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Completion and compliance of childhood vaccinations in the United States

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ABSTRACT

Background: The Advisory Committee on Immunization Practices recommends routine childhood vaccination by age 2 years, yet evidence suggests that only 2% to 26% of children receive vaccine doses at age-appropriate times (compliance). The objective of this study was to estimate vaccine completion and compliance rates between birth and age 2 years using recent, nationally representative data.
Methods: Using a sample of children aged 24 to 35 months from the 2012 National Immunization Survey (NIS), the present study examined completion and compliance of recommended childhood vaccines. A state-specific examination of vaccine completion and compliance was also conducted.
Results: An unweighted sample of 11,710 children (weighted to 4.1 million) was selected. Approximately 70% of children completed all doses of six recommended vaccines by 24 months of age. Completion rates varied by antigen, ranging from 68% completing two or three doses of rotavirus vaccine to 92% completing three doses of inactivated poliovirus vaccine. Vaccine completion rates also varied at different measurement periods, with the lowest rates observed at 18 months. Approximately 26% of children received all doses of six recommended vaccines on time. Among the 74% of children who received at least one late dose, 39% had >7 months of undervaccination. Patterns of completion and compliance also varied by geographic region.
Conclusions: Completion of individual antigens approached Healthy People 2020 targets. However, overall completion of the recommended vaccine series and compliance with the recommended vaccination dosing schedule were low, indicating few children received vaccines at age-appropriate times. Additional clinical, policy, and educational interventions are needed to increase receipt of vaccines at optimal ages.

1. Introduction

The Advisory Committee on Immunization Practices (ACIP) recommends children receive multiple vaccinations between birth and age 2 years to protect against 14 diseases [1]. The recommended series includes completion of four doses of diphtheria, tetanus, and acellular pertussis vaccine (DTaP); three doses of inactivated poliovirus vaccine (IPV); one dose of measles, mumps, and rubella vaccine (MMR); three or four doses of *Haemophilus influenzae* type b vaccine (Hib); three doses of hepatitis B vaccine (HepB); one dose of varicella vaccine; and four doses of pneumococcal conjugate vaccine (PCV) (i.e., 4:3:1:3:3:1:4). Additionally, the ACIP recommends receipt of two or three doses of rotavirus vaccine, one or two doses of influenza vaccine; and at least one dose of hepatitis A vaccine (HepA) by age 2 years.

Evidence suggests that appropriate vaccination coverage is linked to improved health outcomes and cost savings [2,3]. A decision-analytic model examining completion of the childhood vaccination schedule in a 2009 United States (US) birth cohort indicated prevention of approximately 42,000 early deaths and 20 million cases of disease in their lifetime. Moreover, the analyses showed that routine vaccination may lead to an offset of approximately $69 billion in total societal costs [3]. The Healthy People 2020 Immunization and Infectious Disease goals targets 90% of children to receive all doses of individual vaccines (i.e., DTaP, IPV, MMR, Hib, HepB, and varicella), 80% to receive all doses of rotavirus

Abbreviations: ACIP, Advisory Committee on Immunization Practices; DTap, diphtheria, tetanus, and acellular pertussis vaccine; HepA, hepatitis A vaccine; HepB, hepatitis B vaccine; Hib, *Haemophilus influenzae* type b vaccine; IIS, immunization information systems; IPV, inactivated poliovirus; MMR, measles, mumps, and rubella vaccine; NIS, national immunization survey; PCV, pneumococcal conjugate vaccine; SCHIP, State Children's Health Insurance Program; US, United States.

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vaccine, and 80% to receive all doses in the 4:3:1:3:3:1:4 series by age 19 to 35 months [2].

Although, vaccination coverage has improved in the US over recent years, data from the National Immunization Survey (NIS) found approximately 68% of 2-year-old children completed all doses in the 4:3:1:3:3:1:4 series in 2012. Furthermore, targets of 90% completion were not achieved for DTaP (83%), PCV (82%), and HepA (82%) vaccines. Similarly, receipt of rotavirus vaccine (69%) was below the target of 80% [4].

Complying with age-appropriate receipt of vaccinations is critical for providing maximum effectiveness against vaccine-preventable diseases [1]. However, prior studies indicate that only 2% to 26% of 2-year-olds actually comply with the age recommendations for each vaccine dose [5,6]. Although these studies provide novel information on vaccination rates, they were conducted approximately 10 years ago. As vaccination recommendations and coverage patterns have changed, recent assessments of vaccine compliance are needed.

In this study, we examined completion and compliance rates of childhood vaccinations among a nationally representative sample of children in the US. We assessed the proportion of children who received recommended doses of vaccine by age 2 years, the number of doses received at age-appropriate times, the cumulative number of days undervaccinated, and geographic variations of completion and compliance.

2. Methods

2.1. Data source: National Immunization Survey

Data for this study were derived from the 2012 NIS Public Use File [7,8]. The NIS is an annual population-based survey conducted by the National Center for Immunization and Respiratory Diseases, the National Center for Health Statistics, and the Centers for Disease Control and Prevention. It consists of a list-assisted random digit-dialing landline and cellular telephone survey (household interview) to guardians of children aged 19 to 35 months to collect demographic and vaccination information. Immunization provider(s) reports the child's vaccination history. Data were weighted to represent the greater US population, adjusting for households with multiple telephone lines, no telephone service, and nonresponse. Detailed NIS methods and institutional review board approval for data analysis are reported elsewhere [9,10]. RTI International's institutional review board determined that this study met all criteria for exemption (ID Number 13523).

2.2. Study sample

The 2012 NIS contains information on 25,736 (unweighted sample) children aged between 19 to 35 months. From this sample, we selected children who completed the survey, lived in the US (excluding the US Virgin Islands), and had adequate vaccination data supplied by their vaccine providers. Children aged less than 24 months at the time of the survey were excluded. This restriction allowed for an equal vaccine capture period for all included children (i.e., birth to 24 months). The final unweighted sample size was 11,710, equating to a weighted sample of 4,083,928 children.

2.3. Study measures

2.3.1. Vaccine completion

ACIP recommendations [1] were used to define vaccine completion at specific time points (8, 18, and 24 months of age). Vaccine completion was defined as the accumulation of the required number of doses by a specific age irrespective of timing of vaccine administration. For example, children receiving three doses of DTaP, two doses of IPV, two or three doses of Hib, two doses of HepB, and three doses of PCV vaccines by 8 months were considered to have completed the appropriate doses in the 4:3:1:3:3:1:4 vaccination series at that time. Rotavirus vaccine was also assessed at each time point. A detailed list of doses required at each time period is presented in Table 1.

As the required number of doses of rotavirus and Hib vaccines are dependent on the product administered, we assessed completion accordingly. For example, a child's vaccination for rotavirus was considered complete if two doses of *Rotarix*™ (GSK Vaccines) or three doses of *RotaTeq* (Merck & Co., Inc.) were administered. These algorithms are detailed in the published vaccine schedule [1].

Although the ACIP recommends two doses of influenza vaccine beginning at age 6 months and one dose of influenza vaccine annually thereafter, we have not included it in this study. Influenza vaccines should be administered prior to or during influenza season. As the NIS data only provide the child's age at which the vaccine was administered, we were unable to assess whether or not the vaccine was given during an influenza season, which prevented computation of accurate completion or compliance measures.

Two doses of HepA are recommended by age 2 years, with the first dose occurring after 12 months and the second dose occurring 6 to 18 months after the first dose. Given the second dose may be received outside of our observation period (birth to 24 months), we were unable to accurately compute completion and compliance of both doses. Therefore, HepA is not included in the present analysis.

Table 1
Total count of doses required to be received by 8, 18, and 24 months of age.

Vaccine	No. of doses recommended by		
	8 months	18 months	24 months
DTaP	3	4	4
IPV	2	3	3
MMR	N/A	1	1
Hib	2 or 3	3 or 4	3 or 4
HepB	2	3	3
Varicella	N/A	1	1
Rotavirus	2 or 3	2 or 3	2 or 3
PCV	3	4	4
4:3:1:3:3:1 series	3 DTaP, 2 IPV, 2 or 3 Hib, and 3 HepB	4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, and 1 varicella	4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, and 1 varicella
4:3:1:3:3:1:4 series	3 DTaP, 2 IPV, 2 or 3 Hib, 3 HepB, and 3 PCV	4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, and 4 PCV	4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, and 4 PCV

DTaP = diphtheria, tetanus, and acellular pertussis vaccine; HepB = hepatitis B vaccine; Hib = *Haemophilus influenzae* type b vaccine; IPV = inactivated poliovirus vaccine; MMR = measles, mumps, and rubella vaccine; N/A = not applicable; PCV = pneumococcal conjugate vaccine. *Source:* Information derived from the CDC's 2012 childhood immunization schedule [1].

2.3.2. Vaccine compliance

The ACIP recommends vaccination at specific ages and intervals to provide maximum effectiveness and to ease scheduling through matching the well-child visit schedule [1]. Therefore, we calculated vaccine compliance as the proportion of children who received each dose during the ACIP's recommended age-appropriate windows (e.g., dose 1 of DTaP at 2 months) (Table 2). The ACIP allows early vaccination as "age-appropriate" if received within a 4-day grace period prior to the minimum age for the dose [13]. Therefore, any vaccines administered during this grace period were included as on time, and any vaccines administered before this grace period were excluded from calculation of the compliance endpoint.

We assessed the number of days a child was undervaccinated using the method proposed in several prior vaccine compliance studies [5,11]. A day undervaccinated was defined as a day where the child had not completed the age-appropriate doses recommended by that day. This was assessed by summing the total number of days a delayed vaccine was given after the recommended age range, per child. Each day of undervaccination was counted as 1 day, regardless of the number of vaccines missed by that day [12]. If a dose was never received by 24 months, the child received the maximum number of days undervaccinated based on the total number of days between the first day of undervaccination and age 24 months. The final measure of vaccine compliance was the total number of days undervaccinated. Accumulation of 7 months or more of undervaccination was categorized as "severely undervaccinated". In addition to reporting total compliance of each dose and series, we also assessed all doses received on time, some doses received on time, and no doses received on time.

2.4. Statistical analyses

Estimates of frequencies, percentages, means, standard errors, and medians were calculated using SAS statistical software, version 9.3 (SAS Institute, Inc., 2011). Survey procedures and domain analysis techniques were used to calculate weighted values and standard errors. To understand geographic trends of completion and compliance, we mapped key measures by state using SAS map procedures.

3. Results

Study sample characteristics are presented in Table 3. Of the mothers of the sampled children, 57% were aged 30 years or older, 63% were married, 38% resided in the South, and 55% were educated beyond high school. Approximately 51% of children were male, 47% were non-Hispanic White, and 75% had siblings in the household. The majority of providers were based in private practice (58%) and had one vaccine provider (66%). About half of children were enrolled in Medicaid or the State Children's Health Insurance Program (SCHIP).

3.1. Vaccine completion

Table 4 describes completion rates for vaccines across at 8, 18, and 24 months. Approximately 66% of children completed all doses in the 4:3:1:3:3:1:4 series and 70% completed all doses in the 4:3:1:3:3:1 series by 24 months. By 24 months, the Healthy People 2020 target of 90% vaccination coverage was achieved for IPV (92%), MMR (90%), and varicella (90%). However, rates of completion for

Table 2
Recommended age ranges for administration by dose.

Vaccine dose	Recommended age	Minimum acceptable age	Recommended interval to next dose	Age in days when undervaccination count initiated
DTaP				
1	2 months	6 weeks	2 months	93
2	4 months	10 weeks	2 months	154
3	6 months	14 weeks	6–12 months	215
4	15–18 months	12 months	–	580
IPV				
1	2 months	6 weeks	2 months	93
2	4 months	10 weeks	2–14 months	154
3	6–18 months	14 weeks	–	580
MMR	12–15 months	12 months	–	489
Hib				
1	2 months	6 weeks	2 months	93
2	4 months	10 weeks	2 months	154
3	6 months	14 weeks	6–9 months	215
4	12–15 months	12 months	–	489
HepB				
1	Birth (0–3 days)	Birth	1–4 months	4
2	1–2 months	4 weeks	2–17 months	93
3	6–18 months	24 weeks	–	580
Varicella	12–15 months	12 months	–	489
Rotavirus				
1	2 months	6 weeks	2 months	93
2	4 months	10 weeks	2 months	154
3	6 months	14 weeks	–	215
PCV				
1	2 months	6 weeks	8 weeks	93
2	4 months	10 weeks	8 weeks	154
3	6 months	14 weeks	6 months	215
4	12–15 months	12 months	–	489

DTaP = diphtheria, tetanus, and acellular pertussis vaccine; HepB = hepatitis B vaccine; Hib = *Haemophilus influenzae* type b vaccine; IPV = inactivated poliovirus vaccine; MMR = measles, mumps, and rubella vaccine; N/A = not applicable; PCV = pneumococcal conjugate vaccine.
Source: Information derived from the CDC's 2012 childhood immunization schedule [1].

Table 3
Background child, family, and vaccination provider characteristics.

Characteristics[a]	Total	
	n	%
Unweighted sample size	11,710	100.00
Weighted sample size	4,083,928	100.00
Maternal age, years		
<20	73,840	1.81
20–30	1,685,493	41.27
>30	2,324,595	56.92
Maternal marital status		
Married	2,560,517	62.70
Maternal education		
<High school	762,406	18.67
High school	1,092,118	26.74
>High school	952,114	23.31
College graduate	1,277,290	31.28
Census region		
Northeast	657,249	16.09
South	1,566,868	38.37
Midwest	14,325	20.90
West	1,006,256	24.64
Poverty status		
At or below poverty line	1,471,796	36.04
Above poverty line	2,425,133	59.38
Unknown	186,999	4.58
Number of children in household		
1	1,024,197	25.08
2–3	2,446,047	59.89
>4	613,685	15.03
Child's race/ethnicity		
Non-Hispanic white	1,904,317	46.63
Non-Hispanic black	561,143	13.74
Hispanic	1,122,030	27.47
Other	496,438	12.16
Child's sex		
Male	2,064,628	50.56
Number of vaccination providers for child		
0	16,779	0.41
1	2,710,147	66.36
2	1,103,784	27.03
>3	253,218	6.20
Type of vaccination providers for child		
Public	497,195	12.17
Private	2,352,572	57.61
Other/mixed	1,200,295	29.39
Unknown	33,867	0.83
Had medicaid or SCHIP[b]		
Yes	2,032,883	49.78

SCHIP = State Children's Health Insurance Program.
[a] All percentage values will be weighted based on National Immunization Survey sampling design.
[b] Less than 2% had unknown insurance status.

DTaP (80%), Hib (79%), HepB (89%), PCV (80%), and rotavirus (68%) were below the target. Drops in completion rates were observed for the majority of vaccines between the 8-month and 18-month time points. This reduction ranged from 1% (IPV) to 13% (DTaP). Completion rates rose again by 24 months and were similar to those observed at 8 months.

3.2. Vaccine compliance

Vaccine compliance varied by type of vaccine (Table 5). Rates ranged from 41% of children receiving all doses of Hib at age-appropriate times to 78% receiving a dose of MMR at age-appropriate times. Among multi-dose vaccines, rotavirus (22%) had the greatest proportion of children with all doses late, followed by PCV (12%), Hib (11%), DTaP (9%), and IPV (7%). More than half of children had at least one late dose in the Hib and PCV series, whereas less than one-quarter of children had a late dose of IPV (24%), MMR (22%), and varicella (22%). Examining compliance rates by vaccination series revealed that only 23% and 26% of children received all doses in the 4:3:1:3:3:1:4 and 4:3:1:3:3:1 series on time, respectively.

Total days undervaccinated and severe undervaccination varied by vaccine. The mean number of days undervaccinated was lowest for MMR (152 days) and varicella (154 days), and highest for rotavirus (475 days) and PCV (258 days). Severe undervaccination occurred more frequently for rotavirus than for any other vaccine, with 33% of children severely undervaccinated and 42% of children with at least one late dose. Approximately one-quarter of children were severely undervaccinated with PCV (26%) and Hib (28%). IPV (9%), MMR (11%), varicella (11%), HepB (13%), and DTaP (15%) had the lowest proportion of children with severe undervaccination. Undervaccination of doses in the 4:3:1:3:3:1 and 4:3:1:3:3:1:4 series was, on average, 261 and 282 days, respectively, and 39% and 43% of children were severely undervaccinated, respectively.

3.3. State-specific completion and compliance

Fig. 1 depicts vaccination completion and compliance rates in the US (detailed in Supplemental Table 1). For the 4:3:1:3:3:1:4 series, the highest completion rates were observed for the Southern states (i.e., Mississippi, Tennessee, Virginia, North Carolina, South Carolina, and Georgia) and some Midwest states (i.e., North Dakota, Nebraska, Iowa, and Wisconsin), with Mississippi having the highest completion rate (77%). Western states (i.e., California, Oregon, Nevada, and Alaska) were among the states with the lowest completion rates. Vaccine completion was lowest in Alaska (55%). Vaccine compliance showed little variation, with the many states in the South, Midwest, and Southwest falling in the 20% to 29% compliance range. Compliance rates were low in some Western states (i.e., California, Oregon, Nevada, and Alaska). Colorado (39%) had the highest compliance rate, while Alaska (2%) had the lowest. The majority of states had severe undervaccination rates over 40%. Severe undervaccination was highest in Alaska (80%) and lowest in New Hampshire (28%).

4. Discussion

Completion rates of several childhood vaccines have met Healthy People 2020 thresholds over the past several years [4]. Consistent with those estimates, we found overall completion rates IPV, MMR, HepB, and varicella were approximately 90%. However, the proportion of children receiving all vaccines in the 4:3:1:3:3:1:4 series was low (66%).

Findings from this analysis revealed that for most of the vaccines, completion rates dropped between age 8 and 18 months, then increased by 24 months. This trend is consistent with Robison and colleagues [14], who found that between 11% and 21% of children whose vaccination is complete at an interim milestone will have incomplete vaccinations by the next milestone. This suggests the current benchmarking method of assessing completion at 2 years of age masks the true dynamic nature of immunization status between birth and age 2 years. It is plausible that children who are considered up-to-date at 2 years of age (or earlier measurement points) may have received vaccines too early or too late prior to the measurement point, thus leaving them vulnerable to vaccine-preventable diseases at earlier times. In a study of pediatric pertussis cases over a 6-year period, researchers found that less than half had received the DTaP immunization at age-appropriate times [15], underlining the importance of age-appropriate vaccinations for timely protection. Measuring vaccine compliance allows us to evaluate levels of protection throughout the first 2 years, a time during which children are most susceptible to severe complications related to vaccine-preventable diseases.

Table 4
Vaccine completion at 8, 18, and 24 months of age.

Completion measure[a]	8 months[b]		18 months[c]		24 months[d]	
	n	(%)	*n*	(%)	*n*	(%)
4 DTaP						
None	179,767	4.40	128,175	3.14	111,293	2.73
All	3,360,503	82.29	2,836,117	69.45	3,286,761	80.48
3 IPV						
None	193,911	4.75	150,573	3.69	136,353	3.34
All	3,744,613	91.69	3,698,565	90.56	3,766,781	92.23
1 MMR						
None	–	–	559,212	13.69	392,365	9.61
All	–	–	3,524,716	86.31	3,691,564	90.39
3 or 4 Hib						
None	190,159	4.66	140,135	3.43	117,924	2.89
All	3,287,144	80.49	2,949,190	72.21	3,239,905	79.33
3 Hib[e]						
None	10,912	5.61	3,807	1.96	0	0.00
All	178,217	91.69	170,025	87.48	175,868	90.48
4 Hib[f]						
None	61,323	1.63	18,404	0.49	0	0.00
All	3,108,927	82.43	2,779,165	73.69	3,064,037	81.24
3 HepB						
None	160,286	3.92	131,355	3.22	124,516	3.05
All	3,699,946	90.60	3,569,000	87.39	3,629,710	88.88
1 Varicella						
None	–	–	576,577	14.12	414,836	10.16
All	–	–	3,507,351	85.88	3,669,093	89.84
4 PCV						
None	240,999	5.90	175,469	4.30	149,926	3.67
All	3,131,998	76.69	3,073,655	75.26	3,260,475	79.84
2 or 3 Rotavirus						
None	712,168	17.44	710,412	17.40	710,340	17.39
All	2,737,066	67.02	2,782,442	68.13	2,783,045	68.15
2 Rotavirus[g]						
None	282	0.06	0	0.00	0	0.00
All	391,700	89.33	392,816	89.58	392,842	89.59
3 Rotavirus[h]						
None	1,547	0.05	72	0.00	0	0.00
All	2,345,366	79.91	2,389,626	81.42	2,390,203	81.44
4:3:1:3:3:1[i]						
None	–	–	–	–	51,847	1.27
All	–	–	–	–	2,855,580	69.92
4:3:1:3:3:1:4[j]						
None	–	–	–	–	138,223	3.38
All	–	–	–	–	2,690,038	65.87

DTaP = diphtheria, tetanus, and acellular pertussis vaccine; HepB = hepatitis B vaccine; Hib = *Haemophilus influenzae* type b vaccine; IPV = inactivated poliovirus vaccine; MMR = measles, mumps, and rubella vaccine; PCV = pneumococcal conjugate vaccine.

[a] All percentage values will be weighted based on National Immunization Survey sampling design.
[b] Total count of doses received at 8 months includes 3 DTaP, 2 IPV, 1 or 2 Hib, 2 or 3 rotavirus, and 3 PCV.
[c] Total count of doses received at 18 months includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, 2 or 3 rotavirus, and 4 PCV.
[d] Total count of doses received at 24 months includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, 2 or 3 rotavirus, and 4 PCV.
[e] Among all children in the sample, 194,367 initiated the Hib series and were classified as needing to complete the 3-dose series by age 24 months.
[f] Among all children in the sample, 3,771,638 initiated the Hib series and were classified as needing to complete the 4-dose series by age 24 months.
[g] Among all children in the sample, 438,485 initiated the rotavirus series and were classified as needing to complete the 2-dose series by age 24 months.
[h] Among all children in the sample, 2,935,104 initiated the rotavirus series and were classified as needing to complete the 3-dose series by age 24 months.
[i] The 4:3:1:3:3:1 series includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, and 1 varicella recommended by age 24 months.
[j] The 4:3:1:3:3:1:4 series includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, and 4 PCV recommended by age 24 months.

Vaccine compliance has been examined in several studies with varying methods [5–7,16,17]. Luman and colleagues [11] found only 9% of 19- to 35-month-old children received all vaccines in the 4:3:1:3:3:1 series within the appropriate age ranges. Our current study found that compliance for both 4:3:1:3:3:1 (26%) and 4:3:1:3:3:1:4 series (23%) was substantially higher. Better compliance rates could be attributed to an improvement in immunization strategies over the past 15 years. Nonetheless, nearly 75% of

Table 5
Vaccine compliance for individual vaccines and series.

Compliance measure[a]	No. doses on time		Some doses on time		All doses on time		Severely undervaccinated[b]		Total number of days undervaccinated[c]		
	n	%	*n*	%	*n*	%	*n*	%	Mean	SE	Median
4 DTaP	361,635	8.86	1,439,299	35.24	2,282,994	55.90	603,353	14.77	214.11	5.72	150.32
3 IPV	265,493	6.50	708,464	17.35	3,109,971	76.15	347,938	8.52	219.54	8.83	86.60
1 MMR	895,268	21.92	–	–	3,188,661	78.08	436,786	10.70	151.88	3.38	177.71
Hib	452,587	11.08	1,938,701	47.47	1,692,640	41.45	1,139,169	27.89	228.46	4.77	163.29
3 Hib[d]	27,860	14.33	105,255	54.15	61,252	31.51	82,158	42.27	271.83	11.01	245.38
4 Hib[e]	306,804	8.13	1,833,446	48.61	1,631,388	43.25	939,088	24.90	203.20	4.66	130.96
3 HepB	343,140	8.40	1,260,679	30.87	2,480,109	60.73	523,497	12.82	220.52	6.92	111.74
1 varicella	911,465	22.32	–	–	3,172,463	77.68	455,983	11.17	154.20	3.36	184.13
4 PCV	499,529	12.23	1,543,825	37.80	2,040,574	49.97	1,051,757	25.75	258.46	5.98	199.20
Rotavirus	908,736	22.25	786,135	19.25	2,389,057	58.50	1,330,680	32.58	474.58	6.87	576.92
2 Rotavirus[f]	30,913	7.05	71,410	16.29	336,162	76.66	47,384	10.81	287.91	25.94	74.11
3 Rotavirus[g]	167,483	5.71	714,725	24.35	2,052,896	69.94	572,956	19.52	364.66	10.32	504.73
4:3:1:3:3:1[h]	164,474	4.03	2,873,725	70.37	1,045,729	25.61	1,587,052	38.86	260.77	4.56	213.24
4:3:1:3:3:1:4[i]	164,474	4.03	2,993,932	73.31	925,522	22.66	1,765,117	43.22	281.88	4.65	241.21

DTaP = diphtheria, tetanus, and acellular pertussis vaccine; HepA = hepatitis A vaccine; HepB = hepatitis B vaccine; Hib = *Haemophilus influenzae* type b vaccine; IPV = inactivated poliovirus vaccine; MMR = measles, mumps, and rubella vaccine; PCV = pneumococcal conjugate vaccine; SE = standard error.

[a] All percentage values will be weighted based on National Immunization Survey sampling design.
[b] Severely undervaccinated is defined as a total of 7 or more months undervaccinated.
[c] Total number of days undervaccinated is defined as the sum of days undervaccinated for at least one vaccine.
[d] Among all children in the sample, 194,367 initiated the Hib series and were classified as needing to complete the 3-dose series by age 24 months.
[e] Among all children in the sample, 3,771,638 initiated the Hib series and were classified as needing to complete the 4-dose series by age 24 months.
[f] Among all children in the sample, 438,485 initiated the rotavirus series and were classified as needing to complete the 2-dose series by age 24 months.
[g] Among all children in the sample, 2,935,104 initiated the rotavirus series and were classified as needing to complete the 3-dose series by age 24 months.
[h] The 4:3:1:3:3:1 series includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, and 1 varicella recommended by age 24 months.
[i] The 4:3:1:3:3:1:4 series includes 4 DTaP, 3 IPV, 1 MMR, 3 or 4 Hib, 3 HepB, 1 varicella, and 4 PCV recommended by age 24 months.

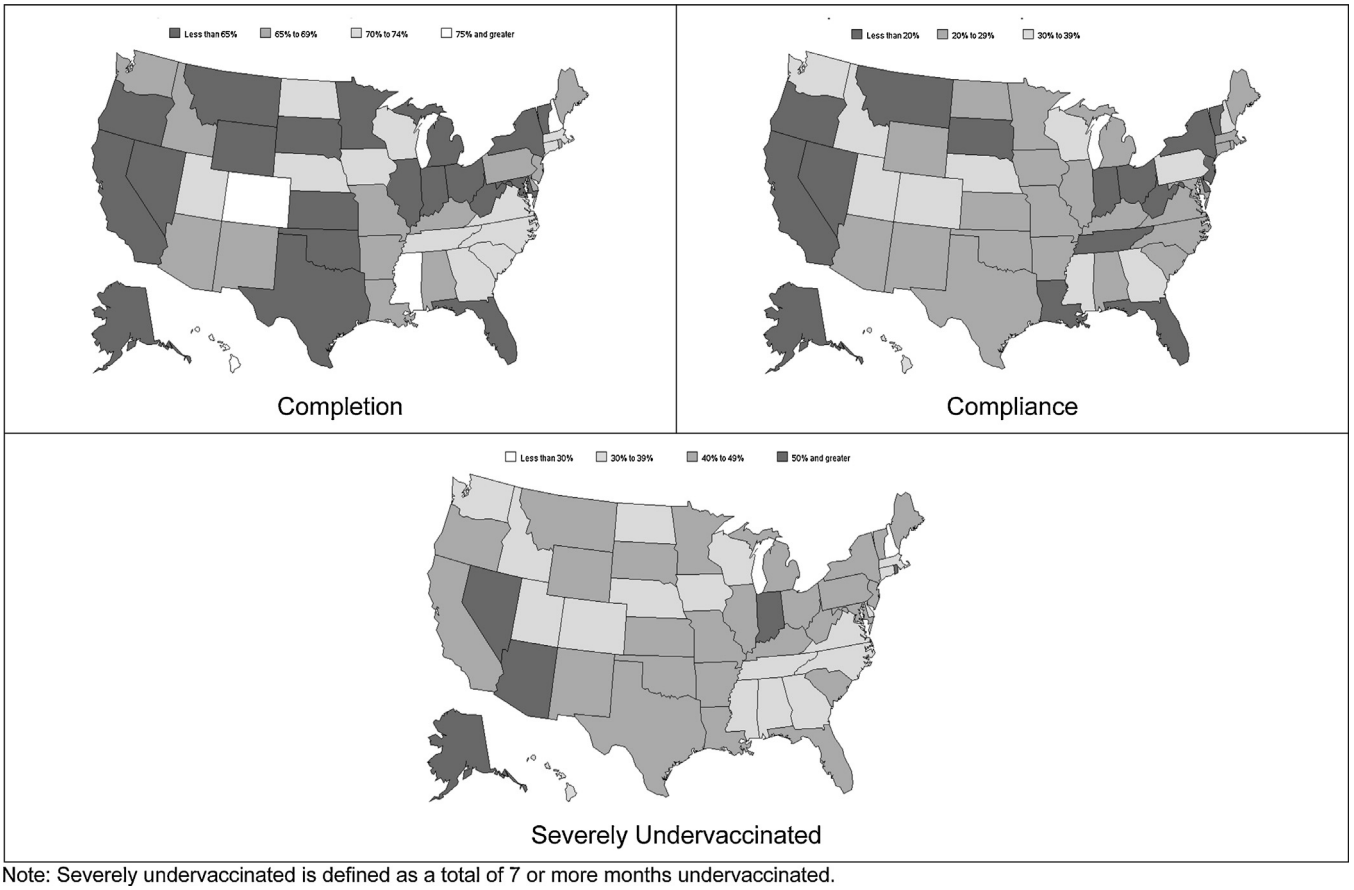

Fig. 1. State-specific analyses of completion and compliance rates of the 4:3:1:3:3:1:4 series.

children do not receive all doses on time, providing further support that a large proportion of children are not adequately immunized between birth and 24 months. We also found that a high proportion of children were severely undervaccinated, which may point to issues with accessing preventative care, vaccine delivery, or intentional refusal to complete the series [5].

In the state-specific analysis, observed regional trends may indicate geographic differences in the factors impacting vaccination behavior and uptake. For example, Western states such as Oregon, California, Nevada, and Alaska had low completion and low compliance rates, indicating that children were not receiving vaccines at all or on time. This trend may be reflective of the high prevalence of vaccine hesitancy in this region [18,19]. However, the Southern states such as Virginia, Tennessee, North Carolina, and South Carolina had among the highest completion rates in the country, yet compliance rates were moderate. This indicates that children were receiving vaccines late, but catching up with the required number of doses by 24 months. Such a trend may suggest issues with access to vaccines or missed opportunities to vaccinate. In addition, vaccine shortages due to increased demand, delays in manufacturing or shipping, new indications, discontinued products, or cold-chain disruption can lead to delayed and incomplete vaccination. At the time of this study, the authors did not find evidence of national vaccine shortages; however, unobserved shortages at the local level may have impacted geographic differences in vaccine completion and compliance.

The NIS has several limitations. The telephone survey methodology relies on the household respondent to identify all vaccine providers and for these providers to accurately report vaccination history. There is potential bias due to households without landline or cell phone service and nonresponse. It is also possible some providers were not identified or that those who were identified did not report the child's entire vaccine history. This could result in some children being misclassified in our study with regard to completion and compliance measures. In addition, the NIS lacks assessment of knowledge, attitudes, beliefs, or other factors related to vaccination that could provide a better understanding of reasons for undervaccination. Although the NIS sample is weighted to represent the national population, sample sizes within each state are small and result in wide confidence intervals. Other data sources, such as vaccine surveillance data captured in state or regional Immunization Information Systems (IIS), include population-level data for a given geographic region and may be utilized to examine local vaccine completion and compliance with a more precise estimate for a specific geographic region or population. Future studies may consider validating NIS estimates with IIS data or other population-based data sources.

5. Conclusions

Despite these limitations, the NIS is a unique, publically available dataset that tracks childhood vaccinations at the state and national level; therefore, it is an important source for measuring vaccination completion and compliance. Our study evaluates a recent cycle of the NIS, adding to the literature on estimating vaccination trends. Our findings indicated that although completion rates were relatively high, a large proportion of children remained undervaccinated for some period before age 2 years, leaving them at risk during a vulnerable period in life. Although vaccine compliance rates improved over the past decade, rates remain low, as only a quarter of children received all age-appropriate vaccinations. As the recommended vaccine schedule is built on evidence of vaccine effectiveness and synchronization with the standard well-child visit schedule, the lack of vaccine compliance may signify underutilization of other preventative care (e.g., developmental milestone assessments). Future research quantifying the impact of missed well-child visits, opportunities for vaccination, and other preventative health interventions should be explored. Use of automated clinical decision support tools, vaccine forecasters, and reminder-recall systems may be integrated into local IIS or medical record systems as they are effective, evidence-based methods for increasing vaccination rates [20]. Programs such as home nurse visits, the Vaccines for Children program, local school and childcare immunization policy, and integration of vaccine forecasting in alternative settings (e.g., Women, Infant, and Children programs) enhancing access to vaccines, which may result in improved vaccination rates. Sustained efforts involving educational, clinical, and policy interventions should continue to reach optimum vaccination levels as recommended by the ACIP.

Trademark statements

Rotarix™ is a trademark of the GSK group of companies. *RotaTeq* is a trademark of Merck & Co., Inc.

Role of the funding source

GlaxoSmithKline Biologicals SA funded this research (GSK study number: HO-14-14321) and was involved together with RTI Health Solutions in all stages of study conduct, including management, analysis of the data and interpretation of the data. GlaxoSmithKline Biologicals SA also took in charge all costs associated with the development and publication of this manuscript.

Author contribution

All authors contributed to method selection and development and provided substantial scientific input to the study report. All authors also reviewed critically the study report and assessed the robustness of the results. KLD and SKK acquired the data, supervised the study and acquired the funding. SKK verified the data, conducted the statistical analyses, reviewed the literature and drafted the study report. KLD provided statistical support for the analysis and reporting of the data. All authors had full access to the data, reviewed and provided important intellectual contribution to the content of the manuscript and gave their final approval before submission.

Note

The analyses, interpretations and conclusions presented here do not necessarily reflect the views or opinions of the National Center for Health Statistics, which is responsible only for the initial data.

Conflict of interest statement

GK is an employee of the GSK group of companies and has ownership of stocks in the GSK group of companies. SKK and KLD are employees of RTI Health Solutions, a contract research organization that received funding from the GSK group of companies to conduct the analysis described in this manuscript. Although RTI Health Solutions was contracted to complete the research study described herein, neither SKK nor KLD were compensated for their contributions as authors on this manuscript. SKK has also received funding from Merck & Co., Inc., Otsuka America Pharmaceutical, Inc., Novartis Pharmaceuticals, Pfizer, Bristol-Myers Squibb, and Eli Lilly for contract research. KLD has also received funding from AstraZeneca, Eli Lilly, Millennium Pharmaceuticals, Inc., Novartis Pharmaceuticals, Pfizer and Shire Pharmaceuticals for contract research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.vaccine.2015.11.011.

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