Impact of the COVID-19 Vaccination Program on case incidence, emergency department visits, and hospital admissions among children aged 5–17 Years during the Delta and Omicron Periods—United States, December 2020 to April 2022

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Abstract

Background

In the United States, national ecological studies suggest a positive impact of COVID-19 vaccination coverage on outcomes in adults. However, the national impact of the vaccination program on COVID-19 in children remains unknown. To determine the association of COVID-19 vaccination with U.S. case incidence, emergency department visits, and hospital admissions for pediatric populations during the Delta and Omicron periods.

Methods

We conducted an ecological analysis among children aged 5–17 and compared incidence rate ratios (RRs) of COVID-19 cases, emergency department visits, and hospital admissions by pediatric vaccine coverage, with jurisdictions in the highest vaccine coverage quartile as the reference.

Results

RRs comparing states with lowest pediatric vaccination coverage to the highest pediatric vaccination coverage were 2.00 and 0.64 for cases, 2.96 and 1.11 for emergency department visits, and 2.76 and 1.01 for hospital admissions among all children during the Delta and Omicron periods, respectively. During the 3-week peak period of the Omicron wave, only children aged 12–15 and 16–17 years in the states with the lowest versus highest coverage, had a significantly higher rate of emergency department visits (RR = 1.39 and RR = 1.34, respectively).
Conclusions

COVID-19 vaccines were associated with lower case incidence, emergency department visits and hospital admissions among children during the Delta period but the association was weaker during the Omicron period. Pediatric COVID-19 vaccination should be promoted as part of a program to decrease COVID-19 impact among children; however, vaccine effectiveness may be limited when available vaccines do not match circulating viral variants.

Introduction

In the United States, Pfizer-BioNTech was recommended on December 12, 2020, for children aged 16–17 years, May 12, 2021, for children aged 12–15 years, and November 2, 2021, for children aged 5–11 years [1–3]. As of May 6, 2022, 62.6% of children aged 16–17 years, 57.6% of children aged 12–15 years, and 28.8% of children aged 5–11 years were fully vaccinated with the Pfizer-BioNTech COVID-19 vaccination series [4].

Although children are less likely to develop severe COVID-19 compared to adults, the pandemic has nonetheless had a serious direct and indirect negative impact on children [5]. Among children aged <18 years, 12,752,227 cases and 1,536 deaths due to COVID-19 have been reported as of May 16, 2022 [6]. Children can also suffer delayed sequelae from COVID-19 including multisystem inflammatory syndrome which usually requires hospitalization and can result in disability and death [7]. In addition, isolation during infection and quarantine after exposure to sick contacts results in fewer days in school where children can access nutritious food and social and mental health support [8].

Prior U.S. national studies of adult populations have shown that people living in areas where COVID-19 vaccination of adults is higher have lower case incidence, lower hospitalization rates, and fewer emergency department visits due to COVID-19 [9,10]. With the introduction of pediatric COVID-19 vaccinations, it is important to assess this impact among children. Previous studies indicate vaccines are effective for the prevention of infection and hospitalization, though the effectiveness is lower during Omicron circulation than for previous variants [11–13]. We conducted an ecological study to determine the association of state-level COVID-19 vaccination rates with case incidence, emergency department visits, and hospital admissions in the pediatric population during two crucial periods of the COVID-19 pandemic when the Delta and Omicron variants predominated.

Methods

Study design

To assess the impact of pediatric vaccination coverage on COVID-19 in children, we analyzed weekly time series data for COVID-19 cases, emergency department visits with diagnosed COVID-19, and hospital admissions of patients with lab-confirmed positive SARS-CoV-2 results from December 13, 2020, to April 30, 2022. We stratified data for COVID-19 cases and emergency department diagnoses by pediatric age groups for children aged 5–11, 12–15, and 16–17 years; we included aggregated hospital weekly admission data among children aged 0–17 years. We defined the analytic period to capture periods before and after COVID-19 vaccine was authorized for each pediatric age group. To compare outcomes in jurisdictions (U.S. states and the District of Columbia) in the lowest quartile for pediatric vaccination coverage to jurisdictions in the highest quartile for pediatric vaccination coverage, we calculated rate ratios
with high coverage jurisdictions used as the reference group for: 1) all weeks included in the analytical period; and 2) date ranges aligning with predominance of the Delta and Omicron variants in the United States, and the 3-week peak periods of Delta and Omicron waves. We aggregated county-level vaccination coverage data into jurisdiction-level data and then grouped jurisdictions into vaccination coverage categories using quartiles for vaccination coverage rate estimates for children aged 5–17 years as of April 2022.

This activity was reviewed by the Centers for Disease Control and Prevention’s (CDC) Human Research Protection Office and determined to be exempt from human participants’ research regulations, including the need for documented written consent, as the activities involved identification, control or prevention of disease in response to an immediate public health threat. It was conducted consistent with applicable federal law and CDC policy (See e.g., 45 C.F.R. part 46, 21 C.F.R. part 56; 42 U.S.C. §241(d); 5 U.S.C. §552a; 44 U.S.C. §3501 et seq.).

Data sources

Cases. Jurisdictional (state (50), territorial (3) and local (2)) health departments voluntarily submit de-identified individual-level data for COVID-19 cases to CDC via the COVID-19 Case Report Form and the National Notifiable Diseases Surveillance System [14,15]. These data sources are aggregated for use as a single dataset. Age was available for 99% of recorded cases. In this analysis, we used data from 33 states, representing 70% of US population under age 18; we excluded jurisdictions if less than 80% of records contained residential county information, if less than 90% of records contained relevant date information, or if the jurisdiction was missing data for more than 1 week in the study period. Jurisdictions included were Alabama, Arizona, Arkansas, California, Colorado, Delaware, Georgia, Idaho, Illinois, Indiana, Kansas, Louisiana, Maine, Massachusetts, Minnesota, Missouri, Montana, Nevada, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oregon, Pennsylvania, South Carolina, Tennessee, Utah, Vermont, Virginia, Washington, and Wyoming.

Emergency department visits. We collected emergency department visit data from the National Syndromic Surveillance Program (NSSP), representing encounters with a diagnosis of COVID-19, defined by having any of the following discharge diagnoses: International Classification of Diseases, Tenth Revision codes U07.1 or J12.82 or Systematized Nomenclature of Medicine (SNOMED) codes 840539006, 84054404, or 840533007. NSSP collects electronic health data from 73% of non-federal hospital facilities across all jurisdictions [16]. We applied data quality filters to only include data from facilities with high completeness of discharge diagnoses (average weekly completeness ≥75%) and consistent reporting over the analytic period. Fewer than 50% of facilities in California, Hawaii, Iowa, Minnesota, and Oklahoma send data to the NSSP; we excluded emergency department visit data from these jurisdictions from this analysis. Additionally, we excluded jurisdictions with low completeness for discharge diagnoses (Missouri) and those with missing data during the analytical period (Maryland).

Hospital admissions. De-identified COVID-19 hospitalization data are reported by over 6,000 hospitals in the United States through the U.S. Department of Health and Human Services Unified Hospital Data Surveillance System (UHDSS), which collects daily hospital-level data from all hospitals registered with the Centers for Medicare and Medicaid Services (CMS) as of June 1, 2020, and data from hospitals not registered with CMS but reporting since July 15, 2020 [17]. Facility subtype designations are determined by CMS. We excluded psychiatric, rehabilitation, and religious non-medical facilities from analyses, because these facilities are required to report per conditions of participation, but do not typically treat or admit patients with acute COVID-19. Data included in analyses represent all jurisdictions and were both consistent and complete during the analytic period (at least 5146 [98%] of 5251 hospitals meeting
inclusion criteria reported COVID-19 admissions data on any given day between December 13, 2020, and April 30, 2022). New admissions of pediatric patients aged 0–17 years with confirmed COVID-19 obtained from UHDSS were available as aggregate counts reported daily during the study period. Reporting of new admissions of patients with confirmed COVID-19 by narrower age ranges (0–4, 5–11, and 12–17 years) began in February 2022. Thus, we conducted analyses of pediatric hospital admissions data for children aged 0–17 years; further stratification by age was not possible due to limited availability of the more granular age-specific admissions data.

**Vaccine administration data.** Individual-level COVID-19 vaccine administration data are submitted to CDC via jurisdictional immunization information systems, the Vaccine Administration Management System, or direct data submission [18,19]. The data are de-duplicated, de-identified, and subjected to systematic quality control checks prior to analysis [20]. For this analysis, we included Pfizer-BioNTech vaccines administered to children aged 5–17 years by April 30, 2022, in all reporting jurisdictions.

**Statistical analysis**

We used U.S. 2019 population estimates to calculate jurisdiction pediatric vaccination coverage rates and cases and hospital admission rates per 100,000 population [21]. We calculated jurisdiction pediatric vaccination coverage quartiles using cumulative percentages for children aged 5–17 years who had completed the COVID-19 vaccination series. To estimate rate ratios comparing jurisdictions with lower vaccination coverage (lowest, second lowest, and second highest vaccination coverage quartiles) to jurisdictions in the highest vaccination coverage quartile, we used Poisson regression models and generalized estimating equations (GEE) to account for clustering of data by state. We calculated 95% confidence intervals (CIs) using robust standard errors.

We calculated ratios for emergency department visits using the total number of visits rather than population-based estimates. To assess differences in lower and highest vaccination coverage jurisdictions over time, we calculated rate ratios for case counts, emergency department visits, and hospital admissions for: 1) all weeks from December 13, 2020, to April 30, 2022; 2) time periods aligning with predominance of the Delta and Omicron variants in the United States (Delta: June 20, 2021–October 31, 2021; Omicron: December 19, 2021–April 30, 2022); and 3) 3-week time periods aligning with peaks in case incidence during the Delta and Omicron variant time periods (Delta: August 22, 2021–September 11, 2021; Omicron: January 2, 2022–January 22, 2022). We calculated jurisdiction coverage quartiles separately for the Delta and Omicron time periods, using coverage estimates from the mid-point of each period (Delta: September 5, 2021; Omicron: February 20, 2022). For weekly rate ratio calculations, we used coverage estimates as of April 30, 2022, to determine jurisdictions in the lowest and highest (reference) coverage quartiles. We kept jurisdictions in the lowest and highest coverage quartiles fixed over the analytic period for weekly rate ratio calculations. For COVID-19 cases and emergency department visits, we calculated rate ratios separately for children aged 5–11, 12–15, and 16–17 years, and for children aged 5–17 years overall. Rate ratio calculations for hospital admissions were limited to children aged 0–17 years. We used R version 4.3.1 for all statistical analyses.

**Results**

As of April 30, 2022, vaccination coverage remained highest for children aged 16–17 years (62.8%), followed by children aged 12–15 (56.7%) and 5–11 (27.3%) years (Fig 1). For the age groups of 5–11 and 12–15 years, the increase in vaccination coverage was greatest in the first
1–2 months following FDA Emergency Use Authorization and CDC recommendation of the COVID-19 and slowed dramatically in subsequent months.

During the Delta and Omicron periods of predominance in the US, case incidence and the percentage of emergency department visits with diagnosed COVID-19 in children aged 5–17 years were 4,206 per 100,000 persons (cases) and 3.24% (emergency department visits) during the Delta period, and 8,724 per 100,000 persons (cases) and 3.81% (emergency department visits) during the Omicron period. Hospital admission rates in children aged 0–17 years during the Delta and Omicron periods were 37 per 100,000 persons and 67 per 100,000 persons, respectively (S1 Table).

In the overall pediatric population, rate ratios comparing jurisdictions in the lowest pediatric vaccination coverage quartile (8%–12% for cases and ED visits, 8%–13% for hospital admissions) (Table 1) to the highest pediatric vaccination coverage quartile (22%–28% for cases, 22%–29% for ED visits and hospital admissions) during the period of Delta predominance were 2.00 (95% CI: 1.50–2.67) for cases, 2.96 (95% CI: 2.13–4.11) for emergency department visits, and 2.76 (95% CI: 2.04–3.74) for hospital admissions (Table 2, Fig 2). In contrast, during the Omicron period of predominance, low coverage jurisdictions (19%–27%) relative to high coverage jurisdictions (46%–56%) were associated with lower case incidence: (0.64 (95% CI: 0.45–0.91)). Vaccination coverage was not associated with emergency department visits (1.11 (95% CI: 0.85–1.44)) and hospital admissions (1.01 (95% CI: 0.80–1.28)) during the Omicron period of predominance (Table 2).

During the 3-week peak period of the Delta variant, rate ratios comparing jurisdictions in the lowest pediatric vaccination coverage quartile to the highest pediatric vaccination coverage quartile were more robust 3.19 (95% CI: 2.11–4.82) for cases, 3.41 (95% CI: 2.41–4.82) for emergency department visits, and 3.73 (95% CI: 2.70–5.14) for hospital admissions (Table 2, Fig 2). During the 3-week peak period of the Omicron variant, this association was more robust for emergency department visits: 1.28 (95% CI: 0.95–1.74).

When assessing the outcomes by age for cases and emergency department visits during the Delta period, differences were observed in the magnitude of the associations (Table 2).
Children aged 12–15 and 16–17 years in the jurisdictions with the lowest vaccination coverage had a similar 2.30 (95% CI: 1.71–3.08) to 2.18 (95% CI: 1.61–2.95)-fold difference in the incidence of cases compared with jurisdictions with highest vaccination coverage, whereas this difference was 1.78-fold for children aged 5–11 years (95% CI: 1.34–2.37). Similarly, for emergency department visits, the strongest association with vaccination coverage levels by quartile were observed in children aged 12–15 (RR: 3.30, 95% CI: 2.38–4.58) and 16–17 (RR: 3.08, 95% CI: 2.28–4.17) years, versus 5–11 (RR: 2.68, 95% CI: 1.89–3.82) years. Findings were even more robust during the 3-week peak period of the Delta variant than during the full Delta period when stratifying by age group. For the Omicron period, low vaccination quartile at the state level coverage was statistically associated with lower case incidence for all age groups. Lowest vaccine coverage was significantly associated with greater emergency department visits among those aged 12–15 (RR: 1.39, 95% CI: 1.02–1.90) and 16–17 (RR: 1.34, 95% CI: 1.00–1.78) years during the 3-week peak period (Table 2).

**Discussion**

In this comprehensive ecological analysis, we found that in the United States, during the period of COVID-19 Delta predominance, the rate of cases, emergency department visits, and hospital admissions were 2.00, 2.96, and 2.76 times as high, respectively, in jurisdictions with the lowest vaccination coverage compared with jurisdictions with the highest vaccination coverage. These associations were even more robust during the 3-week peak period of the Delta variant wave. This overall association was not seen during the 3-week peak period of the Omicron wave; however, children (aged 12–15 and 16–17 years) in jurisdictions with the lowest vaccination coverage had higher emergency department visits during this period. This study mirrors the findings of recent formal vaccine effectiveness (VE) evaluations, which have found lower effectiveness during Omicron predominance compared to Delta.

| Outcome | Coverage Quartile Group | Delta | Omicron |
|---------|-------------------------|-------|---------|
| Cases   | Highest                 | 22–28%| 46–56% |
|         | Second Highest          | 18–22%| 34–45% |
|         | Second Lowest           | 14–17%| 27–34% |
|         | Lowest                  | 8–12% | 19–27% |
| Emergency Department Visits | Highest | 22–29%| 45–56% |
|         | Second Highest          | 17–21%| 34–43% |
|         | Second Lowest           | 13–17%| 27–34% |
|         | Lowest                  | 8–12% | 19–27% |
| Hospital Admissions | Highest | 22–29%| 46–56% |
|         | Second Highest          | 17–22%| 35–46% |
|         | Second Lowest           | 14–17%| 27–34% |
|         | Lowest                  | 8–13% | 19–27% |

*Midpoints of Delta and Omicron periods of predominance defined as August 22, 2021 and February 20, 2022.

*Jurisdictions excluded from case data source include Alaska, Connecticut, District of Columbia, Florida, Kentucky, Hawaii, Iowa, Maryland, Missouri, Mississippi, Nebraska, New Hampshire, Oklahoma, Rhode Island, South Dakota, Texas, Wisconsin, and West Virginia.

*Jurisdictions excluded from emergency department data source include California, Hawaii, Iowa, Minnesota, Oklahoma, Missouri, and Maryland.

*No jurisdictions were excluded from hospital admission data source.

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Table 2. Rate ratios among children aged 5–17 years by outcome comparing COVID-19 pediatric vaccination coverage quartiles of states to states in the highest vaccination coverage quartile during Delta and Omicron predominant periods—by age group and overall.

| Outcome                   | Rate Ratio (95% CIs) | Vaccine Coverage Quartile | Reference |
|----------------------------|----------------------|---------------------------|-----------|
|                            |                      | Full^b Peak^c            | Full^b Peak^c | Full^b Peak^c | Full^b Peak^c | Full^b Peak^c | Full^b Peak^c | Full^b Peak^c | Full^b Peak^c |
|                            |                      | 5–11                      | 12–15        | 16–17        | All^*         |          |          |          |          |
|                            |                      | Delta                      | Omicron      | Delta        | Omicron       | Delta       | Omicron       | Delta       | Omicron       |
| Cases^f                    |                      | Highest                    | Reference    |              |              |            |              |            |              |
|                            |                      | Second Highest             | (0.99, 1.58) | (1.43, 1.98) | (0.81, 1.16) | (0.78, 1.03) | (0.91, 1.09) | (0.81, 1.09) | (0.91, 1.09) |
|                            |                      | Lowest                     | (1.84, 2.50) | (1.38, 2.08) | (1.05, 1.39) | (0.86, 1.24) | (1.09, 1.35) | (0.86, 1.24) | (1.09, 1.35) |
| Emergency Department Visits^g                     |                      | Highest                    | Reference    |              |              |            |              |            |              |
|                            |                      | Second Highest             | (1.13, 1.97) | (1.27, 2.02) | (0.81, 1.29) | (0.84, 1.29) | (0.88, 1.35) | (0.84, 1.29) | (0.88, 1.35) |
|                            |                      | Lowest                     | (1.76, 2.53) | (1.27, 1.89) | (0.86, 1.29) | (0.84, 1.29) | (1.09, 1.35) | (0.84, 1.29) | (1.09, 1.35) |
| Hospital Admissions^h                  |                      | Highest                    | Reference    |              |              |            |              |            |              |
|                            |                      | Second Highest             | (1.12, 3.06) | (2.25, 4.10) | (1.30, 2.69) | (1.22, 2.69) | (1.12, 2.69) | (1.12, 2.69) | (1.12, 2.69) |
|                            |                      | Lowest                     | (1.76, 2.53) | (2.25, 4.10) | (1.30, 2.69) | (1.22, 2.69) | (1.12, 2.69) | (1.12, 2.69) | (1.12, 2.69) |

^a Hospital admission data are only available in aggregate for children aged 0–17 years during these periods. For cases and ED visits, data are shown for pediatric patients aged 5–17 years.

^b Full period of Delta predominance defined as June 20, 2021 through October 31, 2021.

^c Peak period of Delta predominance defined as August 22, 2021 through September 11, 2021.

^d Full period of Omicron predominance defined as December 19, 2021 through April 30, 2022.

^e Peak period of Omicron predominance defined as January 2, 2022 through January 22, 2022.

^f Jurisdictions excluded from case data source include Alaska, Connecticut, District of Columbia, Florida, Kentucky, Hawaii, Iowa, Maryland, Missouri, Mississippi, Nebraska, New Hampshire, Oklahoma, Rhode Island, South Dakota, Texas, Wisconsin, and West Virginia.

^g Jurisdictions excluded from emergency department data source include California, Hawaii, Iowa, Minnesota, Oklahoma, Missouri, and Maryland.

^h No jurisdictions were excluded from hospital admission data source.

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especially for the primary series alone [11–13,22,23]. During both periods, higher VE has been observed for more severe disease (e.g., hospital admissions; death), similar to our finding of a bigger impact of higher coverage on admissions and emergency department visits compared with case counts.

Consistent with our findings, the Coronavirus Disease 19–Associated Hospitalization Surveillance Network (COVID-NET) found large increases in the rates of COVID-19-associated
Fig 2. Weekly rate ratios among children aged 5–17 comparing lowest COVID-19 vaccination coverage quartile states to highest coverage quartile states by outcome: December 13, 2020–April 30, 2022. Vaccine coverage estimates for children aged 5–17 years during the first and last week of the Delta and Omicron periods of predominance in the US: (Delta: 9.21% as of the week of June 20th, 2021, 22.57% the week of October 31, 2021);
hospital admissions during Delta period; the monthly rate in December 2021 among unvaccinated children aged 12–17 years was six times that of vaccinated children [20,22–24].

Several possible explanations may explain the discordant findings regarding higher vaccine coverage and higher case incidence in this study and in an analysis of 68 countries and 2947 counties in the United States [25]. These explanations include unmeasured confounders including differences in population, vaccine products and schedules, and variant circulation during the study periods; very low vaccine coverage among children aged 5–11 years compared with adults [26,27]; and waning vaccine immunity (5 months after completing a vaccine series) [28,29]. In addition to vaccination coverage, other factors may have affected COVID-19 incidence. Differences other than vaccine coverage (e.g., testing patterns, local and state COVID-related policies impacting school closures and mask mandates, behavior, socio-economic status, urban/rural divide) could have impacted rates of disease and were not accounted for in this analysis.

This analysis has several limitations. First, causation between pediatric vaccination coverage and outcomes cannot be inferred since this was an ecological study; pediatric vaccine effectiveness has been shown by other studies [23]. Second, there are limitations within data sources including lack of granular age data prior to February 2022 for hospital admissions data and data quality limitations for both case and emergency department data, leading to exclusion of some localities and jurisdictions. Nonetheless, pediatric populations in the included and excluded states were similar in regard to the distribution of their age groups, sex, and distribution by social vulnerability index [19] (a measure of stressors with negative effects on communities) levels (S2 Table). Third, differences in SARS-CoV-2 testing between jurisdictions with high versus low coverage could not be determined and may have biased our findings. For instance, if low coverage jurisdictions tested less, this would lower estimates of COVID-19 case incidence in these jurisdictions, and thus, potentially bias results showing less impact of the vaccine on cases. However, this would less likely affect severe outcomes (e.g., emergency department visits, and hospital admissions), where a greater impact of vaccination coverage on emergency department visits and hospital admissions was observed, when compared with cases. Fourth, because of the limitations of the data we would not control for potential confounders such as COVID-19 mitigation efforts (e.g., mask utilization, physical distancing), health characteristics, population density, education levels, and socioeconomic status that may have impacted our associations. Finally, boosters were not approved for the youngest pediatric age group during the Delta and Omicron periods; therefore, the analysis was not able not assess the impact of additional doses after completion of the primary series.

In conclusion, during the COVID-19 Delta and Omicron waves, COVID-19 vaccination was associated with reduced COVID-19 burden on the healthcare system. Higher vaccination rates were associated with lower rates of cases, hospital admissions and emergency department visits among pediatric age groups approved to receive COVID-19 vaccine during the Delta period. A reduction in emergency department visits, but not cases or hospital admissions, was observed during the Omicron period. COVID-19 vaccines are safe and effective in preventing severe outcomes among the pediatric population [12]; however, vaccine effectiveness may be limited when available vaccines do not match circulating viral variants. Pediatric COVID-19 vaccinations are recommended to prevent COVID-related outcomes among children [1–3].
Supporting information

S1 Table. Number and rates of COVID-19 cases, emergency department (ED) visits, and hospital admissions in the United States during the Delta and Omicron periods, by age group and overall (5–17 years).

(DOCX)

S2 Table. Demographic characteristics and county classification breakdowns for jurisdictions included vs. excluded for COVID-19 cases.

(DOCX)

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References

1. Oliver SE, Gargano JW, Marin M, Wallace M, Curran KG, Chamberland M, et al. The Advisory Committee on Immunization Practices’ interim recommendation for use of Pfizer-BioNTech COVID-19 vaccine—United States, December 2020. MMWR Morb Mortal Wkly Rep. 2020; 69:1922–1924. https://doi.org/10.15585/mmwr.mm6950e2 PMID: 33332292

2. Wallace M, Woodworth KR, Gargano JW, Scobie HM, Blain AE, Moulia D, et al. The Advisory Committee on Immunization Practices’ interim recommendation for use of Pfizer-BioNTech COVID-19 vaccine in adolescents aged 12–15 years—United States, May 2021. MMWR Morb Mortal Wkly Rep. 2021; 70:749–752. https://doi.org/10.15585/mmwr.mm7020e1 PMID: 34014913

3. Woodworth KR, Moulia D, Collins JP, Hadler SC, Jones JM, Reddy SC, et al. The Advisory Committee on Immunization Practices’ interim recommendation for use of Pfizer-BioNTech COVID-19 vaccine in children aged 5–11 years—United States, November 2021. MMWR Morb Mortal Wkly Rep. 2021; 70:1579–1583. https://doi.org/10.15585/mmwr.mm7045e1 PMID: 34758012

4. Trends in demographic characteristics of people receiving COVID-19 vaccinations in the United States. US Centers for Disease Control and Prevention. Accessed May 24, 2022. https://covid.cdc.gov/covid-data-tracker/#vaccination-demographic-trends.

5. Siebach MK, Piedimonte G, Ley SH. COVID-19 in childhood: Transmission, clinical presentation, complications and risk factors. Pediatr Pulmonol. 2021 Jun; 56(6):1342–1356. https://doi.org/10.1002/ppul.25344 PMID: 33721405

6. COVID Data Tracker. Centers for Disease Control and Prevention. Accessed May 20, 2022. https://covid.cdc.gov/covid-data-tracker.

7. Yasuhara J, Watanabe K, Takagi H, Sumitomo N, Kuno T. COVID-19 and multisystem inflammatory syndrome in children: A systematic review and meta-analysis. Pediatr Pulmonol. 2021; 56(5):837–848. https://doi.org/10.1002/ppul.25245 PMID: 33428826

8. Rajmil L, Hjern A, Boran P, Gunnlaugsson G, Kraus de Camargo O, Raman S. Impact of lockdown and school closure on children’s health and well-being during the first wave of COVID-19: A narrative review. BMJ Paediatr Open. 2021; 5(1):e001043. https://doi.org/10.1136/bmjpo-2021-001043 PMID: 34192198

9. McNamara LA, Wiegand RE, Burke RM, Sharma AJ, Sheppard M, Adjemian J, et al. Estimating the early impact of the US covid-19 vaccination programme on COVID-19 cases, emergency department visits, hospital admissions, and deaths among adults aged 65 years and older: An ecological analysis of national surveillance data. The Lancet. 2022; 399(10320):152–160. https://doi.org/10.1016/S0140-6736(21)02226-1 PMID: 34741818

10. Sutahr AB, Wang J, Seffren V, Wiegand RE, Griffing S, Zell E. Public health impact of covid-19 vaccines in the US: Observational study. BMJ. 2022;377. https://doi.org/10.1136/bmj-2021-069317 PMID: 35477670

11. Fowlkes AL, Yoon SK, Lutrick K, Gwynn L, Burns J, Grant L, et al. Effectiveness of 2-dose BNT162b2 (Pfizer BioNTech) mRNA vaccine in preventing SARS-CoV-2 infection among children aged 5–11 years and adolescents aged 12–17 years—PROTECT Cohort, July 2021–February 2022. MMWR Morb Mortal Wkly Rep. 2022; 71:422–428. https://doi.org/10.15585/mmwr.mm7111e1 PMID: 35298453

12. Klein NP, Stockwell MS, Demarco M, Gagliani M, Kharbanda AB, Irving SA, et al. Effectiveness of COVID-19 Pfizer-BioNTech BNT162b2 mRNA vaccination in preventing COVID-19–associated emergency department and urgent care encounters and hospitalizations among nonimmunocompromised children and adolescents aged 5–17 years—VISION network, 10 states, April 2021–January 2022. MMWR Morb Mortal Wkly Rep. 2022; 71:352–358. https://doi.org/10.15585/mmwr.mm7109e3 PMID: 35239634

13. Fleming-Dutra KE, Britton A, Shang N, Derado G, Link-Gelles R, Accorsi EK et al. Association of Prior BNT162b2 COVID-19 Vaccination With Symptomatic SARS-CoV-2 Infection in Children and Adolescents During Omicron Predominance. JAMA. 2022; 327(22):2210–2219. https://doi.org/10.1001/jama.2022.7493 PMID: 35560036

14. Information for health departments on reporting cases of COVID-19. US Centers for Disease Control and Prevention. Accessed May 4, 2022. https://www.cdc.gov/coronavirus/2019-ncov/php/reporting-pui.html.

15. National Notifiable Diseases Surveillance System (NNDSS). US Centers for Disease Control and Prevention. Accessed May 4, 2022. https://www.cdc.gov/nndss/.

16. National Syndromic Surveillance Program (NSSP). US Centers for Disease Control and Prevention. Accessed May 4, 2022. https://www.cdc.gov/nssp/index.html.

17. Unified hospital dataset 2021. US Centers for Disease Control and Prevention. Accessed May 4, 2022. https://covid.cdc.gov/coviddata-tracker/#abouthospitaldata.
18. About COVID-19 vaccine delivered and administration data 2021. US Centers for Disease Control and Prevention. Accessed May 4, 2022. https://www.cdc.gov/coronavirus/2019-ncov/vaccines/distributing/about-vaccinatedata.html.

19. Hughes MM, Wang A, Grossman MK, Pun E, Whiteman A, Deng L, et al. County-level COVID-19 vaccination coverage and social vulnerability—United States, December 14, 2020–March 1, 2021. MMWR Morb Mortal Wkly Rep. 2021; 70(12): 431–36. https://doi.org/10.15585/mmwr.mm7012e1 PMID: 33764963

20. Marks KJ, Whitaker M, Anglin O, Milucky J, Patel K, Pham H et al. Hospitalizations of children and adolescents with laboratory-confirmed COVID—COVID-NET, 14 states, July 2021–January 2022. MMWR Morb Mortal Wkly Rep. 2022; 71:271–278. https://doi.org/10.15585/mmwr.mm7107e4 PMID: 35176003

21. 2019 Population Estimates by Age, Sex, Race and Hispanic Origin (census.gov). www.census.gov/newsroom/press-kits/2020/population-estimates-detailed.html. Accessed July 1, 2022.

22. Tenforde MW, Self WH, Gaglani M, Ginde AA, Douin DJ, Talbot HK, et al. Effectiveness of mRNA vaccination in preventing COVID-19—associated invasive mechanical ventilation and death—United States, March 2021–January 2022. MMWR Morb Mortal Wkly Rep. 2022; 71:459–465. https://doi.org/10.15585/mmwr.mm7112e1 PMID: 35324878

23. Accorsi EK, Britton A, Fleming-Dutra KE, Smith ZR, Shang N, Derado G, et al. Association between 3 doses of mRNA COVID-19 vaccine and symptomatic infection caused by the SARS-CoV-2 omicron and delta variants. JAMA. 2022; 327(7):639–651. https://doi.org/10.1001/jama.2022.0470 PMID: 39060999

24. Shi DS, Whitaker M, Marks KJ, Anglin O, Milucky J, Patel K, et al. Hospitalizations of Children Aged 5–11 Years with Laboratory-Confirmed COVID—COVID-NET, 14 States, March 2020–February 2022. MMWR Morb Mortal Wkly Rep. 2022; 71(16):574–581. https://doi.org/10.15585/mmwr.mm7116e1 PMID: 35446827

25. Subramanian SV, Kumar A. Increases in COVID-19 are unrelated to levels of vaccination across 68 countries and 2947 counties in the United States. Eur J Epidemiol. 2021; 36(12):1237–1240. https://doi.org/10.1007/s10654-021-00808-7 PMID: 34591202

26. Murthy NC, Zell E, Fast HE, Murthy BP, Meng L, Saelee R, et al. Disparities in First Dose COVID-19 Vaccination Coverage among Children 5–11 Years of Age, United States. Emerg Infect Dis. 2022; 28 (5):986–989. https://doi.org/10.3201/eid2805.220166 PMID: 35226801

27. Diesel J, Sterrett N, Dasgupta S, Kriss JL, Barry V, Vanden Esschert K, et al. COVID-19 Vaccination Coverage Among Adults—United States, December 14, 2020–May 22, 2021. MMWR Morb Mortal Wkly Rep. 2021; 70(25):922–927. Published 2021 Jun 25. https://doi.org/10.15585/mmwr.mm7025e1 PMID: 34166331

28. Mennt C, May A, Polidori L, Louca P, Wolf J, Capdevila J, et al. COVID-19 vaccine waning and effectiveness and side-effects of boosters: a prospective community study from the ZOE COVID Study [published online ahead of print, 2022 Apr 8]. Lancet Infect Dis. 2022;S1473-3099(22)00146-3. https://doi.org/10.1016/S1473-3099(22)00146-3 PMID: 35405090

29. Andrews N, Stowe J, Kursebom F, offa S, Rickeard T, Gallagher E, et al. Covid-19 Vaccine Effectiveness against the Omicron (B.1.1.529) Variant. N Engl J Med. 2022; 386(16):1532–1546. https://doi.org/10.1056/NEJMoa2119451 PMID: 35249272