Epidemiology and Transmission Dynamics of COVID-19 in an Urban Pediatric US Population

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Abstract
Objective: This analysis summarizes observational epidemiologic data and transmission dynamics of SARS-CoV-2 among people aged <18 years to better characterize the pediatric COVID-19 pandemic.

Methods: We conducted a retrospective study of public health surveillance data among children in Denver, Colorado, who were reported to have COVID-19 from March 1, 2020, through September 30, 2021. We used descriptive statistics and bivariate rate ratios (RRs) to describe demographic and clinical characteristics, transmission dynamics, case trends, and ecological associations.

Results: A total of 9815 children and adolescents who had COVID-19 were reported during the study period. Adolescents aged 14-17 years had the highest incidence rate (IR) per 1000 people (IR = 107.5; 3021 of 28 108). Hispanic/Latino children had a 1.6 times higher rate of infection than non-Hispanic White children (RR = 1.57; 95% CI, 1.50-1.65; P < .001). Few hospitalizations (n = 138, 1.4%) and deaths (n = 3, 0%) occurred. Most children were symptomatic (4487 of 5499, 81.6%). Within household clusters, a large proportion of pediatric cases (n = 6136) were a secondary case (n = 3959, 64.5%), followed by index case (n = 1170, 19.1%) and co–index case (n = 1007, 16.4%). Non-Hispanic White children had an increased risk of being an index or co–index case (RR = 1.14; 95% CI, 1.06-1.23; P < .001), while Hispanic/Latino children had an increased risk of being a secondary case (RR = 1.07; 95% CI, 1.03-1.11; P < .001). From 2020 to 2021, the association between pediatric case rates and neighborhoods with higher poverty and households with ≥3 people decreased.

Conclusions: Older children and those identifying as Hispanic/Latino had a disproportionate incidence of disease. A sizable proportion of children were considered index cases or co–index cases. Pediatric prevention strategies, especially vaccinations, are vital for pandemic control.

Keywords
SARS-CoV-2, children, health disparities, Hispanic, household contact
disease, hospitalization, and death. COVID-19 has also disproportionately affected communities traditionally associated with certain social determinants of health and neighborhood attributes, such as lower-income and higher-density households. Although the role of children in virus transmission varies, data suggest that children have a similar risk of COVID-19 infection as adults, are commonly asymptomatic, and are fully capable of transmission. While adults often have a community or nosocomial exposure, most children have a documented household contact, even with a return to in-person learning. Schools with effective prevention strategies have lower or similar levels of community transmission compared with schools without these prevention strategies, especially with low numbers of unvaccinated people in schools. We evaluated the incidence and epidemiology of COVID-19 among children and adolescents to better inform the public health and health systems’ response in an increasingly complex and nuanced environment.

**Methods**

We conducted a retrospective analysis among children and adolescents aged <18 years living in noncongregate settings who had reported laboratory-confirmed COVID-19 in Denver, Colorado, with an earliest known date of infection (EKDI) of March 1, 2020, through September 30, 2021. We defined EKDI as the earliest date of the following: date of self-reported onset of symptoms, laboratory collection date, test date, or date reported. Cases were reported to the Colorado Department of Public Health and Environment’s (CDPHE’s) Colorado Electronic Disease Reporting System (CEDRS) and then assigned for case/contact investigation. The Public Health Institute at Denver Health (PHIDH) used standardized forms for telephone interviews with reported patients or proxies (eg, caregivers/guardians of children or adults). PHIDH conducted medical record reviews when people were hospitalized, had died, or could not be contacted. Data on hospitalization and death were based on information available at the time of reporting and cross-validated by regional electronic health records and vital statistics. Data were securely stored in a REDCap (Vanderbilt University) database and supplemented with data from CDPHE.

**Household Transmission**

We used ArcGIS Pro (Esri) to geocode and standardize all cases with a valid address. We excluded cases without a valid address or without a valid address that could be geocoded (n = 1242). We used all cases, including adults, to quantify household transmission. We considered cases with the same primary address and last name or telephone number to reside in the same household. We defined a suspected household cluster, considered evidence of household transmission, as all household cases with an EKDI ±26 days the EKDI of another household case. The ±26-day household cluster transmission window accounted for a combined 3-day incubation period and 10-day communicable period for both an index and secondary case. We used the EKDI to describe the directionality of transmission within a household cluster. We considered index cases co-occurring on the same day to be co-index cases; we considered subsequent cases to be secondary cases and the result of household transmission. We restricted household transmission dynamics to household clusters with ≥2 cases with ≥1 pediatric case.

**Community-Level Indicators**

We aggregated US Census tract estimates from the American Community Survey for the numbers of households living at ≤150% of the federal poverty level and households with ≥3 people to the neighborhood level to assess the association with pediatric case rates.

**Analysis**

We used descriptive statistics to summarize demographic and clinical characteristics. We used population estimates from the Colorado Department of Local Affairs to calculate incidence rates (IRs). We defined reinfections as a second case of COVID-19 in an individual reported >90 days after the preceding infection and postvaccination infections as laboratory-confirmed COVID-19 occurring >14 days after the second vaccine dose (2-dose series) or the first dose (single-dose vaccines).

We detailed case characteristics via descriptive statistics from January 1 through September 30, 2021, overall and by 3-month windows. Each window represented a different pandemic phase, with variations in the most predominant VOC as well as vaccine rollout: January 1–March 31, 2021 (nonvariants/variants under investigation; early descending age-phased vaccination availability among people aged ≥16 years); April 1–June 30, 2021 (Alpha, B.1.1.7; population-level vaccination availability and expansion to adolescents aged 12-15 years); and July 1–September 30, 2021 (Delta, B.1.617.2; vaccine availability to people aged ≥12 years). We used the Wald \( \chi^2 \) test to determine whether the distribution of reported cases during the 3 windows differed significantly by case characteristics. Epidemiologic case curves illustrated weekly trends and completed pediatric vaccines. We also analyzed the number of cases in household clusters and the estimated dynamics of transmission.

We assessed the bivariate association between quartiles of neighborhood census tract estimates and pediatric case rates using rate ratios (RRs) and 95% CIs. The first quartile of each indicator reflected the lowest level of the indicator (lowest percentage of poverty below the federal poverty level or least percentage of households with ≥3 people) and was the reference category. We illustrated the relationship between pediatric case rates and neighborhood census tract estimates by using maps created in ArcGIS Pro version 2.9.2.

We included reinfections in the calculations for 2021, epidemiologic curves, household clusters, and neighborhood
Table 1. Characteristics of children with reported laboratory-confirmed SARS-CoV-2 infection with an earliest known date of infection from March 1, 2020, through September 30, 2021, Denver, Colorado

| Characteristic                      | Total (N = 9815) | Population estimates (N = 139 175) | Incidence rate per 1000 population | Rate ratio (95% CI) |
|-------------------------------------|------------------|------------------------------------|-----------------------------------|--------------------|
| **Age group, y**                    |                  |                                    |                                   |                    |
| <1                                  | 481 (4.9)        | 8806 (6.3)                         | 54.6                              | 1.0 (Reference)    |
| 1-4                                 | 1602 (16.3)      | 33 955 (24.4)                      | 47.2                              | 0.86 (0.78-0.96) [.005] |
| 5-10                                | 2905 (29.6)      | 46 311 (33.3)                      | 62.7                              | 1.15 (1.04-1.27) [.004] |
| 11-13                               | 1806 (18.4)      | 21 995 (15.8)                      | 82.1                              | 1.50 (1.36-1.66) [.001] |
| 14-17                               | 3021 (30.8)      | 28 108 (20.2)                      | 107.5                             | 1.97 (1.79-2.17) [.001] |
| **Sex**                             |                  |                                    |                                   |                    |
| Male                                | 4818 (50.0)      | 71 289 (51.2)                      | 67.6                              | 1.0 (Reference)    |
| Female                              | 4816 (50.0)      | 67 886 (48.8)                      | 70.9                              | 1.05 (1.01-1.09) [.02] |
| **Race and ethnicity**              |                  |                                    |                                   |                    |
| Non-Hispanic White                  | 2628 (29.0)      | 51 302 (36.9)                      | 51.2                              | 1.0 (Reference)    |
| Non-Hispanic Black                  | 646 (7.1)        | 16 678 (12.0)                      | 38.7                              | 0.76 (0.70-0.88) [.001] |
| Non-Hispanic Asian/Native Hawaiian/Other Pacific Islander | 242 (2.7) | 5964 (4.3) | 40.6 | 0.79 (0.69-0.90) [.001] |
| Non-Hispanic American Indian/Alaska Native | 39 (0.4) | 894 (0.6) | 43.6 | 0.85 (0.60-1.17) [.32] |
| Hispanic/Latino                     | 5197 (57.3)      | 64 337 (46.2)                      | 80.8                              | 1.57 (1.50-1.65) [.001] |
| Non-Hispanic multiple races or Other | 311 (3.4)       | 5964 (4.3)                        | 40.6                              | 0.79 (0.69-0.90) [.001] |
| **Symptomatic status**              |                  |                                    |                                   |                    |
| Symptomatic                         | 4487 (81.6)      | NA                                  | NA                                | NA                 |
| Asymptomatic                        | 1012 (18.4)      | NA                                  | NA                                | NA                 |
| **Hospitalization**                 |                  |                                    |                                   |                    |
| Hospitalization                     | 138 (1.4)        | NA                                  | NA                                | NA                 |
| **Death**                           |                  |                                    |                                   |                    |
| Death                               | 3 (0)            | NA                                  | NA                                | NA                 |
| **Reinfection**                     |                  |                                    |                                   |                    |
| Reinfection                         | 35 (0.4)         | NA                                  | NA                                | NA                 |
| **Postvaccination infection**       |                  |                                    |                                   |                    |
| Postvaccination infection           | 51 (0.5)         | NA                                  | NA                                | NA                 |

Abbreviation: NA, not applicable.

*Data were obtained from public health surveillance, including case investigations and/or medical record reviews, for laboratory-confirmed COVID-19 in Denver, Colorado.

*Percentages reflect the proportion of people with nonmissing values for the characteristic. Data were complete for age, hospitalization, death, reinfection, and postvaccination infection (N = 9843). Data were missing for sex (n = 181) and race and ethnicity (n = 752). Data on symptom status were available for 5499 people.

*Number of unique people; does not include cases considered to be a reinfection.

*Population estimates/incidence rate denominators from 2019 Department of Local Affairs (DOLA) estimates.

*95% CIs for rate ratio per 1000 population.

*Using the Wald χ² test, with differences significant at α = .05.

*Racial and ethnic categories are mutually exclusive. Hispanic people could be of any race. The Other/multiple-race category included people who identified as ≥2 races or who did not identify by the listed race categories or as Hispanic (eg, Burmese, Egyptian, Filipino).

*DOLA estimates not available for non-Hispanic multiple races or Other.

estimates. We conducted all statistical analyses using Stata version 12.1 (StataCorp LLC). The Colorado Multiple Institutional Review Board approved this study as exempt because it was considered public health surveillance.

**Results**

A total of 9815 unique children had an EKDI of SARS-CoV-2 from March 1, 2020, through September 30, 2021, representing 13.2% of 74 237 unique cases in Denver during that period. Adolescents aged 14-17 years had nearly twice the rate of infection (RR = 1.97; 95% CI, 1.79-2.17; P < .001) and children and adolescents aged 11-13 years had 1.5 times the rate of infection (RR = 1.50; 95% CI, 1.36-1.66; P < .001) per 1000 population compared with children aged <1 year (Table 1). Compared with population estimates, the proportion of adolescent patients aged 14-17 years (n = 3021, 30.8%) and 11-13 years (n = 1806, 18.4%) was higher than expected. Compared with non-Hispanic White children, Hispanic/Latino children had 1.6 times the rate of infection per 1000 population (RR = 1.57; 95% CI, 1.50-1.65; P < .001), while non-Hispanic Black (RR = 0.76; 95% CI,
0.70-0.88; $P < .001$) and non-Hispanic Asian/Native Hawaiian/Other Pacific Islander (RR = 0.79; 95% CI, 0.69-0.90; $P < .001$) children had a lower rate of infection.

**Clinical Presentation of Children With SARS-CoV-2 Infection**

Of 5499 (56.0%) children for whom symptom status was available, 4487 (81.6%) were symptomatic. The most reported symptoms were cough (1255 of 2802, 44.8%), fever (1274 of 2864, 44.5%), congestion (325 of 751, 43.3%), runny nose (1158 of 2735, 42.3%), headache (1079 of 2643, 40.8%), fatigue (1030 of 2644, 39.0%), loss of appetite (178 of 470, 37.9%), and sore throat (984 of 2645, 37.2%). Hospitalizations (n = 138, 1.4%), death (n = 3, 0%), reinfections (n = 35, 0.4%), and postvaccination cases (n = 51, 0.5%) were rare. Of 35 cases of reinfection, 2 (5.7%) were considered postvaccination infections and 1 was hospitalized.

**Pediatric Cases Over Time**

The number of pediatric cases generally mirrored the epidemiologic curve of cases among adults aged ≥18 years (Figure 1). Pediatric cases appeared to increase compared with adult cases during April–June 2021 and July–September 2021. From January 1 through September 30, 2021, 4653 (47.4%) pediatric cases were reported. Cases were roughly equally distributed across the 3 periods (Table 2). We found a decreasing trend in cases throughout 2021 among adolescents aged 14-17 years and an increasing trend among children aged 5-10 years. In 2020, cases among Hispanic/Latino children had an IR of 61.8 (95% CI, 60.0-63.6; $P < .001$). The proportion of cases among Hispanic/Latino children declined in 2021 compared with 2020, and we noted increasing trends of cases among non-Hispanic White children. Proportions of reported cases did not differ significantly by sex, hospitalization, or death across the 3 periods.

**Household Transmission**

We were able to geocode most pediatric cases (98.6%, 9673 of 9815). We identified 7496 unique households with ≥1 pediatric case (Table 3). Most households reported ≥1 case (4420 of 7496, 59.0%). We could not determine transmission dynamics for 3537 children who were the only household case and/or had an EKDI outside the transmission window of another household case. Within household clusters, most of the 6136 pediatric cases were a secondary case (n = 3959, 64.5%), followed by index case (n = 1170, 19.1%) or co–index case (n = 1007, 16.4%). Adolescents aged 14-17 years composed a large proportion of index (n = 379, 32.4%) and co–index (n = 278, 27.6%) cases, while children aged 5-10 years composed a large proportion of co–index (n = 319, 31.7%) and secondary (n = 1314, 33.2%) cases. Household pediatric transmission dynamics differed significantly by age group ($P < .001$). Compared with children in other racial and ethnic groups, non-Hispanic White children had an increased risk of being an index or co–index case (RR = 1.14; 95% CI, 1.06-1.23; $P < .001$), while Hispanic/Latino children had an increased risk of being a secondary case (RR = 1.07; 95% CI, 1.03-1.11; $P < .001$).
Community-Level Indicators

We found overlap between the geographic distribution of pediatric case rates, proportion of households ≤150% of the federal poverty level, and proportion of households with ≥3 people (Figure 2). These indicators had notable shifts from 2020 to 2021. In 2020, neighborhoods above the median percentage of families ≤150% of the federal poverty level (>6.4%) had a 35.1% higher pediatric case rate per 1000 population than neighborhoods in the lowest quartile (quartile 4: RR = 1.35 [95% CI, 1.21-1.50; P < .001]; quartile 3: RR = 1.27 [95% CI, 1.14-1.41; P < .001]). Similarly, in 2020, pediatric case rates in neighborhoods with the highest quartile percentage of households with ≥3 people (≥39.0%) were 35.4% higher per 1000 population than rates in neighborhoods with the lowest quartile (RR = 1.35; 95% CI, 1.22-1.50; P < .001). Cumulative 2020-2021 pediatric case rates in neighborhoods in the highest quartile of households with ≥3 people were 16.7% higher per 1000 population than rates in the lowest quartile (RR = 1.17; 95% CI, 1.08-1.26; P < .001). We found no association between poverty and cumulative 2020-2021 pediatric COVID-19 case rates.

Discussion

This retrospective analysis offers unique insight into the demographic and clinical characteristics, transmission dynamics, and selected ecological associations of 9815 children who had COVID-19 in Denver. Consistent with

Table 2. Pediatric cases with reported laboratory-confirmed SARS-CoV-2 infection with an earliest known date of infection from January 1 through September 30, 2021, by window of earliest known date of infection, Denver, Coloradoa

| Characteristic                        | Totalc (N = 4653) | January 1–March 31 (n = 1648) | April 1–June 30 (n = 1422) | July 1–September 30 (n = 1583) | P valued |
|---------------------------------------|-------------------|--------------------------------|----------------------------|--------------------------------|----------|
| Age group, y                          |                   |                                |                            |                                | <.001    |
| <1                                    | 212 (4.6)         | 79 (4.8)                       | 53 (3.7)                   | 80 (5.1)                       |          |
| 1-4                                   | 807 (17.3)        | 284 (17.2)                     | 212 (14.9)                 | 311 (19.7)                     |          |
| 5-10                                  | 1537 (33.0)       | 438 (26.6)                     | 445 (31.3)                 | 654 (41.3)                     |          |
| 11-13                                 | 841 (18.1)        | 300 (18.2)                     | 253 (17.8)                 | 288 (18.2)                     |          |
| 14-17                                 | 1256 (27.0)       | 547 (33.2)                     | 459 (32.3)                 | 250 (15.8)                     |          |
| Sex                                   |                   |                                |                            |                                | .80      |
| Male                                  | 2323 (51.3)       | 849 (51.7)                     | 726 (51.5)                 | 748 (50.1)                     |          |
| Female                                | 2208 (48.7)       | 792 (48.3)                     | 685 (48.5)                 | 731 (49.0)                     |          |
| Race and ethnicitye                   |                   |                                |                            |                                | <.001    |
| Non-Hispanic Asian/Native Hawaiian    | 115 (2.7)         | 42 (2.7)                       | 21 (1.6)                   | 52 (3.7)                       |          |
| Non-Hispanic Black                    | 417 (9.8)         | 103 (6.7)                      | 155 (11.8)                 | 159 (11.4)                     |          |
| Non-Hispanic White                    | 1585 (37.2)       | 586 (38.0)                     | 434 (33.0)                 | 565 (40.5)                     |          |
| Non-Hispanic American Indian/Alaska Native | 25 (0.6)   | 12 (0.8)                       | 8 (0.6)                    | 5 (0.4)                        |          |
| Non-Hispanic multiple races or Other  | 188 (4.4)         | 55 (3.6)                       | 65 (4.9)                   | 68 (4.9)                       |          |
| Hispanic or Latino                    | 1926 (45.3)       | 746 (48.3)                     | 634 (48.1)                 | 546 (39.1)                     |          |
| Symptomatic status                    |                   |                                |                            |                                | <.001    |
| Symptomatic                           | 2312 (82.0)       | 855 (78.4)                     | 716 (83.6)                 | 741 (84.0)                     |          |
| Asymptomatic                          | 507 (18.0)        | 235 (21.6)                     | 140 (16.4)                 | 132 (15.0)                     |          |
| Hospitalization                       | 65 (1.4)          | 20 (1.2)                       | 27 (1.9)                   | 18 (1.1)                       | .17      |
| Death                                 | 1 (0)             | 0                              | 1 (0.1)                    | 0                             | .31      |
| Reinfection                           | 28 (0.6)          | 13 (0.8)                       | 8 (0.6)                    | 7 (0.4)                        | .45      |
| Postvaccination infection             | 53 (1.1)          | 0                              | 1 (0.1)                    | 52 (3.3)                       | <.001    |

aData were obtained from public health surveillance, including case investigations and/or medical record reviews, for laboratory-confirmed COVID-19 in Denver, Colorado.
bPercentages reflect the proportion of people with nonmissing data on the characteristic. Information was complete for age, hospitalization, death, reinfection, and postvaccination infection; data were missing for sex (n = 122) and race and ethnicity (n = 397). Data on symptoms were available for 2819 cases.

cTotal represents the number of reported cases and includes cases considered to be a reinfection.
dUsing the Wald $\chi^2$ test, with differences significant at $\alpha = .05$.
eRacial and ethnic categories are mutually exclusive. Hispanic people could be of any race. The Other/multiple-race category included people who identified as ≥2 races or who did not identify by the listed race categories or as Hispanic (eg, Burmese, Egyptian, Filipino).
Table 3. Household cluster transmission dynamics among pediatric cases with reported laboratory-confirmed SARS-CoV-2 infection with an earliest known date of infection from March 1, 2020, through September 30, 2021, Denver, Colorado*

| Characteristic          | Index casec | Co–index casec | Secondary casec |
|-------------------------|-------------|----------------|-----------------|
|                         | Total, no. (%) | No. (%) | Total, no. (%) | No. (%) | Total, no. (%) | No. (%) |
| Age group, yd           |              |              |                 |
| <1                      | 1170 (19.1)  | 1007 (16.4)  | 3959 (64.5)     |
| 1-4                     | 657 (14.1)   | 43 (4.3)     | 1022 (14.3)     |
| 5-10                    | 917 (17.6)   | 1071 (17.4)  | 2088 (30.1)     |
| 11-13                   | 546 (11.4)   | 771 (12.7)   | 1317 (19.2)     |
| 14-17                   | 622 (13.3)   | 539 (8.9)    | 1175 (17.1)     |
| By race and ethnicitye  |              |              |                 |
| Non-Hispanic Asian/Native Hawaiian | 27 (2.4) | 27 (3.0) | 94 (2.6) |
| Non-Hispanic Black      | 74 (6.6)     | 67 (7.3)     | 205 (5.6)       |
| Non-Hispanic White      | 367 (32.5)   | 242 (26.4)   | 947 (25.7)      |
| Non-Hispanic American Indian/Alaska Native | 2 (0.2) | 4 (0.4) | 20 (0.5) |
| Non-Hispanic multiple races or Other | 36 (3.2) | 36 (3.9) | 117 (3.2) |
| Hispanic or Latino      | 622 (55.1)   | 539 (58.9)   | 2295 (32.4)     |

*The earliest known date of infection (EKDI) was used to describe the directionality of transmission within a household cluster. Data were obtained from public health surveillance, including case investigations and/or medical record reviews, for laboratory-confirmed COVID-19 in Denver, Colorado. The total number of unique households was available only for households with ≥1 pediatric case (N = 7496): 3076 (41.0%) households with 1 case; 2219 (29.6%) households with 2 cases; 1906 (25.4%) household with 3 or 4 cases; and 295 (3.9%) households with ≥4 cases. The total number of cases in a household included children and adults.

Percentages reflect the proportion of cases with nonmissing values for the characteristic. Geocoding was missing for 177 pediatric cases.

Index cases are the first identified cases occurring in the household; cases that are co–occurring on the same day were considered co–index cases; subsequent cases were considered secondary cases and the result of household transmission.

Pediatric case transmission dynamics were excluded for 3537 pediatric cases who were the only reported case in a household cluster (N = 6136).

Data on race and ethnicity were missing for 415 cases. Racial and ethnic categories are mutually exclusive. Hispanic people could be of any race. The Other/multiple-race category included people who identified as ≥2 races or who did not identify by the listed race categories or as Hispanic (eg, Burmese, Egyptian, Filipino).

previous research and national trends, we found that children and adolescents aged 11-17 years have higher case rates than younger children.32-34 Our study found that most children had mild symptoms consistent with respiratory tract infection and that COVID-19–related death, hospitalizations, reinfection, and postvaccination infections were rare.

Hispanic/Latino children were 1.6 times more likely to have had COVID-19 than non-Hispanic White children, similar to reports among adults in Denver.35 Hispanic adults who had COVID-19 were more likely than non-Hispanic adults to be members of larger households, to have had known exposure to people with COVID-19, to work in essential industries, and to face financial constraints that compelled them to work when ill.35-38 Variations in case rates by race and ethnicity may be the result of limited access to testing sites, vaccinations, and adequate prevention support.39

During July 1–September 30, 2021, the proportion of COVID-19 cases among Hispanic/Latino children and adolescents decreased while the proportion of cases among non-Hispanic White children and adolescents increased. Previous research indicated that racial and ethnic disparities decreased as the case incidence increased among non-Hispanic White people.40 Furthermore, in 2020, higher pediatric case rates were found in neighborhoods associated with higher proportions of households living at ≤150% of the federal poverty level and households with ≥3 people; in 2021, this association changed as higher case rates shifted to neighborhoods with smaller proportions of poverty and larger household size. This shift may be the result of increased cases among non-Hispanic children in 2021 and the protective feature of prior infection.41

Within household clusters, most pediatric cases were considered the result of household transmission (64.5%), consistent with previous studies.42 More than one-third of pediatric cases were either an index case or co–index case, whereas other studies have indicated children compose 8% to 22% of index cases.43,44 Household transmission and increased secondary attack rates are associated with indoor exposure to the SARS-CoV-2 virus, an amplified viral load among index cases and other household members, and increased household density.33,45 Hispanic/Latino children had an increased risk of being a secondary case. This finding aligns with previously discussed sociodemographic indicators associated with Hispanic/Latino households contributing to increased household transmission (larger household size and essential industry employment).35-38

Trends in the number of pediatric cases were similar to trends among adults, with some exceptions. During April 1–June 30, 2021, the number of pediatric cases increased while the number of adult cases decreased. This divergent
increase in pediatric cases may have been a by-product of higher rates of COVID-19 vaccinations among adults than among children and adolescents, along with the increased circulation of the more transmissible Alpha variant.\textsuperscript{30,46} By April 1, 2021, 23.3% of adult Denver residents were fully vaccinated.\textsuperscript{47} At that time, only people aged ≥16 years were eligible for vaccination under a US Food and Drug Administration Emergency Use Authorization, later amended on May 12, 2021, to include people aged ≥12 years, and again on November 2, 2021, to include people aged ≥5
We observed a similar divergent increase in pediatric cases during July 1–September 30, 2021. This second divergence may have been a by-product of the Delta variant becoming the dominant VOC,30 with a 10% to 20% higher transmissibility than the Alpha variant51 and the start of Denver Public Schools’ in-person learning on August 23, 2021.52 Secondary transmission of SARS-CoV-2 in schools and childcare programs depends on the background rate of community infection and the use of prevention strategies.21,22 During 2021, we found that the proportion of cases among children aged 5–10 years increased while the proportion of cases among adolescents aged 14–17 years decreased; this increased proportion was most dramatic between the second and third periods with the peak of fully vaccinated children and adolescents aged 12–17 years.

As evidenced by this shift in disease incidence from vaccine-eligible to vaccine-ineligible cohorts, the COVID-19 vaccine is one of the most robust strategies to combat transmission and disease.53,54 Although vaccine hesitancy was initially high among Hispanic/Latino people, this racial and ethnic disparity subsequently narrowed and, as of early 2022, non-Hispanic White people accounted for the largest proportion of unvaccinated people.55,56 Efforts to reduce the number of pediatric cases will require the promotion of pediatric vaccination and vaccination of the entire household, as shown by the extent of index and co–index transmission within households. Until nearly all eligible community members are vaccinated, sustained community education and prevention strategies (eg, wearing face masks indoors, social distancing, routine testing) are paramount, especially when the risk of emerging VOCs, such as Omicron, B.1.1.529, looms. Future efforts are required to address vaccine hesitancy and the inclusion of children as critical in prevention and therapeutic strategies to curtail the COVID-19 pandemic.

Limitations
This study had several limitations. First, the primary source of data was public health surveillance data, with most epidemiologic information being self-reported. Information was not available for patients who could not be contacted or were not hospitalized. Second, the case interview was conducted at the time of reporting and did not include symptoms that emerged after the interview. Third, guidance on SARS-CoV-2 testing varied throughout the study period, where initially only those who were symptomatic were eligible for testing, introducing a reporting bias. By 2021, testing accessibility had increased, including the debut of home testing, the results of which may not have been reported. Variations in testing prevented the comparison of testing practices between children and adults. Fourth, data collection errors may have resulted in incorrect addresses or last names, leading to incomplete accounting of household clusters. The method for linking cases could not account for split households (ie, children who split their time between households), which could have underestimated household transmission. Fifth, determining whether a pediatric case was an index, co–index, or secondary case was dependent on the EKDI; information on onset of symptoms was subject to recall bias. However, within a given household it is unlikely that the accuracy of recall varied greatly. Finally, interpretations of community-level associations should be restricted to a neighborhood level.

Conclusion
In Denver, COVID-19 disproportionately affected adolescents aged 14–17 years, children and adolescents who identified as Hispanic/Latino, and children and adolescents who resided in neighborhoods with ≥3 people. A targeted public health approach that emphasizes culturally appropriate and proven prevention strategies, addresses vaccine hesitancy, focuses on increasing vaccination access for all household members, and promotes community education is vital. The focus of ongoing pandemic response must also include children to ultimately ensure disease control.

Authors’ Note
Thresia Sebastian and Jesse Carlson contributed equally to this work as co–first authors.

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References

1. American Academy of Pediatrics. Children and COVID-19: state data report. November 12, 2020. Accessed November 18, 2021. https://downloads.aap.org/AAP/PDF/AAP%20and%20CHA%20-%20Children%20and%20COVID-19%20State%20Data%20Report%2011.11%20FINAL.pdf

2. Dong Y, Mo X, Hu Y, et al. Epidemiological characteristics of 2143 pediatric patients with 2019 coronavirus disease in China. J Emerg Med. 2020;58(4):712-713. doi:10.1016/j.jemermed.2020.04.006

3. Badal S, Thapa Bajgain K, Badal S, Thapa R, Bajgain BB, Santana MJ. Prevalence, clinical characteristics, and outcomes of pediatric COVID-19: a systematic review and meta-analysis. J Clin Virol. 2021;135:104715. doi:10.1016/j.jcv.2020.104715

4. Miller AD, Zambrano LD, Yousaf AR, et al. Multisystem inflammatory syndrome in children—United States, February 2020–July 2021. Published online December 5, 2021. Clin Infect Dis. doi:10.1093/cid/ciab1007

5. Delahoy MJ, Ujamaa D, Whitaker M, et al. Hospitalizations associated with COVID-19 among children and adolescents—COVID-NET, 14 states, March 1, 2020–August 14, 2021. MMWR Morb Mortal Wkly Rep. 2021;70(36):1255-1260. doi:10.15585/mmwr.mm7036e2

6. Gross CP, Essien UR, Pasha S, Gross JR, Wang SY, Nunez-Smith M. Racial and ethnic disparities in population-level COVID-19 mortality. J Gen Intern Med. 2020;35(10):3097-3099. doi:10.1007/s11606-020-06081-w

7. Wadhera RK, Wadhera P, Gaba P, et al. Variation in COVID-19 hospitalizations and deaths across New York City boroughs. JAMA. 2020;323(21):2192-2195. doi:10.1001/jama.2020.7197

8. Price-Haywood EG, Burton J, Fort D, Seoane L. Hospitalization and mortality among Black patients and White patients with COVID-19. N Engl J Med. 2020;382(26):2534-2543. doi:10.1056/NEJMc2011686

9. Goyal MK, Simpson JN, Boyle MD, et al. Racial and/or ethnic and socioeconomic disparities of SARS-CoV-2 infection and mortality. Pediatrics. 2020;146(4):e202000951. doi:10.1542/peds.2020-00951

10. Centers for Disease Control and Prevention. COVID-19: health equity considerations and racial and ethnic minority groups. Updated January 25, 2022. Accessed April 19, 2021. https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/transmission_k_12_schools.html

11. Adhikari S, Pantaleo AR, Ogedegbe O, Thorpe L, Troxel AB. Assessment of community-level disparities in coronavirus disease 2019 (COVID-19) infections and deaths in large US metropolitan areas. JAMA Netw Open. 2020;3(7):e2016938. doi:10.1001/jamanetworkopen.2020.16938

12. Baidal JW, Wang AY, Zunwalt K, et al. Social determinants of health and COVID-19 among patients in New York City. Res Sq. Preprint published on September 15, 2020. doi:10.21203/rs.3.rs-70959/v1

13. Marko AR, Nash D, Pavilonis BT. COVID-19 and inequity: a comparative spatial analysis of New York City and Chicago hot spots. J Urban Health. 2020;97(4):461-470. doi:10.1007/s11524-020-00468-0

14. Sung B. A spatial analysis of the effect of neighborhood contexts on cumulative number of confirmed cases of COVID-19 in U.S. counties through October 20, 2020. Prev Med. 2021;147:106457. doi:10.1016/j.ypmed.2021.106457

15. Posfay-Barbe KM, Wagner N, Gauthney M, et al. COVID-19 in children and the dynamics of infection in families. Pediatrics. 2020;146(2):e20201576. doi:10.1542/peds.2020-1576

16. Park YJ, Choe YJ, Park O, et al. Contact tracing during coronavirus disease outbreak, South Korea, 2020. Emerg Infect Dis. 2020;26(10):2465-2468. doi:10.3201/eid2610.201315

17. Madewell ZJ, Yang Y, Longini IM Jr, Halloran ME, Dean NE. Household transmission of SARS-CoV-2: a systematic review and meta-analysis. JAMA Netw Open. 2020;3(12):e2031756. doi:10.1001/jamanetworkopen.2020.31756

18. Dawood FS, Porucznik CA, Vezugella V, et al. Incidence rates, household infection risk, and clinical characteristics of SARS-CoV-2 infection among children and adults in Utah and New York City, New York. JAMA Pediatr. 2022;176(1):59-67. doi:10.1001/jamapediatrics.2021.4217

19. Zimmermann P, Curtis N. Coronavirus infections in children including COVID-19: an overview of the epidemiology, clinical features, diagnosis, treatment and prevention options in children. Pediatr Infect Dis J. 2020;39(5):355-368. doi:10.1097/INF.0000000000002660

20. Honein MA, Christie A, Rose DA, et al. Summary of guidance and precautions for adults with COVID-19: interim guidance and precautions for adults with COVID-19. MMWR Morb Mortal Wkly Rep. 2020;69(49):1860-1867. doi:10.15585/mmwr.mm6949e211

21. Centers for Disease Control and Prevention. Science brief: transmission of SARS-CoV-2 in K-12 schools and early care and education programs—updated. Updated December 17, 2021. Accessed April 12, 2022. https://www.cdc.gov/coronavirus/2019-ncov/science/briefs/transmission_k_12_schools.html

22. Lam-Hine T, McCurdy SA, Santora L, et al. Outbreak associated with SARS-CoV-2 B.1.617.2 (Delta) variant in an elementary school—Marin County, California, May–June 2021. MMWR Morb Mortal Wkly Rep. 2021;70(35):1214-1219. doi:10.15585/mmwr.mm7035e2

23. Colorado Department of Public Health and Environment. Electronic Disease Reporting System (CEDRS). Report a disease. Accessed June 1, 2021. https://cdphe.colorado.gov/report-a-disease

24. Guan WJ, Ni ZY, Hu Y, et al. Clinical characteristics of coronavirus disease 2019 in China. N Engl J Med. 2020;382:1708-1720. doi:10.1056/NEJMoa2002032

25. Centers for Disease Control and Prevention. Ending isolation and precautions for adults with COVID-19: interim guidance. Accessed June 28, 2021. https://www.cdc.gov/coronavirus/2019-ncov/hcp/duration-isolation.html/assessment

26. US Census. American Community Survey data, 2019. Accessed May 31, 2021. https://www.census.gov/programs-surveys/acs/data.html

27. Colorado Department of Local Affairs. State demography office data. Accessed April 25, 2022. https://gis.dola.colorado.gov/data/#state-demography-office-data

28. Centers for Disease Control and Prevention. Investigative criteria for suspected cases of SARS-CoV-2 reinfection (ICR). Accessed December 6, 2021. https://www.cdc.gov/coronavirus/2019-ncov/php/invest-criteria.html

29. Centers for Disease Control and Prevention. Stay up to date with your COVID-19 vaccines. Accessed April 21, 2022. https://www.cdc.gov/coronavirus/2019-ncov/vaccines/full-vaccinated.html
30. Centers for Disease Control and Prevention. COVID data tracker: COVID-19 vaccines available statewide for all Coloradans age 5 and up vaccination clinics from Nov. 20 to Nov. 26 [press release]. Colorado Department of Public Health and Environment; November 19, 2021. Accessed December 13, 2021. https://covid19.colorado.gov/press-release/covid-19-vaccines-available-statewide-for-all-coloradans-age-5-and-up-vaccination-0

31. Colorado Department of Public Health and Environment. COVID-19 vaccines available statewide for all Coloradans. November 19, 2021. https://covid19.colorado.gov/data

32. Bailey LC, Razzaghi H, Burrows EK, et al. Assessment of 135 794 pediatric patients tested for severe acute respiratory syndrome coronavirus 2 across the United States. JAMA Pediatr. 2021;175(2):176-184. doi:10.1001/jamapediatrics.2020.5052

33. Leeb RT, Price S, Sliwa S, et al. COVID-19 trends among school-aged children—United States, March 1–September 19, 2020. MMWR Morb Mortal Wkly Rep. 2020;69(39):1410-1415. doi:10.15585/mmwr.mm6939e2

34. Centers for Disease Control and Prevention. COVID data tracker: COVID-19 weekly cases and deaths per 100,000 population by age, race/ethnicity, and sex. Accessed December 15, 2021. https://covid.cdc.gov/covid-data-tracker/#demographicsoveretime

35. Podewils LJ, Burket TL, Mettenbrink C, et al. Disproportionate incidence of COVID-19 infection, hospitalizations, and deaths among persons identifying as Hispanic or Latino—Denver, Colorado March–October 2020. MMWR Morb Mortal Wkly Rep. 2020;69(48):1812-1816. doi:10.15585/mmwr.mm6948a3

36. Cervantes L, Martin M, Frank MG, et al. Experiences of Latinx individuals hospitalized for COVID-19: a qualitative study. JAMA Netw Open. 2021;4(3):e210684. doi:10.1001/jamanetworkopen.2021.0684

37. Cohn D, Passel JS. A record 64 million Americans live in multigenerational households. PEW Research Center. April 5, 2018. Accessed December 14, 2021. https://www.pewresearch.org/fact-tank/2018/04/05/a-record-64-million-americans-live-in-multigenerational-households

38. Landale NS, Orpovesa RS, Bradatan C. Hispanic families in the United States: family structure and process in an era of family change. In: Tienda M, Mitchell F, eds. Hispanics and the Future of America. National Academies Press; 2006:138-178.

39. Flores G, Tomany-Korman SC. Racial and ethnic disparities in COVID-19 incidence by age, sex, and period among persons aged <25 years—16 U.S. jurisdictions, January 1–December 31, 2020. MMWR Morb Mortal Wkly Rep. 2021;70(11):382-388. doi:10.15585/mmwr.mm7011e1

40. Van Dyke ME, Mendoza MCB, Li W, et al. Racial and ethnic disparities in COVID-19 incidence by age, sex, and period among persons aged <25 years—16 U.S. jurisdictions, January 1–December 31, 2020. MMWR Morb Mortal Wkly Rep. 2021;70(11):382-388. doi:10.15585/mmwr.mm7011e1

41. Kojima N, Klausner JD. Protective immunity after recovery from COVID-19 infection. Lancet Infect Dis. 2020;20(5):613-616. doi:10.1016/S1473-3099(20)30985-3

42. Spielberger BD, Goerne T, Geveniger A, Henneke P, Elling R. Intra-household and close-contact SARS-CoV-2 transmission among children—a systematic review. Front Pediatr. 2021;9:613292. Published online April 9, 2021. doi:10.3389/fped.2021.613292

43. Cerami C, Rapp T, Lin FC, et al. High household transmission of SARS-CoV-2 in the United States: living density, viral load, and disproportionate impact on communities of color. Preprint. Posted March 12, 2021. medRxiv. doi:10.1101/2021.03.10.21253173

44. Teherani MF, Kao CM, Camacho-Gonzalez A, et al. Burden of illness in households with severe acute respiratory syndrome coronavirus 2–infected children. J Pediatric Infect Dis Soc. 2020;9(5):613-616. doi:10.1093/jpids/piaa097

45. Marks M, Millat-Martinez P, Ouchi D, et al. Transmission of COVID-19 in 282 clusters in Catalonia, Spain: a cohort study. Lancet Infect Dis. 2021;21(5):629-636. doi:10.1016/S1473-3099(20)30985-3

46. Somekh I, Stein M, Karakis I, Simões EAF, Somekh E. Characteristics of SARS-CoV-2 infections in Israeli children during the circulation of different SARS-CoV-2 variants. JAMA Netw Open. 2021;4(9):e2124343. doi:10.1001/jamanetworkopen.2021.24343

47. Public Health Institute at Denver Health. COVID-19 vaccine summary. Accessed December 6 2021. https://storymaps.arcgis.com/stories/50dbb5c7dbf6495292b571bd7df56d0a

48. Oliver SE, Gargano JW, Marin 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(50):1922-1924. doi:10.15585/mmwr.mm6950e2

49. Wallace M, Woodworth KR, Gargano JW, 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(20):749-752. doi:10.15585/mmwr.mm7020e1

50. Woodworth KR, Moula D, Collins JP, 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(45):1579-1583. doi:10.15585/mmwr.mm7045e1

51. Yang W, Shaman J. COVID-19 pandemic dynamics in India, the SARS-CoV-2 Delta variant, and implications for vaccination. Preprint. Posted November 22, 2021. medRxiv. doi:10.1101/2021.06.21.21259268

52. Denver Public Schools. 2021-2022 School year calendar. Accessed December 6, 2021. https://www.dpsk12.org/wp-content/uploads/2021-22_DPS_Calendar_v_05-06-21.pdf

53. Harder T, Koch J, Vygen-Bonnet S, et al. Efficacy and effectiveness of COVID-19 vaccines against SARS-CoV-2 infection: interim results of a living systematic review, 1 January to 14 May 2021. Euro Surveill. 2021;26(28):2100563. doi:10.2807/1560-7917.ES.2021.26.28.2100563

54. Lopez Bernal J, Andrews N, Gower C, et al. Effectiveness of COVID-19 vaccines against the B.1.617.2 (Delta) variant. N Engl J Med. 2021;385(7):585-594. doi:10.1056/NEJMoa2108891

55. Tai DBG, Sia IG, Doubeni CA, Wieland ML. Disproportionate impact of COVID-19 on racial and ethnic minority groups in the United States: a 2021 update. Published online October 13, 2021. J Racial Ethn Health Disparities. doi:10.1007/s40615-021-01170-w

56. Kaiser Family Foundation. Latest data on COVID-19 vaccinations by race/ethnicity. December 2, 2021. Accessed December 13, 2021. https://www.kff.org/coronavirus-covid-19/issue-brief/latest-data-on-covid-19-vaccinations-by-race-ethnicity