Systematic estimates of global causes of neonatal and under 5 mortality in 2000-24: secondary data analysis using bayesian multinomial logistic regression

Jamie Perin,[1] David Prieto-Merino,[2] Astha Wahi,[1] Sandipan Pramanik,[3] Hallie Eilerts-Spinelli,[1] Francisco Villavicencio,[1,4] Tyler H McCormick,[5] Danzhen You,[6] Abhirup Datta,[3] Kathleen L Strong,[7] Robert E Black[1] Li Liu[1,8]

For numbered affiliations see end of the article

Correspondence to: L Liu lliu26@jhu.edu; (ORCID 0000-0003-3102-6708)

Additional material is published online only. To view please visit the journal online.

Cite this as: *BMJ* 2026;393:e088686 http://dx.doi.org/10.1136/bmj-2025-088686

Accepted: 14 May 2026

ABSTRACT

OBJECTIVE

To estimate cause specific mortality among neonates and children under 5 for 195 countries from 2000 to 2024.

DESIGN

Secondary data analysis using a Bayesian multinomial logistic regression model to estimate cause specific mortality fractions.

DATA SOURCES

PubMed, Embase, Web of Science, SCOPUS, Cochrane, Global Health Index Medicus, PAHO, Global Health OVID, Africa-Wide Information, IndMed, WHO Mortality Database, Demographic and Health Surveys (DHS), Multiple Indicator Cluster Surveys (MICS), and Health and Demographic and Surveillance Systems (HDSS).

INCLUSION CRITERIA

Studies in the general population reporting empirical cause specific mortality for at least two causes in the age groups of interest, with a specified method for cause ascertainment. For studies identifying causes of mortality with verbal autopsy, ≥25 deaths reported with ≤25% of these deaths with unknown cause. For vital registration, ≥80% population completeness and ≤10% deaths assigned to ill defined causes determined by the international classification of diseases, 10th revision.

RESULTS

Cause specific mortality for countries with adequate quality vital registration was estimated with their own data with minor adjustments. For countries with low mortality without adequate quality vital registration, cause specific mortality was modeled by age group and based on vital registration. For high mortality areas, cause specific mortality was modeled primarily on the basis of verbal autopsy data identified in a systematic review. Estimated cause distributions were applied to all cause mortality rates and death counts estimated by the United Nations Inter-agency Group for Child Mortality Estimation. Among 4.9 million estimated global deaths in under 5s in 2024, the most important cause of death was preterm birth complications, with 0.82 (90% uncertainty interval 0.76 to 0.88) million deaths and 6.17 (5.93 to 6.42) deaths for every 1000 live births. This was followed closely by lower respiratory infections at 0.66 (0.60 to 0.71) million deaths, intrapartum related events (0.48 (0.43 to 0.52) million), and malaria (0.45 (0.39 to 0.51) million). Analysis for trends over time showed that the decline in most causes has slowed since 2016.

CONCLUSION

With the recent slowed pace of decline in under 5 mortality for most primary causes of death, many high mortality countries are at risk of missing the sustainable development goal targets of ≤12 neonatal deaths and ≤25 under 5 deaths per 1000 live births without acceleration. Estimates presented here can help countries to determine the most appropriate course of action to reduce under 5 mortality and achieve these targets.

WHAT IS ALREADY KNOWN ON THIS TOPIC

Estimates of the causes of neonatal and under 5 deaths are based on national high quality vital registration data when possible

Countries with the largest number of these deaths do not have adequate quality vital registration with the causes of mortality

Estimates for the causes of neonatal and under 5 mortality in such countries have previously been based on verbal autopsies as reported in publications

WHAT THIS STUDY ADDS

This study uses new methods to systematically correct for the biases of verbal autopsy to estimate the causes of neonatal and under 5 deaths, presenting a new estimate series for 2000-24

This new series also introduces a new estimate of severe acute malnutrition as an underlying cause of under 5 mortality

Introduction

In 2024 an estimated 4.9 (90% uncertainty interval 4.7 to 5.2) million deaths occurred among children before their fifth birthday, including an estimated 2.3 (2.1 to 2.5) million in the first month after birth.[1 2] These numbers reflect steep declines in the under 5 mortality rate during the millennium development goals period.[3] The pace of investment in global health significantly increased and the under 5 mortality rate more than halved between 1990 and 2015, the end year of the millennium development goals.[2] The sustainable development goals were subsequently defined with a target of ≤12 neonatal deaths and ≤25 under 5 deaths per 1000 live births by the year 2030.[4]

Since the inception of the millennium development goals in 2016, the global under 5 mortality rate has decreased from 43 to 37 in 2024, and the neonatal mortality rate has decreased from 19 to 17.[1 2] With this limited progress, a significant gap exists between current levels of neonatal and child mortality and the targets of the sustainable development goals. This gap is evident globally and also in specific areas of

persistently high neonatal and child mortality. To better understand why progress is slowing, and to identify the most appropriate measures for further reduction, estimates of cause specific mortality are needed.

Several different estimates of cause specific mortality have been developed by this research group, starting in 2010 and most recently including a time series from 2000 up to 2021.[5 6] A limitation of previous estimates was their omission of severe acute malnutrition as a cause of under 5 mortality.[7] In addition, despite the use of the best quality data available at the time and rigorous analytical methods,[8 9] these estimates, similar to other estimate series,[10] have been dependent on cause specific mortality assessed by verbal autopsies. Verbal autopsy, an interview with the family of the deceased about the signs, symptoms, and circumstances of the mortal event, is an invaluable tool for measuring cause specific mortality in areas where many deaths occur outside the health system.[11] However, causes of death based only on verbal autopsies may be incorrectly classified.[12] For example, verbal autopsies are unlikely to detect conditions that are difficult to diagnose without medical testing, such as cancer or congenital heart disease.[13] The availability of information on the causal chain of conditions leading to death, derived from extensive immediate postmortem evaluation of neonatal and child deaths,[14] enables us for the first time to adjust for misclassification of verbal autopsy based causes, as found in recent publications.[15 16] We present here an updated series of cause specific estimates of neonatal and child mortality from 2000 to 2024, using an updated framework with adjustment for the misclassification of verbal autopsy and inclusion of the number of under 5 deaths due to severe acute malnutrition.

Methods

We identified countries with adequate quality cause specific mortality registration for each age group by using publicly available vital registration data compiled by the World Health Organization.[17] We assumed country years with ≥80% completeness of age specific deaths relative to the United Nations Inter-agency Group for Child Mortality Estimation (UNI IGME) all cause mortality envelopes and <10% of deaths assigned to ill defined causes to be of adequate quality.[18] We assumed countries with at least three years of adequate quality vital registration since 2000 to have overall adequate quality vital registration. For these countries, we estimated cause specific mortality by using vital registration with minor adjustments, which was interpolated between gaps in reported vital registration and extrapolated to cover the time period from 2000 up to 2024. We then applied these cause specific mortality fractions estimated from vital registration to the all cause, age specific deaths estimated by the UN IGME.[1]

For countries without adequate quality vital registration, representing most global deaths, our estimation process paralleled that for previous estimates.[5 16 19 20] We modeled cause specific mortality separately by age group (0-27 days and 1-59 months) and mortality level. We developed a model for low mortality settings based on cause specific mortality from vital registration and a separate model for high mortality settings based on verbal autopsy studies. We applied these models to each country by year, such that country years with low neonatal or under 5 mortality were estimated separately from country years with high neonatal or under 5 mortality. Country years with moderate all cause mortality (10-20 per 1000 live births for neonates and 25-35 per 1000 live births for under 5s) were interpolated between low and high mortality estimates. Thus, cause specific mortality for low mortality country years was extrapolated from vital registration data, and cause specific mortality for high mortality country years was extrapolated from verbal autopsies. Further details follow.

We incorporated several notable improvements to previous methods in this approach. For both neonates and 1-59 month olds, we used the verbal autopsy misclassification rate based on under 5 deaths with highly enriched cause ascertainment from minimally invasive tissue sampling as collected in the Child Health and Mortality Prevention Surveillance (CHAMPS) study.[21] We estimated setting specific misclassification error by bayesian modeling of misclassification error, allowing for heterogeneity across settings where available.[15] We also introduced estimates of under 5 mortality due to severe acute malnutrition as an additional underlying cause.

Data curation

For countries with low mortality rates (defined as neonatal mortality below 10 per 1000 live births or under 5 mortality below 25 deaths per 1000 live births), we used vital registration data to represent cause specific under 5 mortality in countries that have adequate quality vital registration for children under 5 as defined above. We also used these data to create the statistical models to predict the cause specific distributions in countries without adequate vital registration data but with low mortality rates, as explained below. A few countries with adequate quality vital registration had neonatal or 1-59 month mortality higher than these thresholds, and these data were included.

From countries with high under 5 mortality, very few adequate vital registration data were available, so we did a systematic review for cause specific mortality from sources other than vital registration,[22] aiming to identify high quality, population representative surveys with empirical age and cause specific mortality. In brief, we searched public databases including PubMed, EMBASE, and Web of Science for primary verbal autopsy studies in high mortality settings. Two reviewers screened identified literature for studies with ≥25 deaths in the neonatal or 1-59 month periods, identifying causes of mortality with a discernible verbal autopsy method, and <25% of deaths having an undetermined cause. Two reviewers

doi: 10.1136/bmj-2025-088686 | BMJ 2026;393:e088686 | the bmj

did title and abstract screening and full text extraction concurrently, and a third reviewer resolved conflicting reports. These public sources were supplemented by data from investigators known by the authors to be working in the area of causes of under 5 mortality. This systematic review was documented and described in detail elsewhere.[23] The systematic review was not registered. We combined these data with previous systematic reviews conducted from 2012 to 2021.[16 17]

Cause of death data pre-calibration

Before incorporating cause specific mortality data from the systematic review in modeling and cause estimates, we made adjustments for the bias in verbal autopsy. We calibrated all reported causes of death determined by verbal autopsy for area and algorithm specific misclassification error. We estimated this setting specific misclassification error by using a bayesian model among neonatal and 1-59 month deaths from the CHAMPS study.[15 19]

Neonates estimation

For low mortality countries without adequate vital registration data, we estimated the distribution of causes with bayesian multinomial regression incorporating adequate quality vital registration data from the WHO Mortality Database (for specific countries and sources used, see supplementary material S1). We modeled cause specific mortality for deaths in the first week separately from deaths in the latter three weeks.[23] Using a multinomial regression model, we extrapolated cause specific mortality from areas with low mortality and adequate vital registration to areas with low mortality but without vital registration via covarying factors. We focused on a small set of factors reflecting socioeconomic as well as health system level conditions for neonates and controlled the amount of influence of these covariates by using the bayesian least absolute shrink and selection operator (LASSO).[9 24] We identified the most appropriate level of shrinkage (parameterized as λ) for the bayesian LASSO by using the lowest apparent out of sample prediction error determined by 10-fold cross validation. Further details are described in supplementary material S2.

For countries with high neonatal mortality, similarly to the methods for those with low neonatal mortality, we estimated the distribution of causes by using bayesian multinomial regression. We identified the empirical data underpinning this model in the systematic review described above from high mortality settings, much of which ascertained causes of death by using verbal autopsy and were pre-calibrated to correct for misclassification. We incorporated covarying factors related to socioeconomic and health system circumstances in high mortality settings. Similarly to estimates in low mortality areas, we used the bayesian LASSO to control over-fitting while estimating the degree of shrinkage (λ) with 10-fold cross validation across a range of λ.[9] We also incorporated hierarchical random effects as part of the bayesian LASSO multinomial regression, such that empirical data from nationally representative verbal autopsy studies were systematically given additional influence in that country's estimated cause distribution. We fitted the bayesian LASSO multinomial regressions with the pre-calibrated causes of death and used the resulting parameters to estimate country and year specific distributions in the neonatal period. We then applied these estimated cause distributions to the number of neonatal deaths by country and year produced by UN IGME for the number of estimated deaths by cause in all high mortality countries.

For countries with moderate neonatal mortality >10 per 1000 live births but <20, we used an average of the cause distribution estimated by the low mortality and the high mortality models, weighted by the relative distance in the neonatal mortality rate from 10 to 20 for the low and high mortality models, respectively.[5] In addition, to estimate neonatal cause specific mortality in China, we used estimates from well established sample surveillance systems with adjustments.[25]

1-59 month old children estimation

We estimated cause specific mortality for 1-59 month olds in parallel to neonatal mortality by using similar methods. We estimated causes of deaths in countries with adequate vital registration for 1-59 month olds by using cause specific mortality from vital registration applied to the all cause number of deaths in this age group with minor adjustments. For countries without adequate vital registration, we estimated causes of death in low mortality countries separately from those in high mortality areas; both were estimated as a multinomial distribution of fractions which were then applied to the number of deaths in this age group estimated by UN IGME.

For countries with low under 5 mortality without adequate vital registration data, we used adequate quality vital registration data reported to WHO with bayesian multinomial regression. We also used a selection of covarying factors related to the health system and conditions likely related to the health of young children in low mortality settings. These factors were chosen on the basis of interventions and health system factors relevant to this age group and so were different from those for neonates. The remainder of the estimation process paralleled that for neonates. Similarly to methods used for cause estimation among neonates, we estimated cause specific mortality for 1-59 month old children in China by adjusting results from the established sample registration system.[26]

For countries with high under 5 mortality (>35 per 1000 live births), we used mortality data identified from high mortality areas as described above. For countries with high under 5 mortality, we have included severe acute malnutrition among the underlying causes of 1-59 mortality for the first time. To estimate the deaths due to severe acute malnutrition, we included the prevalence of wasting (having weight for height Z score more than two standard deviations below the median of the WHO growth standard[26]) in our bayesian multinomial regression, given the strong evidence

Table 1 | Summary of new and total cause of death input by age and estimation method

	New input data			Total input data		
	Data points	Deaths	Countries	Data points	Deaths	Countries
Neonates						
High quality vital registration	286	313 070	72	1232	1 601 768	72
Low mortality model	693	353 126	72	3110	2 719 660	72
High mortality model	97	61 030	23	332	250 772	47
Children aged 1-59 months						
High quality vital registration	355	356 023	71	1317	2 745 731	71
Low mortality model	255	254 274	50	1097	1 614 987	60
High mortality model	76	54 085	20	411	241 048	42

indicating that the prevalence of wasting is related to the level of mortality due to severe acute malnutrition.[27] For countries with low under 5 mortality, we assumed that no 1-59 month deaths were due to severe acute malnutrition. For countries with under 5 mortality >25 but <35 per 1000 live births, we used an average of the cause distribution estimated by the low mortality and the high mortality models, weighted by the relative distance in the mortality rate from 25 and 35 for low and high mortality models, respectively.[5] Additional details related to these methods are included in supplementary material S2, including ICD-10 (international classification of diseases, 10th revision) codes corresponding to all causes, model parameters, selected covariates, and out of sample cross validation results. Matrices used for calibrating verbal autopsy error for neonates and 1-59 month olds are available in supplementary material S3 and S4 for all data points.

In addition to examining the trends over time in cause specific mortality graphically, we used the average annual rate of reduction (AARR) to describe the change in cause specific mortality over time, defined by $AARR=100*\ln(CSMR_2/CSMR_1)/(Year_1-Year_2)$, where $Year_2 > Year_1$, $CSMR_1$ is the cause specific mortality rate in $Year_1$, and $CSMR_2$ is the cause specific mortality rate in $Year_2$, such that a positive AARR indicates a decrease in the cause specific mortality rate and a negative AARR indicates an increase in the cause specific mortality rate.

Table 2 | Estimated number of deaths by age, cause, and cause specific mortality rate in 2024

	Estimated number (90% UI*; millions)	Cause specific mortality rate (90% UI*; per 1000 live births)
Neonates aged 0-27 days		
Preterm birth complications	0.82 (0.76 to 0.88)	6.17 (5.93 to 6.42)
Intrapartum related events	0.48 (0.43 to 0.52)	3.60 (3.40 to 3.79)
Sepsis/meningitis	0.26 (0.23 to 0.29)	1.96 (1.75 to 2.15)
Lower respiratory infections†	0.25 (0.23 to 0.27)	1.88 (1.76 to 2.01)
Congenital abnormalities	0.22 (0.20 to 0.24)	1.65 (1.56 to 1.75)
Diarrhea	0.04 (0.04 to 0.05)	0.33 (0.30 to 0.37)
Tetanus	0.02 (0.02 to 0.02)	0.14 (0.12 to 0.17)
Injury	0.01 (0.01 to 0.01)	0.05 (0.03 to 0.06)
Other conditions	0.18 (0.17 to 0.20)	1.39 (1.27 to 1.49)
Children aged 1-59 months		
Malaria	0.45 (0.39 to 0.51)	3.40 (2.99 to 3.81)
Lower respiratory infections†	0.41 (0.36 to 0.46)	3.10 (2.78 to 3.42)
Diarrhea	0.33 (0.30 to 0.36)	2.50 (2.28 to 2.71)
Injury	0.17 (0.16 to 0.19)	1.31 (1.22 to 1.40)
Congenital abnormalities	0.14 (0.13 to 0.15)	1.07 (1.02 to 1.13)
Meningitis	0.12 (0.11 to 0.14)	0.93 (0.83 to 1.03)
Severe acute malnutrition	0.12 (0.11 to 0.14)	0.91 (0.81 to 1.01)
Tuberculosis	0.10 (0.07 to 0.12)	0.73 (0.51 to 0.96)
Measles	0.09 (0.06 to 0.12)	0.68 (0.45 to 0.92)
HIV	0.05 (0.04 to 0.06)	0.38 (0.27 to 0.49)
Other conditions‡	0.65 (0.59 to 0.72)	4.95 (4.64 to 5.28)

*Uncertainty interval, defined as 5th-95th centile.
†Formerly referred to as "pneumonia."
‡Other conditions among children aged 1-59 months included causes that originated during perinatal period, cancer, and other specified causes.

Public involvement

As for previous estimates,[5] the estimates presented here have been reviewed by representatives for all countries, of whom many have provided feedback and additional country specific data sources that will be incorporated in future estimates.

Results

Table 1 shows a summary of new empirical data incorporated in these estimates relative to previous estimates.[17] A total of 1.6 million deaths from 72 countries with adequate quality vital registrations were incorporated into these estimates for neonatal mortality, as well as 251 000 neonatal deaths from high mortality areas. For children aged 1-59 months, 71 countries with adequate quality vital registration contributed 2.7 million deaths, and areas with high under 5 mortality contributed 241 000 deaths. In 2024 neonatal cause specific mortality in 50 countries (0.12 million deaths) was estimated using the low mortality model, 44 countries (1.34 million deaths) using the high mortality model, and 28 countries (0.69 million deaths) by a mixture of the high and low mortality models. We included 0.02 million neonatal deaths from China, with causes estimated from their sample registration system. The remaining 72 countries (0.09 million deaths) had cause specific neonatal mortality estimated directly from vital registration.

For 1-59 month old children in 2024, cause specific mortality in 59 countries (0.15 million deaths) were estimated using the low mortality model, 53 countries (2.05 million deaths) using the high mortality model, and 11 countries (0.34 million deaths) by a mixture of the high and low mortality models. We included 0.03 million 1-59 month deaths from China, with causes estimated from their sample registration system. The remaining 71 countries (0.07 million deaths) had

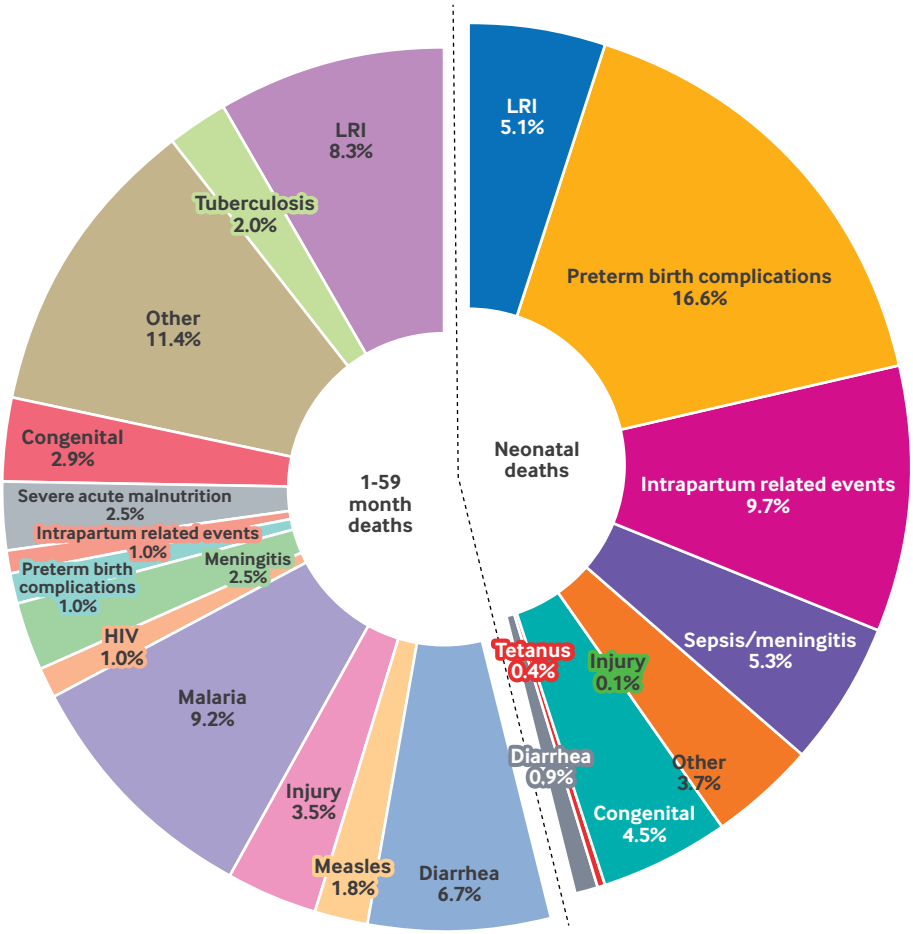

Fig 1 | Estimated global causes of under 5 mortality in 2024. Causes of death among those aged 0-27 days are on the right, and causes among children age 1-59 months are on the left. LRI=lower respiratory infection

cause specific 1-59 month mortality estimated directly from vital registration.

Neonates

The most common cause of death globally among neonates in 2024 was preterm birth complications, at 0.82 million (90% uncertainty interval (UI) 0.76 to 0.88), corresponding to a cause specific mortality rate of 6.17 (90% UI 5.93 to 6.42) per 1000 live births. Intrapartum related events was the second most common global cause of neonatal mortality, with 0.48 (0.43 to 0.52) million deaths and 3.60 (3.40 to 3.79) deaths per 1000 live births. Sepsis and meningitis together were also a common cause of global neonatal mortality at 0.26 (0.23 to 0.27) million deaths and 2.00 (1.79 to 2.19) neonatal deaths per 1000 live births. The eight most common causes of neonatal mortality are shown in table 2 and figure 1.

The trends over time in neonatal cause specific mortality rates are shown in the top panel of figure 2, and the annual average rate of reduction by cause for two time periods for the seven most important causes by age in figure 3. Most cause specific mortality rates decreased among neonates in the period between 2000 and 2015, indicated by positive annual average rates of reduction in figure 3. The exception is mortality due to congenital abnormalities, which is largely unchanged over the time period. During 2015 to 2024, however, estimated annual average rates of reduction are low across causes, indicating that mortality rates were not declining in this period as fast as in 2000-15. This slowdown in progress is also indicated by the change in the all cause neonatal mortality rate, which did not notably decrease in 2024 (17.2, 90% UI 16.3 to 18.8) from 2015 (19.4, 18.9 to 20.1).

Figure 4 shows the percentages of cause specific mortality by region. The global distribution of cause specific mortality masks considerable heterogeneity among regions in both the composition and level of neonatal mortality. Although the largest proportion of deaths in 2024 for all regions was from preterm birth complications, the rates of mortality from these causes ranges from 1.56 deaths per 1000 live births in North America to 7.87 in West and Central Africa and 8.30 in South Asia (supplementary material S5). Regions with most deaths in high income countries such as North America and Europe tend to have lower neonatal deaths due to infectious causes including sepsis, meningitis, and lower respiratory infections and a larger fraction of neonatal mortality due to congenital abnormalities.

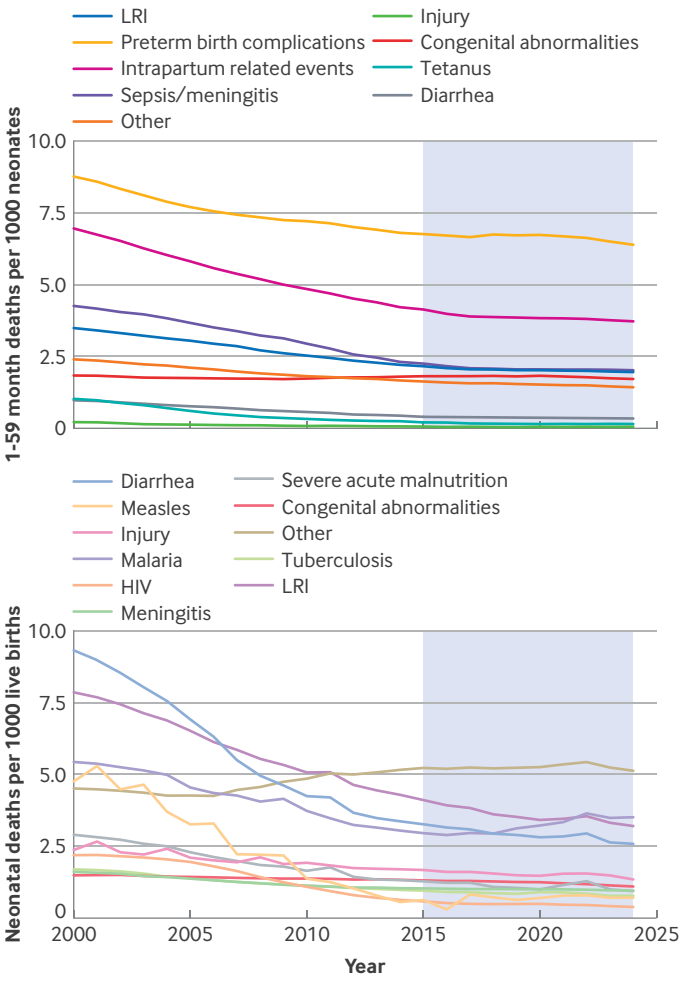

Fig 2 | Global cause specific mortality rates by age from 2000 to 2024. The sustainable development goals era is shaded in gray. LRI=lower respiratory infection

The cause specific mortality rate by region from 2000 to 2024 is shown in supplementary material S5.

The countries with the highest number of neonatal deaths in 2024 include India, Nigeria, and Pakistan, with 0.39, 0.30, and 0.25 million neonatal deaths, respectively. In India, the most common cause of neonatal mortality was premature birth complications at 160 000 deaths and 6.9 deaths per 1000 live births, whereas in Nigeria the most common cause of neonatal death was intrapartum related events (77 000 deaths; 10 per 1000 live births), and in Pakistan the most common neonatal cause was preterm birth complications (94 000; 13.74 per 1000 live births). The cause specific mortality rates over time are shown for all countries in supplementary material S6.

1-59 month old children

The most common cause of death globally among 1-59 month olds in 2024 was malaria, at 0.45 (90% UI 0.39 to 0.51) million and 3.40 (2.99 to 3.81) deaths per 1000 1 month olds. This was closely followed by lower respiratory infections at 0.41 (0.36 to 0.46) million and 3.1 (2.8 to 3.4) per 1000. Diarrhea was the third most common cause of death globally in 2024 in this age group, at 0.33 (0.30 to 0.36) million and 2.5 (2.3 to 2.7) per 1000. Injury, congenital abnormalities, meningitis, and severe acute malnutrition were also important causes of 1-59 month old mortality, each with >0.1 million deaths and at or near 1.0 death per 1000. The 12 most common causes of global 1-59 month mortality for this age group are shown in table 2 and in figure 1.

In the period 2000-24, the diarrhea specific mortality rate declined steeply from 10.0 (9.5 to 10.4) in 2000 to 2.50 in 2024. Sharp declines also occurred in the mortality due to lower respiratory infections from 8.4 to 3.1 and in measles and HIV related mortality from 4.6 to 0.8 and 2.2 to 0.4, respectively. Malaria related mortality and mortality related to severe acute malnutrition and injury have also declined since 2000, although not as markedly as for other primary causes in this age group (fig 2).

Much of the decline in cause specific mortality for 1-59 month olds since 2000 occurred in the years leading up to 2015. In the nine years after 2015, a marked reduction occurred in the annual rate of decline in the mortality rate across most causes. Malaria in particular has changed course, with decreasing mortality during 2000-15 but increasing mortality from 2015 to 2024.

Figure 4 shows the composition of 1-59 month mortality across regions. The primary cause of 1-59 month mortality in 2024 was congenital abnormalities in many low mortality regions, including East Asia and Pacific at 1.2 deaths per 1000 neonates, Latin America and the Caribbean (1.5), and Western Europe (0.5). In North America and Eastern Europe/Central Asia, the primary cause of 1-59 month mortality was injury at 0.8 and 1.2, respectively. In West and Central Africa, the region with the largest number of 1-59 month deaths, the cause with the highest fraction of mortality was malaria at 17.8 (90% UI 16.5 to 19.0) per 1000 neonates. The cause specific mortality rates for HIV, lower respiratory infections, malaria, and diarrhea have declined very substantially in West and Central Africa since 2000, although most of this decline occurred before 2015. Other regions have also seen large declines in specific causes, whereas other causes have not declined as substantially, including tuberculosis in South Asia as well as injuries and congenital abnormalities in low mortality regions (supplementary material S5). See supplementary material S6 for estimated cause specific mortality rates for all countries.

The countries with the highest number of 1-59 month deaths in 2024 include Nigeria, the Democratic Republic of Congo, and India, with 0.56, 0.28, and 0.23 million deaths, respectively. In Nigeria, the most common 1-59 month cause of mortality was malaria at 165 000 deaths and 23.4 deaths per 1000 live births, and malaria was also the most common cause of 1-59-month death in the Democratic Republic of Congo (105 000; 22.1 per 1000 live births). In India, the most common cause was tuberculosis (36 000; 1.6 per 1000 live births).

doi: 10.1136/bmj-2025-088686 | *BMJ* 2026;393:e088686 | the bmj

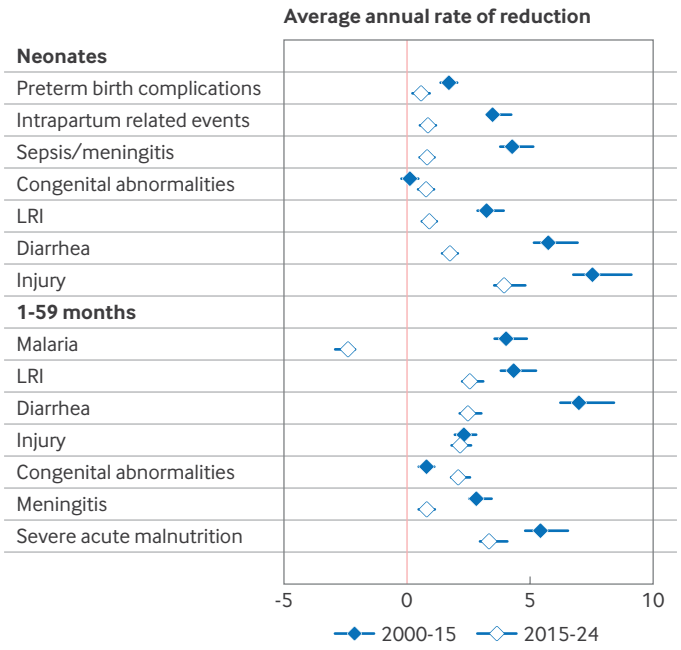

Fig 3 | Estimated average annual rate of reduction (%) for cause specific mortality rates in 2000-15 and 2015-24, for the top seven causes by age group. LRI=lower respiratory infection

Discussion

We have identified the most common causes of neonatal and 1-59 month mortality, identifying the most important causes including preterm birth complications, intrapartum related events, sepsis/meningitis, and lower respiratory infections among neonates and malaria, lower respiratory infections, diarrhea, and injury among children aged 1-59 months. We found that the pace of decline for most causes of under-5 mortality has slowed since 2015, particularly malaria and preterm birth complications.

Strengths and limitations of study

We present a systematic approach to estimating cause of death for children under 5, including a systematic review to identify empirical cause specific mortality information, a statistical approach that includes automated covariate selection with the bayesian LASSO and robust out of sample prediction with out of sample error minimized by cross validation. We have also improved the validity of verbal autopsy with a robust calibration approach that incorporates high quality cause of death determination based on results from the multi-country CHAMPS study. We have given nationally representative country mortality data additional influence in country estimates by using random effects. This systematic incorporation of country specific data allows our estimates to more sensitively reflect country data, which may further motivate countries for more empirical data collection. However, these estimates are no replacement for consistent and timely high quality cause of death information from vital registration systems, which ideally would cover all populations with medically certified reporting.

These estimates also have limitations, particularly around the causes that are difficult to measure with verbal autopsy.[12 28] These estimates may especially underestimate causes that are difficult for lay people to identify. For example, the importance of congenital abnormalities in under 5 mortality may be underestimated, primarily because verbal autopsies are not a sensitive instrument for capturing congenital abnormalities.[29 30] The extrapolation of cause specific mortality data from countries having verbal autopsy studies to countries without verbal autopsy data is also a limitation, even though the resulting estimates represent the most likely scenario given the existing data related to cause specific mortality in high mortality settings.

Comparison with other studies

Compared with other estimates of cause specific mortality for these age groups, our estimates have lower resolution by age and cause and use distinct approaches and source data. The Global Burden of Disease (GBD) project estimates cause specific mortality for children under 5 for a larger number of causes and for finer age resolution. GBD estimates are not modeled simultaneously, but separately by cause, which may affect precision.[31] In addition, to our knowledge, GBD has not publicly released its source data, making comparison with other estimates difficult. GBD estimates higher mortality due to HIV as well as tuberculosis for children under 5 than the estimates presented here. However, owing to differences in both methods and data incorporated and inaccessible details, determining from where these differences arise is not possible.

These estimates differ from previous versions from this research group in several important ways. These include, using the definition provided by the international classification of diseases,[32] the estimated mortality directly caused by severe acute malnutrition. This information is new for many countries and will make an important contribution to health system planning. Under 5 mortality due to HIV in countries with generalized HIV epidemics is higher than in previous estimates, especially in Namibia, Mozambique, and Botswana. These estimates reflect updated country specific surveillance data including lower coverage among pregnant women of antiretrovirals to prevent vertical transmission to their newborns.[27] These estimates were also developed assuming a higher chance of vertical transmission before retroviral therapy than previously.[33] The sepsis and meningitis specific mortality is also higher among neonates than in previous estimates. This difference is the result of both new input data and the statistical adjustment for the misclassification of cause specific mortality by verbal autopsy, resulting in more deaths attributed to sepsis/meningitis.

Differences in estimates from previous versions also reflect new nationally representative verbal autopsies (five countries), as well as new vital registration (255 country years). As described above, nationally representative verbal autopsy studies have additional

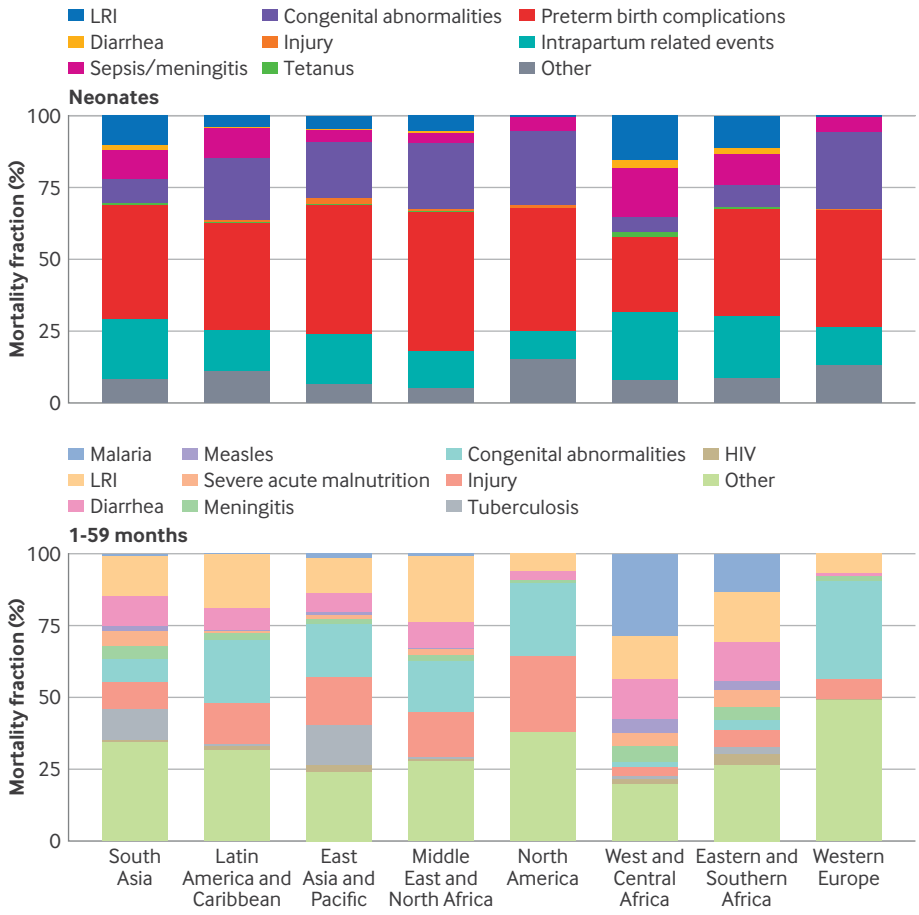

Fig 4 | Percentage of neonatal and 1-59 month mortality in 2024 by cause and region. LRI=lower respiratory infection

influence in a country's estimated cause distribution through hierarchical random effects, so countries with nationally representative data are more likely to have significantly updated cause of death estimates (see supplementary material S7).

Policy implications

These estimates have implications for public health programs, particularly at the country level. These estimates are incorporated into the Lives Saved Tool, which includes current information about health interventions for specific causes of mortality and morbidity and is publicly available.[34] Many low cost interventions with known effectiveness in low and middle income countries are available to reduce neonatal and under 5 mortality.

The pace of decline for all cause and cause specific child mortality has slowed in the sustainable development goal era since 2015 compared with the millennium development goal era of 2000-15. We speculate about possible reasons behind such deceleration and organize them into distal socioeconomic and demographic reasons versus proximate reasons of public health investment and interventions.[35] For the distal reasons, compared with 2000-15, more countries have been affected by conflict since 2015, and more children and women have been displaced.[36-39] Economic growth in low and middle income countries enabled support for child survival programs in the millennium development goal era, but growth has slowed since 2015 along with increased government debt.[40 41] Demographically, the number of deaths due to, for example, malaria has been gradually increasing in sub-Saharan Africa even though the risk (represented by probability of dying from malaria) has plateaued, and this is partially due to an increasing number of live births in the region as a result of population momentum.[42]

For proximate reasons of public health investment and interventions, external financial aid for maternal and child health increased greatly in the millennium development goal era but plateaued from 2016 to 2024 except for aid related to covid-19.[38] Global priority for maternal and child health has stagnated since 2016, with the sustainable development goals focusing on a broader set of health targets compared with the maternal and child survival focused millennium development goals.[38] Severe food insecurity has increased in low and middle income countries, which could have led to slower progress in mortality reduction.[38] To further improve neonatal survival, additional inpatient care for small and sick newborns, tackling prematurity, intrapartum complications, jaundice, infections, and congenital abnormalities, needs to be scaled up.[43]

doi: 10.1136/bmj-2025-088686 | *BMJ* 2026;393:e088686 | the bmj

These interventions are not only financially more costly to adopt and scale up but also require highly functioning health system capacity to sustain operation. As a result, scaling up these interventions has been slower than for interventions scaled up in 2000-15. Coverage of key maternal and child health services had substantial increases in the millennium development goal era but has been facing slower increases since 2015.[38] This may be expected in countries that have achieved high coverage, but the slowdown was worse in low income countries where coverage of a set of key maternal and child interventions plateaued at about 50%.[38] In the millennium development goal era, declines in deaths due to diarrhea, pneumonia, and malaria were major drivers of the reduction in the 1-59 month mortality, largely owing to increased coverage of prioritized interventions such as oral rehydration salts, care seeking for respiratory infections, and insecticide treated bed nets for children in sub-Saharan Africa. The coverage of these interventions has changed little in the past 10 years. Taken together, these slower changes in intervention coverage likely contributed to the slower mortality reductions from diarrhea and pneumonia or plateauing mortality from malaria in the past 10 years compared with the millennium development goal era.[38]

Future research needs

Future research is urgently needed to determine how best to inform health systems in low resource settings. The verbal autopsy approach is evolving in the face of computational advances,[44] which will likely have implications for downstream applications such as estimation of cause specific mortality in low resource areas. Beyond methods related to verbal autopsy, research is needed on how to improve mortality surveillance more broadly. This research agenda includes how to improve sample registration systems in areas with nascent mortality surveillance, how to expand vital registration to low resource settings, and how to digitize mortality surveillance to expedite reporting and facilitate global coordination. Ideally mortality information would come from high quality national health information systems permitting informed decisions for sub-national population levels.[45] Improved quality data on causes of newborn and child mortality are needed to inform national health policies and guide programs to improve survival of these vulnerable populations.

Conclusions

With the recent slowed pace of decline in under 5 mortality for most primary causes of death, many high mortality countries are at risk of missing the sustainable development goal targets of ≤12 neonatal deaths and ≤25 under 5 deaths per 1000 live births without acceleration. The estimates presented here can be used to guide countries and the international health community to select the best interventions so that the reduction in under 5 mortality can be accelerated to meet the sustainable development goals by 2030.

AUTHOR AFFILIATIONS

[1]Department of International Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA

[2]Universidad de Alcalá, Madrid, Spain

[3]Department of Biostatistics, Johns Hopkins Bloomberg School of Public Health, Baltimore USA

[4]Department of Economic, Financial and Actuarial Mathematics, University of Barcelona, Barcelona, Spain

[5]Department of Statistics, Department of Sociology, University of Washington, Seattle, WA, USA

[6]UNICEF Office of Strategy and Evidence – Innocenti, New York, New York, USA

[7]Department of Maternal, Newborn, Child and Adolescent Health, World Health Organization, Geneva, Switzerland

[8]Department of Population, Family, and Reproductive Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA

Contributors: REB and LL conceived of the study and guided the analysis, AW did the systematic review, and SP and AD calibrated the causes of deaths from studies using verbal autopsy. JP, DPM, HES, FV, and THM did the statistical analysis. DY and KLS worked with countries to interpret their estimates and incorporate feedback. JP wrote the first draft, and all authors contributed to subsequent revisions of the manuscript. JP is the guarantor. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Funding: This research was generously supported by the Gates Foundation (INV-038624). SP and AD were also supported by Gates Foundation investment INV-070577, and SP was additionally supported by the Eunice Kennedy Shriver National Institute of Child Health K99 NIH Pathway to Independence Award 1K99HD114884-01A1. The funder had no role in the conduct or the decision to publish the results of this systematic review.

Competing interests: All authors have completed the ICMJE uniform disclosure form at https://www.icmje.org/disclosure-of-interest/ and declare: no support from any organization for the submitted work; no financial relationships with any organizations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: Not needed.

Data sharing: The source code, primary inputs, and cause of death data collected and estimated are publicly available for research purposes on a GitHub repository at https://github.com/JHU-CACODE/BMJ2026-MortUnder5. All the estimates on causes of death under 20 years of age produced by the CA CODE group are publicly available at https://childmortality.org/.

Transparency: The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: As stated above, estimates presented here have been reviewed by representatives for all countries. In addition, estimates have also been disseminated as part of the 2025 UN IGME report.[2]

Provenance and peer review: Not commissioned; externally peer reviewed.

This article is part of a collection proposed by UNICEF, WHO, and Johns Hopkins University. The three organizations provided funding for the collection. Johns Hopkins University funded the open access fees for this article. *The BMJ* peer reviewed, edited, and decided to publish this article. Elizabeth Loder, Navjoyt Ladher, and Paul Simpson were the lead editors for *The BMJ*.

1 Sharrow D, Hug L, Lin Y, Fell GW, You D. Global, regional, and national levels and trends in under 5, infant, and neonatal mortality during 1990-2024 with scenario based projections to 2030: modelling study. *BMJ* 2026;393:e088684.

2 United Nations Inter-agency Group for Child Mortality Estimation (UN IGME). Levels & Trends in Child Mortality: Report 2025. Estimates developed by the United Nations Inter-agency Group for Child Mortality Estimation. 2026. https://data.unicef.org/resources/levels-and-trends-in-child-mortality-2025/#main
3 United Nations. The Millennium Development Goals report 2015. 2015. https://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf
4 UN General Assembly. Transforming our world: the 2030 Agenda for Sustainable Development. 2015. https://docs.un.org/en/A/RES/70/1
5 Black RE, Cousens S, Johnson HL, et al, Child Health Epidemiology Reference Group of WHO and UNICEF. Global, regional, and national causes of child mortality in 2008: a systematic analysis. *Lancet* 2010;375:1969-87. doi:10.1016/S0140-6736(10)60549-1
6 Villavicencio F, Perin J, Eilerts-Spinelli H, et al. Global, regional, and national causes of death in children and adolescents younger than 20 years: an open data portal with estimates for 2000-21. *Lancet Glob Health* 2024;12:e16-7. doi:10.1016/S2214-109X(23)00496-5
7 Paganelli CR, Kassebaum N, Strong K, et al. Guidance for systematic integration of undernutrition in attributing cause of death in children. *Clin Infect Dis* 2021;73(Suppl_5):S374-81. doi:10.1093/cid/ciab851
8 Johnson HL, Liu L, Fischer-Walker C, Black RE. Estimating the distribution of causes of death among children age 1-59 months in high-mortality countries with incomplete death certification. *Int J Epidemiol* 2010;39:1103-14. doi:10.1093/ije/dyq074
9 Mulick AR, Oza S, Prieto-Merino D, Villavicencio F, Cousens S, Perin J. A Bayesian hierarchical model with integrated covariate selection and misclassification matrices to estimate neonatal and child causes of death. *J R Stat Soc Ser A Stat Soc* 2022;185:2097-120doi:10.1111/rssa.12853.
10 GBD 2023 Causes of Death Collaborators. Global burden of 292 causes of death in 204 countries and territories and 660 subnational locations, 1990-2023: a systematic analysis for the Global Burden of Disease Study 2023. *Lancet* 2025;406:1811-72. doi:10.1016/S0140-6736(25)01917-8
11 Kalter HD, Gray RH, Black RE, Gultiano SA. Validation of postmortem interviews to ascertain selected causes of death in children. *Int J Epidemiol* 1990;19:380-6. doi:10.1093/ije/19.2.380
12 Kalter HD, Perin J, Black RE. Validating hierarchical verbal autopsy expert algorithms in a large data set with known causes of death. *J Glob Health* 2016;6:010601. doi:10.7189/jogh.06.010601
13 Mahesh BPK, Hart JD, Acharya A, et al. Validation studies of verbal autopsy methods: a systematic review. *BMC Public Health* 2022;22:2215. doi:10.1186/s12889-022-14628-1
14 Salzberg NT, Sivalogan K, Bassat Q, et al, Child Health and Mortality Prevention Surveillance (CHAMPS) Methods Consortium. Mortality surveillance methods to identify and characterize deaths in child health and mortality prevention surveillance network sites. *Clin Infect Dis* 2019;69(Suppl 4):S262-73. doi:10.1093/cid/ciz599
15 Pramanik S, Wilson E, Kalter HD, et al. Country-specific estimates of misclassification rates of computer-coded verbal autopsy algorithms[A: Updated from preprint to full publication. OK?]. *BMJ Glob Health* 2026;11:e021747. doi:10.1136/bmjgh-2025-021747
16 Pramanik S, Zeger S, Blau D, Datta A. Modeling structure and country-specific heterogeneity in misclassification matrices of verbal autopsy-based cause of death classifiers. *Ann Appl Stat* 2025;19:1214-39doi:10.1214/24-AOAS2006.
17 World Health Organization. WHO Mortality Database. Geneva: World Health Organization. 2025. https://www.who.int/data/data-collection-tools/who-mortality-database
18 Liu L, Johnson HL, Cousens S, et al, Child Health Epidemiology Reference Group of WHO and UNICEF. Global, regional, and national causes of child mortality: an updated systematic analysis for 2010 with time trends since 2000. *Lancet* 2012;379:2151-61. doi:10.1016/S0140-6736(12)60560-1
19 Perin J, Mulick A, Yeung D, et al. Global, regional, and national causes of under-5 mortality in 2000-19: an updated systematic analysis with implications for the Sustainable Development Goals. *Lancet Child Adolesc Health* 2022;6:106-15. doi:10.1016/S2352-4642(21)00311-4
20 Liu L, Oza S, Hogan D, et al. Global, regional, and national causes of child mortality in 2000-13, with projections to inform post-2015 priorities: an updated systematic analysis. *Lancet* 2015;385:430-40. doi:10.1016/S0140-6736(14)61698-6
21 Bassat Q, Blau DM, Ogbuanu IU, et al, Child Health and Mortality Prevention Surveillance (CHAMPS) Network. Causes of Death Among Infants and Children in the Child Health and Mortality Prevention Surveillance (CHAMPS) Network. *JAMA Netw Open* 2023;6:e2322494. doi:10.1001/jamanetworkopen.2023.22494
22 Wahi A, Perin J, Eilerts-Spinelli H, et al. Consolidating Cause-of-Death Evidence for Children and Adolescents through an Updated Systematic Review and Known Investigator-Tracing. *SSRN* 2026doi:10.2139/ssrn.6339658.
23 Oza S, Cousens SN, Lawn JE. Estimation of daily risk of neonatal death, including the day of birth, in 186 countries in 2013: a vital-registration and modelling-based study. *Lancet Glob Health* 2014;2:e635-44. doi:10.1016/S2214-109X(14)70309-2
24 Park T, Casella G. The Bayesian Lasso. *J Am Stat Assoc* 2008;103:681-6doi:10.1198/016214508000000337.
25 He C, Liu L, Chu Y, et al. National and subnational all-cause and cause-specific child mortality in China, 1996-2015: a systematic analysis with implications for the Sustainable Development Goals. *Lancet Glob Health* 2017;5:e186-97. doi:10.1016/S2214-109X(16)30334-5
26 de Onis M, WHO Multicentre Growth Reference Study Group. Assessment of differences in linear growth among populations in the WHO Multicentre Growth Reference Study. *Acta Paediatr Suppl* 2006;450:56-65.
27 Black RE, Allen LH, Bhutta ZA, et al, Maternal and Child Undernutrition Study Group. Maternal and child undernutrition: global and regional exposures and health consequences. *Lancet* 2008;371:243-60. doi:10.1016/S0140-6736(07)61690-0
28 Murray CJ, Lozano R, Flaxman AD, et al. Using verbal autopsy to measure causes of death: the comparative performance of existing methods. *BMC Med* 2014;12:5. doi:10.1186/1741-7015-12-5
29 Modell B, Berry RJ, Boyle CA, et al. Global regional and national causes of child mortality. *Lancet* 2012;380:1556, author reply 1556-7. doi:10.1016/S0140-6736(12)61878-9
30 Christianson A, Howson CP, Modell B. March of Dimes Global Report on Birth Defects: The Hidden Toll of Dying and Disabled Children. 2006. https://www.prevencioncongenitas.org/wp-content/uploads/2017/02/Global-report-on-birth-defects-The-hidden-toll-of-dying-and-disabled-children-Full-report.pdf
31 Li L, Rysavy MA, Bobashev G, Das A. Comparing methods for risk prediction of multicategory outcomes: dichotomized logistic regression vs. multinomial logit regression. *BMC Med Res Methodol* 2024;24:261. doi:10.1186/s12874-024-02389-x
32 World Health Organization. International Classification of Diseases 11th Revision (ICD-11). https://icd.who.int/
33 Walters MK, Bulterys MA, Barry M, et al. Probability of vertical HIV transmission: a systematic review and meta-regression. *Lancet HIV* 2025;12:e638-48. doi:10.1016/S2352-3018(25)00132-8
34 Walker N, Tam Y, Friberg IK. Overview of the lives saved tool (LiST). *BMC Public Health* 2013;13(Suppl 3):S1. doi:10.1186/1471-2458-13-S3-S1
35 Mosley WH, Chen LC. An analytical framework for the study of child survival in developing countries. 1984. *Bull World Health Organ* 2003;81:140-5.
36 Uppsala Conflict Data Program. https://ucdp.uu.se/
37 Rustad SA. Conflict trends: a global overview, 1946-2024. 2025. https://www.prio.org/publications/14453
38 Amouzou A, Barros AJD, Requejo J, et al. The 2025 report of the Lancet Countdown to 2030 for women's, children's, and adolescents' health: tracking progress on health and nutrition. *Lancet* 2025;405:1505-54. doi:10.1016/S0140-6736(25)00151-5
39 Bendavid E, Boerma T, Akseer N, et al, BRANCH Consortium Steering Committee. The effects of armed conflict on the health of women and children. *Lancet* 2021;397:522-32. doi:10.1016/S0140-6736(21)00131-8
40 World Bank Group. GDP per capita, PPP (constant 2021 international $). https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD
41 Kurowski C, Evans DB, Tandon A, et al. From double shock to double recovery: implications and options for health financing in the time of COVID-19. 2021. https://openknowledge.worldbank.org/entities/publication/d964eff2-d6b8-5aea-96d5-c0a628a13706
42 United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects 2024. https://population.un.org/wpp/
43 World Health Organization. Standards for improving the quality of care for small and sick newborns in health facilities. 2020. https://www.who.int/publications/i/item/9789240010765
44 Blanco A, Perez A, Casillas A, Cobos D. Extracting cause of death from verbal autopsy with deep learning interpretable methods. *IEEE J Biomed Health Inform* 2021;25:1315-25. doi:10.1109/JBHI.2020.3005769
45 Phillips DE, AbouZahr C, Lopez AD, et al. Are well functioning civil registration and vital statistics systems associated with better health outcomes?*Lancet* 2015;386:1386-94. doi:10.1016/S0140-6736(15)60172-6

Web appendixes: Supplementary materials S1–S7