MEDICINE AND SOCIETY

Contagious Diseases in the United States from 1888 to the Present

Willem G. van Panhuis, M.D., Ph.D., John Grefenstette, Ph.D., Su Yon Jung, Ph.D., Nian Shong Chok, M.Sc., Anne Cross, M.L.I.S., Heather Eng, B.A., Bruce Y. Lee, M.D., Vladimir Zadorozhny, Ph.D., Shawn Brown, Ph.D., Derek Cummings, Ph.D., M.P.H., and Donald S. Burke, M.D.

Public health programs — especially vaccination programs — have led to dramatic declines in the incidence of contagious diseases in the United States over the past century.[1-3] However, some contagious diseases are now on the rise despite the availability of vaccines. Pertussis vaccines have been available since the 1920s, but the worst pertussis epidemic since 1959 occurred in 2012, with more than 38,000 cases nationwide reported by last December.[4,5] Outbreaks of measles also continue to occur, even though a measles vaccine has been licensed in the United States since 1963.[6]

The current low overall incidence of contagious diseases has resulted in a perception that the risk of these diseases is low and, paradoxically, in increased concern about the costs and consequences of vaccination programs (e.g., adverse events, expenses, and inconvenience).[7-9] Low perceived risk of disease at the individual level can lead to lower participation in control programs, with negative consequences for the entire community — a well-known game-theory principle that applies to vaccination programs as well.[10,11] Parents who question the risk–benefit balance of vaccination may refuse or delay immunization of their children, which leads to local variations in vaccine coverage and increased risk of disease outbreaks owing to localized disruptions of herd immunity.[12] Both pertussis and measles outbreaks have been attributed at least in part to intentional undervaccination.[7,8,13] Organized antivaccination movements amplify these problems.[14,15] The medical community needs to seriously address parental concerns about the value of immunization at the individual and community levels by introducing scientific evidence in the context of trusting clinician–parent relationships.[8,9,16]

The interpretation of long-term disease patterns at the local level has heretofore been hampered by a lack of access to high-resolution historical data in computable form. In cases in which detailed long-term data have been available (e.g., with regard to measles and pertussis in the United Kingdom or dengue in Thailand), pattern analysis has yielded new insights into disease-transmission dynamics.[17-20] In the United States, cases of contagious diseases have been reported at weekly intervals to health authorities for more than a century, but these data have not been publicly available in a computable format, so their use and value have been limited.

DATA AND ANALYSIS

In an effort to overcome these limitations, we digitized all weekly surveillance reports of nationally notifiable diseases for U.S. cities and states published between 1888 and 2011. This data set, which we have made publicly available (www.tycho.pitt.edu), consists of 87,950,807 reported individual cases, each localized in space and time. We used these data to derive a quantitative history of disease reduction in the United States over the past century, focusing particularly on the effect of vaccination programs.

We obtained all tables containing weekly surveillance data on nationally notifiable diseases that were published between 1888 and 2011 in the *Morbidity and Mortality Weekly Report* and its precursor journals from various online and hard-copy sources.[21-24] We digitized all data available in tabular format that listed etiologically defined cases or deaths according to week for locations in the United States. Reported counts (weekly tallies) of cases or deaths and the reporting locations, periods, and diseases

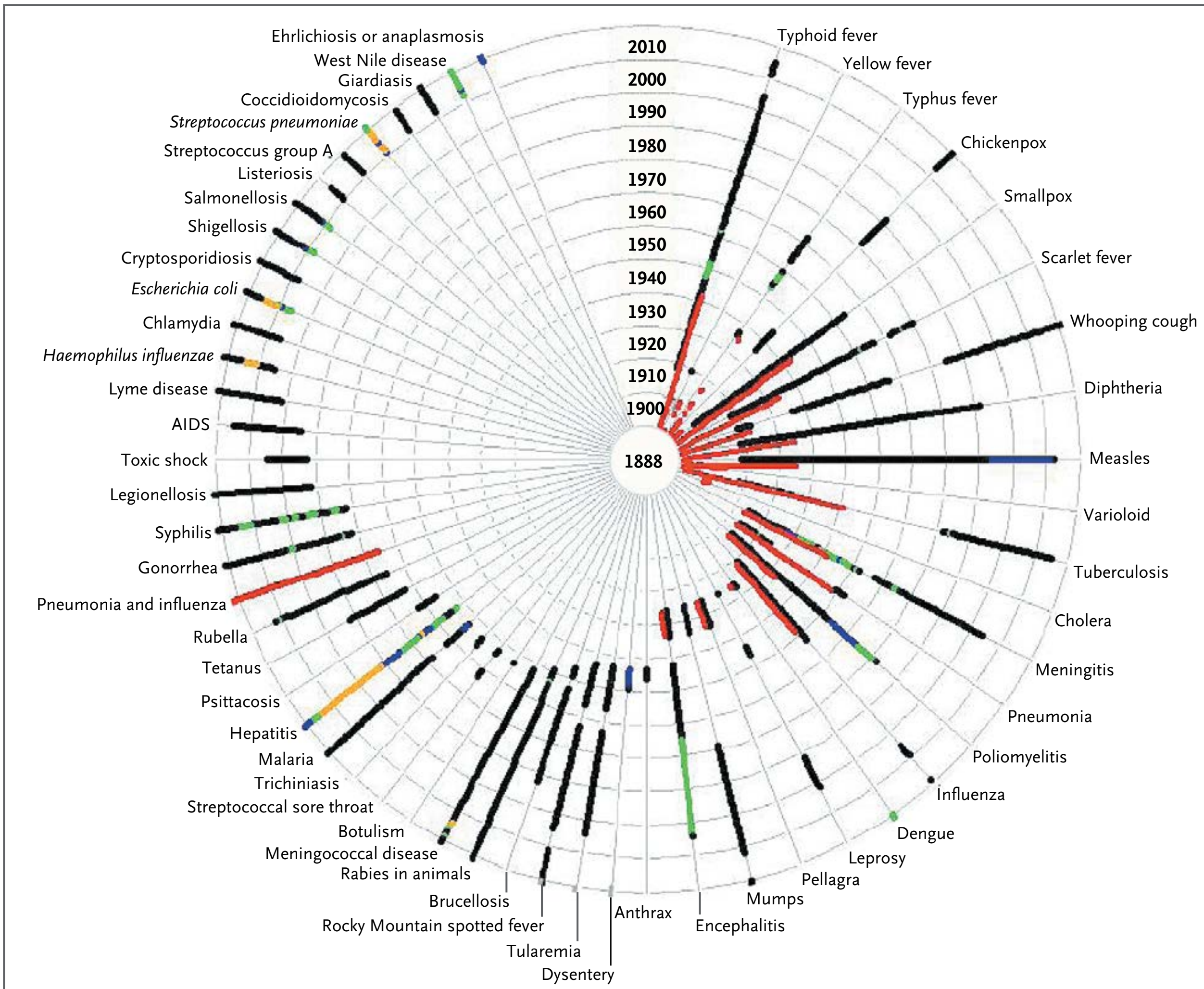


Figure 1. Availability of Weekly Counts of Reported Diseases from Any U.S. Location, 1888–2011.

Each concentric circle represents a decade, starting with 1888 in the center. No single disease was reported weekly throughout the entire period, and for many diseases, the type of reports changed over time, as represented by different colors: red represents reports of death, and other colors represent reports of cases in different numbers of disease categories (e.g., hepatitis A and B) as follows: black, 1 category; green, 2; blue, 3; and orange, more than 3.

were extracted from these data and standardized. Then we selected eight vaccine-preventable contagious diseases for more detailed analysis and computed weekly incidence rates, deriving a quantitative history of each disease.

We estimated the number of cases that have been prevented since the introduction of vaccines for seven of the eight diseases. (Since there were no data from the era before the introduction of the smallpox vaccine in 1800, we could not quantify the number of smallpox cases that were prevented by the vaccine.) We estimated the numbers of cases of polio, measles, rubella, mumps, hepatitis A, diphtheria, and pertussis that were prevented by vaccines by subtracting the reported number of weekly cases after the introduction of vaccines from a simulated counterfactual number of cases that would have occurred in the absence of vaccination, assuming that there were no other changes that would have affected incidence rates. We used the year of vaccine licensure as the cutoff year to separate the prevaccine period from the vaccination period. Counterfactual numbers were estimated by multiplying the median weekly incidence rate from prevaccine years with population estimates for vaccination years. (A full description of data sources and methods, along with additional figures and tables, is provided in the Supplementary Appendix, available with the full text of this article at NEJM.org.)

A total of 56 notifiable diseases were reported at weekly intervals at some time between 1888 and the present in U.S. cities, counties, and states. No single disease was reported continuously throughout this interval. Changes in the conditions that were reportable reflected shifting public health challenges and priorities (Fig. 1).

DECLINE OF CONTAGIOUS DISEASES

We examined historical temporal transmission patterns at the state or city level for eight vaccine-preventable diseases. For each disease, temporal patterns started with high incidence rates and disease epidemics that often had seasonal recurrence, followed by a period of persisting reduced transmission (Fig. 2; and the interactive graphic, available at NEJM.org). The smallpox vaccine was introduced in the United States around 1800 by Benjamin Waterhouse, who received the vaccine from British physician John Haygarth, who received it from Edward Jenner, an English country doctor. Severe smallpox caused by the variola major virus was already eliminated from the United States by 1927, but annual epidemics of the less severe variola minor virus continued until the disease was eradicated in the late 1940s.

An interactive graphic showing disease elimination is available at NEJM.org

The inactivated Salk polio vaccine was licensed in 1955, and incidence rates for polio decreased substantially in the succeeding years. An additional reduction followed the licensure of the Sabin live attenuated oral polio vaccine in 1961, until eradication was achieved in 1979.

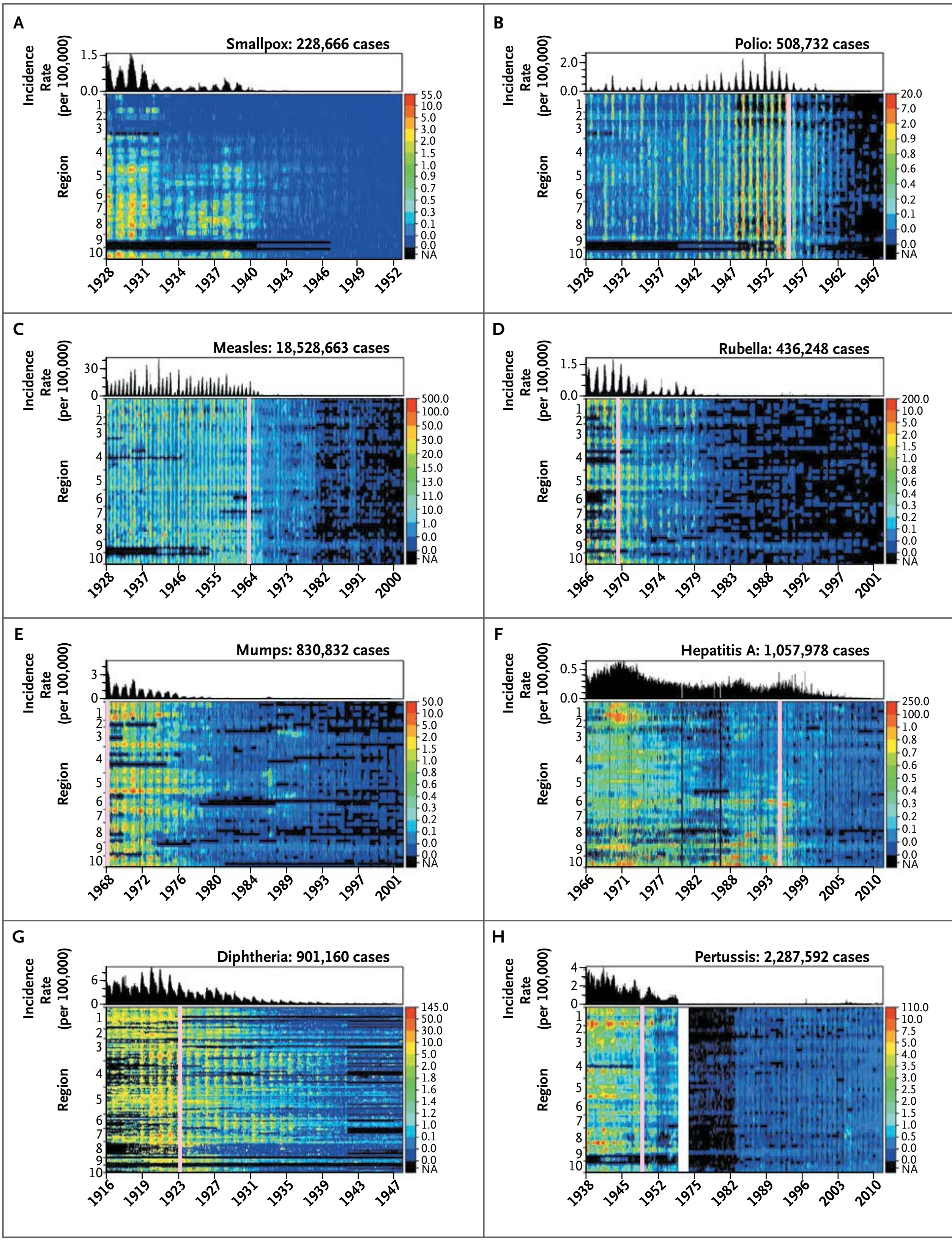
Measles, rubella, and mumps occurred in well-characterized epidemics that occurred yearly or every other year, with a median incidence rates before the introduction of a vaccine of 317.1, 28.1, and 89.5 cases per 100,000 population, respectively. The Edmonston measles vaccine was licensed in 1963, and incidence rates for measles declined rapidly afterward, whereas rubella and mumps persisted until the late 1970s, despite vaccine licensure in 1969 and 1967, respectively. Vaccination programs that started in the late 1970s (the Measles Elimination Program and the Childhood Immunization Initiative) and the introduction of the combined measles–mumps–rubella (MMR) vaccine in 1978 led to major reductions in transmission of these diseases.

Figure 2 (facing page). Snapshots of Disease Elimination in the United States.

Weekly incidence rates per 100,000 population are shown for the entire country in the black graph at the top of each panel, along with the total numbers of cases of the disease. In the colored graphs, weekly incidence rates per 100,000 population are shown for states (for all diseases except diphtheria) or cities (for diphtheria), grouped according to the epidemiologic region in the following order: region 1, Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont; region 2, New Jersey and New York; region 3, Delaware, District of Columbia, Maryland, Pennsylvania, Virginia, and West Virginia; region 4, Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee; region 5, Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin; region 6, Arkansas, Louisiana, New Mexico, Oklahoma, and Texas; region 7, Iowa, Kansas, Missouri, and Nebraska; region 8, Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming; region 9, Arizona, California, Hawaii, and Nevada; and region 10, Alaska, Idaho, Oregon, and Washington. The year of vaccine licensure is indicated by a vertical pink line. The smallpox vaccine was introduced in the United States around 1800, so its licensure is not indicated. Weekly reports for pertussis were unavailable from 1955 to 1974 (white space), and an approximate year of vaccine licensure was used. NA denotes data not available (i.e., not included in weekly reports).

Incidence rates of hepatitis A infection declined across large parts of the United States in the late 1970s, presumably because of improved water and sanitation, but high transmission rates (a median yearly incidence rate of 24.5 cases per 100,000 population; 10th to 90th percentiles of annual prevaccine incidence rates, 12.3 to 40.2) continued in some regions (e.g., the South, the Northwest, and the Pacific Coast). Hepatitis A vaccine was licensed in 1995, and its routine use in 11 states with elevated transmission levels was recommended 4 years later. In 2006, this vaccine was recommended for all states, leading to a wide-scale reduction in hepatitis A throughout the United States.

Diphtheria immunization started with the use of toxin–antitoxin around 1914, but annual epidemics continued until the introduction of heat-inactivated diphtheria toxoid, which was discovered by Gaston Ramon in 1923. Until 1928, data on diphtheria were available only at the city level. Large variation was found in rates of diph-


A
Smallpox: 228,666 cases
Incidence Rate (per 100,000)
1.5
0.0
Region
1 2 3 4 5 6 7 8 9 10
55.0 10.0 5.0 3.0 2.0 1.5 1.0 0.9 0.7 0.5 0.3 0.1 0.0 0.0 NA
1928 1931 1934 1937 1940 1943 1946 1949 1952
B
Polio: 508,732 cases
Incidence Rate (per 100,000)
2.0
0.0
Region
1 2 3 4 5 6 7 8 9 10
20.0 7.0 2.0 0.9 0.8 0.6 0.4 0.2 0.1 0.0 0.0 NA
1928 1932 1937 1942 1947 1952 1957 1962 1967
C
Measles: 18,528,663 cases
Incidence Rate (per 100,000)
30
0
Region
1 2 3 4 5 6 7 8 9 10
500.0 100.0 50.0 30.0 20.0 15.0 13.0 11.0 10.0 1.0 0.0 0.0 NA
1928 1937 1946 1955 1964 1973 1982 1991 2000
D
Rubella: 436,248 cases
Incidence Rate (per 100,000)
1.5
0.0
Region
1 2 3 4 5 6 7 8 9 10
200.0 10.0 5.0 2.0 1.5 1.0 0.8 0.6 0.4 0.3 0.2 0.1 0.0 0.0 NA
1966 1970 1974 1979 1983 1988 1992 1997 2001
E
Mumps: 830,832 cases
Incidence Rate (per 100,000)
3
0
Region
1 2 3 4 5 6 7 8 9 10
50.0 10.0 5.0 2.0 1.5 1.0 0.8 0.6 0.4 0.3 0.2 0.1 0.0 0.0 NA
1968 1972 1976 1980 1984 1989 1993 1997 2001
F
Hepatitis A: 1,057,978 cases
Incidence Rate (per 100,000)
0.5
0.0
Region
1 2 3 4 5 6 7 8 9 10
250.0 100.0 1.0 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0 0.0 NA
1966 1971 1977 1982 1988 1993 1999 2005 2010
G
Diphtheria: 901,160 cases
Incidence Rate (per 100,000)
6
0
Region
1 2 3 4 5 6 7 8 9 10
145.0 50.0 30.0 10.0 5.0 2.0 1.8 1.6 1.4 1.2 1.0 0.1 0.0 0.0 NA
1916 1919 1923 1927 1931 1935 1939 1943 1947
H
Pertussis: 2,287,592 cases
Incidence Rate (per 100,000)
4
2
0
Region
1 2 3 4 5 6 7 8 9 10
110.0 10.0 7.5 5.0 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 0.0 NA
1938 1945 1952 1975 1982 1989 1996 2003 2010

theria reduction among cities after the toxoid became available, probably owing to varying policies on vaccine introduction. The whole-cell pertussis vaccine was already licensed in the United States around 1914 but not widely recommended until it was combined with diphtheria toxoid and tetanus toxoid in the diphtheria–tetanus–pertussis (DTP) vaccine in 1948. Until then, major pertussis epidemics occurred annually throughout the country.

Assuming that the difference between incidence rates before and after vaccine licensure for these diseases was attributable solely to vaccination programs, we estimated that a total of 103.1 million cases of these contagious diseases have been prevented since 1924 on the basis of median weekly prevaccine incidence rates. Estimates based on the 10th and 90th percentile of weekly prevaccine incidence rates were 72.3 million and 147.8 million cases, respectively. Of those hypothetical cases, approximately 26 million were prevented in the past decade. Sensitivity analyses that used different methods for imputing missing data and for simulating counterfactual cases resulted in estimates ranging from about 75 million to 106 million prevented cases. The number of cases that were prevented per disease depended on the incidence rate before vaccination and the duration of the vaccination program.

Diphtheria emerged at the top of the list of cases that were prevented by vaccination (about 40 million), since the disease had the second-highest prevaccination incidence rate (237 cases per 100,000 population per year) and the longest-standing vaccination program (since 1924). An estimated 35 million measles cases have been prevented, even though vaccination started relatively recently (1963). The measles incidence rate before the vaccine was introduced (318 cases per 100,000 population per year) was the highest among the diseases we studied, and the proportion of cases that were prevented increased rapidly in the years after vaccine licensure, which suggests that the vaccine rollout program was fast and widespread.

The proportion of cases of each disease that were prevented increased in the years after vaccine licensure, but the rates of decrease varied. The disease with the most rapid increase in the number of prevented cases was measles, with 22.2% more cases prevented each year, on average, during the first 5 years after vaccine licensure (10th to 90th percentiles of additional cases prevented per year, 12.8 to 29.7%). Rubella and polio were next, with annual increases in the number of prevented cases of 16.2% and 15.3%, respectively. By year 5 after vaccine licensure, 95% of measles cases had been prevented, a milestone reached for polio in year 8 — as compared with 19 years for diphtheria and 17 for pertussis, presumably owing to much slower vaccine rollouts in a different era.

RECENT RESURGENCES

Despite successful vaccination programs, multiple resurgences of measles, rubella, mumps, and pertussis have occurred since the 1980s. Measles outbreaks were continuously reported throughout the country during the 1980s, and a major resurgence in 1989–1990 affected the entire country. Since the early 1980s, the rubella incidence rate has been elevated in California, and a large outbreak occurred in 1990–1991. A major resurgence of mumps occurred in 1986–1987 in multiple states, and the incidence rate has continued to be elevated in some of those states ever since. Pertussis is the only vaccine-preventable disease that has been consistently on the rise in the United States, with yearly incidence rates increasing since 1976. In 2003–2005 and again in 2010, there were resurgences of pertussis throughout the country, with the highest incidence rates in the Midwest to Northwest and in the Northeast. Last year (2012), the largest pertussis outbreak since 1959 was reported in the United States, with more than 38,000 cases nationwide.

IMPLICATIONS FOR IMMUNIZATION PROGRAMS

Our digitization project, called Project Tycho (named after Tycho Brahe, the Danish astronomer whose comprehensive data set was used by Johannes Kepler to derive the laws of planetary motion[25]), led to descriptions of population-scale disease patterns that provide strong evidence of the value of vaccination programs. We estimate that 103 million cases of childhood diseases (95% of those that would otherwise have occurred) have been prevented since 1924; in the past decade alone, 26 million cases (99% of those that would otherwise have occurred) were prevented. These results are consistent with previous estimates of 92 to 100% of cases prevented in 2006 and 86 to 100% of cases prevented in 2010.[1,3]

For some diseases, including measles, hepatitis A, diphtheria, and pertussis, incidence rates had variable baseline patterns before the vaccine-introduction years, possibly owing to factors not related to the use of vaccines (e.g., sanitation, hygiene, or demographic factors) or to the use of early vaccine formulations (diphtheria toxin–antitoxin or early whole-cell pertussis vaccines). In the absence of clear-cut trends, and given known seasonal and multiyear dynamics and complex interactions, we cannot disentangle the causes of variable baselines in incidence without detailed historical data that are currently not available.

In contrast, the striking and persistent reductions in disease incidence rates after vaccine licensure strongly support the conclusion that vaccination programs were a leading cause. As in previous studies,[1,26] we made the simplifying assumption of attributing the entire difference between incidence rates during the prevaccination period and those during the vaccination period to immunization programs. The range of 75 million to 106 million cases prevented by vaccines is probably an underestimate, since we could not include all vaccine-preventable diseases. We also could not adjust for underreporting of cases, but that would have increased the number of cases prevented, given that the underreporting rate was probably higher in the prevaccine period than it was after a vaccine was in use. Detailed historical demographic data, such as birth rates and age-specific disease incidence rates, would enable such adjustment but are currently available only for a small number of locations and for limited periods.

Multiple resurgences of four contagious diseases (measles, rubella, mumps, and pertussis) have occurred despite ongoing vaccination programs. Local gaps in vaccine coverage can disrupt local herd immunity, resulting in outbreaks when people come into contact with pathogens because of imported cases or relocation (e.g., college enrollment).[6,27] Reported rates of vaccine refusal or delay are increasing.[7-9,12,13] The 1989–1990 measles resurgence occurred mostly among preschool children in ethnic minority groups in which the vaccination rate was only 19%. Other outbreaks have been linked to similarly low immunization rates.[28-30] Failure to vaccinate is believed to have contributed to the reemergence of pertussis, including the large 2012 epidemic. Between 1980 and 1989, 64% of almost 10,000 U.S. children with pertussis had not been appropriately vaccinated, and 37% of them had never received even one dose of the DTP vaccine.[31]

Our analysis shows how high-resolution spatiotemporal data can be effectively used to illustrate these trends at the national and local levels and to inform public opinion about the necessity of vaccination programs. Detailed spatiotemporal public health data have too often remained inaccessible and therefore underutilized. Lack of access to historical epidemiologic data constrains scientific understanding of the dynamics of disease transmission, hampers disease-control programs, and limits public health education programs. We believe that open access to large disease surveillance data sets in computable form should become a worldwide norm.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

From the Departments of Epidemiology (W.G.P., S.Y.J., N.S.C., H.E., D.S.B.) and Biostatistics (J.G., A.C., S.B.), Graduate School of Public Health, the Department of Medicine, School of Medicine (B.Y.L.), and the Graduate Information Science and Technology Program, School of Information Sciences (V.Z.), University of Pittsburgh, Pittsburgh; and the Department of Epidemiology, Bloomberg School of Public Health, Johns Hopkins University, Baltimore (D.C.).

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