7. Glanz JM, McClure DL, Magid DJ, et al. Parental refusal of pertussis vaccination is associated with an increased risk of pertussis infection in children. *Pediatrics*. 2009;123(6):1446–1451
8. Majumder MS, Nguyen CM, Cohn EL, et al. Vaccine compliance and the 2016 Arkansas mumps outbreak. *Lancet Infect Dis*. 2017;17(4):361–362
9. Omer SB, Enger KS, Moulton LH, Halsey NA, Stokley S, Salmon DA. Geographic clustering of nonmedical exemptions to school immunization requirements and associations with geographic clustering of pertussis. *Am J Epidemiol*. 2008;168(12):1389–1396
10. Diekema DS. Improving childhood vaccination rates. *N Engl J Med*. 2012;366(5):391–393
11. Kennedy A, Lavail K, Nowak G, Basket M, Landry S. Confidence about vaccines in the United States: understanding parents' perceptions. *Health Aff (Millwood)*. 2011;30(6):1151–1159
12. Siddiqui M, Salmon DA, Omer SB. Epidemiology of vaccine hesitancy in the United States. *Hum Vaccin Immunother*. 2013;9(12):2643–2648
13. Assessing the state of vaccine confidence in the United States: recommendations from the National Vaccine Advisory Committee: approved by the National Vaccine Advisory Committee on June 9, 2015 [corrected] [published correction appears in Public Health Rep. 2016;131(1):218]. *Public Health Rep*. 2015;130(6):573–595
14. Gowda C, Dempsey AF. The rise (and fall?) of parental vaccine hesitancy. *Hum Vaccin Immunother*. 2013;9(8):1755–1762
15. Kennedy A, Basket M, Sheedy K. Vaccine attitudes, concerns, and information sources reported by parents of young children: results from the 2009 HealthStyles survey. *Pediatrics*. 2011;127(suppl 1):S92–S99
16. Madlon-Kay DJ, Harper PG. Too many shots? Parent, nurse, and physician attitudes toward multiple simultaneous childhood vaccinations. *Arch Fam Med*. 1994;3(7):610–613
17. Committee on the Assessment of Studies of Health Outcomes Related to the Recommended Childhood Immunization Schedule, Board on Population Health and Public Health Practice, Institute of Medicine. *The Childhood Immunization Schedule and Safety: Stakeholder Concerns, Scientific Evidence, and Future Studies*. Washington, DC: National Academies Press; 2013
18. Kempe A, O'Leary ST, Kennedy A, et al. Physician response to parental requests to spread out the recommended vaccine schedule. *Pediatrics*. 2015;135(4):666–677
19. Wallace AS, Mantel C, Mayers G, Mansoor O, Gindler JS, Hyde TB. Experiences with provider and parental attitudes and practices regarding the administration of multiple injections during infant vaccination visits: lessons for vaccine introduction. *Vaccine*. 2014;32(41):5301–5310
20. Healy CM, Montesinos DP, Middleman AB. Parent and provider perspectives on immunization: are providers overestimating parental concerns? *Vaccine*. 2014;32(5):579–584
21. Sobo EJ, Huhn A, Sannwald A, Thurman L. Information curation among vaccine cautious parents: Web 2.0, Pinterest thinking, and pediatric vaccination choice. *Med Anthropol*. 2016;35(6):529–546
22. Maman K, Zöllner Y, Greco D, Duru G, Sendyona S, Remy V. The value of childhood combination vaccines: from beliefs to evidence. *Hum Vaccin Immunother*. 2015;11(9):2132–2141
23. Hough-Telford C, Kimberlin DW, Aban I, et al. Vaccine delays, refusals, and patient dismissals: a survey of pediatricians. *Pediatrics*. 2016;138(3):e20162127
24. Prislin R, Dyer JA, Blakely CH, Johnson CD. Immunization status and sociodemographic characteristics: the mediating role of beliefs, attitudes, and perceived control. *Am J Public Health*. 1998;88(12):1821–1826
25. Smith PJ, Chu SY, Barker LE. Children who have received no vaccines: who are they and where do they live? *Pediatrics*. 2004;114(1):187–195
26. Smith PJ, Kennedy AM, Wooten K, Gust DA, Pickering LK. Association between health care providers' influence on parents who have concerns about vaccine safety and vaccination coverage. *Pediatrics*. 2006;118(5). Available at: www.pediatrics.org/cgi/content/full/118/5/e1287
27. Dunn AC, Black CL, Arnold J, Brodine S, Waalen J, Binkin N. Childhood vaccination coverage rates among military dependents in the United States. *Pediatrics*. 2015;135(5). Available at: www.pediatrics.org/cgi/content/full/135/5/e1148

28. Weinberg M, Dietz S, Potter R, Swanson R, Miller C, McFadden J. Vaccine shot-limiting: estimating the prevalence, indicators, and impact on vaccination status - Michigan, 2012. *Vaccine*. 2017; 35(7):1018–1023

29. Robison SG, Kurosky SK, Young CM, Gallia CA, Arbor SA. Immunization milestones: a more comprehensive picture of age-appropriate vaccination. *J Biomed Biotechnol*. 2010;2010:916525

30. Chen W, Elam-Evans LD, Hill HA, Yankey D. Employment and socioeconomic factors associated with children's up-to-date vaccination status. *Clin Pediatr (Phila)*. 2017;56(4):348–356

31. Hu T, Decker SL, Chou SY. Medicaid pay for performance programs and childhood immunization status. *Am J Prev Med*. 2016;50(5, suppl 1):S51–S57

32. Kurosky SK, Davis KL, Krishnarajah G. Completion and compliance of childhood vaccinations in the United States. *Vaccine*. 2016;34(3):387–394

33. Parashar UD, Alexander JP, Glass RI. Prevention of rotavirus gastroenteritis among infants and children. Recommendations of the Advisory Committee on Immunization Practices (ACIP). *MMWR Recomm Rep*. 2006; 55(RR):1–13

34. Cortese MM, Parashar UD; Centers for Disease Control and Prevention (CDC). Prevention of rotavirus gastroenteritis among infants and children: recommendations of the Advisory Committee on Immunization Practices (ACIP) [published correction appears in MMWR Recomm. Rep. 2010;59(33):1074]. *MMWR Recomm Rep*. 2009;58(RR):1–25

35. Fiore AE, Wasley A, Bell BP; Advisory Committee on Immunization Practices (ACIP). Prevention of hepatitis A through active or passive immunization: recommendations of the Advisory Committee on Immunization Practices (ACIP). *MMWR Recomm Rep*. 2006; 55(RR):1–23

36. Luman ET, Barker LE, Shaw KM, McCauley MM, Buehler JW, Pickering LK. Timeliness of childhood vaccinations in the United States: days undervaccinated and number of vaccines delayed. *JAMA*. 2005;293(10):1204–1211

37. Luman ET, Shaw KM, Stokley SK. Compliance with vaccination recommendations for U.S. children. *Am J Prev Med*. 2008;34(6):463–470

38. Nadeau JA, Bednarczyk RA, Masawi MR, et al. Vaccinating my way–use of alternative vaccination schedules in New York State. *J Pediatr*. 2015;166(1): 151–156

39. U.S. Department of Health and Human Services (DHHS). *The 2014 National Immunization Survey*. Hyattsville, MD: National Center for Health Statistics, Centers for Disease Control and Prevention; 2015

40. Glanz JM, Newcomer SR, Jackson ML, et al. White Paper on studying the safety of the childhood immunization schedule in the Vaccine Safety Datalink. *Vaccine*. 2016;34(suppl 1):A1–A29

41. Bednarczyk RA, Curran EA, Orenstein WA, Omer SB. Health disparities in human papillomavirus vaccine coverage: trends analysis from the National Immunization Survey-Teen, 2008-2011. *Clin Infect Dis*. 2014;58(2):238–241

42. Hale J, Thompson D, Darden P. Calculating subset weighted analysis using PROC SURVEYFREQ and GENMOD. 2013. Available at: http://support.sas.com/resources/papers/proceedings13/272P-2013.pdf. Accessed July 20, 2018

43. Stokes ME, Davis CS, Koch GG. Logistic Regression II: Polytomous Response. In: *Categorical Data Analysis Using the SAS System*, 2nd ed. Cary, NC: The SAS Institute; 2000

44. Agresti A. *Categorical Data Analysis*. Hoboken, NJ: John Wiley & Sons, Inc; 2002

45. Centers for Disease Control and Prevention. Datasets and related documentation for the National Immunization Survey - child, 2010-2014. Available at: https://www.cdc.gov/nchs/nis/data_files.htm. Accessed March 28, 2017

46. Salmon DA, Dudley MZ, Glanz JM, Omer SB. Vaccine hesitancy: causes, consequences, and a call to action. *Vaccine*. 2015;33(suppl 4):D66–D71

47. Paterson P, Meurice F, Stanberry LR, Glismann S, Rosenthal SL, Larson HJ. Vaccine hesitancy and healthcare providers. *Vaccine*. 2016;34(52): 6700–6706

48. Smith PJ, Humiston SG, Parnell T, Vannice KS, Salmon DA. The association between intentional delay of vaccine administration and timely childhood vaccination coverage. *Public Health Rep*. 2010;125(4):534–541

49. Crouch E, Dickes LA. A prediction model of childhood immunization rates. *Appl Health Econ Health Policy*. 2015;13(2): 243–251

50. Kawachi I, Daniels N, Robinson DE. Health disparities by race and class: why both matter. *Health Aff (Millwood)*. 2005;24(2):343–352