

Global, regional, and national vaccination coverage and immunization system indicators in 195 countries from 1980-2016

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Abstract

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Vaccinations have made enormous contributions to global public health over the past several decades. Increases in vaccination coverage have played a large role in the declines seen in child mortality over the Millennium Development Goal (MDG) period. However, vaccine-preventable diseases are still responsible for nearly quarter of annual child deaths. In conjunction with the transition to the Sustainable Development Goal (SDG) period, the Global Vaccine Action Plan (GVAP) outlined an integrative framework to continue progress towards achieving universal vaccination coverage. Robust estimates of routine and new vaccination coverage are essential for assessing global, regional, and country level progress towards reaching the SDG and GVAP targets. To date, estimates produced jointly by the WHO and UNICEF serve as the main source of coverage estimates for both public and private organizations in the global health community. However, limitations in their methodology limit the accuracy and interpretation of these estimates. In this study, we seek to fill in these gaps by using robust modeling techniques to estimate vaccination coverage for all new and routine vaccinations recommended by the WHO for 195 countries from 1980 to 2016. We additionally estimate comprehensive and comparable estimates of an overall vaccine indicator (estimated as a geometric mean across all vaccinations), drop-out, timeliness, and administrative bias at the global, regional, and country level.

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Introduction

Vaccination has made enormous contributions to global public health over the past several decades, leading to the eradication of smallpox, the near eradication of polio, and significant progress in lowering the incidence of diphtheria, tetanus, whooping cough, and measles¹. As one of the most successful and cost-effective health interventions known, it is estimated that between two and three million child deaths are averted each year through vaccination against diphtheria, tetanus, pertussis, and measles. Recent introduction and future development of new vaccines has the potential to further impact the health of our populations. However, vaccine-preventable diseases are still responsible for nearly a quarter of 10 million annual child deaths^{2,3}.

To align the multitude of global efforts around renewed vaccination targets set forth by the Sustainable Development Goals (SDGs), the Global Vaccine Action Plan (GVAP) functions as a collaboration between public and private global health actors including the Bill & Melinda Gates Foundation, Gavi, the WHO, UNICEF, governments, and various NGOs⁴. Launched in 2012, the plan laid out a number of objectives, among them the aim of improving the quality of immunization coverage and other system indicators. Access to timely, high-quality information is critical for ensuring efficient, equitable, and sustainable delivery of vaccinations. Although the quality and timeliness of data reporting have improved steadily over the years, they still remain inadequate in many countries^{1,4}.

There exist two main sources of data to assess vaccination coverage: administratively derived estimates and sample surveys. Administrative estimates, typically estimated using data from service registries, are frequently inconsistent and subject to reporting biases⁵⁻⁷. Recent introduction of the web-based DHIS2 health information system in many low and middle income countries has helped to improve the quality of these estimates. Sample surveys such as the demographic and health surveys (DHS) or country specific surveys serve as a gold standard of coverage estimates but are costly and not routinely administered. Using both administrative and survey data, the WHO and UNICEF jointly publish annual estimates of national and global vaccination coverage⁸. To date, these data serve as the main source of coverage estimates for both public and private organizations in the global health community including Gavi. While the WHO and UNICEF aim to reconcile differences between administrative and survey data, their estimates are not produced in a reproducible manner and are not reported with estimates of uncertainty. Reliance on these data impede the global effort to accurately track vaccination coverage, progress, and the impact of vaccination policies and programs.

Coverage estimates, alone, do not fully capture enough information to comprehensively assess the strength of the immunization system. Estimates of complete vaccination (coverage of all vaccinations in the national schedule), drop-out rate, timeliness of coverage, and empirical estimates of data quality (difference between administrative and survey estimates) provide crucial information about different aspects of the efficiency and strength of an immunization system⁹. Each can help identify actionable gaps in vaccine delivery in ways that coverage estimates, in isolation, cannot. However, global and national estimates of such indicators are not routinely produced, contributing to a lack of comparable estimates to assess immunization system performance over time.

In this study, we seek to fill in these gaps by using robust modeling techniques to estimate vaccination coverage for all new and routine vaccinations recommended by the WHO for 195 countries from 1980 to 2016. We additionally estimate comprehensive and comparable estimates of an overall vaccine indicator (estimated as a geometric mean across all vaccinations), drop-out, timeliness, and administrative bias at the global, regional, and country level.

Methods

Overview

In this analysis, we focused the set of 8 vaccinations included in the WHO recommended routine immunizations for children under 5¹⁰. These include diphtheria, pertussis, and tetanus (DTP, 1 and 3 doses), polio (3 doses oral or inactivated polio vaccine), measles-containing vaccine (MCV, 1 dose), BCG (BCG, 1 dose), hepatitis B (HepB, 3 doses), Haemophilus type b (Hib, 3 doses), pneumococcal conjugate (PCV, 3 doses), and rotavirus vaccines (RotaC, 2 or 3 doses). We adopted the indicator definitions used by the WHO Indicator Measurement Registry (WHO IMR), which defines coverage as the proportion of children between 12-23 months of age who have received the respective vaccination. Our analysis included 195 countries and territories in the 21 GBD regions for the years 1980 to 2016.

Data

The present study used data from household level surveys as well as administrative reports of immunization coverage. Survey data which provided person-level information on immunization were identified and extracted. Major multi-country survey programs included in the analysis include the Demographic and Health Surveys (DHS), Multiple Indicator Cluster Surveys (MICS), Reproductive Health Surveys (RHS), Living Standards Measurement Study (LSMS) surveys, and World Health Surveys (WHS). We also conducted a comprehensive search of the Global Health Data Exchange (GHDx), as well as targeted internet searches and review of Ministry of Health websites, to identify national surveys and other multi-country survey programs. Vaccination coverage in household-surveys is based on vaccination cards where possible, and from maternal recall when cards are not available. We calculated the mean proportion of children who were vaccinated by single year age groups (12-23 months, 24-35 months, 36-47 months, and 48-59 months) and localized to the year in which the children were 12-23 months of age.

Administrative estimates of immunization coverage were obtained from the Joint Reporting Process (JRF), through which the WHO and UNICEF collates annual estimates of immunization coverage reported UN member states. These immunization coverage estimates are separate from those synthesized by WHO, and are calculated by dividing the number of doses of a given vaccine delivered to the target population (ie, children aged 12 to 23) by the number of individuals in that target population.

We excluded all data sources that were not nationally representative or had high levels of missingness. We applied survey weights based on survey sampling frames whenever they were available to generate weighted national estimates of vaccination coverage accompanied by estimates of standard error (SE). Estimates of SE, as well as sample sizes, were used to calculate uncertainty, as described below. Any point estimates with sample sizes less than 50 were reviewed to ensure that were not substantive outliers and would otherwise have an undue influence on our analysis.

In total, we utilized 820 sources of data, totaling 33,160 country-years of data across all vaccinations. Appendix Table 1 provides a comprehensive list of all sources included in the estimation of vaccination coverage.

Bias adjustments

Intervention coverage estimates based on administrative sources can be biased, yet the direction and magnitude of such biases are not universal. Some studies show that immunization coverage estimates from administrative data source are systematically higher than those of survey-based estimates, while other studies show that bias directionality is more heterogeneous^{5,11}. Such biases may arise for a number of reasons, including discrepancies in the accurate reporting of services or interventions provided (eg, number of vaccine doses administered) and target population (eg, number of children in need of vaccines), as well as capturing these data in a timely manner from both public and private sector facilities and healthcare providers.

For immunization coverage, we view individual-level data collected through population health surveys as the most accurate and least biased source of information of vaccination coverage, particularly for geographies with incomplete health information systems. However, because household-surveys are costly and not carried out routinely, administrative estimates provide a more complete estimate of coverage over time. Assuming that the level of bias is unchanging by country over time, we used vaccination coverage estimates from household surveys to adjust calculate a country-specific adjustment factor to correct for the biases.

For each given vaccination, using the following equation, we calculated an adjustment factor to correct for the administrative bias:

$$\text{logit}(P_{s,c,t}) = \beta_0 + \beta_1 \text{logit}(P_{a,c,t}) + \sum \beta_k S_k + \epsilon_{c,t}$$

where $P_{s,c,t}$ is the survey-based estimate for immunization coverage (s) in country c for year t; $P_{a,c,t}$ is the administrative estimate for coverage in country c in year t; S_k is a spline basis used to capture the secular trend in coverage; β_1 is the estimated adjustment factor used to correct for the administrative bias; and ϵ is the error term for country c in year t. Models were run separately by vaccination and country. The adjustment factors were applied by country and vaccine to shift the coverage level of the administrative estimates.

To quantify uncertainty for bias-adjusted estimates from the mixed-effects model described above, we calculated prediction error, ($\hat{P}E$), as follows:

$$\hat{P}E = X^2 \text{var}(\beta)$$

where $\text{var}(\beta)$ is the variance for the estimated fixed-effects coefficient of the adjustment factor and X is the independent variable. Proper estimation of prediction errors is crucial as the data synthesis procedure, Gaussian process regression (GPR) (as described in the subsequent section), accounts for uncertainty from point estimates and bias adjustments when generating fitted values. More weight is given to data with less uncertainty. Prediction errors estimated from the bias adjustment were incorporated into the sampling variance and propagated through the GPR step to obtain estimates of coverage and uncertainty intervals (UIs).

Modeling of vaccination coverage across time

Overview

We used a spatiotemporal Gaussian process regression (ST-GPR) to synthesize point estimates from multiple data sources and derive a complete time series of coverage for each vaccine. This method has been used extensively in the Global Burden of Disease and related studies, and accounts for uncertainty pertaining to each point estimate while borrowing strength across geographic space and time^{12,13}. The approach is a stochastic modeling technique that is designed to detect signals amidst noisy data.

Unlike classical linear models that assume that the trend underlying the data follows a definitive functional form, GPR assumes that the trend of interest follows a Gaussian Process $g(\cdot)$ that is defined by a mean function $m(\cdot)$ and covariance function $Cov(\cdot)$. Let $P_{c,t}$ be the vaccination coverage, in logit space, observed in country c at time t:

$$P_{c,t} = g_c(t) + \epsilon_{c,t} \epsilon_{c,t} \sim \text{Normal}(0, \sigma_p^2) g_c(t) \sim GP(m_c(t), Cov(g_c(t)))$$

The derivation of the mean and covariance function, along with a more detailed description of the error variance (σ_p^2) is described below.

Mean function

We estimated the mean function using a two-step approach. Specifically, $m_c(t)$ can be expressed as:

$$m_c(t) = X\beta + h(\epsilon_{c,t})$$

where $X\beta$ is a linear model and $h(r_{c,t})$ is a smoothing function for the residuals that accounts for smoothing across geographies and over time; and $\epsilon_{c,t}$ are the residuals derived from the linear model.

The following linear model was used to model DPT3, polio3, MCV1, and BCG coverage:

$$\text{logit}(P_{c,t}) = \beta_0 + \beta_1 \text{HAQ}_{c,t} + \alpha_c + \gamma_{R[c]} + \omega_{SR[c]} + \epsilon_{c,t}$$

where $P_{c,t}$ is vaccination coverage for country c year t ; $\text{HAQ}_{c,t}$ is value of the Healthcare Access and Quality Index (HAQ) for country c and year t ; α_c , $\gamma_{R[c]}$, and $\omega_{SR[c]}$ are country, region, and super-region random intercepts, respectively. The HAQ index was created as a summary index of mortality amenable to personal health care using data from the GBD 2015 study, and serves as a proxy for healthcare access and quality¹⁴.

Given their recent introduction, there is limited coverage data for HepB3, Hib3, PCV3, and RotaC. To leverage the relatively data-rich DPT3 estimates, we modeled the ramp-up of each vaccine by modeling their ratio with DPT3 coverage. We first calculated the ratio of each vaccine with DPT3 by survey-year. We then modeled the full time series of the ratio using ST-GPR. Finally, we estimated coverage by multiplying the modeled ratio by the final estimated DPT3 coverage by location-year. The following linear model was used in the mean function for the HepB3, Hib3, PCV3, and RotaC coverage ratio with DPT3:

$$\text{logit}(P_{c,i}) = \beta_0 + \beta_1 \text{HAQ}_{c,i} + \alpha_c + \gamma_{R[c]} + \omega_{SR[c]} + \epsilon_{c,i}$$

where $P_{c,i}$ is vaccination coverage for country c year since introduction i ; $\text{HAQ}_{c,i}$ is value of the Healthcare Access and Quality Index (HAQ) for country c and year since introduction i ; α_c , $\gamma_{R[c]}$, and $\omega_{SR[c]}$ are country, region, and super-region random intercepts, respectively.

Error variance

σ_p^2 represents the error variance including the sampling variance of the estimates, the prediction error from the administrative bias correction, and an estimate of the non-sampling variance. We approximated non-sampling variance as the inverse variance weighted residual between the smoothed prior and linear prior.

Gaussian Process Regression

The estimates from the linear model were then run through the second stage process, where the residuals were smoothed using a LOESS estimator, weighted across geography and time. Smoothing weights across time (λ) were calculated as function of the scaled distance in time between two observations. Smoothing weights across geographies (ζ) were calculated using the GBD location hierarchy, where points within the same country receive more weight than points within the same region, and so forth. Full details of the smoothing functions and their respective hyper-parameters have been described previously in detail^{12,13}.

The mean prior was run through a Gaussian process regression utilizing a Matern-Euclidean covariance function, which offers the flexibility to model a wide spectrum of trends with varying degrees of smoothness:

$$M(t, t') = \sigma^2 \frac{2^{1-v}}{\Gamma(v)} \left(\frac{d(t, t')\sqrt{2v}}{l} \right)^v K_v \left(\frac{d(t, t')\sqrt{2v}}{l} \right)$$

where $d(\cdot)$ is a distance function; σ^2 , v , l , and K_v are hyper-parameters of the covariate function. Specifically, σ^2 is the marginal variance, v is the smoothness parameter that defines the differentiability of the function, l

is the length scale, which roughly defines the distance between which two points become uncorrelated, and K_v is the Bessel function. We approximated σ^2 with $MAD(r'_{c,t})$, the median absolute deviation of the residuals between the smoothed prior and the linear prior for each country, region, or super-region depending on data coverage at a given location hierarchy level. We integrated over $g_c(t)$ to predict the full time series for a given vaccine for country c and time t .

Random draws of 1,000 samples were obtained from the distributions above for every country for a given vaccine. Ninety-five percent uncertainty intervals were calculated by taking the ordinal 2.5 and 97.5th draws from the sample distribution.

To assess the accuracy of our modeled estimates and to select for the ST-GPR hyper-parameters that minimized error in the estimation process, we performed cross-validation analyses using a knockout structure that mimicked patterns of data missingness across time. Full details of the holdout structure have been described previously. ST-GPR hyper-parameters were selected on models that minimized the overall root-mean squared error (RMSE) of the model across a set of 10 knockouts.

Immunization system strength indicators

Overall vaccine indicator

In addition to estimating coverage for each vaccination separately, we calculated a composite vaccination index. This indicator serves as a proxy for SDG Indicator 3.b.1, the proportion of the target population covered by all vaccines included in the national program¹⁵.

We used the geometric mean of coverage of the eight vaccines considered in this analysis based on their inclusion in the national vaccine schedule. Newer generation vaccinations (HepB, Hib, PCV and Rota) are introduced in the country-year's calculation only after the vaccine has been introduced into the national schedule. To account for the scale-up period for newly introduced vaccines, we include new vaccines in the geometric mean two years after the year of introduction. Vaccines that are removed from the national schedule (eg, BCG in several European countries, Australia, New Zealand) are included in the country's calculation up until the year that it is removed from the schedule.

National vaccine schedules and vaccine introduction dates were used as reported from the WHO or from the country's Ministry of Health website where otherwise unavailable. Dates of policy changes for the BCG vaccine were used as reported by the BCG Atlas¹⁶ or directly from the country's ministry of health website.

Estimates of vaccination drop-out

Drop-out rates between vaccination doses help assess the strength of a health and immunization system, particularly its ability to maintain repeated contact with its target population. In strong health systems, children are able to maintain follow-up contact at the appropriate times to ensure proper vaccination coverage.

We measure the difference in coverage between the first and third doses of DPT (DPT1 and DPT3) as the measure of vaccination drop-out. The first dose of DPT is typically given at 6 weeks after birth and the second and third doses are given 4-8 weeks after each subsequent dose. Drop-out between the first and third dose of DTP thus represents the ability of an immunization system to maintain contact with children for at least 14 weeks after the first dose. Drop-out rates more than 10% are considered problematic by health experts.

Timeliness of vaccination

Timely receipt of the recommended number of doses for a given vaccination is necessary to develop adequate immunity to the disease^{17,18}. Delays in vaccination may expose a child to prolonged risk of disease and contribute to the transmission of VPDs. The timeliness of vaccinations is therefore an important aspect for evaluating the performance of immunization systems. Only considering coverage leads to incorrect assumptions about transmission risk.

We calculate the proportion of DTP3 vaccinations that are timely using the subset of data where it is possible to calculate age at vaccination (ie, children with vaccination cards). Vaccination age was calculated using the birth month and year and the month and year of administration recorded on the vaccination card. We considered DTP3 vaccinations administered until the age of 12 months timely. Because we only include the subset of the population with a vaccination card, these estimates are only representative of those with a vaccination card and likely overestimate overall timely vaccination.

Results

Global, regional, and national levels and trends of vaccination coverage

Routine vaccinations

The global level of vaccination coverage has increased substantially over the period from 1980 to 2016. Among the routine immunizations, DPT3 saw the most remarkable increase over the period, for which coverage at the global level increased from 52.9 (95% UI: 47.4-55.9) to 87.1 (95% UI: 86.2-87.8). Progress was most rapid from the early 1980s through the 1990s. Trends in DTP1, polio, MCV1, and BCG coverage saw similar patterns of rapid growth and subsequent plateau—each reaching well over 85% coverage by 2016.

Despite global improvements in vaccination coverage, there was still considerable variation in progress across geographic regions. Figure 1 illustrates coverage rates of DPT3, Polio3, MCV1, and BCG globally and by region from 1980 to 2016. Coverage of MCV1 increased rapidly from the 1980 through the early 1990s in Latin America, North Africa, and Southeast Asia, and High-income countries, each reaching above 90% coverage by 2016. South Asia and Sub-Saharan Africa saw steadier growth over the entire period, but both have yet to reach 85% coverage by 2016. Central African Republic (60.3 (95% UI: 43.6-76.3)), Ethiopia (61.5 (95% UI: 43.3-77.1)), Somalia (48.6 (95% UI: 31.8-66.2)), South Sudan (69.8 (95% UI: 56-81.9)), Chad (67.1 (95% UI: 54.7-77.8)), Liberia (67.9 (95% UI: 50.5-81.7)), and Nigeria (50 (95% UI: 35.1-64.8)) each still have MCV1 coverage less than 70%.

Countries in South Asia, Latin America, and the Middle East had some of the most rapid increases in DPT3, MCV1, BCG, and Polio3 over the period. Many saw rapid increases in coverage from 1980 through 1990, followed by a slower increase in coverage for the rest of the period, including Bangladesh (2016 coverage: 93.5 (95% UI: 89.1-96.2)), Nepal (83.6 (95% UI: 75.3-90.1)), Jordan (99.4 (95% UI: 99.1-99.6)), Colombia (96.9 (95% UI: 94.6-98.3)), and Mexico (82.5 (95% UI: 78.6-85.9)).

Afghanistan and India saw more gradual increases over the entire period, reaching DPT3 coverage rates of 62.5 (95% UI: 56.4-68.3) and 86.2 (95% UI: 84.2-87.9) by 2016, respectively. Ukraine saw troubling declines in coverage from 2005 onward, with DPT3 coverage declining from 90.2 (95% UI: 83.5-94.6) in 2005 to 58.5 (95% UI: 38.3-76.3) in 2016.

We assessed the GVAP goal of reaching 90% coverage for DPT3 in all countries by 2015. As of 2015, 125 countries have reached this target, and while several are on target to reach the goal by 2020—including the Philippines, Rwanda, Cambodia, and Zambia—many are far from reaching the goal.

The full set of estimates by country over 5 year period from 1980-2016 can be found in Appendix Table 1.

Scale-up of newer vaccinations

By 2016, most countries have introduced the HepB (n = 176) and Hib vaccination (n = 187), but fewer have introduced PCV (n = 134) and only 84 countries have introduced rotavirus vaccination. Introductions have been much more rapid over the past decade years, with 89 countries introducing Hib since 2005 (nearly 3 decades after its first introduction in 1986 in Canada and Finland) and 84 countries introducing PCV since 2000 (a decade after its first introduction in 2000 in the USA). Most countries have been slow to introduce rotavirus, despite high burden of diarrhea, including Chad, Nigeria, the Central African Republic, South Sudan, and Somalia. Figure 2 shows the proportion of countries within a region that have introduced each vaccination over time.

Most countries have been able to scale up HepB3, Hib3, PCV3, and RotaC quite rapidly upon introduction. Globally, HepB3 coverage reached 83.3 (95% UI: 82.5-84.1) by 2016—close to global level of DPT3 coverage (Figure 3). Similar trends in coverage can be seen in Hib3, which reached global coverage levels of 68 (95% UI: 67.1-68.9), respectively. As many countries in South Asia, North Africa and the Middle East, Central and Eastern Europe have yet to include PCV and rotavirus vaccination in the national schedule, global coverage remains low at 31.2 (95% UI: 30.8-31.5) and 33.5 (95% UI: 33-34), respectively. Regional patterns of coverage

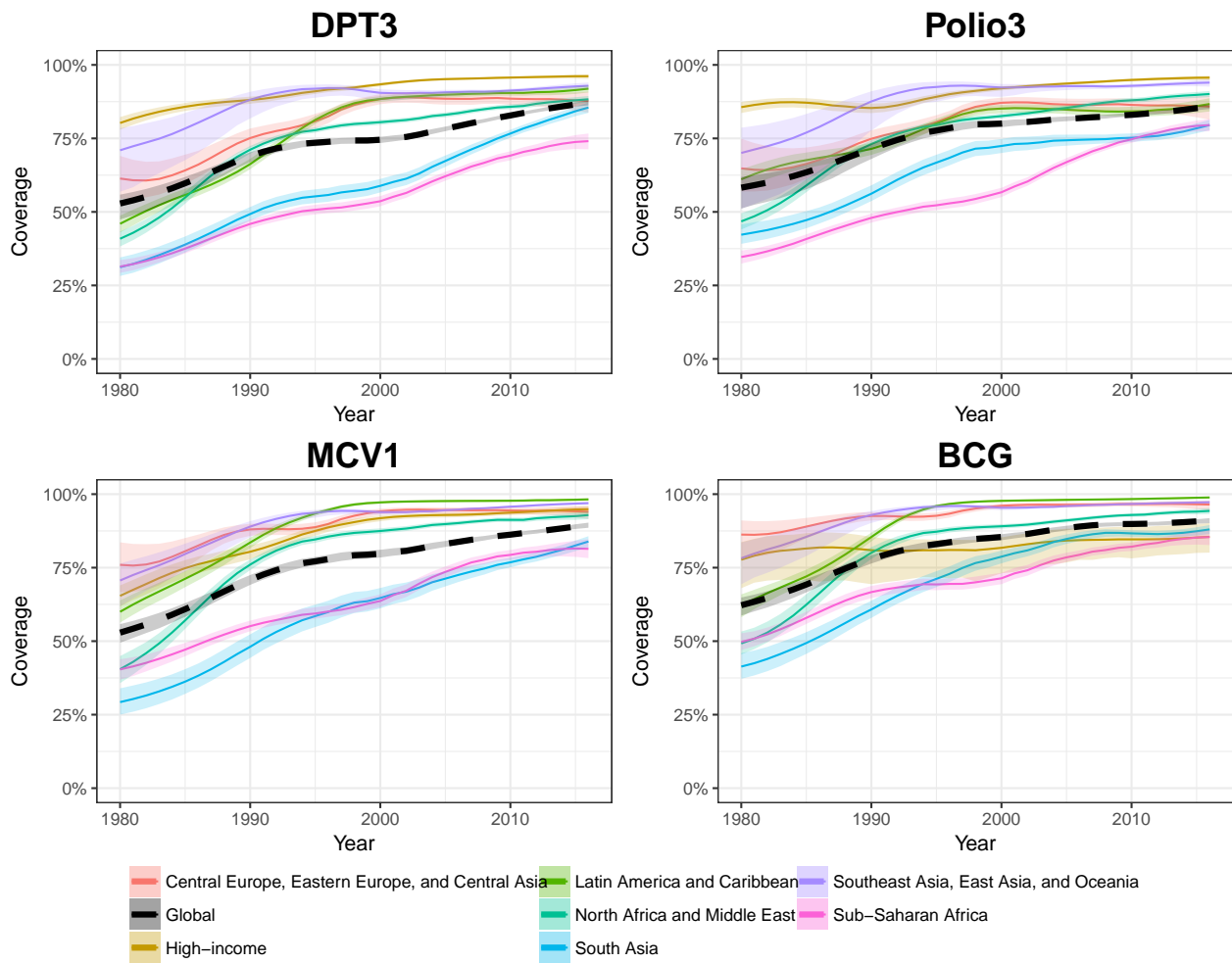


Figure 1: Time series estimates of routine vaccine coverage (DPT3, Polio3, MCV1, BCG) at the global and regional level from 1980-2016.

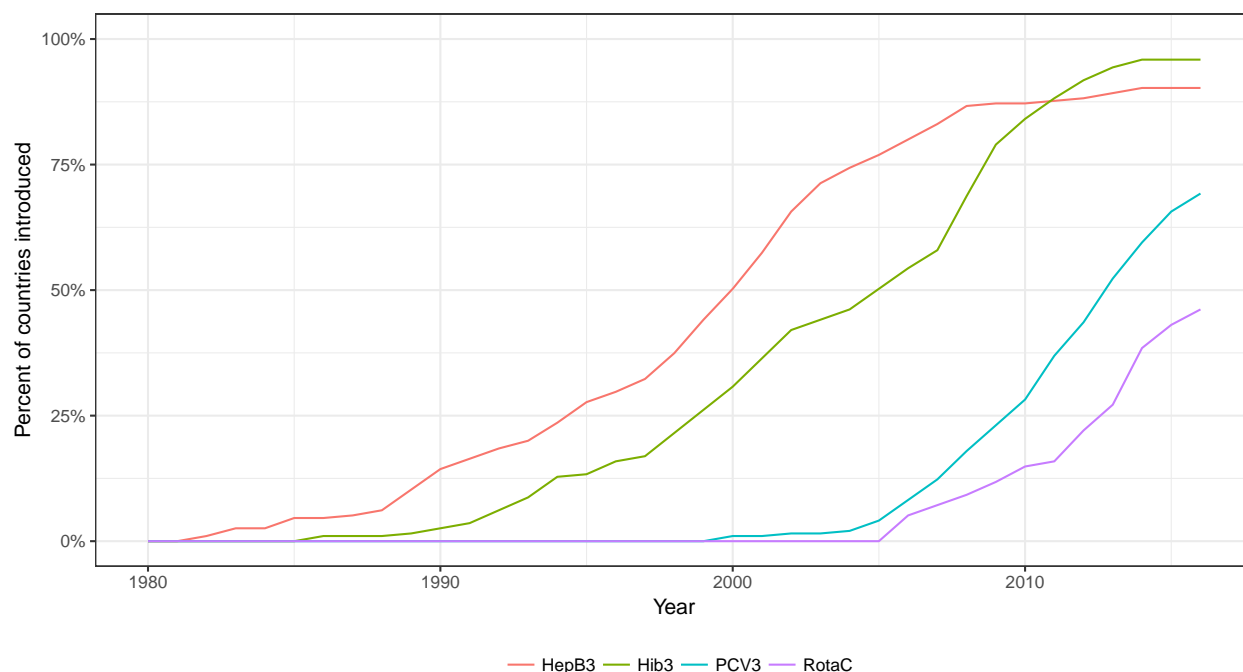


Figure 2: Percent of countries who have introduced new vaccinations (HepB, Hib, PCV, Rota) over time.

are similar to that of the routine vaccinations, though regional variation is much greater for PCV3 and RotaC because of countries that have been slow to introduce.

Immunization system indicators

Overall vaccine indicator

To assess a country’s ability to deliver all vaccinations in the national schedule, we estimated an overall vaccine indicator as the geometric mean of all vaccines in a country’s national schedule. While there was relative progress over the 36 year period, complete coverage at the global level reach only 78.1 (95% UI: 76.9-79.2) by 2016, significantly lower than any of the individual routine coverage levels in the same year (Supplementary Figure 1). There exists much more variation in coverage across regions than compared to that of individual vaccination coverage. By 2016, high income countries reached complete coverage levels of 89.6 (95% UI: 88.3-90.8) while Sub-Saharan Africa reached only 61.1 (95% UI: 58.4-63.7). Latin America, in particular, had a lower complete coverage level relative to each of the individual routine vaccinations, reaching 77.6 (95% UI: 69.9-82.7) by 2016.

Trends in vaccine dropout

Figure 4 illustrates the trend in the DPT1-DPT3 dropout rate, calculated as the percentage difference between DPT1 and DPT3, which highlights the proportion of children who lose contact with the immunization system. Globally, there was a 9.4 (95% UI: 8-11.3) difference in DPT1 and DPT3 coverage in 1980. Over the period, progress was most rapid following the late 2000s, with the drop-out rate reaching 5 (95% UI: 4.5-5.7) by 2016. Latin America and the Middle East showed the most progress in closing the gap in vaccination drop out, ending with dropout rates of 5 (95% UI: 4.5-5.7) and 5 (95% UI: 4.5-5.7) by 2016. Regional patterns in DPT3 coverage matched that of the drop-out rate, suggesting that areas with low coverage also demonstrate issues with immunization service quality. Overall, 17 countries—including Indonesia, Afghanistan, DR Congo, Somalia, and Chad—had drop-out rates greater than 10% by 2016.

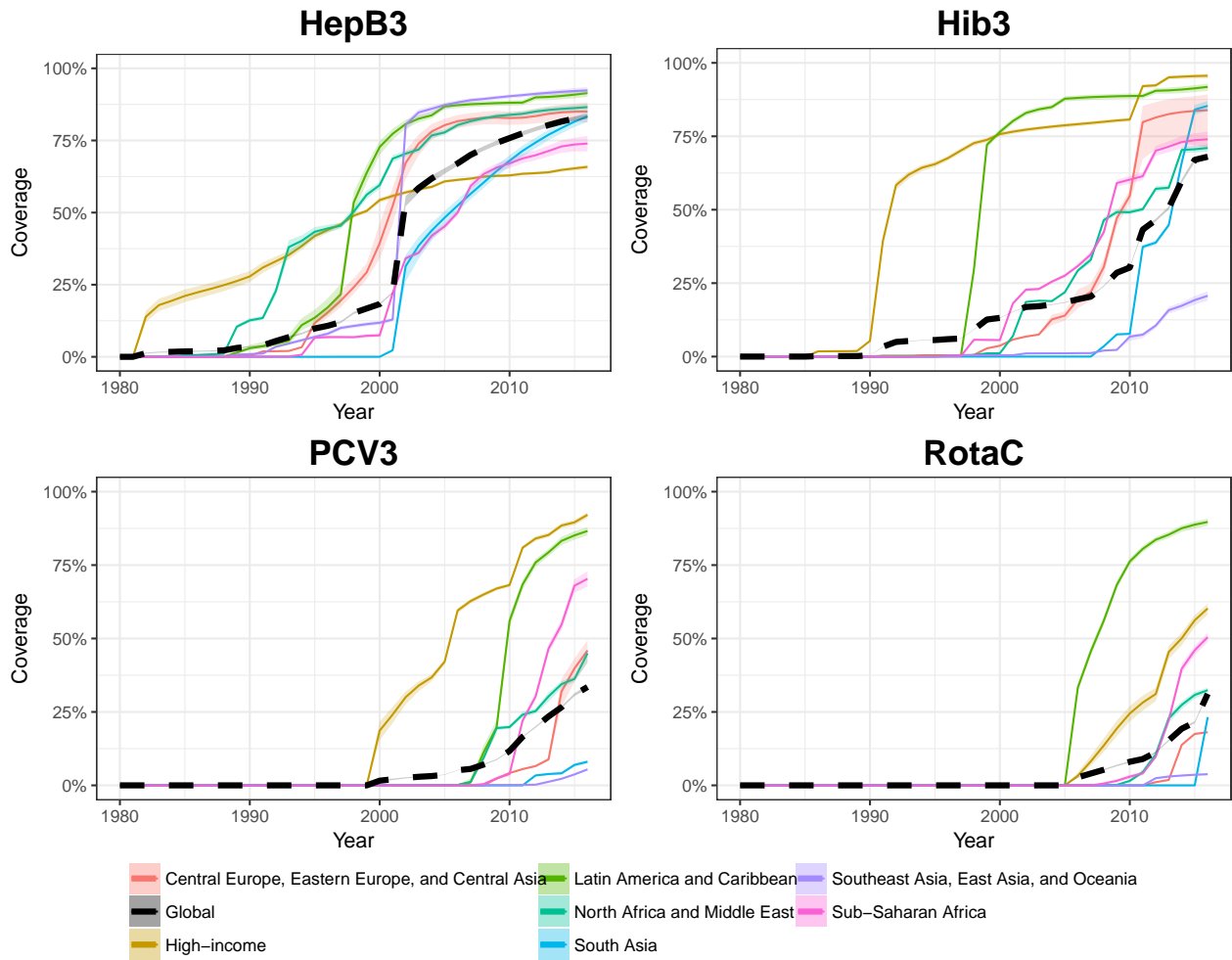


Figure 3: Time series estimates of new vaccine coverage (Hepb3, Hib3, PCV3, RotaC) at the global and regional level from 1980-2016.

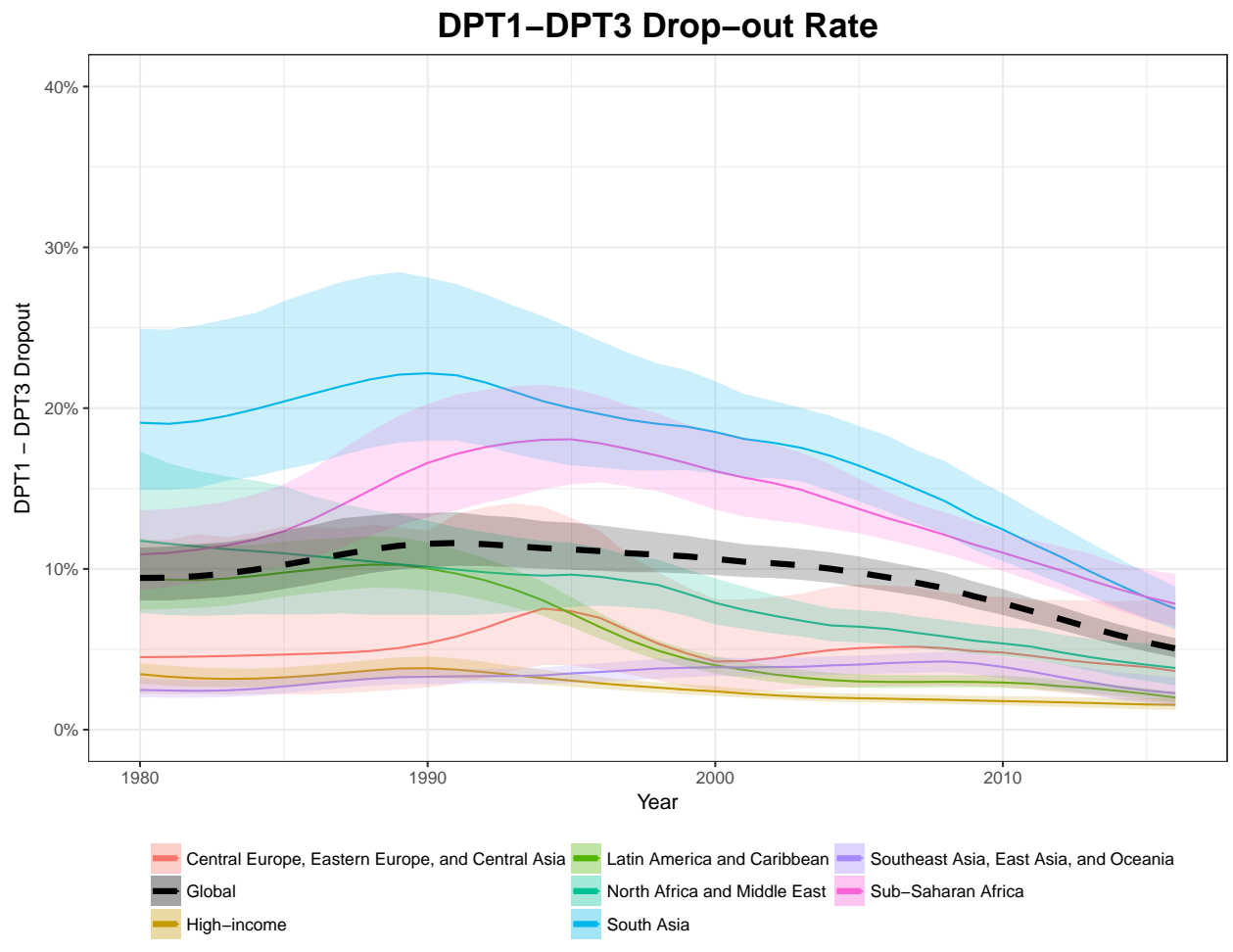


Figure 4: Time series estimates of DPT1-DPT3 drop-out at the global and regional level from 1980-2016.

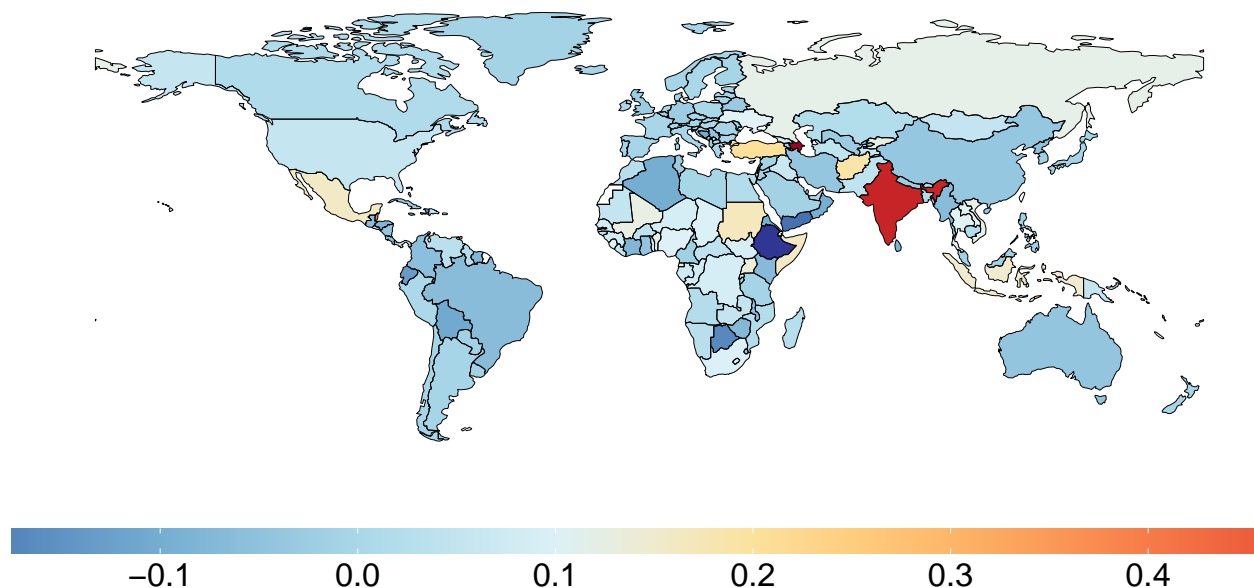


Figure 5: Global map of the estimated administrative bias for DPT3, where positive values represent an upward bias and negative values represent downward bias.

Timeliness

Inability to deliver vaccinations by the recommended time frame introduces children to more opportunity for infection. From a surveillance perspective, only considering coverage—without also considering the validity of coverage—overestimates the effective protection. Moreover, estimates of timeliness help assess the magnitude of barriers to vaccination. Supplemental Figure 2 illustrates the proportion of overall DPT3 coverage that are timely, or where coverage was received before 12 months of age. Globally, proportion of children who received timely DPT3 vaccinations was 80.4 (95% UI: 77.7-82.5). This improved gradually over the 36 year period to 96.5 (95% UI: 95.8-97.1), suggesting the gap in timely vaccinations has largely closed. Several countries, however, still experience sizable delays in vaccinations including Somalia, Chad, South Sudan, Afghanistan, and Central African Republic—each with a proportion of delayed DPT3 vaccinations above 10%.

Administrative bias

To assess the strength of an immunization system’s ability to accurately monitor coverage at the administrative level, we calculated the estimated bias between survey and administrative data in DPT3 coverage for countries where survey data was available. Figure 5 illustrates the estimated bias by country, where a positive value indicates the average percentage magnitude that the administrative estimate is larger than that of surveys. India, Azerbaijan, Somalia, and share some of the largest administrative biases at 56%, 63%, and 16%, respectively. Several other countries in Central Sub-Saharan Africa show relatively sizable magnitudes of bias, suggesting that country derived estimates of vaccination coverage are overestimating actual vaccine coverage by a sizable margin.

Discussion

Overview

This study has estimated the coverage of the set of 8 child vaccinations included in the WHO recommended routine schedule for the years 1980 through 2016. Coverage of routine vaccinations (DPT, Polio, BCG, MCV) has increased substantially over 36 years, with the most rapid growth occurring from the 1980s through 1990s, and more gradual growth for the rest of the period. While global coverage of DPT3 is close to reaching the GVAP target of 90% coverage, substantial regional variation still remains, and countries in South Asia and Sub-Saharan Africa, in particular, lag behind in coverage. Globally, scale-up of newer vaccinations (HepB, Hib, PCV, and RotaC) has been rapid upon introduction, though many countries with comparatively high burden of lower-respiratory infections and diarrhea have yet to introduce PCV or RotaC into their national schedules.

To better assess the progress of national immunization systems, we estimated a series of indicators that underlay other components of the delivery process: complete coverage, drop-out, timeliness, and the magnitude of administrative bias. Each contribute important insights into the strength, efficiency, and quality of an immunization system and help identify barriers to coverage. While the overall vaccine indicator trends followed that of routine immunizations, the absolute level was still relatively low, signaling gaps in quality of delivery. Drop-out rates have decreased significantly over the period, though several countries still have rates over 10%, signaling issues in quality of the health system to deliver services that require multiple visits. According to our findings the gap in timely vaccinations has largely closed for children with vaccination cards. However, the delay in vaccinations for children without cards is likely higher and driven by similar factors that predict card status such as SES, mother's education, household wealth.

Together, these estimates of coverage and system indicators represent a more robust set of information that will be useful assessing retrospective progress in the MDG era, and assist in more targeted planning through the SDG era and the remainder of the GVAP period. The estimates of vaccine coverage and immunization system strength should be used in conjunction as the basis of review and action at the country level—to identify where coverage gaps exist and areas within the system that can be targeted to address said gaps.

We estimated quite significant differences between administrative and survey-based coverage estimates, signaling persistent issues in data quality at the administrative level. As the estimation approaches for official reported estimates differ across time and geography, the administrative biases can arise from multiple areas. Measurement errors across health centers, exclusion of private sector information, or poor estimation of the target population can each contribute to discrepancies between administrative and survey data^{5,6}. Moreover, previous studies have demonstrated that countries involved in performance-based immunization services support funding can incentivize over-reporting of the coverage⁷. More scrutiny must be placed on immunization systems to standardize the methodology behind administrative estimates of coverage for the purposes of understanding performance in between periods when surveys are carried out.

While the WHO-UNICEF estimates of coverage have attempted to address some of the issues in administrative estimates, there remain discrepancies that limit their interpretation and use. In the absence of recent survey or other data—or if survey data is within 10% of the administrative data—WHO and UNICEF use the administrative estimates as is. Survey data, when used, are restricted to children 12-23 months at the time of survey. Moreover, WHO and UNICEF explicitly do not model the coverage estimates as a time series trend, but rather use subjective approaches to incorporate data from multiple sources to construct a temporal trend of coverage. The estimates modeled here using ST-GPR are an empirically based, reproducible synthesis of all available data and their uncertainty. Importantly, they allow for the estimation of uncertainty in coverage where the WHO and UNICEF estimates do not.

While national estimates are important for bench-marking progress towards universal coverage, moving forward, it is critical to address within-country disparities. As seen in our results, the uptake of vaccination coverage has begun to plateau, leaving a non-marginal proportion of the population unvaccinated. This likely reflects the difficulty of national policies or immunization campaigns in reaching traditionally hard-to-reach populations. For many countries who have already reached 90% coverage or higher, this population represents

the remaining barrier towards achieving universal coverage. For example, a recent study found that while national coverage of MCH service indicators was high (e.g. Polio3 81%), there were significant disparities in district-level coverage (e.g. Polio3 ranging from 24% in Mufumbwe to 99% in Chavuma)¹⁹. To continue progress in enhancing coverage, efforts must be made to estimate coverage at a subnational or district-level, such that policy-makers are able to directly pinpoint areas of greatest need and intervene appropriately. Such an approach will be necessary to effectively target efforts for the eradication of polio.

Limitations

We highlight several limitations in our study and estimates. Although household-surveys represent the best empirical source of vaccine coverage data, these data rely partly on maternal self-report and are subject to relevant biases. Existing evidence suggests that there is inconsistency in the direction of the biases and so we do not attempt to correct for them here²⁰. Alternative survey designs can be utilized to address this issue, in which maternal report is asked irrespective of vaccine card status and then validated using the vaccination card. Second, while we attempt to address the issue of administrative data—because estimation methods are inconsistent between countries and over time—our adjustment conservatively assumes a constant bias over time and is subject to the availability of survey data to compare with for a given vaccine and location. In a country where the quality of administrative data may be improving over time, we thus underestimate bias in earlier years and overestimate the bias as it improves. Third, due to data limitations, we estimated an indicator of overall coverage as a proxy for complete vaccination coverage. Future efforts should be made to develop methodology that can better directly estimate SDG Indicator 3.b.1. Finally, due to data constraints and the nature of the modeling process, our estimates may not adequately reflect the impact of acute shocks such as conflict or vaccine outages, which interrupt the routine delivery of vaccinations.

Conclusion

Despite promising improvements in vaccination coverage from 1980 to 2016, there still exist major disparities in coverage, vaccine introduction, and system strength. Future efforts to improve data quality and estimation granularity are necessary to better support the assessment and planning necessary to sustainably and equitably reach vaccine coverage targets.

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