

Measuring routine childhood vaccination coverage in 204 countries and territories, 1980–2019: a systematic analysis for the Global Burden of Disease Study 2020, Release 1



GBD 2020, Release 1, Vaccine Coverage Collaborators*



Summary

Background Measuring routine childhood vaccination is crucial to inform global vaccine policies and programme implementation, and to track progress towards targets set by the Global Vaccine Action Plan (GVAP) and Immunization Agenda 2030. Robust estimates of routine vaccine coverage are needed to identify past successes and persistent vulnerabilities. Drawing from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2020, Release 1, we did a systematic analysis of global, regional, and national vaccine coverage trends using a statistical framework, by vaccine and over time.

Methods For this analysis we collated 55 326 country-specific, cohort-specific, year-specific, vaccine-specific, and dose-specific observations of routine childhood vaccination coverage between 1980 and 2019. Using spatiotemporal Gaussian process regression, we produced location-specific and year-specific estimates of 11 routine childhood vaccine coverage indicators for 204 countries and territories from 1980 to 2019, adjusting for biases in country-reported data and reflecting reported stockouts and supply disruptions. We analysed global and regional trends in coverage and numbers of zero-dose children (defined as those who never received a diphtheria-tetanus-pertussis [DTP] vaccine dose), progress towards GVAP targets, and the relationship between vaccine coverage and sociodemographic development.

Findings By 2019, global coverage of third-dose DTP (DTP3; 81·6% [95% uncertainty interval 80·4–82·7]) more than doubled from levels estimated in 1980 (39·9% [37·5–42·1]), as did global coverage of the first-dose measles-containing vaccine (MCV1; from 38·5% [35·4–41·3] in 1980 to 83·6% [82·3–84·8] in 2019). Third-dose polio vaccine (Pol3) coverage also increased, from 42·6% (41·4–44·1) in 1980 to 79·8% (78·4–81·1) in 2019, and global coverage of newer vaccines increased rapidly between 2000 and 2019. The global number of zero-dose children fell by nearly 75% between 1980 and 2019, from 56·8 million (52·6–60·9) to 14·5 million (13·4–15·9). However, over the past decade, global vaccine coverage broadly plateaued; 94 countries and territories recorded decreasing DTP3 coverage since 2010. Only 11 countries and territories were estimated to have reached the national GVAP target of at least 90% coverage for all assessed vaccines in 2019.

Interpretation After achieving large gains in childhood vaccine coverage worldwide, in much of the world this progress was stalled or reversed from 2010 to 2019. These findings underscore the importance of revisiting routine immunisation strategies and programmatic approaches, recentring service delivery around equity and underserved populations. Strengthening vaccine data and monitoring systems is crucial to these pursuits, now and through to 2030, to ensure that all children have access to, and can benefit from, lifesaving vaccines.

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Introduction

The development and mass distribution of childhood vaccines has been one of the greatest public health achievements in history, underpinning marked progress in child survival and health outcomes worldwide.^{1–4} Initiated by WHO in 1974, the Expanded Programme on Immunisation (EPI) spurred coordinated, country-level progress in routine vaccination (eg, diphtheria, tetanus, pertussis, measles, polio, and BCG), and laid the

foundation for efforts to introduce new vaccines and further increase coverage over the following decades.⁵ National governments and global organisations continue to dedicate substantial resources to vaccines, with total spending on immunisation exceeding US\$107 billion in low-income and middle-income countries alone from 2000 to 2017.⁶ The 2011–20 Global Vaccine Action Plan (GVAP) set forth various targets for childhood vaccination, such as reaching 90% coverage across all

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*Collaborators are listed at the end of the paper

Correspondence to:
Prof Stephen S Lim, Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA, USA
stevelim@uw.edu

or

Dr Jonathan F Mosser, Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA, USA
jmosser@uw.edu

Research in context

Evidence before this study

Rigorous, comparable, and timely estimates of vaccine coverage are needed to inform vaccination policies, programmes, and investments. WHO and UNICEF gather country-reported administrative and household survey data each year, among other immunisation indicators, through the Joint Reporting Form for immunisation, and annually produce the WHO–UNICEF Estimates of National Immunization Coverage (WUENIC) for member states. This estimation process, which has been described as a rule-based approach combining heuristics with expert assessment and decisions, has some strengths, including familiarity for key stakeholders and the ability to integrate expert opinion on vaccine coverage and its drivers. Compared to statistical models, however, the WUENIC approach does not produce quantitative estimates of uncertainty and adjusts only for relatively large discrepancies between country-reported data and household survey coverage estimates. To the best of our knowledge, no other study provides systematic, internally consistent analyses of global, regional, and national vaccine coverage trends based on a statistical framework, by vaccine and over time.

Added value of this study

Drawing from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2020, Release 1, our analysis provides annual estimates of routine vaccine coverage for 11 vaccine-dose combinations from 1980 to 2019 in 204 countries and territories. Our modelling approach incorporates time-varying and location-varying bias adjustments, leverages temporal

trends and covariate relationships to estimate vaccine coverage in the absence of country-specific data, and quantifies uncertainty for all estimates. We use these coverage estimates and GBD population estimates to quantify the number of zero-dose children (ie, children who have never received a dose of a diphtheria-tetanus-pertussis [DTP] vaccine as a proxy) over time; measure progress towards the Global Vaccine Action Plan (GVAP) 2020 targets of at least 90% coverage across all childhood vaccines by 2019; and analyse the relationships between national-level vaccine coverage and sociodemographic development.

Implications of all the available evidence

Over the past four decades, global coverage of both longstanding and more newly available vaccines improved, and the number of zero-dose children declined by nearly 75% since 1980. Yet from 2010 to 2019, much of the world saw progress stagnate or even reverse course. Most locations fell below the 2020 GVAP target of achieving at least 90% coverage across vaccines in 2019, signalling the need to further expand programme reach of unvaccinated or under-vaccinated children. Associations between sociodemographic development and vaccine coverage varied, underscoring the importance of how vaccine programmes operate and reach target populations above and beyond development alone. Continuing to strengthen vaccine data systems and measurement approaches—and leveraging these inputs to inform programme investments and implementation—is crucial to ensure that all children have access to lifesaving vaccines.

vaccines in national immunisation programmes by 2020.⁷ GVAP's successor, the Immunization Agenda 2030 (IA2030), further calls for increased and equitable access to all routine vaccines for everyone, proposing to halve the number of zero-dose children missed by current vaccination programmes in each country by 2030.^{8,9}

Yet as the GVAP era ends and IA2030 begins, acute service delivery challenges have emerged, with the COVID-19 pandemic substantially affecting routine immunisation throughout the world in 2020.^{10–12} At this pivotal juncture, it is important to clearly understand where—and for which vaccines—gains and gaps in coverage occurred before the onset of COVID-19. Robust and comparable estimates of vaccine coverage over time are thus key inputs for evaluating progress towards GVAP targets and serve as a baseline for IA2030's ambitions.

Vaccination data can be sparse, subject to bias, and inconsistent, complicating coverage estimation at both national and global levels. Since 2000, the WHO–UNICEF Estimates of National Immunization Coverage (WUENIC)¹³ have compiled available data sources (ie, country-reported data and household surveys gathered through the Joint Reporting Form [JRF]) for all member states and produced annual coverage estimates, by

vaccine and dose, based on prespecified heuristics and expert judgement.^{13–15} Although WUENIC's approach has its strengths, such as incorporating qualitative knowledge and engagement via country consultation processes, statistical models offer important advantages. For instance, in the WUENIC method, country-reported data are only calibrated to survey-based estimates when both datapoints are available for a given vaccine-country-year and a discrepancy of ten percentage points or more is observed between survey data and country-reported data.¹⁵ Statistical models can account more fully for trends in reporting bias, as well as synthesise discrepant data sources while accounting for data quality and precision, quantify uncertainty, and leverage trends in time and other predictors to improve estimates where data are sparse. Previous research has used statistical methods to quantify discrepancies in administrative versus survey-based coverage over time;^{16,17} however, such work is generally limited to a subset of vaccines, locations, or years. To date, no past research has, to our knowledge, systematically estimated coverage across vaccines, over multiple decades, and by location for all countries within a cohesive statistical modelling framework.

Drawing from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2020, Release 1 (GBD 2020 R1), we estimated coverage for 11 vaccine-dose combinations in 204 countries and territories from 1980 to 2019. These include the well established original EPI vaccines (diphtheria-tetanus-pertussis, first dose [DTP1] and third dose [DTP3] vaccines; measles-containing vaccine, first dose [MCV1]; BCG, first dose; and polio vaccine, third dose [Pol3]), alongside newer vaccines introduced into national immunisation schedules over the past four decades (hepatitis B vaccine, third dose [HepB3]; *Haemophilus influenzae* type b vaccine, third-dose [Hib3]; measles-containing vaccine, second dose [MCV2]; pneumococcal conjugate vaccine, third dose [PCV3]; rubella-containing vaccine, first dose [RCV1]; and completed rotavirus series, two or three doses [RotaC]). We utilised survey and administrative data on vaccine coverage via a multi-step modelling approach that includes bias adjustments for discordance between survey data and administrative data, and propagated uncertainty through each estimation step. Last, we did secondary analyses to further examine relationships between changes in sociodemographic development and vaccine coverage, and explored trends in those children who never received a DTP dose (referred to as zero-dose children,^{9,18,19} proxying for children currently not reached by routine immunisation programmes). This study offers a crucial benchmark for global patterns in vaccine-specific and overall childhood vaccination trends before COVID-19, strengthening our collective understanding of past progress and challenges as the world pursues greater equity in immunisation access and delivery. This report was produced as part of the GBD Collaborator Network and in accordance with the GBD protocol.

Methods

Overview

This analysis is part of the broader GBD 2020 R1, an update from GBD 2019.^{20–22} The Global Health Data Exchange (GHDx) will be updated simultaneously with the release of new GBD rounds; content in these resources will always be synchronous. This analysis complies with the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) statement,²³ with further information provided in the appendix (section 1). All data processing and modelling were done in R statistical software, with more details provided in the appendix (sections 2–4) by analytical step; the source code will be made accessible upon publication and data are available on the GHDx website.

Data

We defined vaccine coverage as the proportion of children who received at least the stated vaccine dose (eg, DTP1) through a routine immunisation programme; we excluded campaign doses when possible.

Of 3118 total sources reviewed, 975 unique sources from 1980 to 2019 were used in this analysis, resulting in 55 326 country-cohort-year-vaccine-dose-specific datapoints across vaccines (appendix; tables S1–S3). We primarily used the GHDx to collate available coverage data sources as described in the appendix (sections 2.1–2.3; figure S2). These sources included household surveys (eg, Demographic and Health Surveys, Multiple Indicator Cluster Surveys, other multi-country survey series, and country-specific surveys) and official country-reported coverage data from the JRF. We excluded sources without data on children aged 12–59 months (aside from country-reported data, which reflect target population ages) and sources that were not nationally representative (ie, geographically or focused on a subgroup of the target population) or did not include dose-specific vaccine coverage from at least one vaccine in or after the country-reported national introduction year. We then reviewed all vaccine coverage observations from sources meeting these criteria and excluded data obtained before introduction of each vaccine or judged to be implausible. Complete inclusion and exclusion criteria and details about all reviewed data sources are summarised in the appendix (section 2.3; figure S2, tables S1–S3). For survey data, children with either home-based records or parental recall indicating vaccine receipt were considered vaccinated. Where individual-level microdata were available, we estimated coverage as the proportion of vaccinated children by vaccine, dose, and age in years, accounting for survey design (appendix section 2.4). We extracted survey report tabulations if microdata were unavailable.

Age-cohort-specific coverage data from children aged 12–59 months were assigned to the year of expected vaccine receipt using country-specific vaccine schedules and vaccine introduction years reported through the JRF.^{24,25} This approach aligns survey-based coverage estimates with those from country-reported data by cohort, facilitating adjustment for administrative bias.

Administrative bias adjustment

To incorporate administrative data while accounting for potential biases,²⁶ we implemented bias adjustments for official country-reported data from the JRF for DTP3, MCV1, BCG, and Pol3. We first estimated the magnitude of potential bias by location-year, using paired observations of survey-based coverage estimates and JRF data for the same year, vaccine, location, and target population cohort. We then modelled administrative bias using a multi-step approach: we first predicted bias using the Healthcare Access and Quality (HAQ) Index (a summary measure of health-care performance²⁷) as a covariate in a two-stage random spline model, and then, for locations with available bias observations, we used spatiotemporal Gaussian process regression (ST-GPR)²⁰ to better account for trends in bias (appendix section 3.4).

For more on **Demographic and Health Surveys** see <https://dhsprogram.com/>

For more on **Multiple Indicator Cluster Surveys** see <https://mics.unicef.org/>

For the **Global Health Data Exchange** see <http://ghdx.healthdata.org>

See Online for appendix

Vaccine-specific coverage estimation

We modelled vaccine-specific coverage using ST-GPR,²⁰ a statistical method that enables non-linear trend estimation and incorporates data uncertainty into final estimates (appendix section 3.2). We used the HAQ Index and GBD mortality estimates from conflict and terrorism per capita as covariates in the first stage of each model, along with a covariate based on country-reported stockouts or other disruptions derived from discontinuities in administrative data (appendix section 3.7).

Relative to DTP3, country-reported data on DTP1 were sparse or not routinely collected from 1980 to 2000. We developed a time-varying model to impute DTP1 from reported DTP3 coverage and trends in DTP1–3 dropout, and used continuation-ratio ordinal regression to ensure internal consistency between DTP1 and DTP3 for the full time period (appendix section 3.3).²⁸

Since more recently introduced vaccines had comparatively less available data, we used the more data-rich DTP3 and MCV1 models to inform estimation of HepB3, Hib3, PCV3, RotaC, MCV2, and RCV1 coverage (appendix section 3.6). We modelled the coverage ratio of newer vaccines relative to reference vaccines (DTP3 or MCV1) on the basis of schedule similarity, using observations from both survey data and unadjusted country-reported data. We used ST-GPR to estimate full time series for each scale-up ratio, then multiplied these ratios by corresponding DTP3 or MCV1 estimates to produce final estimates for all newer vaccines while propagating uncertainty.

We assumed 0% coverage for each vaccine before its formal introduction in national immunisation schedules, with the exception of Hib3, PCV3, and RotaC in China. For these vaccines, which were available in private markets but not yet included in the national immunisation schedule, we constrained estimates using lot release data (China National Institutes for Food and Drug Control²⁹ and Y Teng, Linksbridge SPC, personal communication); further details are provided in the appendix (section 3.8). For DTP3, MCV1, BCG, and Pol3, we used EPI onset information to indicate the introduction of these vaccines and assumed no children were vaccinated with these vaccines before their formal introduction. Where applicable (eg, for BCG), we also assumed 0% coverage for eligible cohorts after removal of a vaccine from national immunisation schedules.

To compute 95% uncertainty intervals (UIs) for location-year-vaccine estimates, we sampled 1000 random draws from the modelled posterior distribution and took the ordinal 2.5th and 97.5th percentile of draws for each measure. National estimates were aggregated to GBD super-regions, groupings based on geographical proximity and epidemiological similarity,³⁰ using GBD 2020 R1 estimates of target age group populations (updated from GBD 2019²² as part of the GBD continuous update cycle).

Assessing coverage trends in relation to sociodemographic development, GVAP target attainment, and zero-dose children

Using these coverage estimates, we did three additional analyses. First, we sought to examine relationships between vaccine coverage and sociodemographic development, a type of benchmarking exercise used to identify potential performance outliers and where improvements in health are occurring faster or more slowly than parallel changes in development.^{22,31,32} For our development metric we used the GBD's Socio-demographic Index (SDI), a summary measure on a scale of 0–100 based on average income per capita, educational attainment, and fertility rates in a given location and year.²² We applied a constrained mixed-effects meta-regression³³ to quantify global averages of expected coverage—estimated levels for any value of SDI—for DTP3, MCV1, and Pol3 across all location-years. We then compared country-level vaccine coverage and SDI estimates from 1980 to 2019 relative to these global averages of expected coverage on the basis of SDI alone. Further details are provided in the appendix (section 4.1).

Second, we evaluated progress towards the 2020 GVAP target of at least 90% national-level coverage across vaccines.⁷ We defined target attainment as a mean coverage estimate of 90% or higher, by vaccine and for all assessed vaccines, in 2010 and 2019. To ensure comparability across vaccines and years, our main analysis included nine vaccines for each location and year, irrespective of vaccine introduction. We then repeated this analysis considering only vaccines included in each location's national immunisation schedule in the year of evaluation (appendix section 4.2).

Third, we estimated the number of zero-dose children as a function of DTP1:

$$DTP0_{iy} = (1 - DTP1_{iy}) \times p_{iy}$$

where $DTP0$ is the number of children younger than 1 year of age without any DTP doses for location i and year y , $DTP1$ is DTP1 coverage, and p is the GBD 2020 R1 population estimate of children younger than 1 year. We used children who did not receive a first dose of a DTP-containing vaccine as a proxy for zero-dose children not reached by routine immunisation services, following the draft IA2030 implementation framework (which has since been published)⁹ and previous studies;¹⁸ additional details are provided in the appendix (section 4.3).

Comparison with WUENIC estimates

We calculated concordance correlation coefficients for each vaccine, comparing coverage estimates to those produced by WUENIC for each location-year. We also aggregated country-level WUENIC coverage estimates to the global level (weighted means using GBD 2020 R1 target population estimates, to provide more direct

comparisons with this study's global estimates; appendix section 4.4, table S8).

Role of the funding source

The funder of this study had no role in study design, data collection, data analysis, data interpretation, or the writing of the report.

Results

Overview

In this section, we present global results and results by GBD super-region. Owing to BCG phase-out or non-introduction in 46 countries as of 2019, the results presented here focus on the remaining vaccines. We present DTP3 coverage estimates for consistency with other vaccines delivered as a three-dose primary series, while using DTP1 coverage to estimate counts of zero-dose children. Coverage estimates by vaccine, including BCG and DTP1, are available for each location from 1980 to 2019, with corresponding WUENIC estimates, in the appendix (figures S18–S28, S31, table S7) and on the GHDx website.

Historical trends and progress in routine vaccination

Globally, vaccine coverage markedly increased from 1980 to 2019 (figure 1). MCV1 coverage more than doubled, rising from 38.5% (95% UI 35.4–41.3) in 1980 to 83.6% (82.3–84.8) in 2019. During this time, DTP3 coverage also increased from 39.9% (37.5–42.1) to 81.6% (80.4–82.7), and Pol3 coverage rose from 42.6% (41.4–44.1) to 79.8% (78.4–81.1).

Overall, progress for these routine vaccines was most rapid from 1980 to 1989 (figure 2). For DTP3 specifically, global coverage increased from 39.9% (95% UI 37.5–42.1) to 64.2% (63.3–65.1). All GBD super-regions saw DTP3 coverage rise, with universal country-level gains in Latin America and the Caribbean, north Africa and the Middle East, and south Asia. These improvements were concentrated among locations starting with lower coverage: for instance, of 123 countries with DTP3 coverage lower than 60% in 1980, 106 (86.2%) had more than a ten-percentage-point gain by 1989. Similar patterns occurred in the next two decades, with 19 (48.7%) of 39 countries with DTP3 coverage lower than 60% increasing by at least ten percentage points from 1990 to 1999, as did 26 (76.5%) of 34 countries from 2000 to 2009.

From 2010 to 2019, however, progress on DTP3, MCV1, and Pol3 coverage stalled or reversed in many locations. For DTP3, 25 countries with at least 90% coverage in 2010 saw levels fall below this threshold in 2019, and 16 countries with coverage ranging from 60% to 90% in 2010 saw declines of five percentage points or more by 2019. Globally, 94 countries and territories recorded decreasing DTP3 coverage since 2010, with countries in Latin America and the Caribbean among those with the largest reductions (figure 2; appendix figure S14). Results were

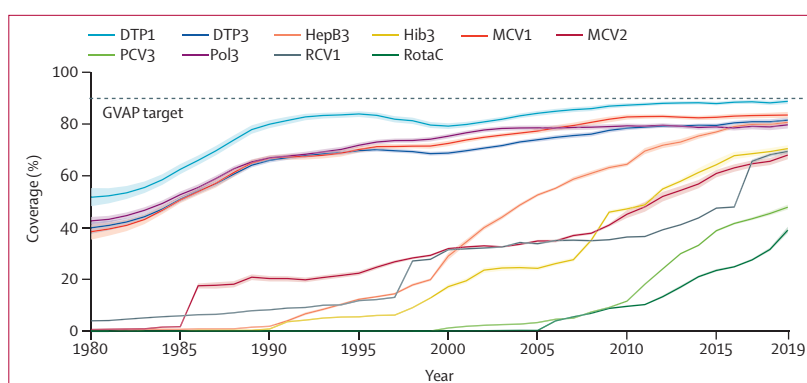


Figure 1: Global vaccine coverage by vaccine, 1980–2019

The dotted line represents the GVAP target of reaching at least 90% coverage by 2020. The solid lines represent the mean estimates for each vaccine. The lighter-coloured shading surrounding the solid lines represents the 95% uncertainty intervals. GVAP=Global Vaccine Action Plan. DTP1=diphtheria-tetanus-pertussis vaccine, first dose. DTP3=diphtheria-tetanus-pertussis vaccine, third dose. HepB3=hepatitis B vaccine, third dose. Hib3=Haemophilus influenzae type b vaccine, third dose. MCV1=measles-containing vaccine, first dose. MCV2=measles-containing vaccine, second dose. PCV3=pneumococcal conjugate vaccine, third dose. Pol3=polio vaccine, third dose. RCV1=rubella-containing vaccine, first dose. RotaC=completed rotavirus series.

similar for MCV1 and Pol3 coverage (appendix figure S14).

Introduction and scale-up of newer vaccines

Since the early 2000s, vaccines such as HepB, Hib, MCV2, PCV, RCV, and RotaC were introduced into many countries' national immunisation schedules and scaled up in an effort to expand protection against these vaccine-preventable diseases. By 2019, global coverage of these newer additions began to approach that of more established vaccines, reaching 80.7% (95% UI 79.5–81.8) for HepB3, 70.6% (69.2–71.9) for Hib3, 69.5% (68.6–70.3) for RCV1, and 68.1% (66.5–69.5) for MCV2 (figure 1). Although global PCV3 and RotaC coverage were somewhat lower in 2019 (47.9% [47.0–48.9] and 39.1% [38.0–40.4], respectively), countries that introduced these vaccines often rapidly increased coverage. For instance, of the 125 countries that introduced PCV into their routine immunisation schedules before 2015, 104 (83.2%) reached PCV3 coverage within five percentage points of DTP3 coverage by 2019; 57 (45.6%) of 79 achieved the equivalent for RotaC coverage.

Progress towards GVAP targets

Benchmarking country performance from 2010 to 2019 provides insight into GVAP trajectories and the likelihood of achieving the 2020 target (figure 3). In 2010, 121 (59.3%) of 204 countries and territories reached at least 90% mean coverage for DTP3, as did 120 (58.8%) of 204 countries and territories for MCV1, and 117 (57.4%) of 204 countries and territories for Pol3; by contrast, in 2019, 109 (53.4%) of 204 countries and territories reached at least 90% mean coverage for DTP3, as did 124 (60.8%) of 204 countries and territories for MCV1, and 109 (53.4%) of 204 countries and territories for Pol3.

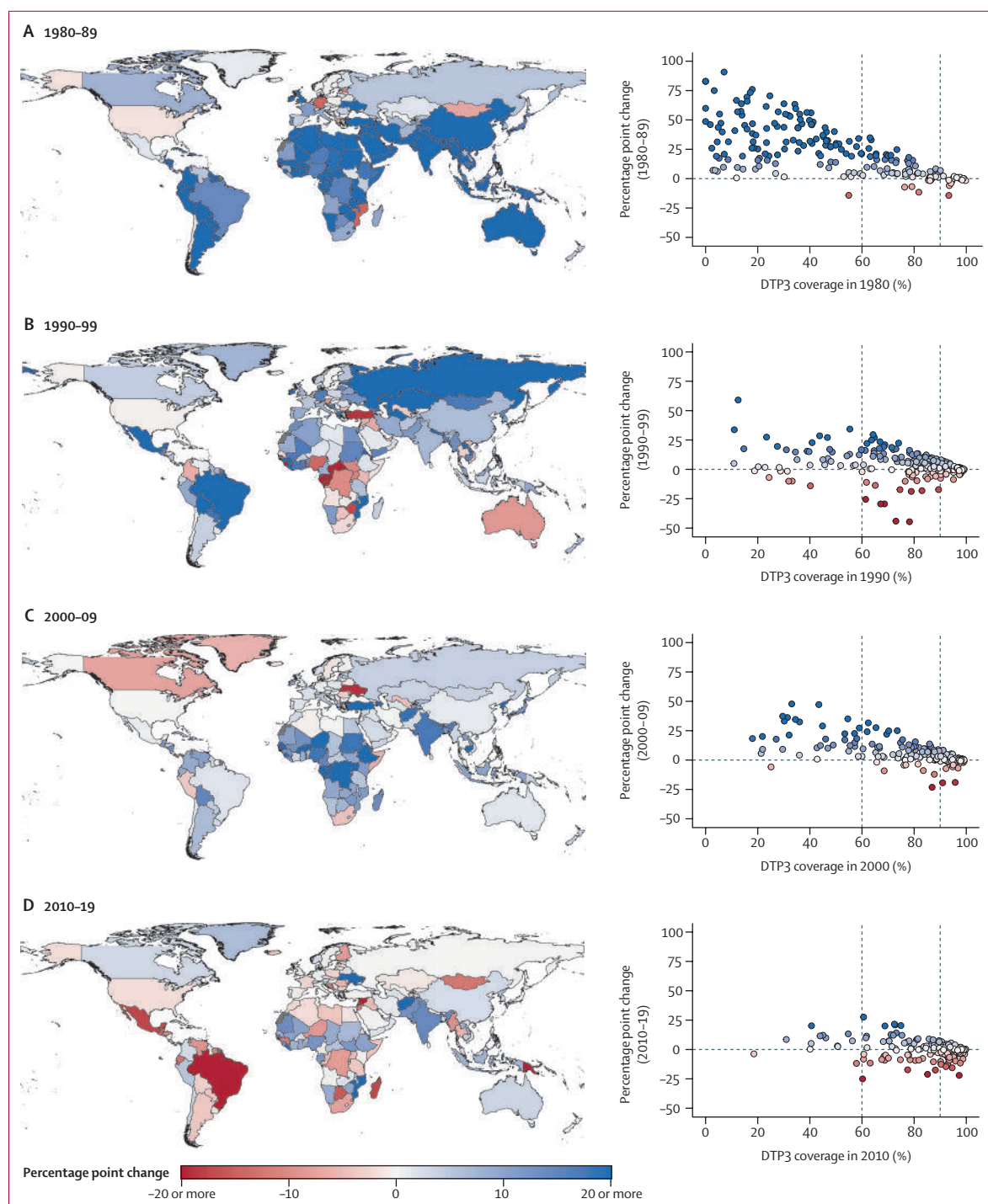


Figure 2: Changes in DTP3 coverage, by decade, from 1980 to 1989 (A), 1990 to 1999 (B), 2000 to 2009 (C), and 2010 to 2019 (D)
 For each decade, maps (left) and scatterplots (right) are colour-coded to reflect absolute changes in DTP3 coverage. Locations not estimated for GBD are shown in grey. Each circle on the scatterplot represents a country or territory, and the same colour is reflected on the corresponding map. For the scatterplots, the horizontal dashed line at 0 indicates no coverage change within the decade; the vertical dashed lines mark 60% and 90% coverage, with the latter being the national GVAP target for 2020. DTP3=diphtheria-tetanus-pertussis vaccine, third dose. GBD=Global Burden of Diseases, Injuries, and Risk Factors Study. GVAP=Global Vaccine Action Plan.

Worsening performance was particularly striking for two GBD super-regions (central Europe, eastern Europe, and central Asia; and Latin America and the Caribbean),

whereas south Asia saw sustained improvement for MCV1. Sub-Saharan Africa had the lowest proportion of countries that met the 90% mean GVAP target in 2019,

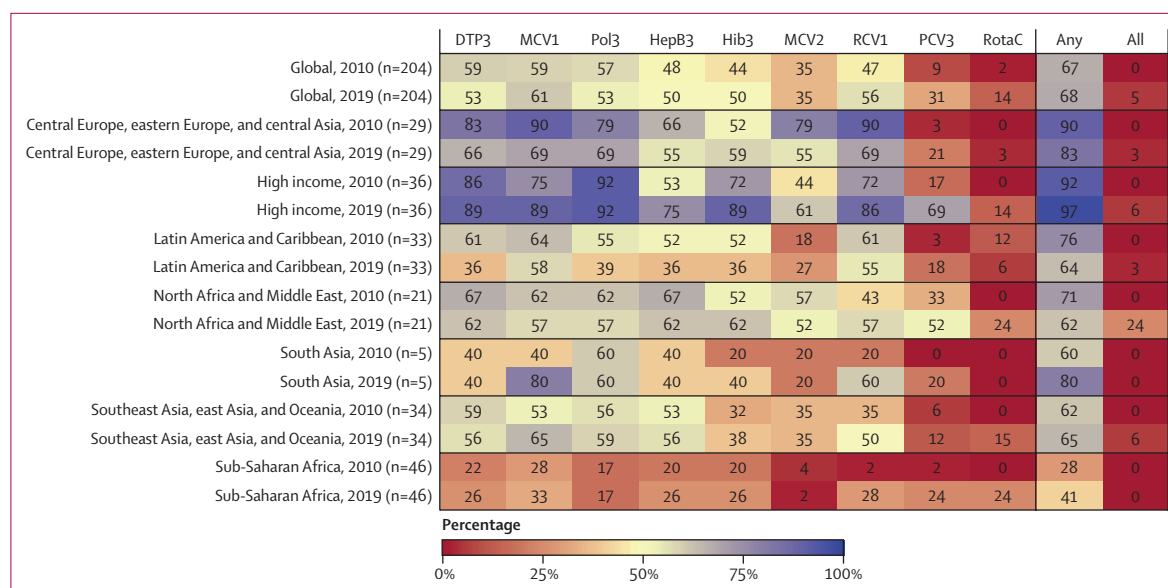


Figure 3: Percentage of locations reaching the GVAP national coverage target in 2010 and 2019, globally and by GBD super-region

Each cell represents the percentage of locations, globally and by GBD super-region, that have reached the GVAP 90% national coverage target in 2010 and 2019 for the assessed vaccines. Percentages are shown for each vaccine separately meeting the target, for at least any single vaccine meeting the target, and for all assessed vaccines listed as meeting the target. Percentages are calculated on the basis of the total number of locations in the GBD super-region, irrespective of whether locations included the vaccine in their national schedule in 2010 or 2019. GVAP=Global Vaccine Action Plan. GBD=Global Burden of Diseases, Injuries, and Risk Factors Study. DTP3=diphtheria-tetanus-pertussis vaccine, third dose. MCV1=measles-containing vaccine, first dose. Pol3=polio vaccine, third dose. HepB3=hepatitis B vaccine, third dose. Hib3=Haemophilus influenzae type b vaccine, third dose. MCV2=measles-containing vaccine, second dose. RCV1=rubella-containing vaccine, first dose. PCV3=pneumococcal conjugate vaccine, third dose. RotaC=completed rotavirus series.

ranging from 2.2% to 32.6% by vaccine, and with 19 (41.3%) of 46 locations meeting this mean target for any vaccine. Globally, 11 countries and territories reached 90% or higher average coverage across nine assessed vaccines in 2019: Armenia, Australia, Bahrain, Mauritius, Morocco, Nicaragua, Niue, Norway, Palestine, Qatar, and Saudi Arabia. Target attainment conditional on vaccine introduction is summarised in the appendix (figure S29).

Changes in vaccine coverage relative to sociodemographic development

On average, higher vaccine coverage was associated with higher SDI (figure 4); however, this relationship was far from linear. For instance, an increase in SDI values from 25 to 35 (on a 0–100 scale) was associated with a greater than 25-percentage-point difference in DTP3 coverage (ie, from expected global averages of 30.3% [95% UI 27.7–32.8] with an SDI of 25 to 58.5% [55.0–61.5] with an SDI of 35). At higher levels of SDI, similar changes in SDI were associated with far less pronounced changes in coverage: changing from an SDI of 75 to 85, for example, corresponded to a 2.0-percentage-point difference in DTP3 coverage (from 95.3% [94.7–95.8] to 97.3% [97.0–97.6]).

Comparing these average global relationships between DTP3 coverage and SDI also helps to identify locations that have outpaced—or are lagging behind—changes in development. Burkina Faso, for example, emerged as far

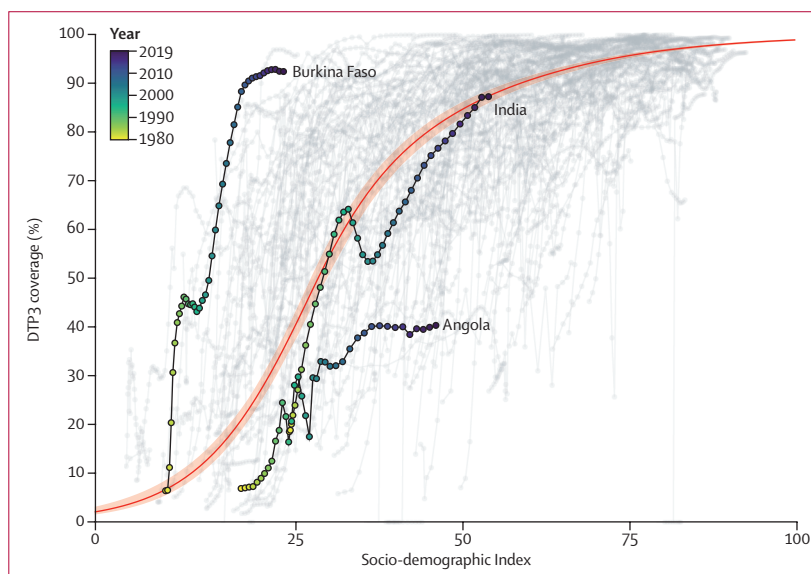


Figure 4: Relationships between national DTP3 coverage and SDI, 1980–2019

The solid red line represents the global average relationship between DTP3 coverage and SDI alone, as estimated across locations and over time; the shading represents the 95% uncertainty interval. Observed SDI estimates and DTP3 coverage estimates for each location are shown in light grey. For selected countries (ie, Burkina Faso, India, and Angola), the colour of each point represents the estimation year, from yellow (1980) to purple (2019). Each location's vaccine coverage estimates relative to SDI can be found in the appendix (figure S15). DTP3=diphtheria-tetanus-pertussis vaccine, third dose. SDI=Socio-demographic Index.

exceeding its expected DTP3 coverage given its SDI, reaching 92.4% (87.3–95.9) coverage in 2019 when its expected DTP3 coverage was 35.6% (32.9–38.2) relative

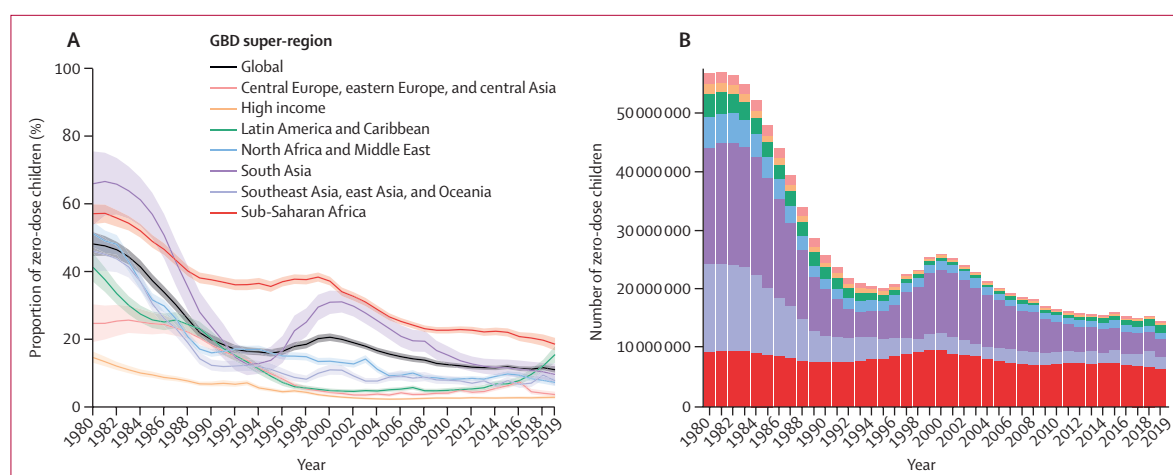


Figure 5: Proportion (A) and total number (B) of zero-dose children, globally and by GBD super-region, 1980–2019

The solid lines represent the proportion of zero-dose children for each GBD super-region, and the lighter-coloured shading surrounding the solid lines represents the 95% uncertainty intervals. Zero-dose children are approximated by subtracting estimates of DTP1 coverage from 100%, and then multiplying percentages by population estimates from GBD. Bar colours denote each GBD super-region. GBD=Global Burden of Diseases, Injuries, and Risk Factors Study. DTP1=diphtheria-tetanus-pertussis vaccine, first dose.

to SDI. By contrast, Angola had among the largest gaps between estimated DTP3 coverage and expected levels on the basis of SDI alone: in 2019, Angola's DTP3 coverage was 40.3% (33.7–47.3), whereas its expected coverage was 81.6% (79.6–83.3). While this gap grew in Angola over time, by 2019 other countries such as India saw observed coverage track more closely to expected estimates on the basis of SDI alone. Similar patterns occurred for MCV1 and Pol3 coverage, with country-by-country comparisons for each vaccine provided in the appendix (figures S15–S16).

Trends in the number of zero-dose children

Globally, the number of zero-dose children fell from 56.8 million (95% UI 52.6–60.9) in 1980 to 14.5 million (13.4–15.9) in 2019, a decrease of nearly 75% (figure 5). Southeast Asia, east Asia, and Oceania had among the largest reductions during this time (86.3% [83.0–89.1]), as did south Asia (84.4% [78.3–89.1]). Trends in counts of zero-dose children involved both changes in DTP1 coverage and population growth. For example, in sub-Saharan Africa, the total number of zero-dose children decreased by 30.1% (21.8–37.8) from 1980 to 2019, with 6.5 million (5.8–7.1) zero-dose children remaining in 2019. Yet the percentage of zero-dose children in sub-Saharan Africa decreased even more drastically, from 57.1% (54.1–59.9) in 1980 to 18.6% (16.8–20.5) in 2019. Conversely, the number and proportion of zero-dose children increased in Latin America and the Caribbean from 2000 onwards, rising from 0.52 million (0.46–0.58) in 2000 to 1.5 million (1.2–1.7) in 2019 and from 5.0% (4.4–5.6) in 2000 to 15.6% (13.2–18.1) in 2019. In 2019, 75% of zero-dose children lived in 14 countries: Angola, Brazil, Chad, China, Democratic Republic of the Congo, Ethiopia,

India, Indonesia, Mexico, Nigeria, Pakistan, Philippines, Somalia, and South Africa.

Comparison with WUENIC estimates

Concordance between GBD-based and WUENIC-based estimates was generally high (ie, from $\rho_c=0.74$ for RCV1 to $\rho_c=0.92$ for DTP3 and MCV1; appendix table S8). Globally, similar coverage trends were observed for DTP3, MCV1, and Pol3, with gains stagnating from 2010 to 2019,^{13,18} and more variation occurred at the country level, as well as by vaccine, over time. Additional comparisons are shown in the appendix (figures S30–S31).

Discussion

Summary of the main findings

This study provides a comprehensive assessment of global patterns in coverage for 11 vaccines from 1980 to 2019, a 40-year period of both notable progress and enduring disparities for routine vaccination. Coverage of longstanding and more recently introduced vaccines improved in much of the world between 1980 and 2010, protecting more children against vaccine-preventable diseases than ever before. Yet from 2010 to 2019, a period in which the introduction and scale-up of new vaccines was largely successful, gains for more established vaccines were minimal; in some locations, particularly in Latin America and the Caribbean, vaccine coverage faltered. These trends imply that, while the GVAP era broadened global access to more vaccines, less progress was made in ensuring routine immunisation services reach all children. In 2019, 14.5 million children worldwide still lacked one dose of DTP, a key indicator of zero-dose children and thus those who are at greatest risk of being left behind. Timely, disaggregated data on the evolving needs for routine immunisation programmes

are crucial to target resources to those who need them the most, particularly if the global ambitions encompassed by IA2030 are to be realised in the next decade.

Global gains and challenges in routine immunisation

The GVAP era followed years of sizeable progress for childhood vaccination: from 1980 to 2010, global coverage of original EPI vaccines such as DTP3 and MCV1 more than doubled, the number of zero-dose children fell steadily, and from the early 2000s initiatives such as Gavi, the Vaccine Alliance, supported the introduction and scale-up of new vaccines.^{18,19,34} Access to HepB and Hib vaccines, as well as PCV and RotaC, vastly improved, and many countries, especially those in sub-Saharan Africa, rapidly increased coverage of these newer vaccines to approach that of more established vaccines. Yet expanding these gains hinges upon increasing the reach of routine immunisation to all children—and the world has been far less successful in this endeavour, as evidenced by the stagnating or even faltering coverage of long-established vaccines between 2010 and 2019. Such trends correspond with other global analyses, such as those from WUENIC, underscoring challenges in further improving and expanding vaccine coverage in the past decade.^{18,19} Although countries across the sociodemographic spectrum have shown these concerning trends, this trajectory has been particularly striking for Latin America and the Caribbean. Past research suggests that compounding factors, including large subnational disparities in access to vaccines and shifting perceptions of vaccine risk, could have contributed to regional declines.^{35–37} By 2019, only 109 of 204 countries and territories reached at least 90% mean estimated coverage for DTP3, while only 11 countries and territories met this threshold across nine of the assessed vaccines.

Improving and sustaining advances in vaccination requires a constellation of local and global factors, and our analysis further emphasises that progress in routine immunisation is far from inevitable. Key determinants that drive childhood vaccination trends are complex and inter-related, ranging from individual and community-level characteristics (eg, parental knowledge, vaccine confidence, and physical and financial access to immunisation services) to health-system capacity and enabling macro-level forces (eg, general health-system strength, political commitment to vaccine programmes, reliable funding, and supportive policies).^{38,39} Longstanding challenges in supply chain or distribution channels can constrain further scale-up and outreach services,⁴⁰ while societal vaccine confidence patterns have been strongly linked to uptake.⁴¹ Prolonged conflict or surges of unrest can contribute to persistently low coverage or abrupt declines in vaccination rates.^{42,43} Widespread infectious disease outbreaks, as underscored by Ebola virus disease and now COVID-19,^{44,45} can strain already fragile health systems and disrupt usual modes of vaccine delivery. How

these factors affect vaccine services differs across locations and over time, and thus warrants further examination to better understand the pathways towards strengthening routine immunisation services.

In light of recent trends, coupled with the effects of COVID-19 on routine immunisation services,^{10–12} accelerating global vaccination gains will require more than a continuation of current programme strategies.^{41,42} By quantifying uncertainty and synthesising multiple sources of coverage data while adjusting for biases, statistically derived coverage estimates provide a robust platform to track progress towards global targets. Moreover, IA2030 marks an evolution in global immunisation priorities, recognising the limitations of the more top-down GVAP⁴⁶ and championing locally tailored approaches for each community. IA2030 also emphasises the need to identify and reach zero-dose children historically missed by routine immunisation services, and that strengthening of such services must occur in tandem with bolstering service access and primary care integration.⁴⁷ To support these efforts, the action-based IA2030 Monitoring and Evaluation Framework supports the use of data not only to track progress but also to continuously improve routine immunisation programmes at all levels of implementation.⁹ This shift in strategy aims to further develop the reach, equity, and sustainability of global immunisation systems within the contexts of primary care and universal health coverage. For these efforts to be successful, however, data must be of sufficient quality to inform policy decisions. As such, our estimates can serve as a useful comparator to those produced by WUENIC:⁴⁸ areas of divergence might indicate low data availability or quality, resulting in high sensitivity to methodological assumptions.

Countries where coverage gains have outpaced the average pace of progress could provide valuable insights for breaking through coverage plateaus. For example, studies of vaccine coverage in Burkina Faso emphasise the importance of leadership and communication from vaccination centres in promoting effective services.^{49,50} Consistency in programme review, funding, and country-led initiatives targeting traditionally marginalised or hard-to-reach populations has been positively associated with vaccine uptake and success.⁵¹ Amid ongoing challenges to equitably improve routine immunisation, our estimates of vaccine coverage aim to augment the evidence base from which more data-driven and strategic planning can occur for global initiatives and national programmes alike.

Limitations

This study is subject to several limitations. First, we could not account for all potential sources of bias in survey data. For example, displaced or otherwise marginalised populations could be under-represented in surveys that base sampling frames on official census data. Parental recall of vaccination is also subject to bias.

We did not apply a recall adjustment, as previous efforts to quantify recall biases show substantial variation in both direction and magnitude.^{52–54} We were also unable to systematically adjust for differences in methodological quality between surveys, as such descriptions were not available for all sources. Second, our approach to leveraging multiple age cohorts maximises the use of available data, but assumes negligible effects of migration, survival bias due to differential mortality by vaccination status, and catch-up vaccination that might not be well captured in survey data. These limitations could result in over-estimation of coverage in some locations (ie, marginalised groups generally have lower access to routine immunisation services than the general population; unvaccinated children might have higher mortality at young ages than vaccinated children and thus are not represented in survey data); however, the precise effects are likely to vary by location and over time. Third, in order to incorporate both administrative and survey data into our current modelling framework, we did not account for the timeliness of vaccination. Future studies should develop methods to estimate age-specific coverage rates where data permit, as such estimates could better reflect trends in schedule adherence and when delays in vaccination are occurring. Fourth, our estimates do not explicitly account for vaccines administered through private markets (aside from selected vaccines in China), vaccines introduced only for certain at-risk populations, or vaccine doses administered through campaigns; as such, coverage might be underestimated in locations where these modes of delivery are common. Fifth, although also utilised elsewhere,^{9,18} using DTP1 coverage to inform zero-dose estimates could over-estimate the total number of children who have never received any vaccine. Future analyses could examine the correlation structures across vaccine-dose combinations at the individual level and ascertain the likelihood of children without DTP1 receiving any other vaccine over time.⁵⁵ Sixth, our study focuses on national-level vaccine coverage, which might obscure important subnational inequalities.^{56,57} To reach children left behind by current vaccination programmes, within-country disparities in childhood vaccination coverage across factors transcending geography (eg, wealth and education, race and ethnicity, and refugee status) must continue to be identified and addressed.

Conclusions

Childhood vaccine coverage has markedly improved since the 1980s, cementing efforts to expand original EPI vaccines and initiatives to scale up new vaccines as among the most important success stories in global health. Yet, stagnation and, in some cases, reversal of gains from 2010 to 2019 serve as warning signs that staying the course today will not deliver universal access to immunisation in the future. The complementary visions of GVAP and now IA2030 conceive of a world

where all children benefit from the protection of safe and effective vaccines and have the opportunity to live full, healthy lives. To meet these goals, it is crucial to address both enduring and new challenges facing childhood vaccination efforts and use evidence-informed strategies for strengthening routine immunisation programmes throughout the world.

Contributors

Please see the appendix (section 5) for more detailed information about individual author contributions to the research, divided into the following categories: managing the estimation or publication process; writing the first draft of the manuscript; primary responsibility for applying analytical methods to produce estimates; primary responsibility for seeking, cataloguing, extracting, or cleaning data; designing or coding figures and tables; providing data or critical feedback on data sources; development of methods or computational machinery; providing critical feedback on methods or results; drafting the manuscript or revising it critically for important intellectual content; extracting, cleaning, or cataloguing data; designing or coding figures and tables; and managing the overall research enterprise.

GBD 2020, Release 1, Vaccine Coverage Collaborators

Natalie C Galles*, Patrick Y Liu*, Rachel L Updike*, Nancy Fullman, Jason Nguyen, Sam Rolfe, Alyssa N Sbarra, Megan F Schipp, Ashley Marks, Gdiom Gebreheat Abady, Kaja M Abbas, Sumra Wajid Abbasi, Hedayat Abbastabar, Foad Abd-Allah, Amir Abdoli, Hassan Abolhassani, Akine Eshete Abosetugn, Maryam Adabi, Abdu A Adamu, Olatunji O Adetokunboh, Qorinah Estiningtyas Sakilah Adnani, Shailesh M Advani, Saira Afzal, Seyed Mohammad Kazem Aghamir, Bright Opoku Ahinkorah, Sohail Ahmad, Tauseef Ahmad, Sepideh Ahmadi, Haroon Ahmed, Muktar Beshir Ahmed, Tarik Ahmed Rashid, Yusra Ahmed Salih, Yonas Akalu, Addis Akilu, Chisom Joyqueenet Akunna, Hanadi Al Hamad, Fares Alahdab, Luciana Albano, Yosef Alemayehu, Keyfalew Addis Alene, Ayman Al-Eyadhy, Robert Kaba Alhassan, Liaqat Ali, Syed Mohamed Aljunid, Sami Almustanyir, Khalid A Altirkawi, Nelson Alvis-Guzman, Hubert Amu, Catalina Liliana Andrei, Tudorel Andrei, Adnan Ansar, Alireza Ansari-Moghaddam, Ippazio Cosimo Antonazzo, Benny Antony, Jalal Arabloo, Morteza Arab-Zozani, Kurnia Dwi Artanti, Judie Arulappan, Asma Tahir Awan, Mamaru Ayenew Awoke, Muluken Altaye Ayza, Ghasem Azarian, Ahmed Y Azzam, Darshan B B, Zaheer-Ud-Din Babar, Senthilkumar Balakrishnan, Maciej Banach, Simachew Animen Bante, Till Winfried Bärnighausen, Hiba Jawdat Barqawi, Amadou Barrow, Quique Bassat, Naranituya Bayarmagnai, Diana Fernanda Bejarano Ramirez, Tariku Tesfaye Bekuma, Habtamu Gebrehana Belay, Uzma Iqbal Belgaumi, Akshaya Srikanth Bhagavathula, Dinesh Bhandari, Nikha Bhardwaj, Pankaj Bhardwaj, Sonu Bhaskar, Kritika Bhattacharyya, Sadia Bibi, Ali Bijani, Antonio Biondi, Archith Boloor, Dejana Braithwaite, Danilo Buonsenso, Zahid A Butt, Paulo Camargos, Giulia Carreras, Felix Carvalho, Carlos A Castañeda-Orjuela, Raja Chandra Chakinala, Jaykaran Charan, Souranshu Chatterjee, Soosanna Kumary Chattu, Vijay Kumar Chattu, Fazle Rabbi Chowdhury, Devasahayam J Christopher, Dinh-Toi Chu, Sheng-Chia Chung, Paolo Angelo Cortesi, Vera Marisa Costa, Rosa A S Couto, Omid Dadras, Amare Belachew Dagnew, Baye Dagnew, Xiaochen Dai, Lalit Dandona, Rakhi Dandona, Jan-Walter De Neve, Meseret Derbew Molla, Behailu Tariku Derseh, Rupak Desai, Abebaw Alemayehu Desta, Deepak Dhamnetiya, Mandira Lamichhane Dhimal, Meghnath Dhimal, Mostafa Dianatinasab, Daniel Diaz, Shirin Djalalinia, Fariba Dorostkar, Bassey Edem, Hisham Atan Edinur, Sahar Eftekharzadeh, Iman El Sayed, Maysaa El Sayed Zaki, Muhammed Elhadi, Shaimaa I El-Jaafari, Aisha Elsharkawy, Shymaa Enany, Ryenchindorj Erkhembayar, Christopher Imokhuede Esezobor, Sharareh Eskandarieh, Ifeanyi Jude Ezeonwumelu, Sayeh Ezzikouri, Jawad Fares, Pawan Sirwan Faris, Berhanu Elfu Feleke, Tomas Y Ferede, Eduarda Fernandes, João C Fernandes, Pietro Ferrara, Irina Filip, Florian Fischer, Mark Rohit Francis, Takeshi Fukumoto,

Mohamed M Gad, Shilpa Gaidhane, Silvano Gallus, Tushar Garg, Biniyam Sahiledengle Geberemariam, Teshome Gebre, Birhan Gebresilassie Gebregiorgis, Ketema Bizuwork Gebremedhin, Berhe Gebremichael, Bradford D Gessner, Keyghobad Ghadiri, Mansour Ghafourifard, Ahmad Ghashghae, Syed Amir Gilani, Ionela-Roxana Glăvan, Ekaterina Vladimirovna Glushkova, Mahaveer Golechha, Kebebe Bekele Gonfa, Sameer Vali Gopalani, Houman Goudarzi, Mohammed Ibrahim Mohialdeen Gubari, Yuming Guo, Veer Bala Gupta, Vivek Kumar Gupta, Reyna Alma Gutiérrez, Emily Haeuser, Rabih Halwani, Samer Hamidi, Asif Hanif, Shafiu Hanif, Harapan Harapan, Arief Hargono, Abdiwahab Hashi, Shoaib Hassan, Mohamed H Hassanein, Soheil Hassanipour, Hadi Hassankhani, Simon I Hay, Khezay Hayat, Mohamed I Hegazy, Golnaz Heidari, Kamal Hezam, Ramesh Holla, Mohammad Enamul Hoque, Mostafa Hosseini, Mehdi Hosseinzadeh, Mihaela Hostiuc, Mowafa Househ, Vivian Chia-rong Hsieh, Junjie Huang, Ayesha Humayun, Rabia Hussain, Nawfal R Hussein, Segun Emmanuel Ibitoye, Olayinka Stephen Ilesanmi, Irena M Ilic, Milena D Ilic, Sumant Inamdar, Usman Iqbal, Lalu Muhammad Irahman, Seyed Sina Naghibi Irvani, Sheikh Mohammed Shariful Islam, Nahlah Elkudssiah Ismail, Ramaiah Itumalla, Ravi Prakash Jha, Farahnaz Joukar, Ali Kabir, Zubair Kabir, Rohallah Kalhor, Zul Kamal, Stanley M Kamande, Himal Kandel, André Karch, Getinet Kassahun, Nicholas J Kassebaum, Patrick DMC Katoto, Bayew Kelkay, Andre Pascal Kengne, Yousef Saleh Khader, Himanshu Khajuria, Ibrahim A Khalil, Ejaz Ahmad Khan, Gulfaraz Khan, Junaid Khan, Maseer Khan, Moien AB Khan, Young-Ho Khang, Abdullah T Khoja, Jagdish Khubchandani, Gyu Ri Kim, Min Seo Kim, Yun Jin Kim, Ruth W Kimokoti, Adnan Kisa, Sezer Kisa, Vladimir Andreevich Korshunov, Soewarta Kosen, Barthelemy Kuate Defo, Vaman Kulkarni, Avinash Kumar, G Anil Kumar, Nithin Kumar, Alexander Kwarteng, Carlo La Vecchia, Faris Hasan Lami, Iván Landires, Savita Lasrado, Zohra S Lassi, Hankil Lee, Yeong Yeh Lee, Miriam Levi, Sonia Lewycka, Shanshan Li, Xuefeng Liu, Stany W Lobo, Platon D Lopukhov, Rafael Lozano, Ricardo Lutzky Saute, Muhammed Magdy Abd El Razek, Alaa Makki, Ahmad Azam Malik, Fariborz Mansour-Ghanaei, Mohammad Ali Mansournia, Lorenzo Giovanni Mantovani, Francisco Rogerlândio Martins-Melo, Philippa C Matthews, John Robert Carabeo Medina, Walter Mendoza, Ritesh G Menezes, Endalkachew Worku Mengesha, Tuomo J Meretoja, Amanual Getnet Mersha, Mohamed Kamal Mesregah, Tomislav Mestrovic, Bartosz Miazgowski, George J Milne, Andreea Mirica, Erkin M Mirrakhimov, Hamid Reza Mirzaei, Sanjeev Misra, Prasanna Mithra, Masoud Moghadaszadeh, Teroj Abdulrahman Mohamed, Karzan Abdulmuhsin Mohammad, Yousef Mohammad, Mokhtar Mohammadi, Abdollah Mohammadian-Hafshejani, Arif Mohammed, Shafiu Mohammed, Archisman Mohapatra, Ali H Mokdad, Mariam Molokhia, Lorenzo Monasta, Mohammad Ali Moni, Ahmed Al Montasir, Catrin E Moore, Ghobad Moradi, Rahmatollah Moradzadeh, Paula Moraga, Ulrich Otto Mueller, Sandra B Munro, Mohsen Naghavi, Mukhammad David Naimzada, Muhammad Naveed, Biswa Prakash Nayak, Ionut Nego, Sandhya Neupane Kandel, Trang Huyen Nguyen, Rajan Nikbaksh, Dina Nur Anggraini Ningrum, Molly R Nixon, Chukwudi A Nnaji, Jean Jacques Noubiap, Virginia Nuñez-Samudio, Vincent Ebuka Nwatah, Bogdan Oancea, Chimedsuren Ochir, Felix Akpojene Ogbo, Andrew T Olagunju, Babayemi Oluwaseun Olakunde, Obinna E Onwujekwe, Nikita Ostavnov, Stanislav S Ostavnov, Mayowa O Owolabi, Jagdish Rao Padubidri, Keyvan Pakshir, Eun-Cheol Park, Fatemeh Pashazadeh Kan, Mona Pathak, Rajan Paudel, Shrikant Pawar, Jeevan Pereira, Mario F P Peres, Arokiasamy Perianayagam, Marina Pinheiro, Majid Pirestani, Vivek Podder, Roman V Polibin, Richard Charles G Pollok, Maarten J Postma, Faheem Hyder Pottot, Mohammad Rabiee, Navid Rabiee, Amir Radfar, Alireza Rafiei, Vafa Rahimi-Movaghar, Mosiur Rahman, Amir Masoud Rahmani, Setyaningrum Rahmawaty, Aashish Rajesh, Rebecca E Ramshaw, Priyanga Ranasinghe, Chythra R Rao, Sowmya J Rao, Priya Rathi, David Laith Rawaf, Salman Rawaf, Andre M N Renzaho, Negar Rezaei,

Mohammad Sadegh Rezai, Maria Rios-Blancas, Emma L B Rogowski, Luca Ronfani, Godfrey M Rwegerera, Anas M Saad, Siamak Sabour, Basema Saddik, Mohammad Reza Saeb, Umar Saeed, Amirhossein Sahebkar, Mohammad Ali Sahraian, Nasir Salam, Hamideh Salimzadeh, Mehrnoosh Samaei, Abdallah M Samy, Juan Sanabria, Francesco Sanmarchi, Milena M Santric-Milicevic, Benn Sartorius, Arash Sarveazad, Brijesh Sathian, Monika Sawhney, Deepak Saxena, Sonia Saxena, Abdul-Aziz Seidu, Allen Seylani, Masood Ali Shaikh, Morteza Shamsizadeh, Pavanchand H Shetty, Mika Shigematsu, Jae Il Shin, Negussie Boti Sidemo, Ambrish Singh, Jasvinder A Singh, Smriti Sinha, Valentin Yurievich Skryabin, Anna Aleksandrovna Skryabina, Amin Soheili, Eyayou Girma Tadesse, Animut Tagele Tamiru, Ker-Kan Tan, Yohannes Tekalegn, Mohamad-Hani Temsah, Bhaskar Thakur, Rekha Thapar, Aravind Thavamani, Ruoyan Tobe-Gai, Hamid Reza Tohidinik, Marcos Roberto Tovani-Palone, Eugenio Traini, Bach Xuan Tran, Manjari Tripathi, Berhan Tsegaye, Gebiyaw Wudie Tsegaye, Anayat Ullah, Saif Ullah, Sana Ullah, Brigid Unim, Marco Vacante, Diana Zuleika Velazquez, Bay Vo, Sebastian Vollmer, Giang Thu Vu, Linh Gia Vu, Yasir Waheed, Andrea Sylvia Winkler, Charles Shey Wiysonge, Vahit Yiğit, Birhanu Wubale Yirdaw, Dong Keon Yon, Naohiro Yonemoto, Chuanhua Yu, Deniz Yuce, Ismaeel Yunusa, Mohammad Zamani, Maryam Zamanian, Dejene Tesfaye Zewdie, Zhi-Jiang Zhang, Chenwen Zhong, Alimuddin Zumla, Christopher J L Murray, Stephen S Lim†, and Jonathan F Mosser†. *Co-first authors, ordered alphabetically. †Co-senior authors, ordered alphabetically.

Affiliations

Institute for Health Metrics and Evaluation (N C Galles MPH, R L Updike MPH, N Fullman MPH, J Nguyen MS, S Rolfe BA, A N Sbarra MPH, M F Schipp MA, A Marks MA, X Dai PhD, Prof L Dandona MD, Prof R Dandona PhD, E Haeuser PhD, Prof S I Hay FMedSci, N J Kassebaum MD, Prof R Lozano MD, Prof A H Mokdad PhD, Prof M Naghavi MD, M R Nixon PhD, R E Ramshaw MPH, E L B Rogowski BA, Prof C J L Murray DPhil, Prof S S Lim PhD, J F Mosser MD), Department of Health Metrics Sciences, School of Medicine (Prof R Dandona PhD, Prof S I Hay FMedSci, N J Kassebaum MD, Prof R Lozano MD, Prof A H Mokdad PhD, Prof M Naghavi MD, B Sartorius PhD, Prof C J L Murray DPhil, Prof S S Lim PhD), Department of Anesthesiology & Pain Medicine (N J Kassebaum MD), Department of Global Health (I A Khalil MD), University of Washington, Seattle, WA, USA; David Geffen School of Medicine (P Y Liu MPH), University of California Los Angeles, Los Angeles, CA, USA; Department of Nursing (G G Abady MSc), Adigrat University, Adigrat, Ethiopia; Department of Infectious Disease Epidemiology (K M Abbas PhD), London School of Hygiene & Tropical Medicine, London, UK; Department of Biological Sciences (S W Abbasi PhD, L Ali PhD), Multidisciplinary Department (A Ullah MS), National University of Medical Sciences (NUMS), Rawalpindi, Pakistan; Advanced Diagnostic and Interventional Radiology Research Center (H Abbastabar PhD), Research Center for Immunodeficiencies (H Abolhassani PhD), Urology Research Center (Prof S Aghamir PhD), Multiple Sclerosis Research Center (S Eskandarieh PhD, Prof M Sahraian MD), Department of Epidemiology and Biostatistics (Prof M Hosseini PhD, M Mansournia PhD), Pediatric Chronic Kidney Disease Research Center (Prof M Hosseini PhD), Department of Medical Immunology (H Mirzaei PhD), Sina Trauma and Surgery Research Center (Prof V Rahimi-Movaghar MD), Non-communicable Diseases Research Center (N Rezaei PhD), Endocrinology and Metabolism Research Center (N Rezaei PhD), Digestive Diseases Research Institute (H Salimzadeh PhD), Tehran University of Medical Sciences, Tehran, Iran; Department of Neurology (Prof F Abd-Allah MD, S I El-Jaafari MD, M I Hegazy PhD), Department of Endemic Medicine and Hepatogastroenterology (A Elsharkawy MD), Cairo University, Cairo, Egypt; Department of Parasitology and Mycology (A Abdoli PhD), Jahrom University of Medical Sciences, Jahrom, Iran; Department of Laboratory Medicine (H Abolhassani PhD), Karolinska University Hospital, Huddinge, Sweden; Department of Public Health (A E Abosetegn MPH, B T Derseh MPH), Department of Nursing

(B G Gebregiorgis MSc), Debre Berhan University, Debre Berhan, Ethiopia; Department of Environmental Health Engineering (G Azarian PhD), Hamadan University of Medical Sciences, Hamadan, Iran (M Adabi PhD); Department of Global Health (A A Adamu PhD, O O Adetokunboh PhD, P D Katoto PhD), Stellenbosch University, Cape Town, South Africa; Cochrane South Africa (A A Adamu PhD), South African Medical Research Council, Cape Town, South Africa (C A Nnaji MPH, Prof C S Wiysonge MD); Centre of Excellence for Epidemiological Modelling and Analysis (O O Adetokunboh PhD), Stellenbosch University, Stellenbosch, South Africa; Department of Midwifery (Q E S Adnani PhD), Karya Husada Institute of Health Sciences, Kediri, Indonesia; Department of Midwifery (Q E S Adnani PhD), Auckland University of Technology, Auckland, New Zealand; Terasaki Institute for Biomedical Innovation, Los Angeles, CA, USA (S M Advani PhD); Department of Oncology (S M Advani PhD), Georgetown University School of Medicine (S M Kamande BS), Georgetown University, Washington, DC, USA; Department of Community Medicine (Prof S Afzal PhD), King Edward Memorial Hospital, Lahore, Pakistan; Department of Public Health (Prof S Afzal PhD), Public Health Institute, Lahore, Pakistan; The Australian Centre for Public and Population Health Research (ACPPHR) (B O Ahinkorah MPH), University of Technology Sydney, Sydney, NSW, Australia; Faculty of Pharmacy (S Ahmad MSc), MAHSA University, Kuala Langat, Malaysia; Department of Epidemiology and Health Statistics (T Ahmad MS), Southeast University, Nanjing, China; School of Advanced Technologies in Medicine (S Ahmadi PhD), Obesity Research Center (R Nikbakht MD), Department of Epidemiology (S Sabour PhD), Shahid Beheshti University of Medical Sciences, Tehran, Iran; Department of Biosciences (H Ahmed PhD), COMSATS Institute of Information Technology, Islamabad, Pakistan; Department of Epidemiology (M B Ahmed MPH), Jimma University, Jimma, Ethiopia; Australian Center for Precision Health (M B Ahmed MPH), University of South Australia, Adelaide, SA, Australia; Department of Computer Science and Engineering (T Ahmed Rashid PhD), University of Kurdistan Hewler, Erbil, Iraq; Database Technology Department (Y Ahmed Salih PhD), College of Informatics (Y Ahmed Salih PhD), Sulaimani Polytechnic University, Sulaymaniyah, Iraq; Department of Medical Physiology (Y Akalu MSc), Department of Human Physiology (B Dagnew MSc), Department of Biochemistry (M Derbew Molla MSc), Department of Surgical Nursing (A A Desta MSc), Department of Midwifery (B Kelkay MSc, A T Tamiru MSc, B W Yirdaw MSc), School of Medicine (A G Mersha MD), University of Gondar, Gondar, Ethiopia; Department of Medical Laboratory Sciences (A Akilu MSc), Department of Midwifery (Y Alemayehu MSc), Department of Public Health (N B Sidemo MPH), Department of Biomedical Sciences (E G Tadesse MSc), Arba Minch University, Arba Minch, Ethiopia; Department of Public Health (C J Akunna DMD), The Inter-country Centre for Oral Health (ICOH) for Africa, Jos, Nigeria; Department of Public Health (C J Akunna DMD), Federal Ministry of Health, Garki, Nigeria; Geriatric and Long Term Care Department (H Al Hamad MD, B Sathian PhD), Rumailah Hospital (H Al Hamad MD), Hamad Medical Corporation, Doha, Qatar; Mayo Evidence-based Practice Center (F Alahdab MSc), Mayo Clinic Foundation for Medical Education and Research, Rochester, MN, USA; Department of Experimental Medicine (L Albano MD), University of Campania Luigi Vanvitelli, Naples, Italy; Faculty of Health Sciences (K A Alene MPH), Curtin University, Perth, WA, Australia; Wesfarmers Centre of Vaccines and Infectious Diseases (K A Alene MPH), Telethon Kids Institute, Perth, WA, Australia; Pediatric Intensive Care Unit (A Al-Eyadhy MD, K A Altirkawi MD, M Tensah MD), Internal Medicine Department (Y Mohammad MD), King Saud University, Riyadh, Saudi Arabia; Institute of Health Research (R K Alhassan PhD), Department of Population and Behavioural Sciences (H Amu PhD), University of Health and Allied Sciences, Ho, Ghana; Department of Health Policy and Management (Prof S M Aljunid PhD), Kuwait University, Safat, Kuwait; International Centre for Casemix and Clinical Coding (Prof S M Aljunid PhD), National University of Malaysia, Bandar Tun Razak, Malaysia; College of Medicine (S Almoustanyir MD), Alfaisal University, Riyadh, Saudi Arabia; Ministry of Health, Riyadh, Saudi Arabia (S Almoustanyir MD); Research Group in Hospital Management and Health Policies (Prof N Alvis-Guzman PhD), Universidad de la Costa (University of the Coast), Barranquilla, Colombia; Research Group in Health Economics (Prof N Alvis-Guzman PhD), University of Cartagena, Cartagena, Colombia; Department of Cardiology (C Andrei PhD), Department of Internal Medicine (M Hostiuc PhD), Department of General Surgery (I Negoai PhD), Carol Davila University of Medicine and Pharmacy, Bucharest, Romania; Department of Statistics and Econometrics (Prof T Andrei PhD, I Glăvan PhD, A Mirica PhD), Bucharest University of Economic Studies, Bucharest, Romania; School of Nursing and Midwifery (A Ansar MPH), La Trobe University, Melbourne, VIC, Australia; International Health Special Interest Group (A Ansar MPH), Public Health Association of Australia, Canberra, ACT, Australia; Department of Epidemiology and Biostatistics (Prof A Ansari-Moghaddam PhD), Zahedan University of Medical Sciences, Zahedan, Iran; Research Center on Public Health (I Antonazzo PhD, P Ferrara MD), School of Medicine and Surgery (P A Cortesi PhD, Prof L G Mantovani DSc), University of Milan Bicocca, Monza, Italy; Menzies Institute for Medical Research (B Antony PhD, A Singh Mtech), University of Tasmania, Hobart, TAS, Australia; Health Management and Economics Research Center (J Arabloo PhD, A Ghashghaee BSc, M Hosseinzadeh PhD), Department of Medical Laboratory Sciences (F Dorostkar PhD), Student Research Committee (A Ghashghaee BSc), Minimally Invasive Surgery Research Center (A Kabir MD), Colorectal Research Center (A Sarvezad PhD), Iran University of Medical Sciences, Tehran, Iran (F Pashazadeh Kan BSN); Social Determinants of Health Research Center (M Arab-Zozani PhD), Birjand University of Medical Sciences, Birjand, Iran; Department of Epidemiology (K D Artanti MSc), Airlangga University, Surabaya, Indonesia; Department of Maternal and Child Health (J Arulappan DSc), Sultan Qaboos University, Al-Khoud, Muscat, Oman; School of Nursing and Health Sciences (A T Awan DrPH), Capella University, Minneapolis, MN, USA; Continuing Education-Grant Writing Academy (A T Awan DrPH), University of Nevada, Las Vegas, NV, USA; Department of Epidemiology and Preventive Medicine (M A Awoke MPH), University of Melbourne, Melbourne, VIC, Australia; Department of Pharmacology and Toxicology (M A Ayza MSc), Mekelle University, Mekelle, Ethiopia; Faculty of Medicine (A Y Azzam MBBCh), October 6 University, 6th October City, Egypt; Kasturba Medical College, Mangalore (D B B MD, R Holla MD, J Padubidri MD, P Rathi MD), Department of Community Medicine (C R Rao MD), Manipal Academy of Higher Education, Manipal, India; Department of Pharmacy (Prof Z Babar PhD), University of Huddersfield, Huddersfield, UK; Department of Medical Microbiology (S Balakrishnan PhD), School of Public Health (B Gebremichael MPH), Department of Psychiatric Nursing (D T Zewdie MSc), Haramaya University, Harar, Ethiopia; Department of Hypertension (Prof M Banach PhD), Medical University of Lodz, Lodz, Poland; Polish Mothers' Memorial Hospital Research Institute, Lodz, Poland (Prof M Banach PhD); Department of Midwifery (S A Bante MSc), Department of Nursing (A B Dagnew MSc), Department of Epidemiology and Biostatistics (B E Feleke MPH), Department of Reproductive Health and Population Studies (E W Mengesha MPH), College of Medicine and Health Sciences (G W Tsegaye MPH), Bahir Dar University, Bahir Dar, Ethiopia; Heidelberg Institute of Global Health (HIGH) (Prof T W Bärnighausen MD, J De Neve MD, S Mohammed PhD), Heidelberg University, Heidelberg, Germany; T H Chan School of Public Health (Prof T W Bärnighausen MD, I Yunusa PhD), Harvard University, Boston, MA, USA; Clinical Sciences Department (H J Barqawi MPhil, Prof R Halwani PhD), College of Medicine (Prof R Halwani PhD), Mass Communication Department (A Makki PhD), Department of Family and Community Medicine (B Saddik PhD), University of Sharjah, Sharjah, United Arab Emirates; Department of Public & Environmental Health (A Barrow MPH), University of The Gambia, Brikama, The Gambia; Epidemiology and Disease Control Unit (A Barrow MPH), Ministry of Health, Kotu, The Gambia; Barcelona Institute for Global Health (Prof Q Bassat MD), University of Barcelona, Barcelona, Spain; Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain (Prof Q Bassat MD); Center for Health Development in Mongolia, Ulaanbaatar, Mongolia (N Bayarmagnai PhD); Department of Medicine (D F Bejarano Ramirez BN), El Bosque University, Bogotá, Colombia; Transplant Service (D F Bejarano Ramirez BN), University Hospital

Foundation Santa Fe de Bogotá, Bogotá, Colombia; Department of Public Health (T T Bekuma MPH), Wollega University, Nekemte, Ethiopia; Department of Midwifery (H G Belay MSc), Debre Tabor University, Debre Tabor, Ethiopia; Department of Oral Pathology and Microbiology (U I Belgaumi MD), Krishna Institute of Medical Sciences "Deemed To Be University", Karad, India; Department of Social and Clinical Pharmacy (A S Bhagavathula PharmD), Charles University, Hradec Kralova, Czech Republic; Institute of Public Health (A S Bhagavathula PharmD), Department of Medical Microbiology & Immunology (Prof G Khan PhD), Family Medicine Department (M A Khan MSc), United Arab Emirates University, Al Ain, United Arab Emirates; School of Public Health (D Bhandari MSc, V Podder HSC), Robinson Research Institute (Z S Lassi PhD), Centre for Heart Rhythm Disorders (J Noubiap MD), University of Adelaide, Adelaide, SA, Australia; Public Health Research Laboratory (D Bhandari MSc), Central Department of Public Health (R Paudel MPH), Tribhuvan University, Kathmandu, Nepal; Department of Anatomy (Prof N Bhardwaj MD), Government Medical College Pali, Pali, India; Department of Community Medicine and Family Medicine (P Bhardwaj MD), School of Public Health (P Bhardwaj MD), Department of Pharmacology (J Charan MD), Department of Surgical Oncology (Prof S Misra MCh), All India Institute of Medical Sciences, Jodhpur, India; Neurovascular Imaging Laboratory (S Bhaskar PhD), NSW Brain Clot Bank, Sydney, NSW, Australia; Department of Neurology and Neurophysiology (S Bhaskar PhD), South West Sydney Local Health District and Liverpool Hospital, Sydney, NSW, Australia; Department of Statistical and Computational Genomics (K Bhattacharyya MSc), National Institute of Biomedical Genomics, Kalyani, India; Department of Statistics (K Bhattacharyya MSc), University of Calcutta, Kolkata, India; Institute of Soil and Environmental Sciences (S Bibi PhD, S Ullah PhD), University of Agriculture, Faisalabad, Faisalabad, Pakistan; Social Determinants of Health Research Center (A Bijani PhD), Student Research Committee (M Zamani MD), Babol University of Medical Sciences, Babol, Iran; Department of General Surgery and Medical-Surgical Specialties (Prof A Biondi PhD, M Vacante PhD), University of Catania, Catania, Italy; Department of Internal Medicine (A Bolor MD), Department of Community Medicine (V Kulkarni MD, N Kumar MD, P Mithra MD, R Thapar MD), Department of Forensic Medicine (P H Shetty MD), Department of Anaesthesiology (S Sinha DNB), Manipal Academy of Higher Education, Mangalore, India; Department of Epidemiology (D Braithwaite PhD), University of Florida, Gainesville, FL, USA; Cancer Population Sciences Program (D Braithwaite PhD), University of Florida Health Cancer Center, Gainesville, FL, USA; Department of Woman and Child Health and Public Health (D Buonsenso MD), Fondazione Policlinico Universitario Agostino Gemelli IRCCS (Agostino Gemelli University Polyclinic IRCCS), Roma, Italy; Global Health Research Institute (D Buonsenso MD), Università Cattolica del Sacro Cuore (Catholic University of Sacred Heart), Roma, Italy; School of Public Health and Health Systems (Z A Butt PhD), University of Waterloo, Waterloo, ON, Canada; Al Shifa School of Public Health (Z A Butt PhD), Al Shifa Trust Eye Hospital, Rawalpindi, Pakistan; Department of Pediatrics (Prof P Camargos PhD), Federal University of Minas Gerais, Belo Horizonte, Brazil; Institute for Cancer Research, Prevention and Clinical Network, Florence, Italy (G Carreras PhD); Research Unit on Applied Molecular Biosciences (UCIBIO) (Prof F Carvalho PhD, V M Costa PhD), Department of Chemical Sciences (R A S Couto MD), Associated Laboratory for Green Chemistry (LAQV) (Prof E Fernandes PhD), Department of Chemistry (M Pinheiro PhD), University of Porto, Porto, Portugal; Colombian National Health Observatory (C A Castañeda-Orjuela MD), National Institute of Health, Bogotá, Colombia; Epidemiology and Public Health Evaluation Group (C A Castañeda-Orjuela MD), National University of Colombia, Bogotá, Colombia; Hospitalist Department (R Chakinala MD), Geisinger Health System, Danville, PA, USA; Department of Microbiology & Infection Control (S Chatterjee MD), Medanta Medicity, Gurugram, India; Department of Public Health (S Chhatta PhD), Texila American University, Georgetown, Guyana; Department of Medicine (V Chhatta MD), University of Toronto, Toronto, ON, Canada; Global Institute of Public Health (GIPH), Thiruvananthapuram, India (V Chhatta MD); Department of Internal Medicine (F R Chowdhury PhD), Bangabandhu Sheikh Mujib Medical University, Dhaka, Bangladesh; Department of Pulmonary Medicine (Prof D J Christopher MD), Christian Medical College and Hospital (CMC), Vellore, India; Center for Biomedicine and Community Health (D Chu PhD), VNU-International School, Hanoi, Vietnam; Department of Health Informatics (S Chung PhD), Department of Infection (Prof A Zumla PhD), University College London, London, UK; Health Data Research UK, London, UK (S Chung PhD); Department of Health Informatics (O Dadras DrPH), Graduate School of Medicine (O Dadras DrPH), Kyoto University, Kyoto, Japan; Public Health Foundation of India, Gurugram, India (Prof L Dandona MD, Prof R Dandona PhD, G Kumar PhD); Indian Council of Medical Research, New Delhi, India (Prof L Dandona MD); Division of Cardiology (R Desai MBBS), Atlanta Veterans Affairs Medical Center, Decatur, GA, USA; Department of Community Medicine (D Dhamnetiya MD), Dr. Baba Sahib Ambedkar Medical College and Hospital, Delhi, India; Policy Research Institute, Kathmandu, Nepal (M L Dhimal PhD); Global Institute for Interdisciplinary Studies, Kathmandu, Nepal (M L Dhimal PhD); Health Research Section (M Dhimal PhD), Nepal Health Research Council, Kathmandu, Nepal; Department of Epidemiology and Biostatistics (M Dianatinasab MSc), Shahrood University of Medical Sciences, Shahrood, Iran; Department of Epidemiology (M Dianatinasab MSc), Department of Parasitology and Mycology (Prof K Pakshir PhD), Shiraz University of Medical Sciences, Shiraz, Iran; Center of Complexity Sciences (Prof D Diaz PhD), National Autonomous University of Mexico, Mexico City, Mexico; Faculty of Veterinary Medicine and Zootechnics (Prof D Diaz PhD, D Z Velazquez MSc), Autonomous University of Sinaloa, Culiacán Rosales, Mexico; Development of Research and Technology Center (S Djalalinia PhD), Ministry of Health and Medical Education, Tehran, Iran; Vaccines and Immunity Theme (B Edem MD), Medical Research Council Unit, The Gambia, Fajara, The Gambia; School of Health Sciences (H A Edinur PhD), Universiti Sains Malaysia (University of Science Malaysia), Kubang Kerian, Malaysia; Division of Urology (S Eftekharzadeh MD), Children's Hospital of Philadelphia, Philadelphia, PA, USA; Biomedical Informatics and Medical Statistics Department (I El Sayed PhD), Alexandria University, Alexandria, Egypt; Reference Laboratory of Egyptian Universities-Cairo (Prof M El Sayed Zaki PhD), Ministry of Higher Education and Scientific Research, Cairo, Egypt; Faculty of Medicine (M Elhadi MD), University of Tripoli, Tripoli, Libya; Department of Microbiology and Immunology (S Enany PhD), Suez Canal University, Ismailia, Egypt; Department of International Cyber Education (R Erkhembayar MD, Prof C Ochir PhD), Mongolian National University of Medical Sciences, Ulaanbaatar, Mongolia; Department of Paediatrics (C I Esezobor MB), Department of Psychiatry (A T Olagunju MD), University of Lagos, Lagos, Nigeria; Department of Paediatrics (C I Esezobor MB), Lagos University Teaching Hospital, Lagos, Nigeria; Institute for Health Science Research Germans Trias i Pujol (I J Ezeonwumelu MSc), Autonomous University of Barcelona, Badalona, Spain; IrsiCaixa AIDS Research Institute, Badalona, Spain (I J Ezeonwumelu MSc); Department of Virology (S Ezzikouri PhD), Pasteur Institute of Morocco, Casablanca, Morocco; Department of Neurological Surgery (J Fares MD), Northwestern University, Chicago, IL, USA; Department of Biology and Biotechnology "Lazzaro Spallanzani" (P S Faris PhD), University of Pavia, Pavia, Italy; Department of Biology (P S Faris PhD), Cihan University-Erbil, Erbil, Iraq; School of Nursing (T Y Ferede MSc), School of Midwifery (G Kassahun MSc, B Tsegaye MSc), Hawassa University, Hawassa, Ethiopia; Center for Biotechnology and Fine Chemistry (J C Fernandes PhD), Catholic University of Portugal, Porto, Portugal; Psychiatry Department (I Filip MD), Kaiser Permanente, Fontana, CA, USA; School of Health Sciences (I Filip MD), A.T. Still University, Mesa, AZ, USA; Institute of Gerontological Health Services and Nursing Research (F Fischer PhD), Ravensburg-Weingarten University of Applied Sciences, Weingarten, Germany; Health Sciences Unit (M R Francis MSc), Faculty of Social Sciences (M R Francis MSc), Tampere University, Tampere, Finland; Department of Dermatology (T Fukumoto PhD), Kobe University, Kobe, Japan; Department of Cardiovascular Medicine (M M Gad MD), Department of Nephrology and Hypertension (M H Hassanein MD), Lerner Research Institute (X Liu PhD), Heart and Vascular Institute (A M Saad MD), Cleveland

Clinic, Cleveland, OH, USA; Gillings School of Global Public Health (M M Gad MD), University of North Carolina Chapel Hill, Chapel Hill, NC, USA; Department of Medicine (S Gaidhane PhD), Department of Community Medicine (Prof D Saxena PhD), Datta Meghe Institute of Medical Sciences, Wardha, India; Department of Environmental Health Sciences (S Gallus DSc), Mario Negri Institute for Pharmacological Research, Milan, Italy; Department of Radiology (T Garg MBBS), King Edward Memorial Hospital, Mumbai, India; Department of Public Health (B S Geberemariam MPH, Y Tekalegn MPH), Department of Surgery (K B Gonfa MD), Madda Walabu University, Bale Robe, Ethiopia; International Trachoma Initiative (T Gebre PhD), Task Force for Global Health, Decatur, GA, USA; Department of Nursing and Midwifery (K B Gebremedhin MSc), Addis Ababa University, Addis Ababa, Ethiopia; Pfizer, Collegeville, PA, USA (B D Gessner MD); Agency of Preventive Medicine, Paris, France (B D Gessner MD); Infectious Disease Research Center (Prof K Ghadiri MD), Pediatric Department (Prof K Ghadiri MD), Kermanshah University of Medical Sciences, Kermanshah, Iran; Department of Medical Surgical Nursing (M Ghafourifard PhD), School of Nursing and Midwifery (H Hassankhani PhD), Biotechnology Research Center (M Moghadaszadeh PhD), Molecular Medicine Research Center (M Moghadaszadeh PhD), Tabriz University of Medical Sciences, Tabriz, Iran; Faculty of Allied Health Sciences (Prof S Gilani PhD), University Institute of Public Health (A Hanif PhD, A A Malik PhD), The University of Lahore, Lahore, Pakistan; Afro-Asian Institute, Lahore, Pakistan (Prof S Gilani PhD); Department of Epidemiology and Evidence-Based Medicine (E V Glushkova PhD, V A Korshunov PhD, P D Lopukhov PhD, R V Polibin PhD), I.M. Sechenov First Moscow State Medical University, Moscow, Russia; Health Systems and Policy Research (M Golechha PhD), Department of Epidemiology (Prof D Saxena PhD), Indian Institute of Public Health, Gandhinagar, India; Hudson College of Public Health (S V Gopalani MPH), University of Oklahoma Health Sciences Center, Oklahoma City, OK, USA; Department of Health and Social Affairs (S V Gopalani MPH), Government of the Federated States of Micronesia, Palikir, Federated States of Micronesia; Department of Respiratory Medicine (H Goudarzi PhD), Center for Environmental and Health Sciences (H Goudarzi PhD), Hokkaido University, Sapporo, Japan; Department of Family and Community Medicine (M I M Gubari PhD), University of Sulaimani, Sulaimani, Iraq; Department of Epidemiology and Preventive Medicine (Prof Y Guo PhD), School of Public Health and Preventive Medicine (S Li PhD), Monash University, Melbourne, VIC, Australia; Department of Epidemiology (Prof Y Guo PhD), Binzhou Medical University, Yantai City, China; School of Medicine (V Gupta PhD), Deakin University, Geelong, VIC, Australia; Department of Clinical Medicine (Prof V K Gupta PhD), Macquarie University, Sydney, NSW, Australia; Department of Epidemiology and Psychosocial Research (R A Gutiérrez PhD), Ramón de la Fuente Muñiz National Institute of Psychiatry, Mexico City, Mexico; School of Health and Environmental Studies (Prof S Hamidi DrPH), Hamdan Bin Mohammed Smart University, Dubai, United Arab Emirates; Research & Scientific Studies Unit (S Haque PhD), Epidemiology Department (M Khan MD), Jazan University, Jazan, Saudi Arabia; Medical Research Unit (H Harapan PhD), Universitas Syiah Kuala (Syiah Kuala University), Banda Aceh, Indonesia; Department of Epidemiology (A Hargono Dr), Universitas Airlangga (Airlangga University), Surabaya, Indonesia; Department of Public Health (A Hashi PhD), Jijiga University, Jijiga, Ethiopia; Center for International Health (CIH) (S Hassan MPhil), Bergen Center for Ethics and Priority Setting (BCEPS) (S Hassan MPhil), University of Bergen, Bergen, Norway; Gastrointestinal and Liver Diseases Research Center (S Hassanipour PhD, F Joukar PhD, Prof F Mansour-Ghanaei MD), Caspian Digestive Disease Research Center (S Hassanipour PhD, F Joukar PhD, Prof F Mansour-Ghanaei MD), Guilan University of Medical Sciences, Rasht, Iran; Independent Consultant, Tabriz, Iran (H Hassankhani PhD); Institute of Pharmaceutical Sciences (K Hayat MS), University of Veterinary and Animal Sciences, Lahore, Pakistan; Department of Pharmacy Administration and Clinical Pharmacy (K Hayat MS), Xian Jiaotong University, Xian, China; Independent Consultant, Santa Clara, CA, USA (G Heidari MD); Department of Applied Microbiology (K Hezam PhD), Taiz University, Taiz, Yemen; Department of Microbiology (K Hezam PhD), Nankai University, Tianjin, China; NHMRC Clinical Trial Centre (M E Hoque PhD), Sydney Medical School (S Islam PhD), Save Sight Institute (H Kandel PhD), University of Sydney, Sydney, NSW, Australia; College of Science and Engineering (Prof M Househ PhD), Hamad Bin Khalifa University, Doha, Qatar; Department of Health Services Administration (V Hsieh PhD), China Medical University, Taichung, Taiwan; Jockey Club School of Public Health and Primary Care (J Huang MD, C Zhong MD), The Chinese University of Hong Kong, Hong Kong, China; Department of Public Health and Community Medicine (Prof A Humayun PhD), Shaikh Khalifa Bin Zayed Al-Nahyan Medical College, Lahore, Pakistan; School of Pharmaceutical Sciences (R Hussain PhD), University of Science Malaysia, Penang, Malaysia; Department of Biomolecular Sciences (N R Hussein PhD), University of Zakho, Zakho, Iraq; Department of Health Promotion and Education (S E Ibitoye MPH), Department of Community Medicine (O S Ilesanmi PhD), Department of Medicine (Prof M O Owolabi DrM), University of Ibadan, Ibadan, Nigeria; Department of Community Medicine (O S Ilesanmi PhD), Department of Medicine (Prof M O Owolabi DrM), University of Ibadan, Ibadan, Nigeria; Faculty of Medicine (I M Ilıc PhD), Prof M M Santric-Milicevic PhD, School of Public Health and Health Management (Prof M M Santric-Milicevic PhD), University of Belgrade, Belgrade, Serbia; Department of Epidemiology (Prof M D Ilıc PhD), University of Kragujevac, Kragujevac, Serbia; Division of Gastroenterology and Hepatology (S Inamdar MD), University of Arkansas for Medical Sciences, Little Rock, AR, USA; College of Public Health (U Iqbal PhD), School of Pharmacy (L M Irham BPharm), Graduate Institute of Biomedical Informatics (D N A Ningrum MPH), Taipei Medical University, Taipei, Taiwan; Independent Consultant, Tabriz, Iran (S N Irvani MD); Institute for Physical Activity and Nutrition (S Islam PhD), Deakin University, Burwood, VIC, Australia; Department of Clinical Pharmacy (Prof N Ismail PhD), MAHSA University, Bandar Saujana Putra, Malaysia; Department of Health Management (R Itumalla PhD), University of Hail, Hail, Saudi Arabia; Department of Community Medicine (R P Jha MSc), Dr. Baba Saheb Ambedkar Medical College & Hospital, Delhi, India; Department of Community Medicine (R P Jha MSc), Banaras Hindu University, Varanasi, India; School of Public Health (Z Kabir PhD), University College Cork, Cork, Ireland; Institute for Prevention of Non-communicable Diseases (R Kalhor PhD), Health Services Management Department (R Kalhor PhD), Qazvin University of Medical Sciences, Qazvin, Iran; Department of Pharmacy (Z Kamal PhD), Shaheed Benazir Bhutto University, Upper Dir, Pakistan; School of Pharmacy (Z Kamal PhD), Shanghai Jiao Tong University, Shanghai, China; Sydney Eye Hospital (H Kandel PhD), South Eastern Sydney Local Health District, Sydney, NSW, Australia; Institute for Epidemiology and Social Medicine (A Karch MD), University of Münster, Münster, Germany; Centre for Tropical Diseases and Global Health (P D Katoto PhD), Catholic University of Bukavu, Bukavu, Democratic Republic of the Congo; Non-communicable Diseases Research Unit (Prof A P Kengne PhD), Medical Research Council South Africa, Cape Town, South Africa; Department of Medicine (Prof A P Kengne PhD), School of Public Health and Family Medicine (C A Nnaji MPH, Prof C S Wiysonge MD), University of Cape Town, Cape Town, South Africa; Department of Public Health (Prof Y S Khader PhD), Jordan University of Science and Technology, Irbid, Jordan; Amity Institute of Forensic Sciences (H Khajuria PhD, B P Nayak PhD), Amity University, Noida, India; Department of Epidemiology and Biostatistics (E A Khan MPH), Health Services Academy, Islamabad, Pakistan; Department of Population Studies (J Khan MPhil), Department of Development Studies (Prof A Perianayagam PhD), International Institute for Population Sciences, Mumbai, India; Primary Care Department (M A Khan MSc), NHS North West London, London, UK; Department of Health Policy and Management (Prof Y Khang MD), Institute of Health Policy and Management (Prof Y Khang MD), Department of Pediatrics (D Yon MD), Seoul National University, Seoul, South Korea; Department of Public Health (A T Khoja MD), Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia; Department of Health Policy and Management (A T Khoja MD), Johns Hopkins University, Baltimore, MD, USA; Department of Public Health (Prof J Khubchandani PhD),

New Mexico State University, Las Cruces, NM, USA; Department of Preventive Medicine (G Kim PhD, Prof E Park PhD), Institute of Health Services Research (Prof E Park PhD), College of Medicine (Prof J Shin MD), Yonsei University, Seoul, South Korea; Department of Genomics and Digital Health (M Kim MD), Samsung Advanced Institute for Health Sciences & Technology (SAIHST), Seoul, South Korea; Public Health Center (M Kim MD), Ministry of Health and Welfare, Wando, South Korea; School of Traditional Chinese Medicine (Y Kim PhD), Xiamen University Malaysia, Sepang, Malaysia; Department of Nutrition (R W Kimokoti MD), Simmons University, Boston, MA, USA; School of Health Sciences (Prof A Kisa PhD), Kristiania University College, Oslo, Norway; Department of Global Community Health and Behavioral Sciences (Prof A Kisa PhD), Tulane University, New Orleans, LA, USA; Department of Nursing and Health Promotion (S Kisa PhD), Oslo Metropolitan University, Oslo, Norway; Independent Consultant, Jakarta, Indonesia (S Kosen MD); Department of Demography (Prof B Kuate Defo PhD), Department of Social and Preventive Medicine (Prof B Kuate Defo PhD), University of Montreal, Montreal, QC, Canada; Department of Community Medicine (A Kumar MD), Manipal Academy of Higher Education, Jamshedpur, India; Department of Biochemistry and Biotechnology (A Kwarteng PhD), Kwame Nkrumah University of Science and Technology, Kumasi, Ghana; Department of Clinical Sciences and Community Health (Prof C La Vecchia MD), University of Milan, Milan, Italy; Department of Community and Family Medicine (F H Lami PhD), University of Baghdad, Baghdad, Iraq; Unit of Genetics and Public Health (Prof I Landires MD), Unit of Microbiology and Public Health (V Nuñez-Samudio PhD), Institute of Medical Sciences, Las Tablas, Panama; Department of Public Health (V Nuñez-Samudio PhD), Ministry of Health, Herrera, Panama (Prof I Landires MD); Department of Otorhinolaryngology (S Lasrado MS), Father Muller Medical College, Mangalore, India; College of Pharmacy (H Lee PhD), Ajou University, Suwon-si, South Korea; Department of Medicine (Prof Y Lee PhD), School of Medical Sciences (Prof Y Lee PhD), University of Science Malaysia, Kota Bharu, Malaysia; Department of Prevention (M Levi PhD), USL Tuscany Center, Firenze, Italy; Department of Health Sciences (M Levi PhD), University of Florence, Florence, Italy; Centre for Tropical Medicine and Global Health (S Lewycka PhD, B Sartorius PhD), Nuffield Department of Medicine (P C Matthews PhD, B Sartorius PhD), Big Data Institute (C E Moore PhD), University of Oxford, Oxford, UK; Oxford University Clinical Research Unit (S Lewycka PhD), Wellcome Trust Asia Programme, Hanoi, Vietnam; Department of Quantitative Health Science (X Liu PhD), Department of Nutrition and Preventive Medicine (Prof J Sanabria MD), Division of Pediatric Gastroenterology (A Thavamani MD), Case Western Reserve University, Cleveland, OH, USA; Department of Professional and Medical Education (S W Lobo PhD), Meharry Medical College, Nashville, TN, USA; Department of Biomedical Sciences (S W Lobo PhD), Mercer University, Macon, GA, USA; Department of Neurosciences and Behavioral Sciences (R Lutzky Saute MD), Department of Pathology and Legal Medicine (M R Tovani-Palone PhD), University of São Paulo, Ribeirão Preto, Brazil; Ophthalmology Department (M Magdy Abd El Razek MSc), Ministry of Health & Population, Aswan, Egypt; Rabigh Faculty of Medicine (A A Malik PhD), King Abdulaziz University, Jeddah, Saudi Arabia; Value-Based Healthcare Unit (Prof L G Mantovani DSc), IRCCS MultiMedica, Sesto San Giovanni, Italy; Campus Caucaia (F R Martins-Melo PhD), Federal Institute of Education, Science and Technology of Ceará, Caucaia, Brazil; Department of Microbiology and Infectious Diseases (P C Matthews PhD), Oxford University Hospitals NHS Foundation Trust, Oxford, UK; Department of Epidemiology and Biostatistics (J C Medina MD), University of the Philippines Manila, Manila, Philippines; Department of Global Health (J C Medina MD), University of the Ryukyus, Nishihara, Japan; Peru Country Office (W Mendoza MD), United Nations Population Fund (UNFPA), Lima, Peru; Forensic Medicine Division (Prof R G Menezes MD), Department of Pharmacology (F H Pottoo PhD), Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia; Breast Surgery Unit (T J Meretoja MD), Helsinki University Hospital, Helsinki, Finland; University of Helsinki, Helsinki, Finland (T J Meretoja MD); School of Medicine and Public Health (A G Mersha MD), University of Newcastle,

Newcastle, NSW, Australia; Department of Orthopaedic Surgery (M K Mesregah MSc), University of Southern California, Los Angeles, CA, USA; Department of Orthopaedic Surgery (M K Mesregah MSc), Menoufia University, Shebin El-Kom, Egypt; Clinical Microbiology and Parasitology Unit (T Mestrovic PhD), Dr. Zora Profozic Polyclinic, Zagreb, Croatia; University Centre Varazdin (T Mestrovic PhD), University North, Varazdin, Croatia; Center for Innovation in Medical Education (B Miazgowski MD), Pomeranian Medical University, Szczecin, Poland (B Miazgowski MD); Department of Computer Science and Software Engineering (Prof G J Milne PhD), University of Western Australia, Perth, WA, Australia; Internal Medicine Programme (Prof E M Mirrakhimov PhD), Kyrgyz State Medical Academy, Bishkek, Kyrgyzstan; Department of Atherosclerosis and Coronary Heart Disease (Prof E M Mirrakhimov PhD), National Center of Cardiology and Internal Disease, Bishkek, Kyrgyzstan; College of Dentistry (T A Mohamed MSc), University of Duhok, Duhok, Iraq; Department of Biology (K A Mohammad PhD), Salahaddin University-Erbil, Erbil, Iraq; Department of Information Technology (M Mohammadi PhD), Lebanese French University, Erbil, Iraq; Department of Epidemiology and Biostatistics (A Mohammadian-Hafshejani PhD), Shahrekord University of Medical Sciences, Shahrekord, Iran; Department of Biology (A Mohammed PhD), University of Jeddah, Jeddah, Saudi Arabia; Health Systems and Policy Research Unit (S Mohammed PhD), Ahmadu Bello University, Zaria, Nigeria; Epidemiology Department (A Mohapatra MD), GRID Council, Bhubaneswar, India; Faculty of Life Sciences and Medicine (M Molokhia PhD), King's College London, London, UK; Clinical Epidemiology and Public Health Research Unit (L Monasta DSc, L Ronfani PhD, E Traini MSc), Burlo Garofolo Institute for Maternal and Child Health, Trieste, Italy; World Health Organization (WHO) Centre on eHealth (M Moni PhD), University of New South Wales, Sydney, NSW, Australia; Department of Medicine (A A Montasir FMD), TMSS Medical College, Bogura, Bangladesh; Department of Medicine (A A Montasir FMD), Sofia Ismail Memorial Medical Centre, Bogura, Bangladesh; Social Determinants of Health Research Center (G Moradi PhD), Department of Epidemiology and Biostatistics (G Moradi PhD), Kurdistan University of Medical Sciences, Sanandaj, Iran; Department of Epidemiology (R Moradzadeh PhD, M Zamanian PhD), Arak University of Medical Sciences, Arak, Iran; Computer, Electrical, and Mathematical Sciences and Engineering Division (P Moraga PhD), King Abdullah University of Science and Technology, Thuwal, Saudi Arabia; Federal Institute for Population Research, Wiesbaden, Germany (Prof U O Mueller MD); Center for Population and Health, Wiesbaden, Germany (Prof U O Mueller MD); Scientific Communications Department (S B Munro PhD), Invitae, Boulder, CO, USA; Laboratory of Public Health Indicators Analysis and Health Digitalization (M Naimzada MD, N Oststavnov BA, S S Oststavnov PhD), Moscow Institute of Physics and Technology, Dolgoprudny, Russia; Experimental Surgery and Oncology Laboratory (M Naimzada MD), Kursk State Medical University, Kursk, Russia; Department of Biotechnology (M Naveed PhD), University of Central Punjab, Lahore, Pakistan; Department of General Surgery (I Negoi PhD), Emergency Hospital of Bucharest, Bucharest, Romania; Bupa Clemton Park (S Neupane Kandel BSN), Bupa, Sydney, NSW, Australia; Institute for Global Health Innovations (T H Nguyen MSc, L G Vu MSc), Faculty of Medicine (T H Nguyen MSc, L G Vu MSc), Institute of Research and Development (A Rahmani PhD), Duy Tan University, Da Nang, Vietnam; Public Health Department (D N A Ningrum MPH), Universitas Negeri Semarang (State University of Semarang), Kota Semarang, Indonesia; Department of Pediatrics (V E Nwatah MD), National Hospital Abuja, Abuja, Nigeria; Department of International Public Health (V E Nwatah MD), University of Liverpool, Liverpool, UK; Administrative and Economic Sciences Department (Prof B Oancea PhD), University of Bucharest, Bucharest, Romania; Advisory Board (Prof C Ochir PhD), Ministry of Health, Ulaanbaatar, Mongolia; Translational Health Research Institute (F A Ogbo PhD), Western Sydney University, Sydney, NSW, Australia; Department of Psychiatry and Behavioural Neurosciences (A T Olagunju MD), McMaster University, Hamilton, ON, Canada; Community Prevention and Care Services (B O Olakunde PhD), National AIDS Control Committee, Abuja, Nigeria; Department of Pharmacology and

Therapeutics (Prof O E Onwujekwe PhD), University of Nigeria Nsukka, Enugu, Nigeria; Department of Project Management (S S Otstavnov PhD), National Research University Higher School of Economics, Moscow, Russia; Research & Development Department (M Pathak PhD), Kalinga Institute of Medical Sciences, Bhubaneswar, India; Department of Genetics (S Pawar PhD), Yale University, New Haven, CT, USA; Department of Orthopedics (J Pereira MS), Yenepoya Medical College, Mangalore, India; Department of Psychiatry (Prof M F P Peres MD), University of São Paulo, São Paulo, Brazil; International Institute for Educational Planning (IIEP) (Prof M F P Peres MD), Albert Einstein Hospital, São Paulo, Brazil; Department of Parasitology and Entomology (M Pirestani PhD), Tarbiat Modares University, Tehran, Iran; Medical College (V Podder HSC), Tairunnessa Memorial Medical College and Hospital, Gazipur, Bangladesh; Institute of Infection and Immunity (R C G Pollok FRCP), St George's University of London, London, UK; University Medical Center Groningen (Prof M J Postma PhD), School of Economics and Business (Prof M J Postma PhD), University of Groningen, Groningen, Netherlands; Biomedical Engineering Department (Prof M Rabiee PhD), Amirkabir University of Technology, Tehran, Iran; Department of Chemistry (N Rabiee MSc), Sharif University of Technology, Tehran, Iran; College of Medicine (A Radfar MD), University of Central Florida, Orlando, FL, USA; Department of Immunology (Prof A Rafiei PhD), Molecular and Cell Biology Research Center (Prof A Rafiei PhD), Pediatric Infectious Diseases Research Center (Prof M Rezaei MD), Mazandaran University of Medical Sciences, Sari, Iran; Department of Population Science and Human Resource Development (M Rahman DrPH), University of Rajshahi, Rajshahi, Bangladesh; Future Technology Research Center (A Rahmani PhD), National Yunlin University of Science and Technology, Yunlin, Taiwan; Department of Nutrition Science (S Rahmawaty PhD), Muhammadiyah University of Surakarta, Surakarta, Indonesia; Department of Surgery (A Rajesh MD), University of Texas Health Science Center at San Antonio, San Antonio, TX, USA; Department of Pharmacology (P Ranasinghe PhD), University of Colombo, Colombo, Sri Lanka; Department of Oral Pathology (S Rao MDS), Srinivas Institute of Dental Sciences, Mangalore, India; WHO Collaborating Centre for Public Health Education and Training (D L Rawaf MD), Department of Primary Care and Public Health (Prof S Rawaf MD), School of Public Health (Prof S Saxena MD), Imperial College London, London, UK; NIHR Biomedical Research Centre (Prof A Zumla PhD), University College London Hospitals, London, UK (D L Rawaf MD); Academic Public Health England (Prof S Rawaf MD), Public Health England, London, UK; School of Medicine (Prof A M N Renzaho PhD), Translational Health Research Institute (Prof A M N Renzaho PhD), Western Sydney University, Campbelltown, NSW, Australia; Center for Health System Research (M Rios-Blancas MPH), National Institute of Public Health, Cuernavaca, Mexico; Department of Internal Medicine (G M Rwegerera MD), University of Botswana, Gaborone, Botswana; CentraleSupélec (M Saeb PhD), Université de Lorraine (University of Lorraine), Metz, France; Biological Production Development Division (U Saeed PhD), National Institute of Health, Islamabad, Pakistan; Department of Research and Development (U Saeed PhD), Islamabad Diagnostic Center Pakistan, Islamabad, Pakistan; Applied Biomedical Research Center (A Sahebkar PhD), Biotechnology Research Center (A Sahebkar PhD), Mashhad University of Medical Sciences, Mashhad, Iran; Department of Microbiology (N Salam PhD), Central University of Punjab, Bathinda, India; Emergency Department (M Samaei MD), Brown University, Providence, RI, USA; Department of Entomology (A M Samy PhD), Ain Shams University, Cairo, Egypt; Department of Surgery (Prof J Sanabria MD), Marshall University, Huntington, WV, USA; Department of Biomedical and Neuromotor Sciences (F Sanmarchi MD), University of Bologna, Bologna, Italy; Faculty of Health & Social Sciences (B Sathian PhD), Bournemouth University, Bournemouth, UK; Department of Public Health Sciences (M Sawhney PhD), University of North Carolina at Charlotte, Charlotte, NC, USA; Department of Population and Health (A Seidu MPhil), University of Cape Coast, Cape Coast, Ghana; College of Public Health, Medical and Veterinary Sciences (A Seidu MPhil), James Cook University, Townsville, QLD, Australia; National Heart, Lung, and Blood Institute (A Seylani BS), National Institute of Health, Rockville, MD, USA; Independent Consultant, Karachi, Pakistan (M A Shaikh MD); Faculty of Caring Science, Work Life, and Social Welfare (M Shamsizadeh MSc), University of Borås, Borås, Sweden; National Institute of Infectious Diseases, Tokyo, Japan (M Shigematsu PhD); School of Medicine (Prof J A Singh MD), University of Alabama at Birmingham, Birmingham, AL, USA; Medicine Service (Prof J A Singh MD), US Department of Veterans Affairs (VA), Birmingham, AL, USA; Department No.16 (V Y Skryabin MD), Moscow Research and Practical Centre on Addictions, Moscow, Russia; Therapeutic Department (A A Skryabina MD), Balashikha Central Hospital, Balashikha, Russia; Nursing Care Research Center (A Soheili PhD), Semnan University of Medical Sciences, Semnan, Iran; Department of Surgery (K Tan PhD), National University of Singapore, Singapore; Division of Biostatistics and Epidemiology (B Thakur PhD), Texas Tech University Health Sciences Center, El Paso, TX, USA; Department of Pediatrics (A Thavamani MD), University Hospitals Rainbow Babies & Children's Hospital, Cleveland, OH, USA; Department of Social Security Empirical Research (Prof R Tobe-Gai PhD), National Institute of Population and Social Security Research, Tokyo, Japan; HIV/STI Surveillance Research Center, and WHO Collaborating Center for HIV Surveillance (H Tohidinik PhD), Kerman University of Medical Sciences, Kerman, Iran; Modestum LTD, London, UK (M R Tovani-Palone PhD); Institute for Risk Assessment Sciences (IRAS) (E Traini MSc), Utrecht University, Utrecht, Netherlands; Department of Health Economics (B X Tran PhD), Hanoi Medical University, Hanoi, Vietnam; Department of Neurology (Prof M Tripathi MD), All India Institute of Medical Sciences, Delhi, India; Department of Zoology (S Ullah PhD), Division of Science and Technology (S Ullah PhD), University of Education, Lahore, Lahore, Pakistan; Department of Cardiovascular, Endocrine-metabolic Diseases and Aging (B Unim PhD), National Institute of Health, Rome, Italy; Faculty of Information Technology (B Vo PhD), Ho Chi Minh City University of Technology (HUTECH), Ho Chi Minh City, Vietnam; Department of Economics (Prof S Vollmer PhD), University of Göttingen, Göttingen, Germany; Center of Excellence in Behavioral Medicine (G T Vu BA), Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam; Foundation University Medical College (Prof Y Waheed PhD), Foundation University Islamabad, Islamabad, Pakistan; Institute of Health and Society (Prof A S Winkler PhD), University of Oslo, Oslo, Norway; Department of Neurology (Prof A S Winkler PhD), Technical University of Munich, Munich, Germany; Department of Health Management (V Yiğit PhD), Süleyman Demirel Üniversitesi, Isparta, Turkey; Department of Neuropsychopharmacology (N Yonemoto MPH), National Center of Neurology and Psychiatry, Kodaira, Japan; Department of Public Health (N Yonemoto MPH), Juntendo University, Tokyo, Japan; Department of Epidemiology and Biostatistics (Prof C Yu PhD), School of Medicine (Z Zhang PhD), Wuhan University, Wuhan, China; Cancer Institute (D Yuce MD), Hacettepe University, Ankara, Turkey; Department of Clinical Pharmacy and Outcomes Sciences (I Yunusa PhD), University of South Carolina, Columbia, SC, USA.

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Quique Bassat reports participation on a data safety monitoring board (DSMB) or advisory board as a member of the Independent Data Monitoring Committee for Respiratory Syncytial Virus vaccine development for the protection of infants (since October, 2015) (GlaxoSmithKline [GSK]) and as DSMB chair for the research project "Phase IV study to evaluate the effectiveness of the inactivated adsorbed vaccine against COVID-19 CoronaVac, among public safety and education workers with risk factors for severity, in Manaus (Amazonas)" outside the submitted work. Sonu Bhaskar reports a leadership or fiduciary role in other board, society, committee or advocacy groups, unpaid with the Rotary Club of Sydney Board of Directors, outside the submitted work. Irina Filip reports payment or honoraria for lectures, presentations, speakers' bureaus, manuscript writing, or educational events from Avicenna Medical and Clinical Research Institute, outside the submitted work. Bradford D Gessner reports participation on a DSMB or advisory board at Sanofi Pasteur with participation on a dengue vaccine and general immunisation advisory board that included honoraria; stock or stock options in Pfizer; and other financial or non-financial interests as

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Data sharing

To download the data used in these analyses and corresponding results, please visit the Global Health Data Exchange at <http://ghdx.healthdata.org>.

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